

A techno-economic evaluation of a waste-to-energy grate incineration power plant for a small South African city

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It all starts here [™]



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ABSTRACT

South Africa is currently facing power shortages due to an increased demand, a failure to invest in additional capacity and insufficient maintenance. Likewise, over the years, municipal solid waste (MSW) generation and management problems have exhibited an upward trend. Furthermore, a significant amount of energy is wasted in the country's landfill and illegal dumping is rampant.

Global trends show that there is a shift towards MSW management strategies that support the goal of sustainable development. Concurrently waste-to-energy (WtE) thermal technologies have the potential to achieve sustainable waste management goals.

South African cities are no exception to power shortages, high unemployment rates and MSW generation and management problems, with landfill and illegal dumping dominating waste management strategies. WtE thermal technologies can be used to harness energy wasted in South African cities' landfill, simultaneously creating employment.

The purpose of this study is to perform a techno-economic evaluation of a WtE grate incineration power plant for a small South African city in the North-West Province, Potchefstroom.

Literature on WtE thermal technologies were surveyed and a technological and performance qualitative assessment was performed. This was followed by quantitative evaluation using an analytical hierarchy process (AHP). The results obtained proved that grate incineration is more economically viable than many other WtE thermal technologies.

Factors that affect WtE grate incineration power plants in South Africa are examined using strengths, weaknesses, opportunities and threats (SWOT) analysis. Tlokwe municipality (Potchefstroom) was used as a case study; its MSW generation and management data were gathered and analyzed. The drivers of WtE grate incineration in South Africa include an average of 90% dominance of landfill over other MSW management strategies, average MSW generation growth rate of 3% per annum, national power shortages, the intermittent nature of solar and wind energy and non-energy recovery methods used in treating health care risk waste (HCRW). However, lack of landfill diversion measures, high capital investment and the local culture of non-payment for services are obstacles in implementing WtE grate incineration technology.

A financial analysis model with four different scenarios was formulated with the objective of determining the financial feasibility of a WtE grate incineration power plant for a small South African city. Net present value and internal rate of return were used as financial indicators.

Sensitivity analysis was performed on four parameters, namely electricity price, power generation efficiency, MSW and medical waste gate fees.

Financial and sensitivity analyses show that a scenario characterized by MSW and medical waste as feedstock, owned by an independent power producer yielded the best financial performance results. This scenario show feasible and most attractive investment option with capital cost of R734.40 million and simple payback period (SPB), return on investment (ROI), net present value (NPV) and internal rate of return (IRR) of 10 years, 10%, R681.77 million and 21.21% respectively.

The scenario in which MSW is feedstock and owned by an investment company yield the least favorable financial performance results.

The conclusion reached is that the price of electricity and medical waste gate fees are the major factors affecting WtE grate incineration power plant financial viability. Investment in a WtE grate incineration power plant is financially feasible on condition that medical waste is diverted to the plant and a waste processing annual throughput of more than 200 000 tonnes of MSW per annum is achieved. The investment became more attractive through accessibility of capital investment subsidy.

A results verification process was performed by means of sensitivity analysis, surveys and consultation with experts in the WtE grate incineration technology industry, as well as publication of the results in the peer-reviewed conference proceedings of the Southern African Universities Power Engineering Conference (SAUPEC) 2015 and the Industrial and Commercial Use of Energy (ICUE) 2015.

Keywords: Grate incineration, Medical waste, Municipal solid waste (MSW), Techno-economic study, Waste-to-energy (WtE) power plant, Economic feasibility, Potchefstroom

OPSOMMING

Suid-Afrika ondervind tans kragtekorte as gevolg van 'n toename in aanvraag, versuim om in bykomende kapasiteit te belê en beperkte onderhoud. Terselfdertyd het probleme met munisipale vaste afval (MVA) en die bestuur daarvan oor die jare toegeneem. Verder word beduidende hoeveelhede energie in die land se stortingsterreine vermors en onwettige storting geskied ongehinderd.

Die internasionale tendens is 'n verskuiwing na bestuurstrategieë vir MVA wat volhoubare ontwikkeling ten doel het. Voorts toon afval-na-energie- (AnE) termiese tegnologie die potensiaal om volhoubare doelwitte vir afvalbestuur te bereik.

Suid-Afrikaanse stede is nie vrygestel van kragtekorte, hoë werkloosheid en MVA-bestuurs probleme nie, terwyl terreinopvulling en onwettige storting afvalbestuurstrategieë oorheers. AnE-termiese tegnologie kan gebruik word om energie wat in Suid-Afrikaanse klein stede se stortingsterreine vermors word, te gebruik en tegelykertyd werk te skep.

Die doel van hierdie studie is om 'n tegnoëkonomiese evaluering van 'n AnE-roosterverbrandingkragstasie vir 'n klein Suid-Afrikaanse stad in die Noordwes-provinsie te doen.

Om dit te bereik, is literatuur oor AnE-termiese tegnologie bestudeer en 'n tegnologiese en werkverrigting-kwalitatiewe assessering uitgevoer. Dit is gevolg deur 'n kwantitatiewe evaluering deur van 'n analitiese hiërargieproses (AHP) gebruik te maak. Die resultate wat verkry is, bewys dat roosterverbranding verkieslik is bo ander AnE-termiese tegnologieë.

Faktore wat AnE-roosterverbrandingkragstasies in Suid-Afrika raak, word ondersoek met behulp van 'n SWOT-analise (sterk punte, swakhede, geleenthede en bedreigings). Tlokwe-munisipaliteit is gebruik as 'n gevallestudie; data oor MVA en die bestuur daarvan is versamel en ontleed. 'n Gemiddeld van 90% oorheersing van terreinopvulling oor ander MVA-bestuurstrategieë, 'n gemiddelde groeikoers van 3% per jaar in die produksie van MVA, nasionale kragtekorte, die onderbroke aard van son- en wind-energie en metodes wat nie energie herwin nie, wat gebruik word in die behandeling van gesondheidsorg-afval, is sommige van die drywers vir roosterverbranding in Suid-Afrika. 'n Gebrek aan maatreëls om die gebruik van stortingsterreine te verminder, die hoë kapitale uitleg wat betrokke is en die plaaslike kultuur van weiering om vir dienste te betaal, is struikelblokke in die weg van implementering van AnE-roosterverbrandingtegnologie.

'n Finansiële ontledingmodel met vier verskillende scenario's is geformuleer met die doel om die finansiële lewensvatbaarheid van 'n AnE-roosterverbrandingkragstasie vir 'n klein Suid-

Afrikaanse stad te bepaal. Netto teenwoordige waarde en interne opbrengskoers is gebruik as finansiële aanwysers. Sensitiwiteitsanalise is uitgevoer op vier parameters, naamlik elektrisiteitsprys, doeltreffendheid van kragopwekking, MVA en hekgeld vir mediese afval.

Finansiële en sensitiwiteitsanalises toon dat 'n scenario waarin MVA en mediese afval die roumateriaal is en besit word deur onafhanklike kragprodusente die beste finansiële prestasie lewer. Hierdie scenario is wesenlik en ook en die mees gunstige beleggingsopsie teen 'n kapitaalkoste van R734.40 miljoen en 'n vereenvoudigde terugbetaal periode, opbrengs op belegging, 'n netto teenwoordige waarde en 'n interne opbrengskoers van 10 jaar, 10%, R681.77 miljoen en 21.21% respektiewelik.

Die gevolgtrekking wat bereik is, is dat die prys van elektrisiteit en hekgeld vir mediese afval die belangrikste faktore is wat AnE roosterverbrandingkragstasies se finansiële wesenlikheid beïnvloed. Belegging in 'n AnE-roosterverbrandingkragstasie is finansiële lewensvatbaar op voorwaarde dat mediese afval na die aanleg gestuur word en dat die jaarlikse deurset van afvalprosessering meer is as 200 000 ton MVA. Die belegging word self meer gunstig deur die toeganklikheid van kapitaalbeleggingssubsidie.

Die resultate is geverifieer aan die hand van sensitiwiteitsanalise, opnames en konsultasie met kundiges in die AnE-roosterverbrandingstechnologie-industrie, sowel as die publikasie van die resultate in die portuurbeoordeelde konferensieverrigtinge van die Suider-Afrikaanse Universiteite se 'Power Engineering Conference' (SAUPEC) 2015 en die Industriële en Kommersiële Gebruik van Energie (ICUE) 2015.

Slutelwoorde: Roosterverbranding, Mediese afval, Munisipale vaste afval (MVA), Klein Suid-Afrikaanse stad, Tegnoëkonomiese analise, Afval-na-energiekragstasie, Ekonomiese lewensvatbaarheid, Potchefstroom

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LIST OF ABBREVIATIONS

Abbreviation	Term
AHP	Analytical hierarchy process
APC	Air pollution control
CI	Consistency index
CR	Consistency ratio
DEA	Department of Environmental Affairs
DEAT	Department of Environmental Affairs and Tourism
DNT	Department of National Treasury
DoE	Department of Energy
EPRI	Electric Power Research Institute
ESP	Electrostatic precipitator
EU	European Union
GJ	gigajoules
GWh	gigawatt hour
HCl	Hydrochloric acid
HCRW	Health care risk waste
HF	Hydrogen fluoride
ICRC	International Committee of the Red Cross
ICUE	Industrial and Commercial Use of Energy
IEA	International Energy Agency
IPP	Independent power producer
IRR	Internal rate of return
LHV	Lower heating value
kg	kilogram
kWh	kilowatt hour
MJ	mega joule
MMSW	Mixed municipal solid waste
Mol	Mole
MSW	Municipal solid waste
MW	megawatt
MWh	megawatt hour
NPV	Net present value
NSCR	Non-selective catalytic removal
R	Rand
3R	Reduce, re-use and recycle

REDISA	Recycling and economic development initiative of South Africa
REIPPP	Renewable energy independent power production procurement program
RI	Random consistency index
ROI	Return on investment
SANS	South African National Standards
SAUPEC	Southern African Universities Power Engineering Conference
SCR	Selective catalytic removal
SO ₂	Sulfur dioxide
SPB	Simple payback period
SWOT	Strength, weakness, opportunities and treats
WEC	World Energy Council
WP	Waste processed
WT	Waste vehicle tyre
WtE	Waste-to-energy

CHAPTER 1

INTRODUCTION

1.1 Introduction

South Africa is currently facing power shortages due to increase in demand, failure to invest in additional capacity and limited maintenance. Simultaneously, over the years, municipal solid waste (MSW) generation and management problems have escalated (DEA, 2012:1; Godfrey *et al.*, 2014:1) in response to constant population growth and expansion of urbanization.

Economic growth, industrialization, urbanization and rapid population growth are a combination of factors bound to increase both MSW production and electric power shortages in many countries (Kathiravale & Yunus, 2008:359; Sethi *et al.*, 2012:97).

In the last part of 2007 South Africa started experiencing widespread power shortages as supply fell behind demand, threatening to destabilize the national grid (Calldo, 2008:1). Electric power demand in South Africa is estimated to be increasing by 4% per year, which will result in demand for an additional 40 GW by 2025 (DoE, 2011:1).

A significant amount of energy is wasted in South African landfill, as over 90% of MSW is disposed of in landfill and dumped illegally without energy recovery (Godfrey *et al.*, 2014:1). Landfill poses a number of environmental problems, such as greenhouse gases (methane and carbon dioxide) emissions, leakages into groundwater and inefficient space utilization (Meisen & Morgan, 2010:1).

The global trend is that the focus in waste management strategies has shifted to harmonize with the goal of sustainable development through electrical power generation and minimization of the adverse effects of landfill (IEA Bioenergy, 2010:5; Sethi *et al.*, 2012:97). MSW can now be viewed as a useful resource and can be used as an alternative renewable energy source.

Waste-to-energy (WtE) thermal technologies have the potential to meet the goal of sustainable waste management (Brunner & Rechberger, 2014:3). Developed countries that have implemented WtE thermal technologies have boosted their recycling rates, minimized the adverse impacts of landfill and increased the renewable energy generation level (Eurostat, 2009:433; IEA Bioenergy, 2010:5).

1.2 Problem statement

South African cities are faced with power shortages, high unemployment rates and MSW generation and management problems, with landfill and illegal dumping dominating waste management strategies. WtE thermal technologies can be used to harness energy wasted in the

landfill of South African cities, at the same time creating employment. Uncertainty about the techno-economic feasibility of the technologies is as an obstacle to the implementation of WtE thermal technologies in South African cities.

1.3 Research aim

The aim of this research project is to perform a techno-economic evaluation of a WtE grate incineration power plant for a small South African city using the Tlokwe municipality (Potchefstroom) as a case study.

1.4 Research objectives

The objectives of this research project are to:

- a. identify and evaluate possible WtE thermal technologies that can be implemented in South African cities;
- b. identify and organize factors that have an impact on WtE grate incineration power plants in South Africa, using strengths, weakness, opportunities and threats (SWOT) analysis;
- c. investigate MSW generation trends and management strategies for a small South African city in the North-West Province, Potchefstroom;
- d. develop a WtE grate incineration power plant conceptual model for the city of Potchefstroom; and
- e. perform financial evaluation and sensitivity analyses of a WtE grate incineration power plant for the small city.

1.5 Research background

The global energy scenario is that the energy crisis is on the rise. According to the Infrastructure Consortium for Africa, the power crisis in Southern Africa has been deepening over the past years. This is a result of an increase in population and rapid urbanization in the region, resulting in a significant increase in energy demand and consumption. Rapid depletion of non-renewable resources has been noticed. Failure to invest in additional capacity and limited maintenance contributed to the current electrical energy crisis in the region.

Power generation in South Africa is dominated by coal plants, which are owned and operated by Eskom. About 86% of South Africa's electricity is generated from coal fuel power plants (Singh, 2011:1). The energy mix in South Africa is currently dominated by the use of fossil fuels, while the contribution of renewable energy sources is insignificant (Singh, 2011:1).

In a bid to ensure energy security and improve electric power supply efficiency, the South African cabinet decided that Eskom should share generation capacity of electricity with independent power producers (IPP). Eskom's new power-generation capacity is estimated to be 70%, while IPP will generate approximately 30% (Eberhard, 2014:1). To meet this goal, research and implementation of alternative power-generation technologies are urgent need in South Africa.

The Department of Energy's (DoE) strategic plan is to transform the energy sector in South Africa by promoting a diverse energy mix and providing quality and affordable energy (DoE, 2011:1). The aim is to minimize the contribution of coal-powered plants to 46% and allow renewable energy to contribute about 26% of the national energy mix by 2030 (Singh, 2011:1). The move by the DoE requires thoughtful consideration of research into and implementation of alternative power-generation technologies such as WtE thermal technologies.

In South Africa, municipalities and their customers are the major consumers of electricity; their consumption percentage ranges roughly from 40% to 42% (Calldo, 2008:1). WtE thermal technologies can serve as alternative energy sources for municipalities.

Using landfill to manage MSW is regarded as a missed opportunity (Yassin *et al.*, 2009:315). Globally MSW generation has been increasing owing to urbanization, an increase in population and economic development (Kathiravale & Yunus, 2008:359; Sethi *et al.*, 2012:97). Landfill is the traditionally used MSW management strategy, though it poses significant environmental problems.

European countries such as Switzerland, Luxembourg, Denmark, the Netherlands, Sweden, Belgium, Germany and Austria have been working towards eradicating MSW disposal by landfill in an attempt to achieve sustainable development (Eurostat, 2009:433). WtE thermal technologies have become a popular waste management strategy in European countries.

Reduce, reuse and recycle (3R) are preferred waste management options though they have failed to address the landfill problems worldwide. Large amounts of combustible residual MSW is sent to landfill sites without being recovered. Combining 3R with WtE thermal technologies can significantly promote the goal of eradicating landfill.

3R as waste management strategies are compatible with WtE thermal technologies. European countries, such as Denmark, Sweden and the Netherlands, which have utilized WtE, witnessed high recycling ratios, proving the compatibility of WtE with recycling (Eurostat, 2009:433).

WtE thermal technologies play a crucial role in green energy production. The share of energy from waste in the world energy mix is approximated at 0.4% (Massarutto, 2015:45). In 2009, WtE had the capacity to generate 3425 MW and 6280 MW of electricity and heat respectively

(Manders, 2013:1). The contribution of WtE in Europe was estimated at 5822 MW and 9475 MW electricity and heat respectively in 2012 (Stengler, 2012:1).

WtE thermal technologies include grate incineration, fluidized bed, plasma gasification and pyrolysis. Grate incineration, a commercially proven technology, has been in use for more than 130 years. The technology has proven to be dominant among other thermal treatment technologies (Lombardi *et al.*, 2015:26; Martin *et al.*, 2014:147; Stantec Consulting Ltd, 2011:1.1). In Europe, 90% of WtE plants use grate incineration and there are more than 800 WtE plant installations across the world (IEA Bioenergy, 2010:5).

The utilization of WtE thermal technologies in Africa is insignificant, with no grate incineration plants in use. A 50 MW grate incineration power plant pilot project was initiated in Addis Ababa in 2013 (ESI-Africa, 2013).

WtE facilities convert MSW into gaseous, liquid and solid conversion products, simultaneously releasing heat energy, which is recovered through boilers. The recovered heat can be converted into electricity or directly exported to district heating systems (Stantec Consulting Ltd, 2011:1.1).

There are a number of WtE grate incineration technology drivers. Though grate incineration technology has faced attacks from environmentalists in the past years, because of advancement in technology, most WtE incinerator plants are operated with very clean emissions and the process is cleaner than household burning (Meisen & Morgan, 2010:1). WtE grate incineration technology has significantly contributed to diverting waste from landfill.

Grate incineration is capable of processing waste ranging from general to hazardous and infectious waste. The feedstock requires minimum pre-processing, such as removal of recyclables, reusable material and bulky materials (European Commission, 2006:19; IEA Bioenergy, 2010:5; Rand *et al.*, 2000:118). Recent grate incineration boiler designs have been using nickel base alloys. This results in high steam temperatures and pressure, thus power efficiency of more than 30% is achieved (IEA Bioenergy, 2010:5; Lombardi *et al.*, 2015:26).

The unemployment rate in South Africa was estimated at about 25.4% by the fourth quarter of 2014 (Trading Economics, 2015). The unemployment rate in Potchefstroom is estimated at 21.6% (Government, 2013). WtE grate incineration power plants create jobs that range from highly skilled to unskilled jobs. In Europe it is estimated that WtE grate incineration plants provide approximately 56 000 direct and indirect jobs (Stengler, 2012:1).

Modern WtE plants have managed to achieve the goal of sustainable development. Resources such as energy, material and land have been conserved through WtE initiatives. Implementation of WtE has significantly contributed to protection of the environment (Cucchiella *et al.*, 2014:719).

Potchefstroom is not an exception to rapid population growth, resulting in high energy demand, MSW challenges and a high rate of unemployment. The population of Potchefstroom is estimated at 300 000, with 52 537 households. The population growth is estimated at 2.38% per year (Government, 2013).

Felophepa is a state-of-the-art municipal landfill, constructed in 2004 to cater for Potchefstroom MSW management. The landfill is filling up at an unexpected rate in response to an increase in waste production in the city (Botha, 2011). Illegal dumping of waste has also recently occurred in Potchefstroom, indicating increased production of MSW (Boqo, 2012).

The recycling rate in Potchefstroom is approximated at 1.39% of the total waste produced in the city. Landfill is the predominant waste management strategy in the small city of Potchefstroom. Combustible materials are dumped at the landfill and no energy recovery takes place. According to Botha (2011), an average person contributes about 1.37 kg per day or 500 kg of MSW in a year.

1.6 Research methodology

Figure 1.1 outlines the research roadmap followed to achieve the stated objectives in Section 1.5. Technological and performance qualitative evaluation was performed on four WtE thermal technologies, namely grate incineration, fluidized bed, pyrolysis and gasification. Feedstock pre-treatment, the thermal process, energy recovery, air pollution control, residual waste management and the potential revenue stream were the criteria used in the evaluation.

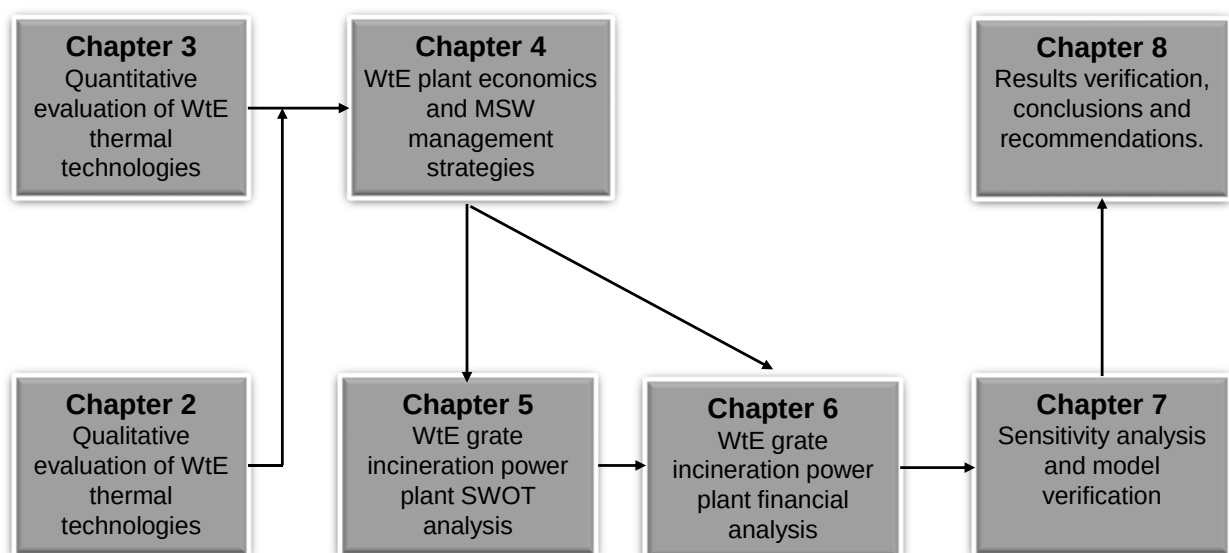


Figure 1.1: Research roadmap

A quantitative evaluation of the four technologies mentioned was carried out using the analytical hierarchy process (AHP). The ranking criteria were formulated and criteria weights were calculated. The purpose of the qualitative and quantitative evaluations was to rank the WtE thermal technologies in order of preference.

An assessment of WtE grate incineration power plant economics was carried out. This was done with the objective of identifying parameters that affect the financial viability of a WtE power plant. Evaluation of waste management strategies was performed to determine the compatibility of WtE grate incineration with other waste management strategies.

Information required to develop the technical and financial model was gathered through interviews and general surveys with the Tlokwe city council waste management department. An established WtE grate incineration power plant in the Netherlands was identified to obtain practical input data. A SWOT analysis for a WtE grate incineration power plant for Potchefstroom, a small city in the North-West Province of South Africa, was carried out to identify issues that affect a WtE grate incineration power plant.

A WtE grate incineration power plant conceptual model was developed for the small city of Potchefstroom. This was followed by the formulation of a financial analysis model with four different scenarios to determine its financial feasibility.

The final stage was to perform a sensitivity analysis on parameters that affect the financial viability of such a WtE power plant. The results of the analysis were used to rank the four scenarios according to performance in terms of net present value (NPV) and internal rate of return (IRR).

The deliverables of this study will be a WtE grate incineration power plant financial model for a small South African city, and recommendations and a conclusion presented in a mini-dissertation. The study contributed two academic papers in the peer-reviewed conference proceedings of Southern African Universities Power Engineering Conference (SAUPEC) 2015 and Industrial and Commercial Use of Energy (ICUE) 2015.

1.7 Scope of the research

The research project aims at performing a techno-economic performance evaluation of a WtE grate incineration power plant for a small South African city, though the results can be implemented in medium to large cities. This mini-dissertation will focus on the technological performance evaluation and comparison of four WtE thermal technologies: grate incineration, fluidized bed incineration, gasification and pyrolysis. Grate incineration is singled out for further investigation. A WtE grate incineration conceptual model for the small city is developed. Financial evaluations and sensitivity analysis for the conceptual model are performed. Sensitivity analysis

is carried out on four parameters that affect the financial viability of a WtE grate incineration power plant, namely electricity price, power generation efficiency, MSW and medical waste gate fees. The final stage is to compile a research conclusion and recommendations. Waste vehicle tyres (WT), carbon tax and carbon credits are discussed and not included in the financial and sensitivity analysis. The study will not embark on a life cycle assessment of WtE grate incineration or the implementation of the research outcome.

1.8 Research outline

The mini-dissertation presents a techno-economic evaluation of a WtE grate incineration power plant for a small South African city in eight chapters. The chapters are summarized as follows:

Chapter 1 presents the overall problem background and problem statement that motivated this research work. The research aim, objectives and methodology followed in this work are outlined in this chapter.

Chapter 2 evaluates four WtE thermal technologies, namely grate incineration, fluidized bed, gasification and pyrolysis. A performance comparison of these four WtE thermal technologies is achieved in this chapter.

Chapter 3 reports on quantitative evaluation of WtE thermal technologies. AHP was used as the evaluation tool. The WtE technologies are ranked, taking into account multiple factors and selection objectives.

Chapter 4 provides a WtE grate incineration power plant economics evaluation. WtE thermal technologies are compared with other waste management strategies in this chapter. Evaluation of medical waste management strategies is included.

Chapter 5 focuses on a WtE grate incineration power plant SWOT analysis. The chapter presents a detailed waste management and generation trends, health care risk waste (HCRW) management, an energy scenario of South Africa and a case study of Tlokwe municipality (Potchefstroom).

Chapter 6 reports on financial analysis methodology and the results of the analysis before discussing financial analysis results.

Chapter 7 outlines the sensitivity analysis methodology and the results. The discussion of the results is incorporated in this chapter.

Chapter 8 gives results verification, conclusions and recommendations for the techno-economic evaluation of a WtE grate incineration power plant for a small South African city.

1.9 Conclusion

Against the background provided in this chapter, the purpose of this mini-dissertation was defined as the performance of a techno-economic evaluation of a WtE grate incineration power plant for a small South African city. The chapter presented the problem background, research problem statement, aim and objectives of the research, the research methodology, the scope and the outline of the mini-dissertation.

The next chapter focuses on a technological and performance evaluation of four proven WtE thermal technologies. The technologies evaluated are grate incineration, fluidized bed incineration, gasification and pyrolysis.

CHAPTER 2

WASTE-TO-ENERGY TECHNOLOGICAL AND PERFORMANCE EVALUATION

2.1 Introduction

The aim of this study is to perform a techno-economic evaluation of a WtE grate incineration power plant for a small South African city. The purpose of this chapter is to perform technological and performance qualitative evaluation of WtE thermal technologies. Four WtE thermal technologies are evaluated, namely grate incineration, fluidized bed, gasification and pyrolysis. Figure 2.1 shows the research roadmap's current position.

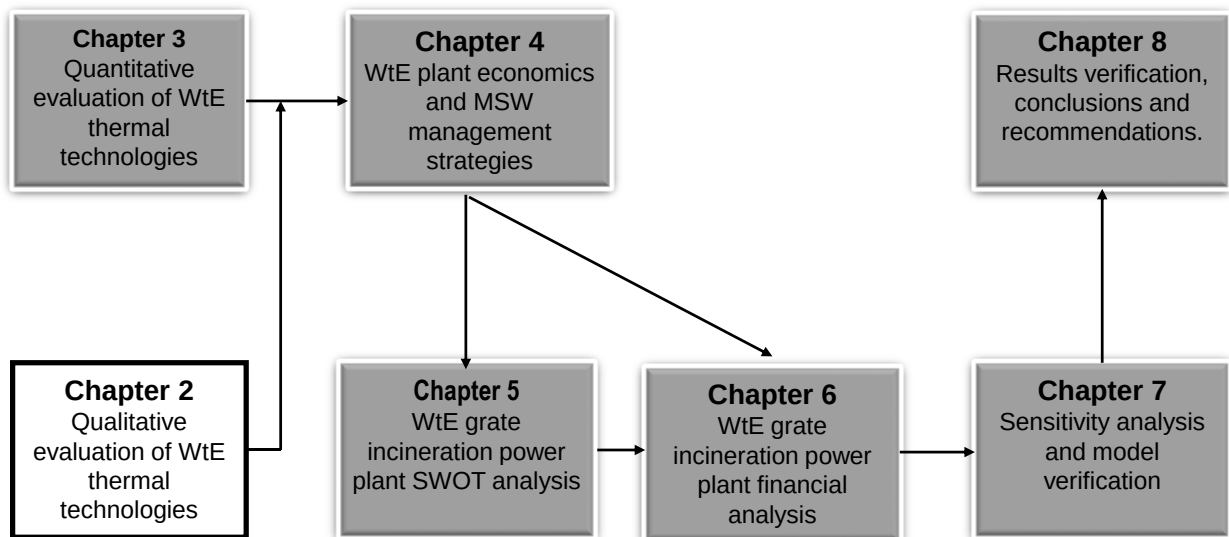


Figure 2.1: Research roadmap position 2

Waste management strategies that are environmentally and economically sound contribute to sustainable development (Cucchiella *et al.*, 2014:719; IEA Bioenergy, 2010:5). According to Stengler (2012:1), WtE technologies contribute significantly to clean energy production and sustainable waste management systems.

WtE grate incineration, in developed countries, has contributed to the goal of economic, social and environmentally sustainable development (Manders, 2008:1; Stengler, 2012:1). WtE thermal technologies are associated with high capital cost, which is a major implementation hindrance. In this chapter WtE grate incineration technology is evaluated against other thermal technologies.

The chapter presents an overview on WtE in section 2.2. This is followed by a technological (Section 2.3) and performance (section 2.4) evaluation of WtE thermal technologies. A discussion of qualitative evaluation results is presented in section 2.5. The conclusion of the chapter is given in Section 2.6.

2.2 Waste-to-energy overview

WtE technologies are waste treatment processes that generate energy in the form of electricity, heat and synthetic fuels from a waste source. These technologies can be classified into two categories, namely biological technologies and thermal technologies (WEC, 2013:7b.1). Figure 2.2 shows the categories of WtE technologies, according to waste treatment processes.

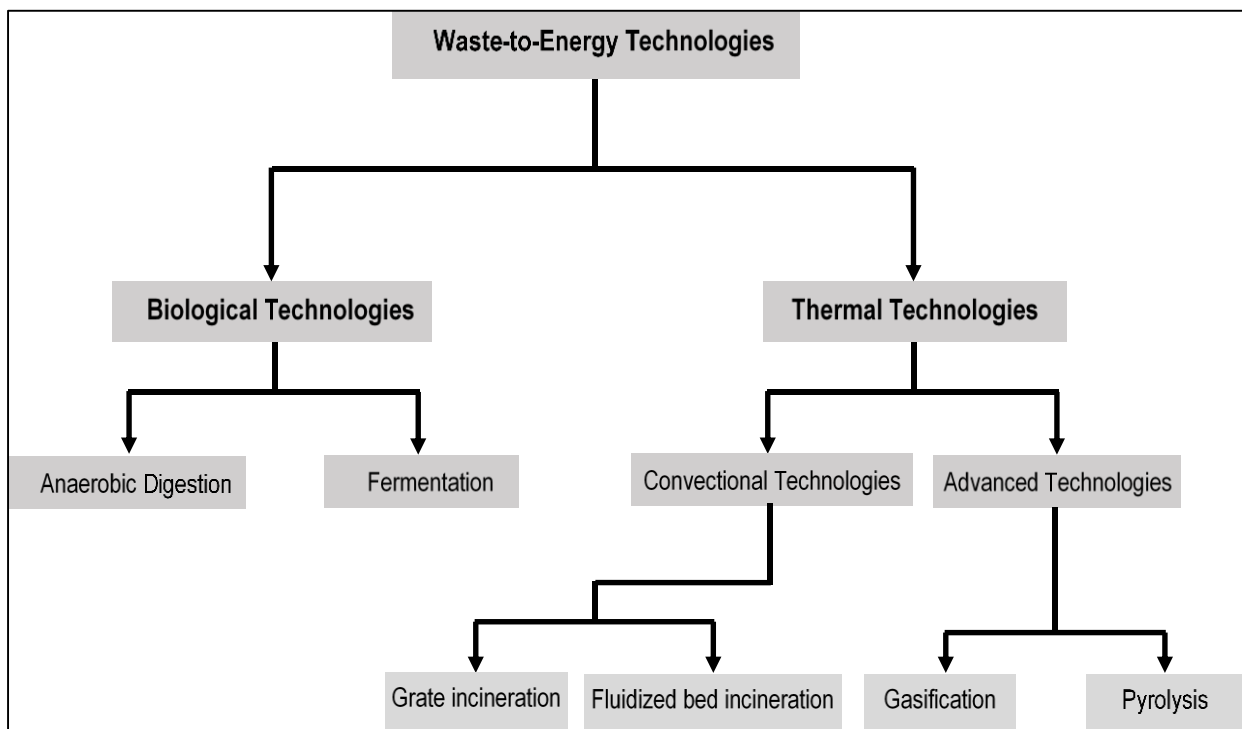


Figure 2.2: Categorization of WtE technologies (WEC, 2013:7b.1)

WtE thermal technology facilities convert MSW into gaseous, liquid and solid conversion products, simultaneously releasing heat energy, which is recovered through boilers. The recovered heat can be converted into electricity or directly exported to district heating systems (Rand *et al.*, 2000:118; Stantec Consulting Ltd, 2011:1.1).

WtE thermal technologies are generally classified as convectional and advanced technologies, as shown in Figure 2.2 (Stantec Consulting Ltd, 2011:1.1).

The convectional thermal technologies are commonly referred to as excess air combustion technologies (IEA Bioenergy, 2010:5). The general process followed by convectional thermal technology is illustrated in Figure 2.3.

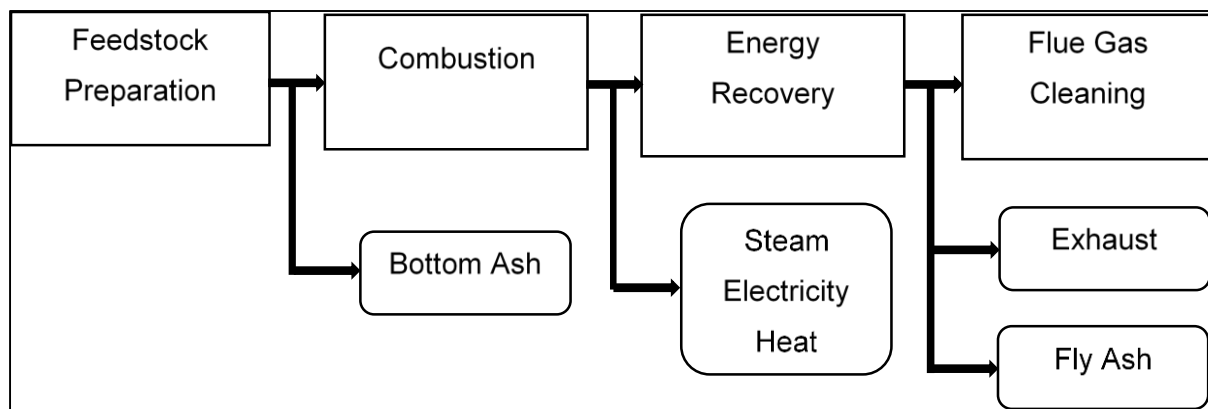


Figure 2.3: Convectional thermal technologies process flow overview (Stantec Consulting Ltd, 2011:1.1)

The advanced thermal technologies process flow overview is shown in Figure 2.4. The advanced thermal technologies are based on the principle of gasification and pyrolysis.

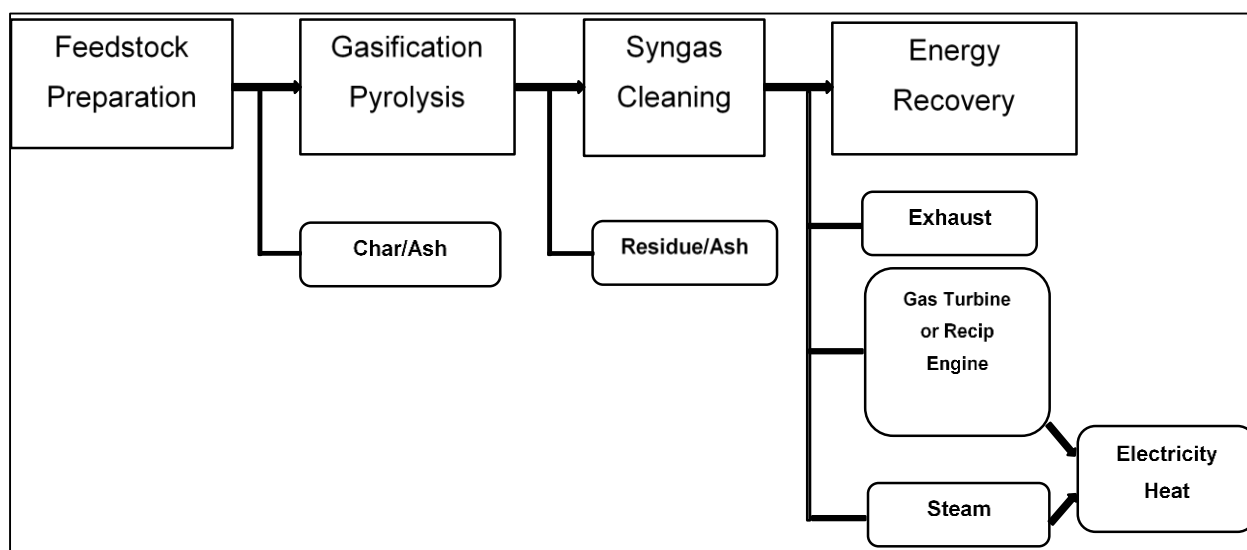


Figure 2.4: Advanced technologies process flow overview (Stantec Consulting Ltd, 2011:1.1)

2.3 Waste-to-energy thermal technologies evaluation

Four WtE thermal technologies, namely grate incineration, fluidized bed incineration, gasification and pyrolysis, are evaluated in this section. The technologies are evaluated on the basis of waste pre-treatment (Section 2.3.1), the thermal process (Section 2.3.2), energy recovery (Section

2.3.3), air pollution control (Section 2.3.4) and residual management (Section 2.3.5). Table 2.1 is a summarized comparison of WtE thermal technologies.

Table 2.1: Comparison of WtE thermal technologies (Boehmer *et al.*, 2008:15; European Commission, 2006:19; IEA Bioenergy, 2010:5; Rand *et al.*, 2000:118; Stantec Consulting Ltd, 2011:1.1)

Parameter	Grate	Fluidized bed	Gasification	Pyrolysis
Waste type	Mixed waste from waste streams with no pre-treatment, LHV of 6 MJ/kg to 12 MJ/kg.	Homogenized and pre-treated waste, specific particle size required, LHV of < 5 MJ/kg to >20 MJ/kg.	Homogenized and pre-treated waste.	Homogenized and pre-treated waste.
Thermal process	Complete combustion in excess air.	Complete combustion in excess air.	Partial thermal degradation in limited oxygen.	Decomposition of organic substances in the absence of oxygen.
Operating parameters	Temperature – 800°C to 1450°C, pressure – 1 bar.	Temperature – 800°C to 1450°C, pressure – 1 bar.	Temperature – 500°C to 1000°C, pressure – 1 bar to 50 bar.	Temperature – 250°C to 700°C, pressure – 1 bar.
Energy recovery	Heat energy in off-gas of a combustion process is recovered in a boiler as process steam, heat and electricity.	Heat energy in off-gas of a combustion process is recovered in a boiler as process steam, heat and electricity.	Syngas either directly combusted and heat recovered in a boiler as process steam, and electricity or syngas processed into other fuels.	Syngas directly combusted and heat recovered in a boiler as process steam, and electricity or syngas processed into other fuels.

2.3.1 Waste pre-treatment process

The first stage in a WtE plant is the storage and pre-treatment of the feedstock. Each technology has different feedstock quality and characteristics requirements, hence the objective of pre-treatment is to ensure that waste is in an appropriate form for the combustion process (Boehmer *et al.*, 2008:15; European Commission, 2006:19; IEA Bioenergy, 2010:5; Singh, 2011:1; Stantec Consulting Ltd, 2011:1.1).

Grate incineration processes MSW with minimum pre-treatment, such as the removal of recyclables, reusable material and bulky materials. Waste fuel is mixed and homogenized with overhead cranes before being transferred to the incinerator hopper (European Commission, 2006:19; IEA Bioenergy, 2010:5; Rand *et al.*, 2000:118).

Fluidized bed incineration, gasification and pyrolysis handle waste fuel/feedstock of limited particle size and specific characteristics. These technologies are limited to homogenous waste streams, hence effort is required in the waste pre-treatment process. Waste pre-treatment

involves size reduction combined with removal of metallic material (Boehmer *et al.*, 2008:15; European Commission, 2006:19; IEA Bioenergy, 2010:5; Rand *et al.*, 2000:118; Stantec Consulting Ltd, 2011:1.1).

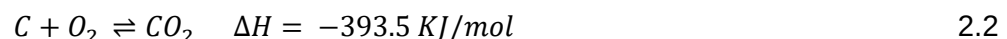
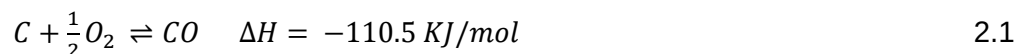
2.3.2 Thermal process

WtE thermal technologies are distinguished through the thermal process applied. Thermal processes are classified into three categories, namely combustion/incineration, pyrolysis and gasification. The principal distinguishing feature of these processes is the oxygen content in the process atmosphere and operating temperature range (European Commission, 2006:19; IEA Bioenergy, 2010:5; Stantec Consulting Ltd, 2011:1.1).

The pyrolysis process is the thermal decomposition or fragmentation of organic matter in a strictly inert atmosphere. The reaction temperature affects the proportion of gaseous, liquid and solid products. The temperature varies directly with the amount of gaseous products, whereas solid residues vary inversely with temperature. The pyrolysis gas produced is directly combusted to recover energy because of its complex composition, which requires extensive gas cleaning to remove sulfur compounds and other impurities (European Commission, 2006:19; IEA Bioenergy, 2010:5; Stantec Consulting Ltd, 2011:1.1).

The gasification process is the partial decomposition of feedstock in the presence of insufficient oxygen to oxidize the fuel. The main product of this process is synthetic gas, commonly referred to as syngas. Syngas from gasification of MSW is commonly used in a combustion chamber for energy recovery (European Commission, 2006:19; IEA Bioenergy, 2010:5; Stantec Consulting Ltd, 2011:1.1).

Grate incineration and fluidized bed incineration recover heat through complete combustion of waste fuel, an exothermic chemical process with the main energy releasing chemical reactions, shown in equations 2.1 and 2.2 (Boehmer *et al.*, 2008:15; European Commission, 2006:19; IEA Bioenergy, 2010:5; Rand *et al.*, 2000:118; Stantec Consulting Ltd, 2011:1.1).



2.3.3 Energy recovery

Thermal process technologies that use MSW as feedstock are designed so that the chemical energy in the fuel is finally released into the off-gas of a combustion process and the energy is recovered in a boiler. The energy from waste, auxiliary fuels and pre-heated air is converted

during the combustion process and transferred to a water steam circle (Boehmer *et al.*, 2008:15; IEA Bioenergy, 2010:5).

Gasification and pyrolysis of waste and waste-derived fuels are in principle two-stage processes designed to allow direct combustion of process products (IEA Bioenergy, 2010:5).

Recovered heat from the boiler can be used in three alternatives, namely direct export for district heating, conversion to electricity using turbines and combined heat and power. Figure 2.5 and Figure 2.6 show the hot water boiler circuit and the Rankine circuit used for heat recovery options (Boehmer *et al.*, 2008:15; European Commission, 2006:19; IEA Bioenergy, 2010:5; Rand *et al.*, 2000:118).

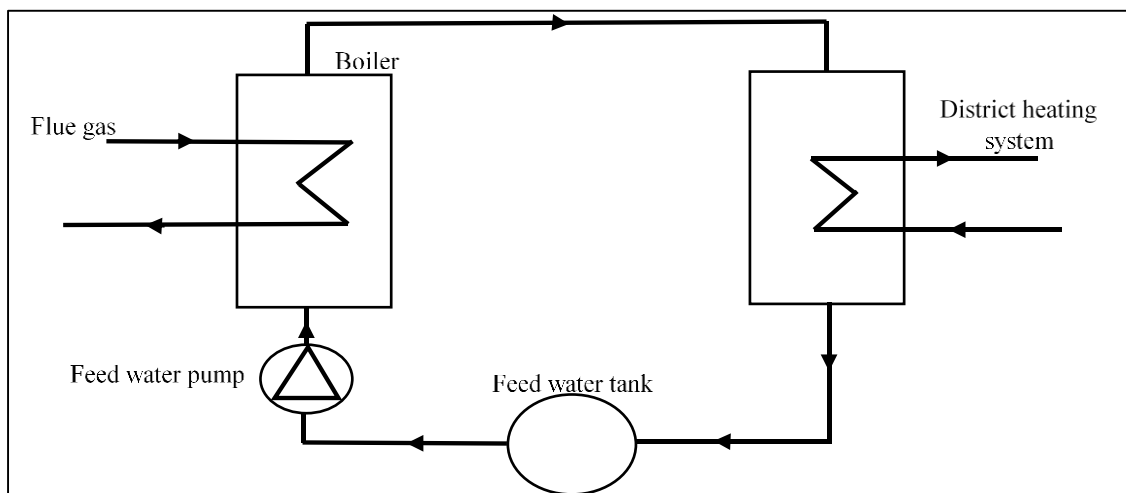


Figure 2.5: Hot water boiler circuit (Rand *et al.*, 2000:118)

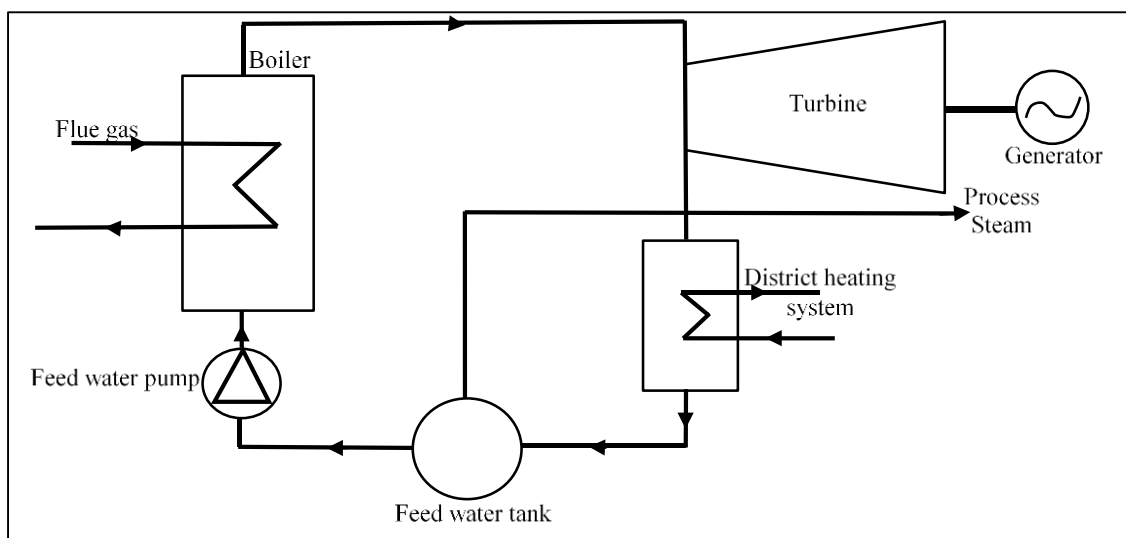


Figure 2.6: Rankine circuit (Rand *et al.*, 2000:118)

Factors that affect the choice of an energy cycle/circuit include the quality and quantity of waste, possibility of energy sales, availability of water sources, acceptable noise levels and space available.

2.3.4 Air pollution control

The removal of pollutants from the flue gas is one of the most important and most expensive process stages in a WtE plant. The design and operation of the air pollution control system technology is highly influenced by the required reduction in emissions to meet regulations, the compatibility of system components with one another and investment, operation and maintenance costs (IEA Bioenergy, 2010:5; Stantec Consulting Ltd, 2011:1.1).

The air pollution control system components are classified according to their functions, namely removal of fly ash, removal of acid gases and removal of specific contaminants such as mercury and nitrogen oxides (IEA Bioenergy, 2010:5).

Combination of air pollution control components is determined by the system component to clean acidic gases, such as sulfur dioxide (SO₂), hydrogen chloride and hydrogen fluoride. Hence these components are selected first, then the selection of compatible and appropriate components to remove particulate matter, dioxins, mercury and NO_x follows (Stantec Consulting Ltd, 2011:1.1).

Flue gas acidic compounds are cleaned using three options, namely dry/semi-dry scrubbing, wet scrubbing and semi-wet scrubbing systems. In this regard, there are three possible combinations of air pollution control system components (European Commission, 2006:19; IEA Bioenergy, 2010:5; Stantec Consulting Ltd, 2011:1.1).

Fly ash can be removed using cyclones; electrostatic precipitators (ESP) and fabric filters or bag house systems (European Commission, 2006:19). Cyclones have limited removal efficiency for fine particles and are not commonly used in modern WtE plants. ESP is the technique mostly applied owing to its design simplicity, low pressure loss and easy operation. The Morden ESP system can achieve dust removal efficiencies greater than 99% for particle sizes between 0.01 and >100 µm. The lowest emission, in a range of less than 1 mg/m³, is achieved through a fabric filter system (IEA Bioenergy, 2010:5).

Nitrogen oxide control is achieved through either non-catalytic removal (NSCR) or selective catalytic removal (SCR). NSCR uses the principle of injecting ammonia or another nitrogen-containing compound into the hot flue gases in the first flue of the boiler. SCR is done at the end of the gas-cleaning system at a temperature level of 250°C to 300°C (IEA Bioenergy, 2010:5).

2.3.5 Residue management

WtE facilities generate three categories of residue, namely bottom ash, fly ash and air pollution control (APC) residues. Fly ash and APC residue are deposited in the landfill. Ferrous and non-ferrous metal can be separated from raw bottom ash for a further recycling process. Gravel-size fractions of the bottom ash can be sieved and used in the construction industry, mainly road construction and brick pavement manufacturing (IEA Bioenergy, 2010:5; Rand *et al.*, 2000:118).

2.4 Waste-to-energy thermal technologies performance

This section will evaluate the performance of the four WtE thermal technologies in terms of plant capacity and scalability (Section 2.4.1), energy production (Section 2.4.2), flue gas production (Section 2.4.3), residual waste production (Section 2.4.4), potential revenue streams (Section 2.4.5) and technological reliability (Section 2.4.6). An analysis of potential revenue streams from each technology is carried out in this section. Table 2.2 summarizes WtE thermal technologies' performance evaluation.

Table 2.2: WtE technologies' performance evaluation (Boehmer *et al.*, 2008:15; European Commission, 2006:19; IEA Bioenergy, 2010:5; Rand *et al.*, 2000:118; Stantec Consulting Ltd, 2011:1.1)

Parameter	Grate	Fluidized bed	Gasification	Pyrolysis
Capacity	3 tonnes to 40 tonnes/hr for a single-line, compatible with multiple lines.	3 tonnes to 15 tonnes/hr for a single line.	1 tonne to 11 tonnes/hr for each single line.	2.5 tonnes to 8.3 tonnes/hour.
Scalability	Various sizes, large installations of greater than 100 000 tonnes/year can be economically viable.	Small installation.	Small installation with modularized designs.	Small installation.
Boiler efficiency	75% to 85%>.	75% to 85%>.	>80%.	75% to 85%>.
Power efficiency	Power only – 31%, CHP - >70%.	Power only – 25%, CHP - >70%.	Power – 20% to 22%.	Power – 15%.
Raw bottom ash	20% to 25%.	20% to 25%.	10% to 20%.	More than 30%.
Potential revenue streams	Electricity, heat and process steam, construction material, ferrous and non-ferrous metals.	Electricity, heat and process steam.	Combustion – process steam and electricity. Catalytic conversion – alcohols, chemicals, and synthetic diesel.	Combustion – process steam and electricity. Catalytic conversion – Pyrolysis oil, transportation fuel.

2.4.1 Plant capacity and scalability

WtE thermal technologies' capacity is measured in terms of the amount of waste that can be processed at any given time per individual line. A single installation can have a number of lines and the number of lines installed is directly proportional to overall size per installation.

Grate incineration records the highest capacities because of its ability to treat unprocessed waste. Single-line capacity ranges from 3 tonnes to 40 tonnes per hour. The technology can process waste with calorific values in the range 6 MJ/tonne to 12 MJ/tonne (IEA Bioenergy, 2010:5). Grate incinerators can be scaled to various sizes, with a capability of multiple lines installation. However, only large installations of greater than 100 000 tonnes/year can be economically viable.

Fluidized bed incinerators' single-line capacity ranges from 3 tonnes to 15 tonnes per hour. The technology can process waste with a calorific value of 5 MJ/tonne to 20 MJ/tonne (IEA Bioenergy, 2010:5).

Gasification has a processing capacity of 1 tonne to 11 tonnes per hour for each single line. Gasification reactors can have modularized designs, which are suitable for small installations (IEA Bioenergy, 2010:5; Stantec Consulting Ltd, 2011:1.1).

Pyrolysis thermal processing technology has the lowest capacity range of 2.5 tonnes to 8.3 tonnes per hour. Annual installed capacity ranges from 28 000 tonnes to 140 000 tonnes (IEA Bioenergy, 2010:5).

2.4.2 Energy production

The choice of a WtE thermal technology is influenced by the energy efficiency of a plant. Energy can be recovered as heat and/or electricity.

Grate technology has primary boiler efficiency in a range of 75% to greater than 85%. Modern facilities have power efficiencies that can reach as high as 31% and for heat only or combined power efficiency reach more than 70% (IEA Bioenergy, 2010:5). Where grate incinerator plants are operated in combination with power plants, an efficiency of more than 40% can be reached.

Gasification in different types of reactors has boiler efficiency of more than 80%. Depending on plant size and waste, power efficiencies are found to be in the range of 22% to 33% (IEA Bioenergy, 2010:5).

Fluidized bed incinerator boilers have primary efficiency of 80% to more than 85%. The overall power efficiency reaches up to 25% and for heat and combined power it can surpass 70% (IEA Bioenergy, 2010:5).

Pyrolysis boiler efficiency can reach as high as that of grate incineration and the fluidized bed process. Power efficiency can be as low as 15% (IEA Bioenergy, 2010:5).

2.4.3 Flue gas production

The performance of a WtE plant can be measured in terms of the composition of the raw flue gas from the thermal process. The production of acidic substances, heavy metals and dust particulate are the best indicators in measuring the performance of a WtE plant.

Gasification and pyrolysis produce synthetic gases that are used in direct combustion for energy recovery or can be further cleaned and processed to be used in other applications. Pollutants of concern in these processes are hydrochloric acid and sulfur dioxide (IEA Bioenergy, 2010:5; Stantec Consulting Ltd, 2011:1.1). Gasification and pyrolysis aim to minimize gas cleaning obligations by lowering flue-gas volumes (European Commission, 2006:19).

Grate and fluidized bed incineration produce raw flue gases that have a high margin of deviation from the minimum emission requirements. The conventional thermal process must be equipped with efficient air pollution control systems to meet emission requirements (IEA Bioenergy, 2010:5; Stantec Consulting Ltd, 2011:1.1).

2.4.4 Residual waste production

Grate and fluidized incineration produce bottom ash amounting to 20% to 25% by weight of the incinerated waste. The bottom ash can be used in other applications, which can reduce residue disposed into the landfill to about 5% by weight of the incinerated waste. Grate and fluidized bed incineration conserve landfill capacity up to 90% to 95% (Stantec Consulting Ltd, 2011:1.1).

The gasification process is capable of minimizing bottom ash to about 10% to 20% by weight of the incinerated waste. The bottom ash for gasification is highly marketable for other applications and residual disposal to the landfill can be minimized to 1% by weight of the incinerated waste. Gasification has the potential of reducing landfill capacity consumption by 90% to 95% (Stantec Consulting Ltd, 2011:1.1).

Pyrolysis produces residue of more than 30% by weight of the incinerated waste. However, if the residue can be treated, landfill disposal is reduced from 30% to 10% by weight of the incinerated waste. Pyrolysis has the capability of conserving landfill capacity up to 90% (Stantec Consulting Ltd, 2011:1.1).

2.4.5 Potential revenue streams

Potential revenue streams of a WtE thermal plant vary with the technology applied. The common revenue stream is the sale of process steam, heat and electricity. Other streams of revenue include construction aggregate recovered from bottom ash, recyclable ferrous and non-ferrous metals recovered from bottom ash, syngas and pyrolysis oil (Stantec Consulting Ltd, 2011:1.1).

Modern plants using grate incineration technology have electricity production rates of between 0.75 MWh and 0.85 MWh/annual tonne of MSW. Gasification and pyrolysis energy production is in the range 0.4 MWh to 0.8 MWh/annual tonne of MSW and 0.5 MWh to 0.8 MWh/annual tonne of MSW respectively (Stantec Consulting Ltd, 2011:1.1).

Raw bottom ash from the incineration of mixed MSW contains huge amounts of ferrous and non-ferrous metals, amounting to about 10% by weight of the input incinerated waste. Post-processing of bottom ash, disposal and utilization depend on the total organic carbon of the ash (IEA Bioenergy, 2010:5).

2.4.6 Reliability of technology

Grate technology is a commercially proven technology used in more than 500 plants worldwide, with proven operational success (Lombardi *et al.*, 2015:26; Stantec Consulting Ltd, 2011:1.1). The technology operates with minimum challenges, with some plants having been in operation for 15 years to 30 years. Grate technology is reported to have both scheduled and unscheduled downtime of less than 10% of operating time. The technology is less complex in comparison with other thermal processes (IEA Bioenergy, 2010:5; Stantec Consulting Ltd, 2011:1.1).

Though commercially proven, fluidized bed incineration is faced with operational challenges with MSW as feedstock. About 50 plants worldwide use this technology, with many plants found in Japan for smaller throughputs (Stantec Consulting Ltd, 2011:1.1).

Gasification has been used for more than a century with other fuels and recently MSW has been used as feedstock. The technology operates with scheduled and unscheduled downtime at approximately 20% (IEA Bioenergy, 2010:5; Stantec Consulting Ltd, 2011:1.1)

Pyrolysis of waste is applied in only a few commercial-scale plants, hence there is limited information on the reliability of the process. The technology has limited capability to process MSW.

2.5 Discussion of results

The qualitative investigations proved that WtE thermal technologies could be a valuable alternative source of energy and a solution to ever increasing MSW and other waste streams, such as medical waste.

WtE convectional and advance thermal technologies have significant potential to contribute to renewable energy and mitigate adverse effects of landfill. WtE thermal technologies can noticeably contribute to the recovery of materials such as metals.

The investigation of WtE thermal technologies indicates that grate incineration remains the preferred and most economical thermal technology in view of its reliability, capability to incinerate assorted waste, lower operational complexity and higher power efficiency.

Advanced thermal technologies face both operational and economic drawbacks. Gasification and pyrolysis continue to experience limitations due to their complexity, difficulty in treating waste of various streams and lower net energy recovery.

However, in view of technological advancements, pyrolysis and gasification may be preferred in future. Advanced thermal technologies are cleaner than convectional technologies because they emit less flue gas.

2.6 Conclusion

The purpose of this chapter was to perform a qualitative investigation into the technology and performance of WtE thermal technologies. Part of the work presented in this chapter was published in the peer-reviewed conference proceedings of the SAUPEC 2015 (Appendix A).

In the next chapter, the qualitative investigations are weighted in quantitative manner using AHP process. Quantitative evaluation provides a systematic methodology for ranking WtE thermal technologies.

CHAPTER 3

WASTE-TO-ENERGY THERMAL TECHNOLOGIES QUANTITATIVE EVALUATION

3.1 Introduction

The purpose of this research is to perform a techno-economic evaluation of a WtE grate incineration power plant for a small South African city. A qualitative evaluation of WtE thermal technologies and their performance is carried out in this chapter. Figure 3.1 shows how the chapter fits into the research roadmap.

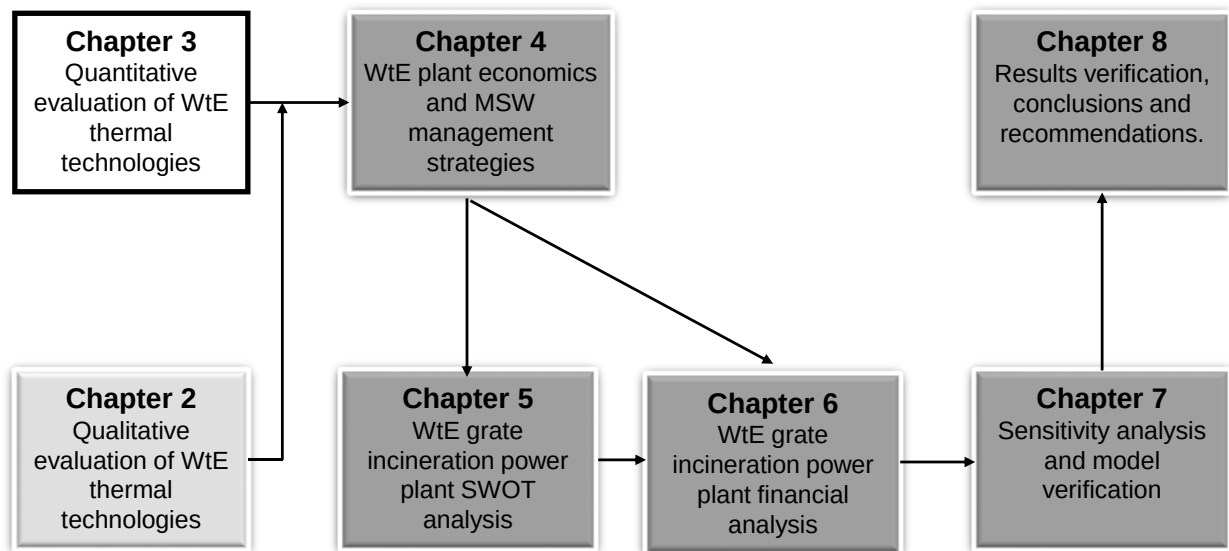


Figure 3.1: Research roadmap position 2

The quantitative evaluation of WtE thermal technologies facilitates technological ranking using multiple criteria. The ranking of WtE thermal technologies is a multi-criteria decision-making problem with contradicting and different objectives. An AHP process, as a multi-criteria decision-making tool to make informed and bias-free decisions, is used to rank the technologies.

This chapter starts by discussing AHP (Section 3.2), and is followed by application of AHP (Section 3.3) in ranking the four WtE thermal technologies discussed in the previous chapter. Section 3.4 presents a WtE thermal technologies AHP model. Criteria weights (Section 3.5) and alternative rating (Section 3.6) calculations are carried out. This is followed by synthesizing the global weights and rating score (Section 3.7). The quantitative analysis results are discussed in section 3.8 and the conclusion of the chapter is presented in section 3.9.

3.2 Analytical hierarchy process

AHP is a multi-criteria decision-making tool that was developed by Thomas Saaty to assist in making the best decision systematically. AHP uses the approach of building a ranking of decisions using pairwise comparisons, which allows both qualitative and quantitative judgements and enhances the precision of results (Dalalah *et al.*, 2010:567). The pairwise comparisons are used to produce weighting scores that measure the importance of each criterion against others.

AHP has proven to be applicable in complex situations where decision-making is required. AHP can be used in engineering and manufacturing related evaluation and decision-making processes. AHP has been used in advanced technology process selection to achieve rapid product development. AHP has been used extensively in favor of conventional methods, since it involves both systematic problem-solving steps and the relationship among decision factors (Vaidya & Kumar, 2006:1).

AHP has a number of industrial applications, such as integrated manufacturing, evaluation of technology investment decisions, flexible manufacturing systems and other engineering problems (Triantaphyllou & Mann, 1995:35).

3.3 Application of analytical hierarchy process in ranking WtE thermal technologies

WtE thermal technologies, namely grate incineration, fluidized bed incineration, gasification and pyrolysis, were qualitatively evaluated in chapter 2. The technologies were investigated and compared on the basis of waste processed, operating parameters, capacity and scalability, potential revenue streams and residual waste production. This was performed with the objective of finding the WtE thermal technology with the best performance.

The evaluation and analysis carried out demonstrated that WtE thermal technology selection is a multi-criterion decision-making problem with conflicting and diverse objectives. The goal is to determine if grate incineration is the appropriate technology rather than the others.

A number of factors that affect the ranking of WtE thermal technology were deduced from the evaluation process of chapter 2. Table 3.1 presents the factors that affect technology selection and the objective to be met.

Table 3.1: WtE technology selection criteria

Criteria	Objective
Waste process	The objective is to process all mixed residual MSW. The technology has to be capable of processing medical waste and WT.

Operating temperature	The operating temperature must be capable of combusting a wide range of waste. Temperatures above 1000°C are most appropriate. The operating temperature affects the waste streams that can be processed by the chosen technology.
Capacity	The technology to be selected must be compatible with fluctuations in the availability of waste.
Scalability	The selected technology must be capable of operating with multiple lines to enhance reliability.
Potential revenue streams	The main revenue stream must be electrical energy sales. Other alternatives to be considered are heat sales, process steam sales and fuels in the case of gasification and pyrolysis

3.4 Analytic hierarchy process based on waste-to-energy thermal technologies model

The principal goal in the analytical hierarchical process model is to rank WtE thermal technologies, namely grate incineration, fluidized bed incineration, gasification and pyrolysis. The selection is performed by co-ordinating the effects of the sub-goals according to their weights of importance. The following criteria entries are to be considered:

- waste processed;
- operating temperature;
- capacity;
- scalability; and
- potential revenue streams.

The waste processed criterion has sub-criteria entries, namely mixed MSW, medical waste and WT. Likewise, potential waste streams have five sub-criterion entries, namely electricity, heat, process steam, ferrous and non-ferrous metals and synthetic diesel/ oils.

Grate incineration, fluidized bed incineration, pyrolysis and gasification are considered to be the alternatives in this study. Figure 3.2 is a graphical representation of the hierarchical structure, with the first level indicating the goal. Next to this level are five criteria, under which sub-criteria are presented. The four alternatives, which are the technologies, appear in the last level of the hierarchy.

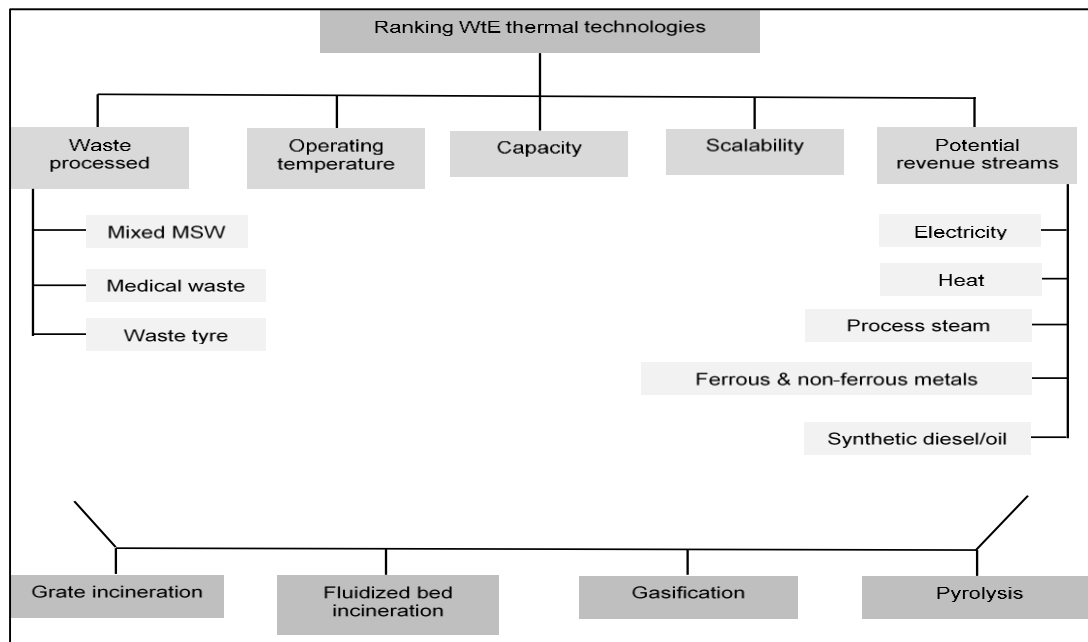


Figure 3.2: WtE technological selection hierarchy of goal, criteria, sub-criteria and alternatives

3.5 Criteria weights calculations and consistency checking

Pairwise comparison of criteria was performed for each level, resulting in pairwise comparison square matrices. The matrices were normalized and weights for each criterion and sub-criterion were calculated.

To validate the analysis results, the consistency index (CI) is calculated first using equation 3.1.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad 3.1$$

where λ_{max} = the maximum eigenvalue of the judgement matrix and n = the order of the comparison square matrix.

Table 3.2 is used to find the random consistency index (RI). This is a standard number selected on the basis of order of the comparison matrix (n) (Bhushan & Rai, 2004:171).

Table 3.2: Random consistency index scale (Saaty, 1987:161)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

The consistency ratio (CR) is calculated as the ratio of CI to RI, as shown in equation 3.2.

$$CR = \frac{CI}{RI} \quad 3.2$$

The comparison matrix is regarded as having acceptable consistency if $CR < 0.1$. Thus the pairwise comparison matrices are checked for consistency using equation 3.2.

The complete AHP analysis to obtain criteria, sub-criteria and global weights results in section 3.5.1 to section 3.5.4 is presented in Appendix C1.

3.5.1 Criteria matrix

The criteria matrix compares the five criteria, namely waste processed (WP), operating temperature (OT), capacity (C), scalability (S) and potential revenue streams (PRS).

$$\text{Criteria matrix} = \begin{pmatrix} & \text{WP} & \text{OT} & \text{C} & \text{S} & \text{PRS} \\ \text{WP} & 1.00 & 3.00 & 2.00 & 2.00 & 4.00 \\ \text{OT} & 0.33 & 1.00 & 2.00 & 2.00 & 2.00 \\ \text{C} & 0.50 & 0.50 & 1.00 & 1.00 & 2.00 \\ \text{S} & 0.50 & 0.50 & 1.00 & 1.00 & 2.00 \\ \text{PRS} & 0.25 & 0.50 & 0.50 & 0.50 & 1.00 \end{pmatrix}$$

The criteria matrix was normalized by dividing each element in each column by the sum of the element in the respective column to give the normalized matrix shown below.

$$\text{Normalized matrix} = \begin{pmatrix} & \text{WP} & \text{OT} & \text{C} & \text{S} & \text{PRS} \\ \text{WP} & 0.39 & 0.55 & 0.31 & 0.31 & 0.36 \\ \text{OT} & 0.13 & 0.18 & 0.31 & 0.31 & 0.18 \\ \text{C} & 0.19 & 0.09 & 0.15 & 0.15 & 0.18 \\ \text{S} & 0.19 & 0.09 & 0.15 & 0.15 & 0.18 \\ \text{PRS} & 0.10 & 0.09 & 0.08 & 0.08 & 0.09 \end{pmatrix} \quad \begin{pmatrix} \text{Weights} \\ 0.39 \\ 0.23 \\ 0.15 \\ 0.15 \\ 0.09 \end{pmatrix}$$

The weight of each criterion is calculated by averaging elements in the same row of the normalized matrix. Waste processed (WP) weighs most at 0.39 while potential revenue streams (PRS) weighs least at 0.09. The CR of the criteria matrix was calculated and the results are displayed in Table 3.3.

Table 3.3: Criteria matrix results consistency check

CI	RI	CR	Validity Check
0.04	1.12	0.03	$CR < 0.1$

3.5.2 Sub-criteria matrix₁

The sub-criteria matrix₁ for waste processed compares three criteria, namely mixed MSW (MMSW), medical waste (Mw) and WT.

$$\text{Sub-criteria matrix}_1 = \begin{pmatrix} & \text{MMSW} & \text{Mw} & \text{WT} \\ \text{MMSW} & 1.00 & 2.00 & 5.00 \\ \text{Mw} & 0.50 & 1.00 & 3.00 \\ \text{WT} & 0.20 & 0.30 & 1.00 \end{pmatrix}$$

The sub-criteria matrix₁ was normalized by dividing each element in each column by the sum of the element in the respective column to give the normalized matrix₁ shown below. The sub-criteria weights are then obtained by averaging the elements in each row of the normalized matrix₁.

$$\text{Normalized matrix}_1 = \begin{pmatrix} & \text{MMSW} & \text{Mw} & \text{WT} \\ \text{MMSW} & 0.59 & 0.60 & 0.56 \\ \text{Mw} & 0.29 & 0.30 & 0.33 \\ \text{WT} & 0.12 & 0.10 & 0.11 \end{pmatrix} \begin{pmatrix} \text{Weights} \\ 0.58 \\ 0.31 \\ 0.11 \end{pmatrix}$$

The weights show that MMSW has the largest weight of 0.58, while WT has the lowest weight of 0.11. The consistence of the sub-criteria matrix₁ was checked and the results are displayed in Table 3.4.

Table 3.4: Sub-criteria matrix₁ results consistency check

CI	RI	CR	Validity Check
0.0018	0.58	0.0032	CR < 0.1

3.5.3 Sub-criteria matrix₂

The sub-criteria matrix₂ for PRS is formulated by comparing five criteria, namely electricity (E), heat (H), process steam (PS), ferrous and non-ferrous metals (FNFM) and synthetic diesel/oil (SD).

$$\text{Sub-criteria matrix}_2 = \begin{pmatrix} & \text{E} & \text{H} & \text{PS} & \text{FNFM} & \text{SD} \\ \text{E} & 1.00 & 3.00 & 3.00 & 7.00 & 8.00 \\ \text{H} & 0.33 & 1.00 & 1.00 & 2.00 & 2.00 \\ \text{PS} & 0.33 & 1.00 & 1.00 & 2.00 & 2.00 \\ \text{FNFM} & 0.14 & 0.50 & 0.50 & 1.00 & 1.00 \\ \text{SD} & 0.13 & 0.50 & 0.50 & 1.00 & 1.00 \end{pmatrix}$$

The normalized matrix₂ was obtained by dividing each element in each column by the sum of the element in the respective column of sub-criteria matrix₂. The sub-criteria weights are determined by averaging the elements in each row of normalized matrix₂.

$$\text{Normalized matrix}_2 = \begin{pmatrix} & \text{E} & \text{H} & \text{PS} & \text{FNFM} & \text{SD} \\ \text{E} & 0.52 & 0.50 & 0.54 & 0.57 & 0.53 \\ \text{H} & 0.17 & 0.17 & 0.17 & 0.15 & 0.14 \\ \text{PS} & 0.17 & 0.17 & 0.17 & 0.15 & 0.14 \\ \text{FNFM} & 0.17 & 0.08 & 0.08 & 0.08 & 0.07 \\ \text{SD} & 0.06 & 0.08 & 0.08 & 0.08 & 0.07 \end{pmatrix} \begin{pmatrix} \text{Weights} \\ 0.53 \\ 0.16 \\ 0.16 \\ 0.08 \\ 0.08 \end{pmatrix}$$

The weights indicate that electricity (E) has the largest weight of 0.53, while synthetic diesel/oil (SD) has the lowest weight of 0.08. Table 3.5 shows the results of the consistency check for the sub-criteria matrix₂.

Table 3.5: Sub-criteria matrix₂ results consistency check

CI	RI	CR	Validity Check
0.0023	1.12	0.0021	CR < 0.1

3.5.4 Global weights calculations

The sub-criteria's global weights are calculated by multiplying each sub-criteria weight with respective criteria weight (Appendix C1). The criteria and sub-criteria global weights are then combined to formulate the global weights that will be used in ranking the WtE thermal technologies. Table 3.6 shows the global weights of each criterion and sub-criterion, namely mixed MSW (MMSW), medical waste (Mw), WT, operating temperature (OT), capacity (C), scalability (S), electricity (E), heat (H), process steam (PS), ferrous and non-ferrous metals (FNFM) and synthetic diesel/oil (SD).

Table 3.6: Global weights results

Criterion	MMSW	Mw	WT	OT	C	S	E	H	PS	FNFM	SD
Weight	0.22	0.12	0.04	0.23	0.15	0.15	0.04	0.01	0.01	0.01	0.01

3.6 Alternatives rating calculations and consistency checking

Similar to criteria weight calculations, pairwise comparison of alternatives with respect to each criterion or sub-criterion was performed. The resultant square matrices are normalized and

alternative ratings are determined. The complete AHP analysis to obtain alternative matrix, rating matrix and synthesizing weights and rating score is presented in Appendix C2.

3.6.1 Alternative matrix

The alternative matrix was determined by performing pairwise comparison, with selection preference based on MMSW. The alternative matrix compares four technologies, namely grate incineration (GI), fluidized bed incineration (FBI), gasification (G) and pyrolysis (P).

$$\text{Alternative matrix}_1 (\text{MMSW}) = \begin{pmatrix} & \text{GI} & \text{FBI} & \text{G} & \text{P} \\ \text{GI} & 1.00 & 5.00 & 7.00 & 7.00 \\ \text{FBI} & 0.20 & 1.00 & 2.00 & 2.00 \\ \text{G} & 0.14 & 0.50 & 1.00 & 1.00 \\ \text{P} & 0.14 & 0.50 & 1.00 & 1.00 \end{pmatrix}$$

The alternative matrix₁ (MMSW) is normalized by dividing each element in each column by the sum of the element in the respective column to give the normalized matrix₃. Selection preference rating with respect to MMSW is determined by averaging row elements in the normalized matrix₃ relative to each alternative.

$$\text{Normalized matrix}_3 = \begin{pmatrix} & \text{GI} & \text{FBI} & \text{G} & \text{P} \\ \text{GI} & 0.673 & 0.714 & 0.636 & 0.636 \\ \text{FBI} & 0.135 & 0.143 & 0.182 & 0.182 \\ \text{G} & 0.096 & 0.071 & 0.091 & 0.091 \\ \text{P} & 0.096 & 0.071 & 0.091 & 0.091 \end{pmatrix} \begin{pmatrix} \text{Rating} \\ 0.665 \\ 0.160 \\ 0.087 \\ 0.087 \end{pmatrix}$$

The ratings indicate that, based on mixed MSW, grate incineration is preferred, with a rating score of 66.5%. Table 3.7 shows the alternative matrix consistency results.

Table 3.7: Alternative matrix results consistency check

CI	RI	CR	Validity Check
0.0053	0.9	0.0059	CR < 0.1

3.6.2 Rating matrix

The rating process with respect to other criteria and sub-criteria is repeated in the same manner as with mixed MSW (Appendix C2). The rating matrix is obtained by combining the alternative rating scores with respect to each criteria and sub-criteria. Rating of alternatives with respect to each criterion or sub-criterion result are presented in the ratings matrix below.

$$\text{Rating matrix} = \begin{pmatrix} & \text{MMSW} & \text{Mw} & \text{WT} & \text{OT} & \text{C} & \text{S} & \text{E} & \text{H} & \text{PS} & \text{FNFM} & \text{SD} \\ \text{GI} & 0.67 & 0.44 & 0.50 & 0.52 & 0.54 & 0.11 & 0.42 & 0.38 & 0.38 & 0.63 & 0.05 \\ \text{FBI} & 0.16 & 0.24 & 0.17 & 0.24 & 0.23 & 0.23 & 0.23 & 0.38 & 0.38 & 0.13 & 0.05 \\ \text{G} & 0.09 & 0.16 & 0.17 & 0.12 & 0.14 & 0.33 & 0.23 & 0.13 & 0.13 & 0.13 & 0.45 \\ \text{P} & 0.09 & 0.16 & 0.17 & 0.12 & 0.08 & 0.33 & 0.12 & 0.13 & 0.13 & 0.13 & 0.45 \end{pmatrix}$$

3.7 Synthesizing weights and rating score

The final stage in finding the preference rankings for the alternatives is to synthesize the criteria global weights with alternative rating scores. The global weights are arranged in an 11 x 1 matrix and are pre-multiplied with the rating matrix. The resultant matrix gives the final rating matrix.

$$\text{Rating matrix} = \begin{pmatrix} & \text{MMSW} & \text{Mw} & \text{WT} & \text{OT} & \text{C} & \text{S} & \text{E} & \text{H} & \text{PS} & \text{FNFM} & \text{SD} \\ \text{GI} & 0.67 & 0.44 & 0.50 & 0.52 & 0.54 & 0.11 & 0.42 & 0.38 & 0.38 & 0.63 & 0.05 \\ \text{FBI} & 0.16 & 0.24 & 0.17 & 0.24 & 0.23 & 0.23 & 0.23 & 0.38 & 0.38 & 0.13 & 0.05 \\ \text{G} & 0.09 & 0.16 & 0.17 & 0.12 & 0.14 & 0.33 & 0.23 & 0.13 & 0.13 & 0.13 & 0.45 \\ \text{P} & 0.09 & 0.16 & 0.17 & 0.12 & 0.08 & 0.33 & 0.12 & 0.13 & 0.13 & 0.13 & 0.45 \end{pmatrix} \begin{pmatrix} \text{Weights} \\ 0.22 \\ 0.12 \\ 0.04 \\ 0.23 \\ 0.15 \\ 0.15 \\ 0.04 \\ 0.01 \\ 0.01 \\ 0.01 \\ 0.01 \end{pmatrix}$$

$$\text{Final rating matrix} = \begin{pmatrix} \text{GI} & 0.47 \\ \text{FBI} & 0.22 \\ \text{G} & 0.16 \\ \text{P} & 0.15 \end{pmatrix}$$

The preferences of each alternative are deduced from the final rating matrix above. The results of the analysis process are presented in Table 3.8.

Table 3.8: Quantitative evaluation of WtE thermal technologies results

Technology	Rating Score	Comments
Grate incineration	47%	1 st preference
Fluidized bed incineration	22%	2 nd preference
Gasification	16%	3 rd preference
Pyrolysis	15%	4 th preference

3.8 Discussion of results

The consistency check process proved that all the pairwise comparison matrices were within the acceptable CR. The best matrix CR achieved was 0.0021, while the worst CR was 0.03. According to a comparison of these ratios with the validity value of $CR < 0.1$, the assumptions made are valid.

Quantitative evaluation of WtE thermal technologies results rates grate incineration best with a rating score of 47%. This results agrees with the qualitative analysis results in the previous chapter. The 25% score margin between grate incineration and fluidized bed, the next preferred technology, is noticeable. This means that grate incineration is significantly preferred over other thermal technologies.

Pyrolysis has the lowest rating score of 15%, making it the least preferred WtE thermal technology. This technology has not been proven commercially, though there has been significant advancement in establishing it in the market.

The desirability of gasification over pyrolysis is insignificant, with a score margin of 1%. This is due to the operational limitations associated with these WtE advanced thermal technologies.

3.9 Conclusion

The purpose of this chapter was to perform quantitative evaluation of four WtE thermal technologies discussed in chapter two. A scientific and systematic way of making a decision, AHP, was used in the ranking of WtE thermal technologies.

The qualitative and quantitative evaluation results ranked grate incineration above the other technologies that were included in the evaluations. This was based on the reliability of the technology, capability to incinerate assorted waste, lower operational complexity and higher power efficiency. WtE grate incineration power plant economics and waste management strategies are investigated in the next chapter.

CHAPTER 4

WASTE-TO-ENERGY ECONOMICS AND WASTE MANAGEMENT STRATEGIES

4.1 Introduction

The aim of this research project is to perform a techno-economic evaluation of a WtE grate incineration power plant for a small South African city. The purpose of this chapter is to review WtE grate incineration power plant economics and waste management strategies.

MSW is regarded as the main WtE plant feedstock. In this regard, the chapter also evaluates WtE in comparison with other MSW management strategies. Medical waste management strategies are included in this chapter.

Figure 4.1 shows the research roadmap, highlighting how the discussion is related to the wider research. The chapter starts by discussing capital cost (Section 4.2), followed by deliberations on operating costs (Section 4.3) of a WtE grate incineration power plant. It continues by looking into MSW management assessment (section 4.4) and medical waste management (Section 4.5). The conclusion of the chapter is presented in section 4.6.

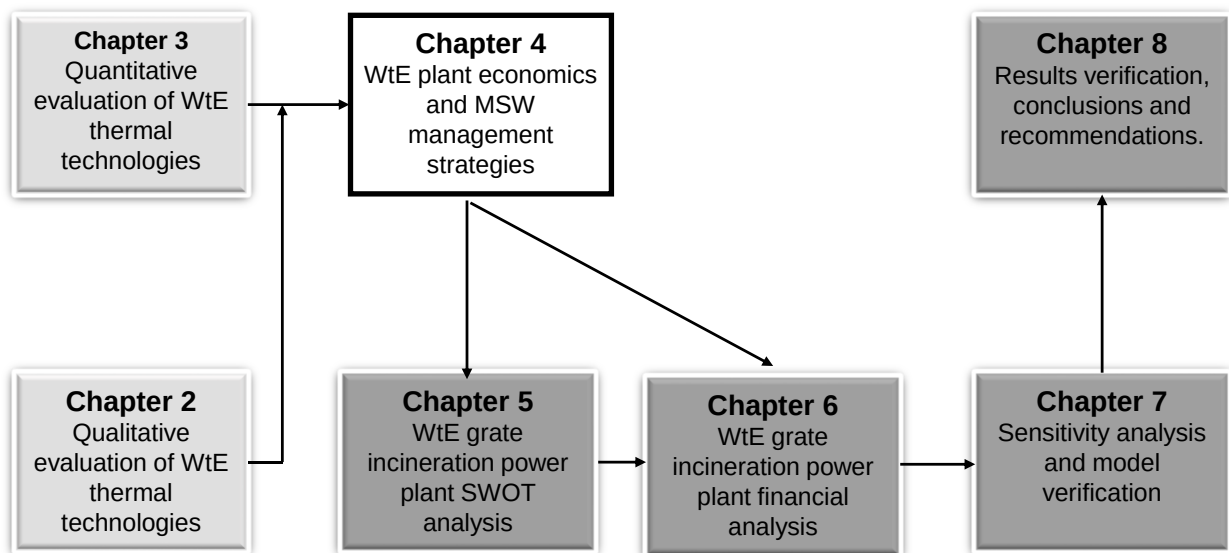


Figure 4.1: Research roadmap position 3

4.2 Waste-to-energy plant capital cost

Capital cost is the main cost of a WtE grate incineration power plant. According to Stantec (2011:1.1), capital investment cost can be split into components, as shown in Table 4.1. Thermal processing equipment makes the highest contribution to the total capital investment cost. The cost of machinery is influenced by the type of energy recovered. Energy can be recovered as heat, electricity or combined heat and power. The flue gas treatment system cost is determined by the quality of the pollution control to be achieved (Rand *et al.*, 2000:118).

Table 4.1: WtE capital investment cost components (Stantec Consulting Ltd, 2011:1.1)

System component	Capital cost contribution (%)
Thermal processing equipment (incinerator/boiler)	40
Energy production equipment (turbines and generators)	10
APC system (flue gas treatment)	15
Building (civil works)	25
Miscellaneous (approvals, general site works, ash processing, electrical transmission and interconnect etc.)	10

4.3 Waste-to-energy plant operating costs

WtE grate incineration power plant operating cost comprises fixed and variable operating costs and maintenance cost. Table 4.2 is an overview of operating cost in a WtE grate incineration power plant.

Table 4.2 : Operating costs overview (Rand *et al.*, 2000:118)

Category	Cost component
Fixed cost	Administration
	Salaries
Variable cost	Flue gas cleaning chemical
	Water and handling waste water
	Residue disposal
Maintenance cost	Machinery maintenance
	Building maintenance

The fixed costs are highly influenced by the number of employees, ratio of skilled to unskilled employees and local salary levels. Variable cost depends on the flue gas system in use. The total maintenance cost is estimated to be 3.5% of the total investment cost (Rand *et al.*, 2000:118).

Investigations proved that gate fees and energy sales are the revenue streams that significantly influence a WtE plant financial performance. Figure 4.2 shows the major revenue streams of a WtE grate incineration power plant (Rand *et al.*, 2000:118).

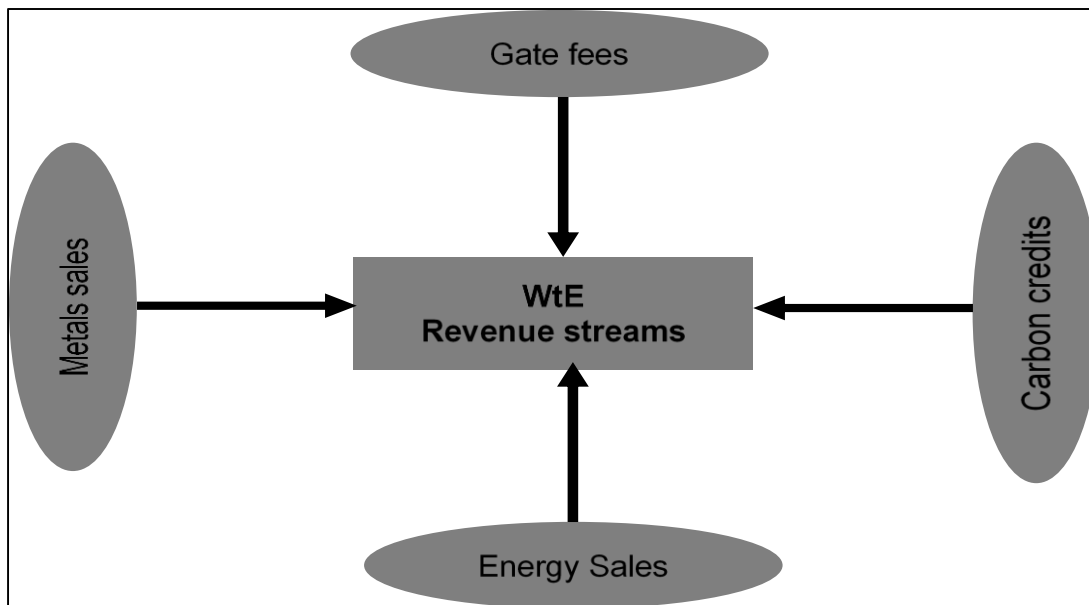


Figure 4.2: WtE main revenue streams (Rand *et al.*, 2000:118; Maisiri *et al.*, 2015:170)

Energy sales are a significant revenue stream of a WtE plant. Income from energy sales has the potential of covering up to 80% of the total capital and operational cost. Energy can be sold as heat, electricity or process steam (Rand *et al.*, 2000:118).

The lower heating value (LHV) of waste significantly affects the amount of electricity generated and thus has an impact on energy sales. Figure 4.3 shows the variation of energy output with LHV of a WtE plant.

Gate fees make a noticeable contribution to the revenue stream in countries where a ban on landfill is the major driver of WtE. Countries with successful WtE have managed to achieve a negative market price for waste. This means that waste producers have to pay for their waste to be processed (IEA Bioenergy, 2010:5).

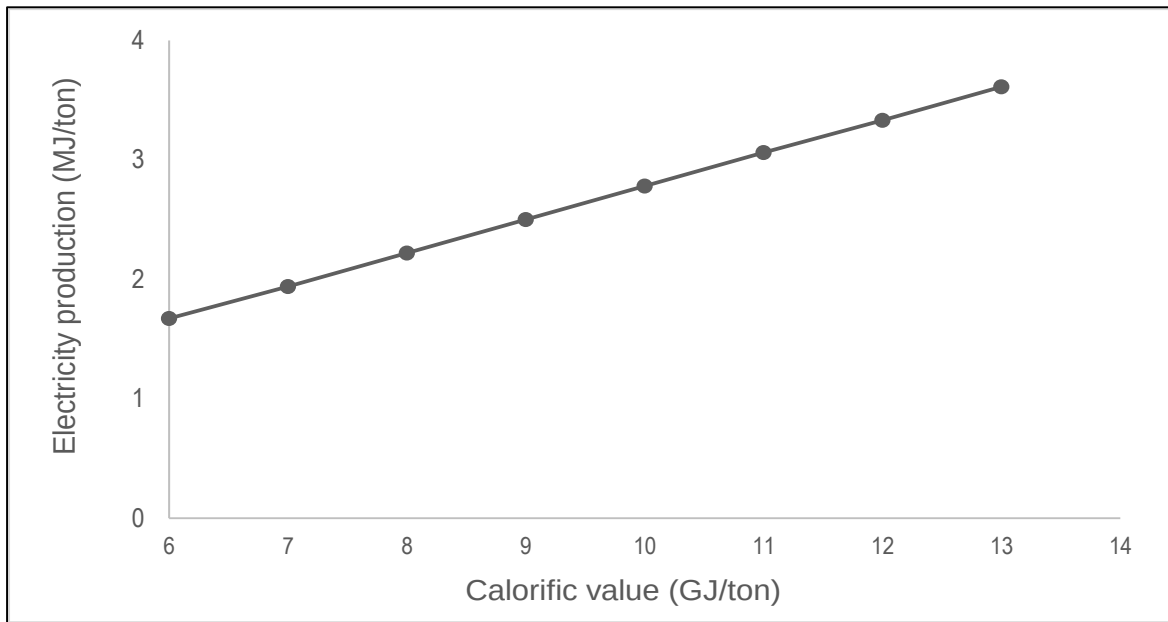


Figure 4.3: Variation of electricity production with calorific value for a plant operating at 30% efficiency electricity production (Rand *et al.*, 2000:118)

4.4 Municipal solid waste management assessment

The global scenario, with fast growing economies, proves MSW generation and management problems to be on the rise (Sethi *et al.*, 2012:97). MSW can be defined as any solid material discarded in urban areas and its management is the responsibility of the municipality (Cheng *et al.*, 2007:7509). The goal of waste management is to protect man and the environment and conserve resources (Brunner & Rechberger, 2014:3).

This section discusses MSW management strategies in view of their advantages and detriments. The section is organized as follows: MSW management strategies hierarchy (section 4.4.1), waste management strategies evaluation (section 4.4.2) and MSW management policies (section 4.4.3).

4.4.1 Municipal solid waste management strategies hierarchy

Investigations show that an integrated MSW management system does not depend on a single strategy, but rather uses multiple strategies and involves all the stakeholders (Guo & Liu, 2014:3). 3R, recovery, composting and landfill are among the commonly used MSW management strategies. Figure 4.4 shows the prioritization hierarchy of waste management strategies. The waste management priority hierarchy in Figure 4.4 is universal for all types of waste, including medical waste and WT. Avoidance of waste and reduction are the preferred strategies, while landfill is the least favored strategy in the list.

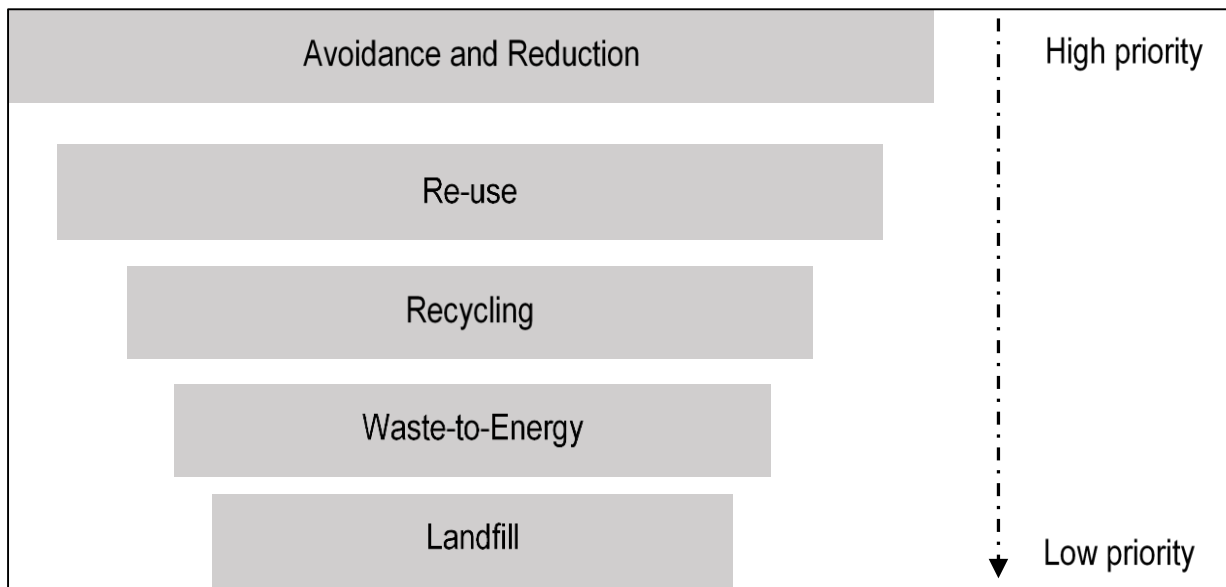


Figure 4.4: Waste management priority hierarchy (Meisen & Morgan, 2010:1)

4.4.2 Evaluation of waste management strategies

Effective waste management commences with avoiding and reducing waste production. This is highly dependent on people's culture and behavior. According to the European Commission (2006:9), reducing waste production will minimize waste management challenges, as the global population continues to increase and natural resources are continuously depleted.

In a situation where waste cannot be avoided, re-use and recycling are the best strategies. Re-use results in a reduction in the consumption of raw materials and minimization of land, water and air pollution (Modoi *et al.*, 2013:166).

Source separation of waste results in an effective and efficient recycling program. Investigations show that most people advocate recycling in managing waste (Ma *et al.*, 2014:23). Materials such as paper, glass, plastic and metals can easily be recycled if waste is separated from the source. Developed countries have adopted the strategy of source separation in their waste management strategies (European Commission, 2006:19).

MSW is composed of combustible materials, much of which cannot be recycled or re-used. Globally, the focus has shifted to view MSW as a useful resource that has been used as the major feedstock in WtE plants (Abila, 2014:182). Electricity and heat energy are generated and the burden on landfill sites is reduced.

Figure 4.5 shows the percentage contribution of WtE incineration, recycling and landfill in managing MSW in Europe. Countries that have used WtE, such as the Netherlands, Sweden, Denmark and Germany, show high recycling ratios (Eurostat, 2009:433). This can serve as proof

that WtE is compatible with recycling. Investigations prove that WtE facilities have become recycling facilities through recovery of materials. Metals can be recovered from APC and bottom ash residue (Brunner & Rechberger, 2014:3).

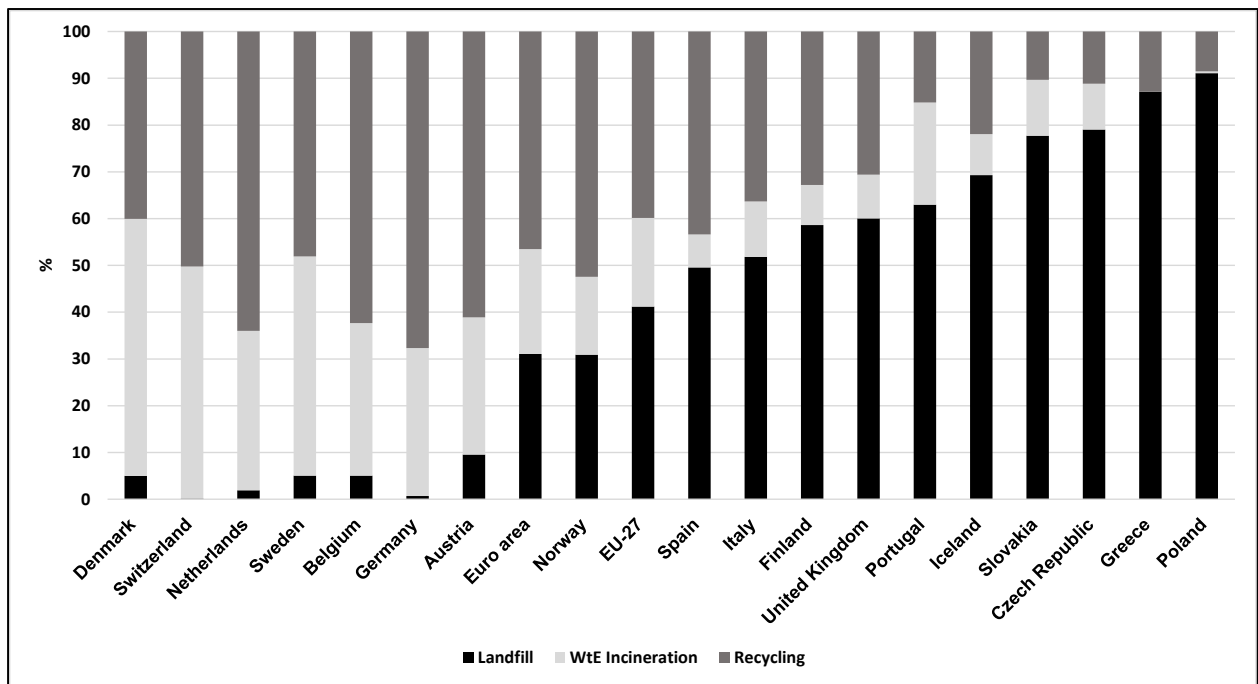


Figure 4.5: Percentage contribution of WtE incineration, recycling and landfill in managing MSW in EU (Eurostat, 2009:433)

Landfill is a missed and ‘wasted’ opportunity and hinders the goal of sustainable waste management (Yassin *et al.*, 2009:315). Landfill has been the predominant MSW management strategy in many countries irrespective of its adverse impact on the environment. Disposal of waste with no material or energy recovery is the least desirable waste management option, since it is an end-of-pipe solution (Modoi *et al.*, 2013:166).

The adverse effects of landfill include greenhouse emissions and leachate development, which results in land, water and air pollution (Meisen & Morgan, 2010:1). Because of this, efforts have been made to divert waste from landfill. WtE has great potential to divert waste from landfill (Tabasová *et al.*, 2012:146). Figure 4.6 shows the percentage contribution of landfill in MSW management trends in European countries. The priority of landfill in managing MSW has been decreasing in European countries.

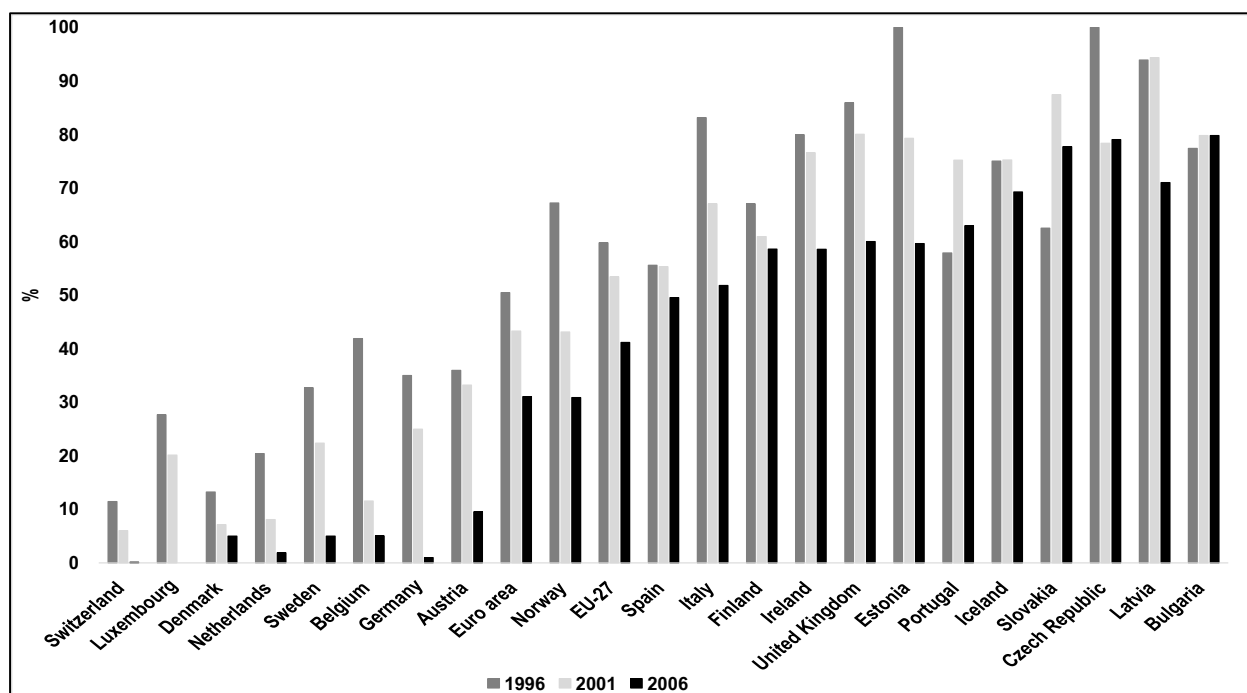


Figure 4.6: Percentage contribution of landfill in management of MSW trends in European countries (Eurostat, 2009:433)

4.4.3 Municipal solid waste management policy

Countries in the European Union (EU) have been guided by a landfill directive policy that aims at diverting MSW from landfill, which has been the major driver of WtE in these countries (IEA Bioenergy, 2010:5).

It has been noted that MSW regulations in countries in the EU are guided by the waste hierarchy presented in Figure 4.4. The MSW management policy is aimed at the desire to decrease landfill and promote resource recovery. This is achieved by levying a charge on material destined for landfill and banning specific waste streams to the landfill (IEA Bioenergy, 2010:5).

Optimization of resource recovery has been achieved by supporting source separation, recycling and recovery activities in countries' waste policies. This has resulted in an increase in recycling and a decline in landfill levels (IEA Bioenergy, 2010:5). Waste management practices have also been influenced by other policies, such as energy and climate change policies.

EU waste policy directives support treatment of residual MSW in WtE facilities. This is on condition that the WtE plants maintain high environmental standards and high energy efficiency. WtE has been included in the renewable energy policy as a contributor to renewable energy targets (IEA Bioenergy, 2010:5).

4.5 Medical waste management

Medical waste is regarded as waste that is generated in all medical health care services and medication activities and is classified into general waste and hazardous waste (ICRC, 2011:12). Seventy-five percent to 90% of medical waste can be classified as general waste and can be treated as MSW, while 10% to 25% can be classified as hazardous waste (ICRC, 2011:12).

Medical waste requires a proper waste management system so as to minimize its risks to human beings and the environment in general. The waste management hierarchy presented in section 2.6.1 is applied in the management of medical waste.

Waste reduction from the source can be achieved through careful selection of products that generate minimum waste, selecting suppliers who re-use containers such as those for cleaning materials, minimizing wastage in the course of health care and selecting materials that can be re-used rather than discarded (ICRC, 2011:12).

Thermal treatment of medical waste is the best strategy in treating hazardous medical waste. Thermal treatment of medical waste can be classified as low and high temperature treatment methods (ICRC, 2011:12).

The low temperature treatment operates in a temperature range of 100°C to 180°C. Low temperature treatment methods can further be classified as vapor methods, which include autoclaves, or hot air methods (ICRC, 2011:12).

High temperature treatment occurs in a temperature range of 200°C to >1000°C. Incineration at high temperature has the ability of treating hazardous medical waste so as to minimize its adverse impacts on the environment and people (ICRC, 2011:12).

Using a high temperature (>1000°C) to incinerate medical waste has advantages, such as complete destruction of waste, a significant reduction in waste volume and weight, treatment of large quantities of waste and being suitable for all types of waste (ICRC, 2011:12).

4.6 Conclusion

The aim of the chapter was to review WtE grate incineration power plant economics and waste management strategies. WtE thermal technologies are associated with high capital investment, operational and maintenance cost. The plant economics are influenced by factors such as the size and design of the facility, legal aspects, labor cost, the cost of consumables, potential for heat utilization and the market price for energy, among others (Moora *et al.*, 2012:237; Rand *et al.*, 2000:118).

The review work on WtE grate incineration power plant capital (Section 4.2) and operating (Section 4.3) cost was published in the peer-reviewed conference proceeding of ICUE 2015 (Appendix B).

The high capital cost involved in a WtE grate incineration power plant is the major hindrance to the implementation of this technology.

WtE grate incineration proves to meet the goal of sustainable waste management, which is to protect man and the environment and conserve resources. The operating temperature of WtE grate incineration technology allows it to treat hazardous medical waste safely.

WtE thermal technologies have not been implemented in many developing countries, inclusive of South Africa. The next chapter is aimed at performing a SWOT analysis of WtE grate incineration for a small South African city.

CHAPTER 5

WASTE-TO-ENERGY GRATE INCINERATION PLANT SWOT ANALYSIS

5.1 Introduction

The purpose of this study is to perform a techno-economic evaluation of a WtE grate incineration power plant for a small South African city. MSW management challenges, electricity power shortages and high unemployment rates can be viewed as WtE grate incineration technology opportunities. The objective of this chapter is to carry out a SWOT analysis for a WtE grate incineration power plant for a small city in the North-West Province, Potchefstroom, as portrayed in Figure 5.1.

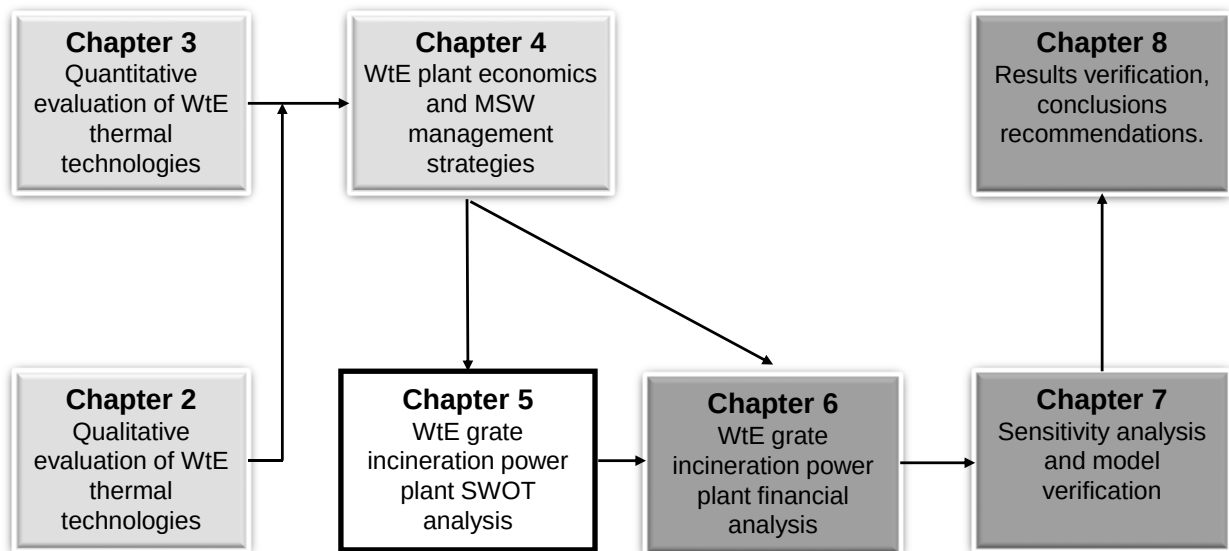


Figure 5.1: Research roadmap position 4

The chapter begins by presenting a WtE grate incineration power plant SWOT analysis in section 5.2. MSW management (Section 5.3) and generation (Section 5.4) trends in South Africa are discussed. This is followed by deliberating on HCRW generation and management (Section 5.5), South Africa's energy scenario (Section 5.6) and WT management (Section 5.7). Section 5.8 present carbon tax and carbon credits scenario in South Africa. WtE grate incineration power plant threats in South Africa are presented (Section 5.9). A case study on Tlokwe municipality (Potchefstroom) is positioned in section 5.10 and the chapter concludes in section 5.11.

5.2 Waste-to-energy grate incineration power plant SWOT analysis.

SWOT analysis is a tool used for analysing internal and external environments in order to ensure a systematic approach and support in making decisions (Kurttila *et al.*, 2000:41). Strengths and weaknesses are regarded as internal factors, while opportunities and threats are external factors (Hill & Westbrook, 1997:46; Kurttila *et al.*, 2000:41; Pickton & Wright, 1998:101).

In this study, SWOT analysis is applied by regarding WtE drivers and barriers for the small city case study as internal factors, while drivers and barriers outside the small city but within South Africa are regarded as external factors. Table 5.1 summarizes the strengths, weaknesses, opportunities and threats associated with establishing a WtE grate incineration power plant in Potchefstroom, a small city in the North-West Province.

Table 5.1: South African small city (Potchefstroom) WtE grate incineration power plant SWOT analysis

Small city internal WtE investment drivers and barriers	
Strength - MSW characterized by more than 80% of combustible material (Section 5.10.4). - Significant percentage of metals promotes material recovery (Section 5.10.4). 98.3% dominance of landfill as MSW management strategy for the small city (Section 5.10.3). - Average MSW generation growth rate 3.04% per annum (Section 5.10.1). - Increased illegal dumping in the small city (Section 5.10.3).	Weakness - Dominance of wet months in a year in the small city (Section 5.10.5). - MSW yearly tonnages fluctuations (Section 5.10.2). - Local culture of non-payment for service especially in the African and colored settlements (Section 5.9.4). - Absence of landfill diversion measures evidenced by no cost to dump waste at the landfill (Section 5.9.2).
Small city external WtE investment drivers and barriers	
Opportunities 90% dominance of landfill as MSW strategy at national level (Section 5.3). - National waste generation growth rate estimated 3.0% per annum (Section 5.4). 34% of non-recyclable combustible waste in the national MSW characterization (Section 5.4). - National power crisis, promotion of renewable energy (Section 5.6) - Intermittent nature of solar and wind energy (Section 5.6). - Non-energy recovery methods used to treat HCRW (Section 5.5). - Accumulation of waste vehicle tyre stockpile nationwide (Section 5.7). - Anticipated implementation of carbon tax and offset incentives in the country (Section 5.8)	Threats - WtE thermal technologies are not allocated generating capacity in the REIPPP (Section 5.6.4). - Lack of enforcement of environmental legislation in the country hampers technological innovation in the waste sector (Sections 5.9.1 and 5.9.2). - High capital cost that requires access to investment subsidy from government institutions (Section 5.9.3).

5.3 Municipal solid waste management trends

The constitution of South Africa offers every individual the right to a safe and healthy environment and promotes sustainable protection of the environment. This aligns with the global generic goal of waste management, which is to protect man and the environment and conserve resources (Brunner & Rechberger, 2014:3).

South Africa's waste hierarchy was amended in the national waste management strategy of 2011. The waste hierarchy lists in order of decreasing priority, waste avoidance, re-use, recycling, energy recovery and landfill (Muzenda, 2014:105). The strategy was aimed at alignment with the globally accepted waste management hierarchy (DEA, 2011:1).

Investigations reveal that landfill dominates other waste management strategies in South Africa, regardless of the amendment of the waste hierarchy in 2011 (Godfrey *et al.*, 2014:1; Muzenda, 2014:105). Landfill accounts for approximately 90.1% of waste generated in the country. It was noticed that MSW accumulation in uncontrolled dumpsites is rampant in South African cities (Godfrey *et al.*, 2014:1).

Investigations indicate that WtE thermal technologies make no contribution to the country's current MSW management strategies (Godfrey *et al.*, 2013:1). The current MSW management trends in South Africa offer an opportunity to implement WtE thermal technologies.

Significant waste divergence from landfill can be achieved in the country through WtE thermal technology initiatives. Figure 4.4 reflects the experience of countries that have implemented WtE thermal technologies. There is a noticeable decrease in landfill usage in countries that employ WtE thermal technologies.

The contribution of recycling to national waste management is estimated at 9.8% of the total waste generated (DEA, 2012:1). The informal sector is the major contributor to the country's recycling activities. A survey carried out by the DST shows that 60 000 to 90 000 South Africans are sustained by recycling activities (Godfrey *et al.*, 2013:1).

WtE thermal technologies can boost recycling activities in the country considerably. Countries that have implemented WtE thermal technologies attest that WtE facilities appreciably improve material recovery. WtE facilities promotes recycling through metals recovered from APC and bottom ash residue and in the feedstock preparation stage (Brunner & Rechberger, 2014:3).

5.4 Municipal solid waste generation trends.

The government of South Africa has moved towards recognizing the waste sector as an industry that can contribute positively to economic growth and job creation (Godfrey, Strydom *et al.*,

2013:1; Godfrey, Rivers *et al.*, 2014:1). South Africa has been identified as an emerging market with exciting possibilities in the waste management sector (Godfrey *et al.*, 2014:1).

According to the national waste information baseline report of 2012, the national average per capita waste generation is estimated at 349 kg/capita/annum (DEA, 2012:1). The per capita waste generation per province is shown in Figure 5.2.

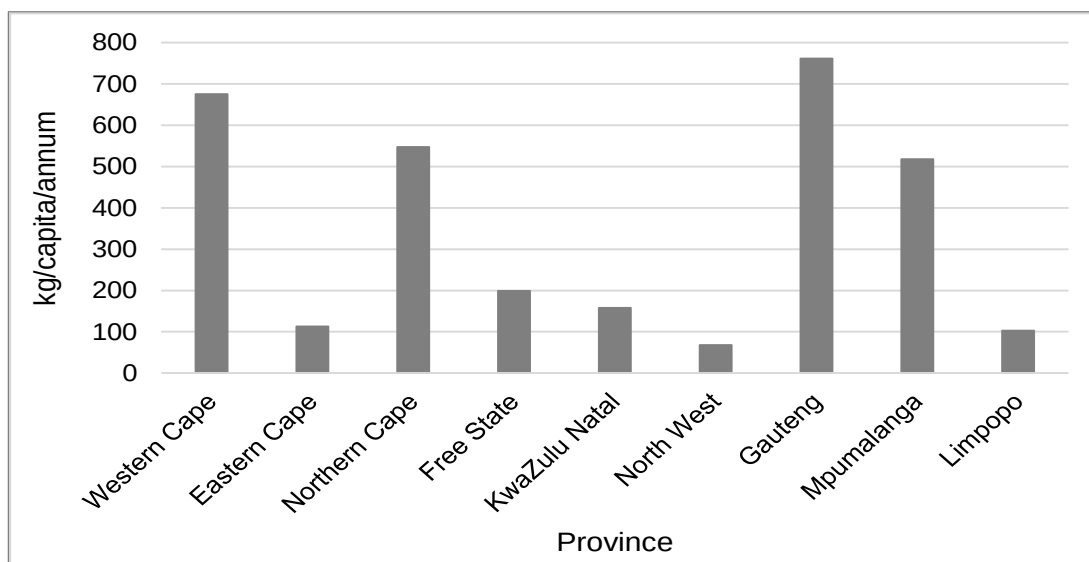


Figure 5.2: Provincial waste generation per capita per annum (DEA, 2012:1)

MSW national generation was at 59 million tonnes in 2011. The national waste generation growth rate is estimated at 3.0% per annum (DEA, 2012:1). The provincial percentage contribution to MSW generation is shown in Figure 5.3.

The MSW composition is dominated by combustible non-recyclable waste with a percentage contribution of 34%. Table 5.2 shows South Africa's general waste composition by 2011.

WtE thermal technologies stand the best chance of managing combustible non-recyclable waste in a sustainable manner. Large quantities of combustible non-recyclable waste and organic waste offer a noticeable opportunity of implementing WtE thermal technologies. Investigations also proved that South African industries produce large quantities of biomass waste, estimated at 36 tonnes per annum (Godfrey *et al.*, 2014:1).

MSW generation trends and characteristics, as well as industrial biomass generation trends, present an opportunity to employ WtE thermal technologies in the country's waste management strategies mix.

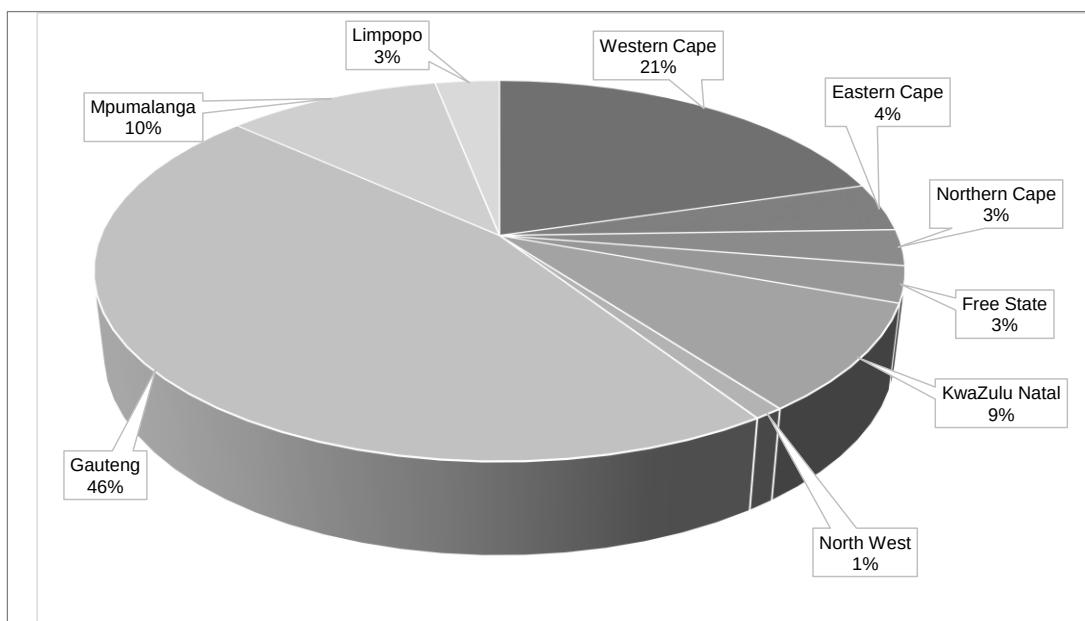


Figure 5.3: Provincial percentage contribution to South Africa total MSW generation (DEA, 2012:1)

Table 5.2: General waste composition (DEA, 2012:1)

Waste type	Percentage contribution (%)
Glass	4
Plastics	6
Paper	7
Tyres	1
Combustible non-recyclable MSW	34
Organic waste	13
Construction and demolition waste	21
Metals	14

5.5 Health care risk waste generation and management

The number of South African health care facilities has been increasing since 1994 and by 2014 there were approximately 4200 public health care facilities (Tibane & Vermeulen, 2014:226). HCRW calls for a proper waste management system to minimize its risks to human beings and the environment.

HCRW in South Africa includes infectious waste, sharps, pathological waste, chemical waste and radioactive waste (Otto & Clements, 2008:1).

HCRW generators are classified as major and minor generators, as shown in Table 5.3. The Waste Act section 16(1) states that it is the duty of the waste generator to ensure waste is treated and disposed of in an environmentally sound manner. SANS (2004:5) further affirms that it is the responsibility of the HCRW generator to ascertain that the HCRW is managed, treated and disposed in a safe manner.

Table 5.3: HCRW generators in SA (Otto & Clements, 2008:1)

Major HCRW generators	Minor HCRW generators
Hospitals – owned and operated by provincial government, the private sector, mines.	Laboratories - Private and public pathology laboratories, as well as research laboratories.
Clinics - owned and operated by provincial government, local government, the private sector and industries.	Pharmaceutical industry, veterinary services, specialized institutions and private homes.
Blood transfusion services.	Health care practitioners such as doctors, dentists, specialists and allied practitioners such as acupuncturists, chiropractors and various therapists.

In South Africa HCRW generation was estimated at 45 232 tonnes per annum in 2011. Gauteng province made the highest percentage contribution to HCRW (DEA, 2012:1; Otto & Clements, 2008:1). Figure 5.4 shows the HCRW generation percentage contribution per province.

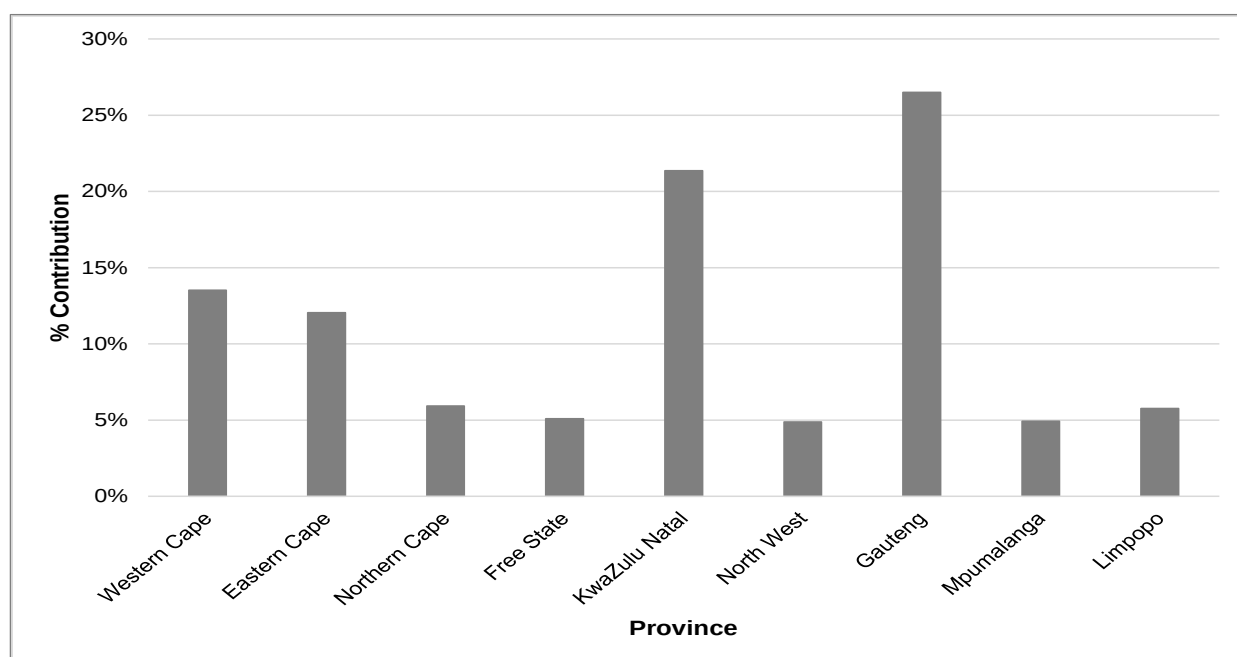


Figure 5.4: HCRW generation percentage contribution by province (Otto & Clements, 2008:1)

Waste incineration is the recommended HCRW management strategy. A survey done by DEAT proves that South Africa has sufficient incineration treatment capacity. Nevertheless, the

treatment facilities are not decentralized and there is no energy recovery during incineration (Otto & Clements, 2008:1; Purnell, 2014:1). Significant illegal dumping of HCRW has been witnessed, with Gauteng recording most HCRW illegal dumping incidents (Otto & Clements, 2008:1).

According to Otto (2008:1), the viable treatment cost using incineration in 2008 was on average R3 700 per tonne of HCRW. Consultation with the local health care facility revealed that the cost of HCRW treatment was estimated at R6 300 per tonne in 2014.

WtE grate incineration power plants operate at temperatures in the range of 800°C to 1450°C. The temperature range experienced in a WtE power plant is suitable for treating HCRW. Treating HCRW in WtE grate incineration facilities has the following advantages: energy recovery, low treatment cost and large treatment capacities. Tapping into the opportunity of HCRW as secondary feedstock in a WtE grate incineration power plant can significantly transform the HCRW management system in South Africa.

5.6 South Africa's energy scenario

In 2014, South Africa was hit with blackouts in its major cities due to a shortfall in electrical energy generation capacity (Wentworth, 2014:1). The shortfall in generation capacity was a result of increased demand, failure to invest in additional supply and limited power plant maintenance.

The higher demand for electricity in South Africa is result of a combination of factors, such as economic growth and industrialization and the move to improve the lives of people through household electrification (Pegels, 2010:4945).

The current energy crisis in the country is a repetition of the 2008 electrical energy shortages. According to Singh (2011:1), South Africa will experience a great risk of electrical energy supply interruptions between 2018 and 2024, necessitating increased generation capacity to mitigate the anticipated supply interruptions.

The next section discusses the energy scenario in South Africa as a driver for the use of WtE grate incineration thermal technology in power generation and is outlined as follows: South Africa's energy mix (Section 5.6.1), the move to renewable energy (Section 5.6.2), the intermittent nature of solar and wind energy (Section 5.6.3), and IPP in South Africa (Section 5.6.4).

5.6.1 South Africa's energy mix

Power generation in South Africa is dominated by coal plants, which are owned and operated by Eskom (Serfontein, 2014:1). About 86% of South Africa's electrical energy is generated from coal-fueled power plants (Singh, 2011:1). This is followed by nuclear-powered plants, which contributes about 4% of the country's electrical energy. Figure 5.5 shows the percentage

contribution by source to South Africa's energy mix in 2010. Fossil fuels, gas, coal and oil dominate with a total percentage contribution of 92% to the country's energy mix.

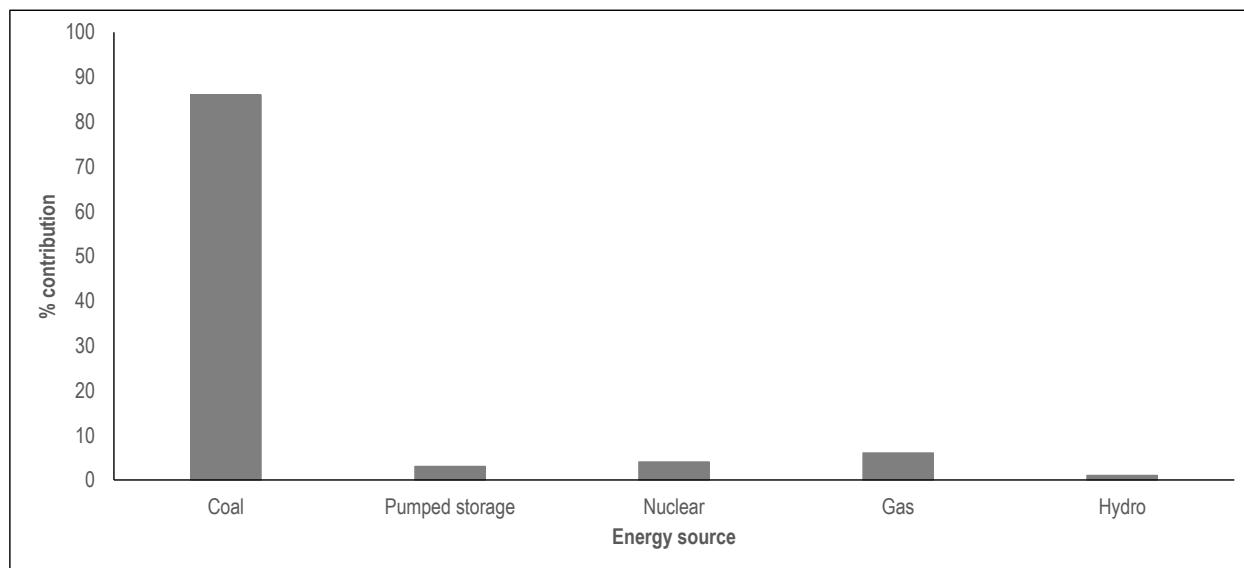


Figure 5.5: Percentage contribution by source to the South Africa energy mix in 2010 (Singh, 2011:1)

In a move to promote sustainable development through renewable energy, the DoE proposed a shift in the country's energy mix. Figure 5.6 shows the anticipated energy mix by 2030. The move is also seen as a measure to secure diversity in the supply of electrical energy in the future (DoE, 2011:1).

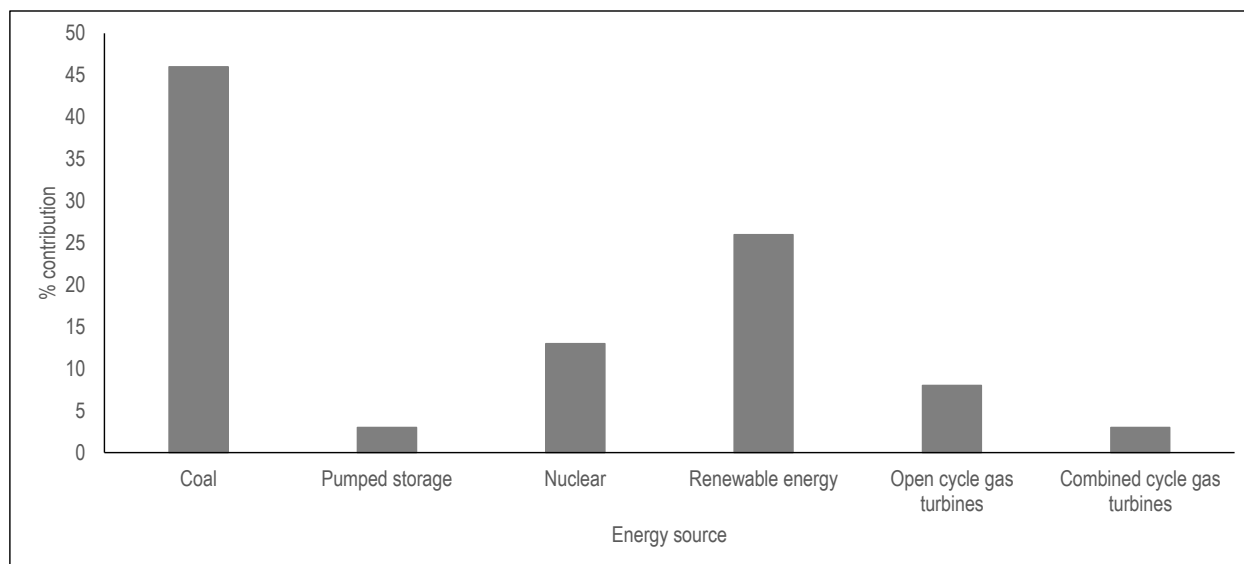


Figure 5.6: South Africa's anticipated energy mix by 2030 (Singh, 2011:1)

The promotion of renewable energy is a driver in the implementation WtE thermal technologies in South Africa. Section 5.6.2 discusses the move by the DoE towards renewable energy sources as a way of promoting a sustainable energy mix in the country.

5.6.2 South Africa's move to renewable energy

The DoE's strategic plan is to transform the energy sector in South Africa by promoting a diverse energy mix and providing quality and affordable energy. The DoE also seeks to ensure sustainable development through securing energy security activities (DoE, 2011:1). Renewable energy sources are encouraged in an attempt to meet global targets on minimizing the adverse effects of energy production (DoE, 2011:1; DoME, 2004:1).

Renewable energy is the fastest growing technology in the global energy mix, with a growing rate estimated at 8.2% by 2010 (Singh, 2011:1). In line with global trends, the DoE Integrated Resource Plan promotes renewable energy contribution to South Africa's energy mix as illustrated in Figure 5.6.

The renewable energy mix in South Africa comprise wind, solar energy, small-scale hydro generation, biomass and bagasse. MSW is also listed as a potential source of energy in the country. It is estimated that MSW equivalent to 11 000 GWh is wasted in South African landfill per annum (DoE, 2011:1).

The wasted energy in the landfill can be harnessed through direct incineration and by using methane gas. WtE thermal technologies best suit urban areas where a large amount of waste is produced and the costs of landfill sites are relatively high (Stengler, 2012:1).

International Energy Agency statistics point out that residual MSW has the potential of replacing 2% of fossil fuel in South Africa (IEA Bioenergy, 2010:5), thus WtE technology can make a significant contribution to the country's renewable energy mix.

5.6.3 The intermittent nature of solar and wind energy

South Africa's renewable energy sector is dominated by wind and solar energy. According to Serfontein (2014:1), increasing the share of wind and solar power in the national grid might result in a long-term crisis. A large amount of intermittent renewables in the grid causes grid crush (Serfontein, 2014:1). This is due to their spasmodic nature, which is unable to supply power at all times and when it is needed most.

Solar energy power output is fixed to a daylight time frame. This means on a cloudy day and during the night concentrated solar power and solar photovoltaic cells will not produce power (Serfontein, 2014:1). Wind power output fluctuates with the presence of wind. The load factor of

both wind and solar energy facilities is noticeably low. According to Serfontein (2014:1), the intermittency of wind and solar power can result in national grid instability with catastrophic consequences for the economy.

Unlike wind and solar energy, a WtE grate incineration power plant has load flowing characteristics and has no intermittency problem. A WtE grate incineration power plant can be classified among peaking technologies and can operate 24 hours a day. The capacity factor of a WtE power plant is approximated at 90%. Implementation of WtE grate incineration technology can significantly boost renewable energy and increase national grid security in South Africa.

Intermittent renewable technologies are significantly affected by day-time electricity prices. Consideration of day-time prices makes wind and solar power less favorable (Serfontein, 2014:1). In contrast to intermittent technologies, WtE grate incineration is not affected by day-time prices because of its load-flowing nature.

5.6.4 Independent power producers in South Africa

In a bid to ensure energy security and improve electric power supply efficiency the cabinet of South Africa decided that Eskom should share electricity generation capacity with IPP. The newly adopted electricity generation capacity is shared between Eskom and IPP in the ratio of 7:3 (Eberhard, 2014:1).

The promotion of IPP in the country coincided with the move by the DoE for a greener energy mix by 2030. To achieve the anticipated greener energy mix, the contribution of IPP is of significance. The phasing in of IPP in the renewable energy sector increases the potential of WtE grate incineration implementation in the country.

The elevation of IPP has been boosted by government's renewable energy procurement process through the DoE. The current competitive tender procurement process, referred to as the renewable energy independent power producer procurement program (REIPPP), replaced the feed-in tariffs strategy of 2009, which was initially adopted by the DoE (Eberhard, 2014:1).

The REIPPP is designed to promote renewable energy to match global trends and uphold the goal of sustainable development. There have been four bidding windows between 2011 and 2014, with 4 116 MW generation capacity procured from IPP by the DoE. The DoE had entered into agreements with 62 bidders by 11 December 2014 (DoE, 2015:1).

With regard to bidding window 4, the department selected 13 preferred bidders out of 77 bidders. A total of 1 105 MW generation capacity was allocated. Stiff bidder competition was noted in solar

and wind power, resulting in a price drop of respectively 25% and 21% from bidding window 3 (DoE, 2015:1).

With reference to REIPPP bidding windows 3 and 4, there has been little participation by biomass and landfill gas technology bidders. In bidding window 3, 15 MW and 0 MW generating capacity was awarded to landfill and biomass respectively. Bidding window 4 had 0 and 25 MW generating capacity allocated to landfill and biomass respectively. Table 5.4 shows summarized results of REIPPP generation capacity allocation in bidding windows 1 to 4.

Table 5.4: REIPPP total allocated and remaining generation capacity (DoE, 2015:1)

Technology	Total allocated and remaining generation capacity (MW) in bidding windows 1 to 4					
	Window 1 allocated capacity (MW)	Window 2 allocated capacity (MW)	Window 3 allocated capacity (MW)	Window 4 allocated capacity (MW)	Total allocated capacity (MW)	Total remaining capacity (MW)
Solar photovoltaic	632	417	435	415	1899	626
Onshore wind	634	563	787	676	2660	660
Concentrated solar power	150	50	200	0	400	0
Small hydro (< 40MW)	0	14	0	5	19	116
Landfill gas	0	0	18	0	18	7
Biomass	0	0	16	25	41	19
Biogas	0	0	0	0	0	60
WtE thermal technologies	0	0	0	0	0	0

The participation of bidders in landfill gas and biomass technologies is minimal, with no bidder for landfill gas and only one for biomass technology in bidding window 4 (DoE, 2015:1). WtE thermal technologies were not allocated generating capacity in the REIPPP. There has thus been no participation in WtE thermal technologies (Rycroft, 2013:1). The results of this study are aimed at promoting WtE grate incineration as a viable source of green energy in South Africa.

Minimum competition in technologies related to WtE thermal technologies has resulted in a favorable bidding price per MW. In bidding window 4 biomass was awarded at R1.45 per kWh.

5.7 Waste vehicle tyre management

Waste vehicle tyre (WT) has excellent thermal properties with their net caloric value comparable to that of good quality coal (Secretariat, 2002:1). Thus WT can be used as supplementary sources of energy through energy recovery methods such as WtE grate incineration and pyrolysis

(Sharma *et al.*, 2000:381). This section include a discussion on WT composition (section 5.7.1), WT thermal properties (section 5.7.2) and WT scenario in South Africa (section 5.7.3)

5.7.1 Waste vehicle tyre composition

Vehicle tyres are largely composed of rubber compound, 80% in light and 75% in heavy vehicles by weight. WT on average have a total mass of 6.5 kg and 53 kg for passenger and truck vehicles (Secretariat, 2002:1). Table 5.5 shows material composition of light and heavy WT. Large amount of metals can be recovered from WT as indicated by composition in Table 5.5.

Table 5.5: Waste vehicle tyre composition (Secretariat, 2002:1; Sharma *et al.*, 2000:381)

Material	Passenger Car (%)	Truck (%)
Rubber/ Elastomers	47	45
Carbon Black	21.5	22
Metal	16.5	25
Textile	5.5	--
Zinc Oxide	1	2
Sulphur	1	1
Additives	7.5	5

5.7.2 Waste vehicle tyres thermal properties

WT are an excellent potential fuel with a tonne of WT derived fuel caloric value equivalent to about 0.7 ton of fuel oil. Table 5.6 shows the comparison of WT derived fuel calorific value with other commonly used fuels.

Table 5.6: Comparison of Waste vehicle tyre caloric value with other fuels (Secretariat, 2002:1)

Fuel	Grade	Heat content (MJ/kg)
Gas	Natural	2.3
WT derived fuel	WT derived fuel	36.0
Coal	Sub-bituminous	24.4
Coal	Bituminous	29.5
Wood	Wet wood –hog fuel	10.1

WT can be utilized as supplementary fuel in a WtE grate incineration power plant because of its high calorific value and dry nature. Seasonal changes affects the low heating value (LHV) of

MSW and thus affect operational efficiency of WtE grate incineration plant. To this end WT can be used to stabilize variations in LHV of MSW, thus resulting in increased system efficiency.

5.7.3 Waste vehicle tyre scenario in South Africa

Muzenda (2014:105) maintains that South Africa is currently faced with problems in WT management. It is stated that there are over 60 million WT in South Africa. The illegal dumping and disposal of WT poses significant environmental problems. Landfill and stockpiling are the commonly used WT management strategy in South Africa (Muzenda, 2014:105).

The millions of WT lying in stockpiles, landfill and scattered in residential, industrial and rural areas are posing serious environmental and health problems. WT stockpiling causes significant problems such as breeding of insects and rodents, as well as risk of uncontrollable burning, which cause air pollution (Muzenda, 2014:105; Secretariat, 2002:1).

In a bid to mitigate the ever increasing WT problem in the country, the recycling and economic development initiative of South Africa (REDISA) was established. REDISA is a non-profit organization that was formed with the aim of implementing integrated WT management and its plan was approved by the Minister of Water and Environmental Affairs, according to Government Gazette No. 35927. The plan was designed using the Waste Act 28 (1) and was to be implemented throughout South Africa.

The waste hierarchy promotes re-use and recycling first and energy recovery as the last resort in WT management (Government, 2012:1). Disposal by landfill is not permitted, though illegal dumping is rampant (Muzenda, 2014:105). Figure 5.7 show the REDISA WT management hierarchy.

The 3R waste management strategies will not match the rate of WT accumulation in South Africa (Muzenda, 2014:105). To this end energy recovery, using WtE thermal technologies, can be implemented to make up for untreated WT.

The management of WT using WtE grate incineration has a number of advantages, namely energy-recovery in form of electricity and process steam, low air-pollution emissions and reduction in carcass volume by 90% (Sharma *et al.*, 2000:381).

Including WT as a supplementary feedstock to a WtE grate incineration power plant has the potential of improving its financial model performance. This is possible through improving the feedstock LHV, thus boosting power generated. WT can also be used as revenue income stream through gate fees. This however cannot be a sustainable source of income as there is possibility that as the demand of WT rises, WT producers can require payment. Therefore, instead of WT

being a revenue stream, it will cost WtE plant to process them.

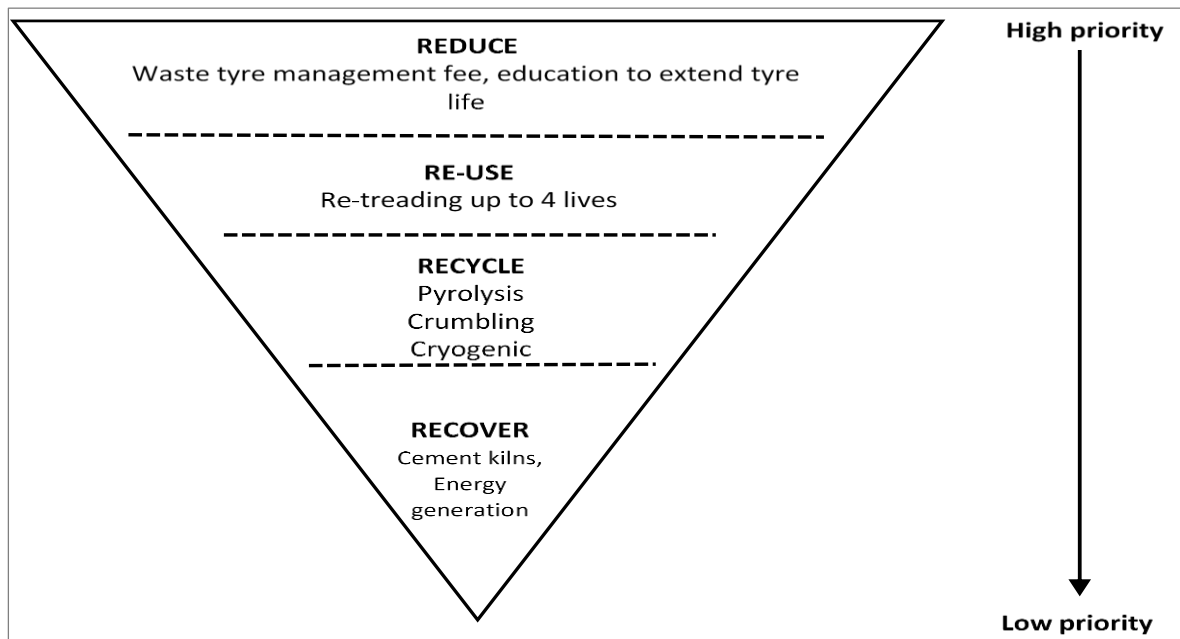


Figure 5.7: REDISA waste tyre management hierarchy

Regulations state that WT must be included in a recycling or energy recovery process within five years (Government, 2012:1). This implies that energy recovery is promoted in mitigating environmental problems caused by WT.

5.8 Carbon tax and carbon credits

Since 2007, South Africa has been in the process of proposing carbon tax, a measure towards reducing green-house gases emissions through energy efficiency, reduction in use of fossil fuels and promoting renewable energy (DNT, 2014b:1). Carbon tax policy and carbon offsets paper were published in 2013 and 2014 respectively by the Department of National Treasury (DNT). This was in a bid to facilitate the process of implementing carbon tax in the country.

The DNT states that carbon tax will be introduced to facilitate transition to a low-carbon economy. The government of South Africa is moving towards cutting green-house emissions by 34% and 42% in 2020 and 2025 respectively (DNT, 2013:1). The move is significantly subject to the availability of sufficient financial, technological and capacity-building support by developed countries.

In order to include the cost of pollution on goods and services, carbon tax will be used as instrument that will ensure polluters, both producers and consumers, held accountable (DNT, 2013:1). To this end, major consumers of electricity such as municipalities will incur large carbon tax. The use of alternative green energy such as WtE grate incineration can assist in offsetting such huge amount carbon tax.

The carbon tax policy paper also states that subsidies can be offered to projects and investments that promote environmental improvements. WtE grate incineration minimize the use of landfill, thus reducing green-house gas emissions in form of methane. Therefore, such provisions can be a source of revenue for a WtE grate incineration plant.

WtE grate incineration reduce green-house gas emissions by approximately 13 000 tonnes carbon-dioxide equivalent for every 100 000 tonnes of MSW processed. For combined heat and power systems, green-house gas emission are lowered by roughly 23 000 tonnes carbon-dioxide equivalent (IEA Bioenergy, 2010:5). This means for a 200 000 tonnes capacity WtE grate incineration plant, carbon credits equivalent to 26 000 tonnes carbon-dioxide equivalent can be earned.

The carbon tax rate was proposed at R120 per tonne carbon-dioxide equivalent, planned with effective from 1 January 2015 (DNT, 2013:1). The proposal further states that the carbon tax was supposed to increase a rate of 10% per annum until December 2019. This could not be implemented due to uncertainties in the process. The new proposed carbon tax implementation date is set to be January 2016.

Carbon offset is defined as, “an (external) investment that allows a firm to access GHG mitigation options in a manner that is cheaper than investment in its own operations” (DNT, 2014a:1). Investment in projects that reduce and avoid green-house gas emissions are regarded as carbon offsets. WtE grate incineration power plant qualifies on carbon offsets since it is classified as source of green energy. South Africa major green-house emitters, such as Eskom and Sasol with emission estimated at 250 million tonnes and 70 million tonnes carbon-dioxide equivalent per year (Urban Earth, 2012:1), can invest in WtE grate incineration to acquire carbon offset incentives.

Carbon tax and carbon offset credits are incentives that can significantly contribute positively to the financial performance of a WtE grate incineration. However, the financial analysis model in this study did not include carbon tax and carbon offset credits due to uncertainties in the implementation of these initiatives in South Africa.

5.9 Threats to waste-to-energy technology in South Africa

The South African environment presents implementation possibilities for WtE thermal technologies. MSW and HRCW generation trends and the waste management and energy scenarios in South Africa are WtE thermal technologies drivers. However, high capital cost, landfill diversion measures and the local culture of refusal to pay for services are barriers to the implementation of WtE thermal technologies.

5.9.1 Legislative framework

National environmental management in South Africa facilitated the development of regulations that support the Waste Act. These regulations are aimed at supporting innovation and divergence of waste streams from landfill (Godfrey *et al.*, 2014:1). However, lack of enforcement of environmental legislation has hampered technological innovation in the waste sector.

Investigations show that the authorization of waste management licenses has been hindering novelty and implementation of new technologies in the waste sector. The authorization process is expensive and unrealistically long. Reports of corruption in the system have been received (Godfrey *et al.*, 2014:1).

Enforcement of environmental legislation will encourage different stakeholders to implement alternative technologies in the waste management sector. An effective, efficient and transparent authorization process will attract innovation in the country's waste management sector.

5.9.2 Landfill diversion measures

In developed countries landfill diversion is a major driver of WtE technologies (IEA Bioenergy, 2010:5). Measures such as high fees charged on waste managed through landfill have been instituted. WtE grate incineration power plants' gate fees are relatively low compared to landfill gate fees. This leave waste producers with no other option than using the WtE grate incineration plant as an alternative waste management strategy.

Contrary to this, investigations by Maisiri revealed that no landfill gate fee is levied in South Africa. This makes landfill the cheapest waste management option and waste producers consequently choose this method. Local residents only pay an insignificant flat fee, embedded in their property bills, to local municipalities. Refuse collection fees vary with residential areas.

5.9.3 Waste-to-energy thermal technologies high capital investment

WtE thermal technologies involves high capital investment, operational and maintenance costs. In comparison with other renewable energy technologies, the capital cost of a WtE power plant makes it an unfavorable investment option. South Africa has no operating WtE thermal technologies at present. The capital-intensive nature of WtE thermal technologies calls for long-term security to investors.

The capital cost of WtE technologies in South Africa has not been well researched (Purnell, 2014:1). The capital investment figures used are taken from the experience of other countries that use WtE thermal technologies. Because of the availability and low cost of material, the estimated capital cost of WtE thermal technologies in South Africa might be significantly lower.

5.9.4 Local culture

The financial viability of a WtE grate incineration power plant in developed countries is noticeably influenced by the MSW gate fees. A negative price on waste has resulted in the success of many WtE grate incineration power plant projects. This means that waste producers must pay a fee to the plant operator for their waste to be processed (IEA Bioenergy, 2010:5).

The local culture of non-payment for service, mainly encountered in African and colored communities (Fjeldstad, 2004:539), promotes failure of the waste negative price model. This adversely affects the financial viability of a WtE power plant.

Non-compliance with services rates in South Africa is due to the culture of non-payment and entitlement as well as poverty, among other factors (Fjeldstad, 2004:539). The culture of non-payment is common among township residents who believe that public services, such as housing, water, electricity, health and refuse collection, must be free of charge. Most residents believe that they fought for their political liberation, hence they are entitled to free services (Fjeldstad, 2004:539).

The local culture might necessitate a WtE plant financial model that will have a positive price on waste. This means that the WtE plant operator will have to pay waste generators for their waste to be processed. This decreases the anticipated revenue streams and may cause financial instability in a WtE grate incineration power plant. Nevertheless, that model will grantee residual waste stockpile for the plant.

5.10 Tlokwe municipality case study

An MSW management survey was performed for the Tlokwe municipality of Potchefstroom in the North-West Province. Data were collected through interviews (Appendix D) with representatives from the department of waste management. The collected data were analyzed and this section presents the data analysis results. Part of the work in this chapter was published in the peer-reviewed conference proceedings of ICUE 2015, shown in Appendix B.

This section is organized as follows: MSW generation trends (Section 5.10.1), projected MSW generation trends (Section 5.10.2), MSW management strategies (Section 5.10.3), MSW characterization (Section 5.10.4) and MSW dampness (Section 5.10.5).

5.10.1 Municipal solid waste generation trends

MSW generation is on an upward trend due to the expansion of the small city and population growth. Figure 5.8 shows MSW generation trends for Tlokwe municipality. The average MSW generation growth rate was calculated at 3.04% per year.

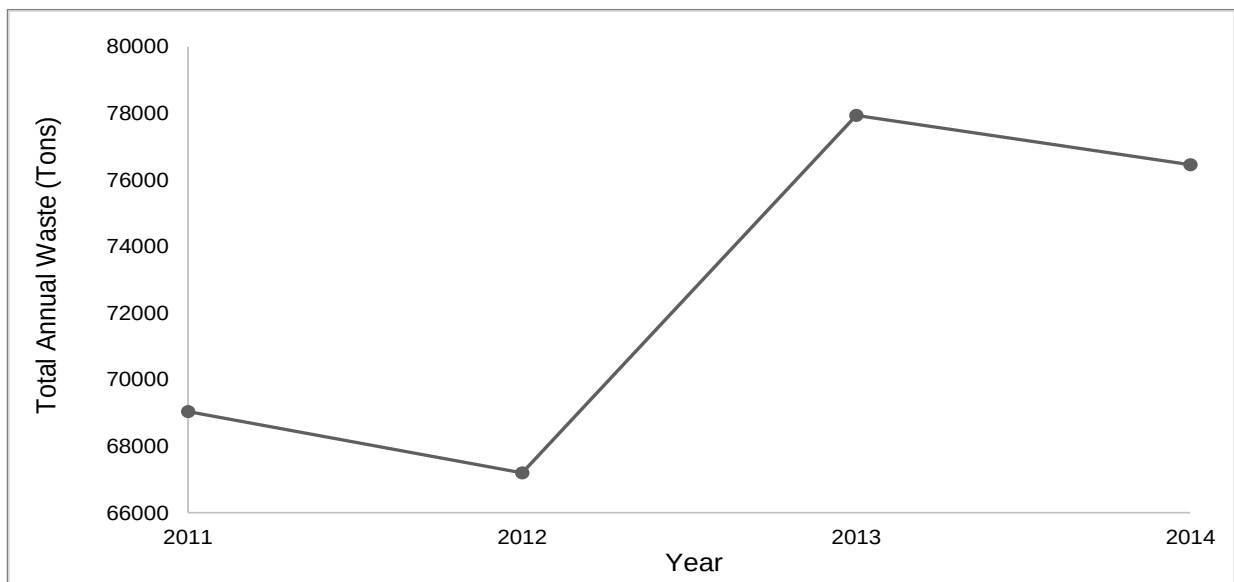


Figure 5.8: MSW generation trends for Tlokwe municipality (Potchefstroom)

5.10.2 Projected municipal solid waste generation trends

A WtE grate incineration power plant's life is estimated at 30 years. MSW generation tonnage was projected using the current average generation growth rate. The linear projection method was used in this analysis. Figure 5.9 shows the projected MSW generation annual tonnage up to 2045.

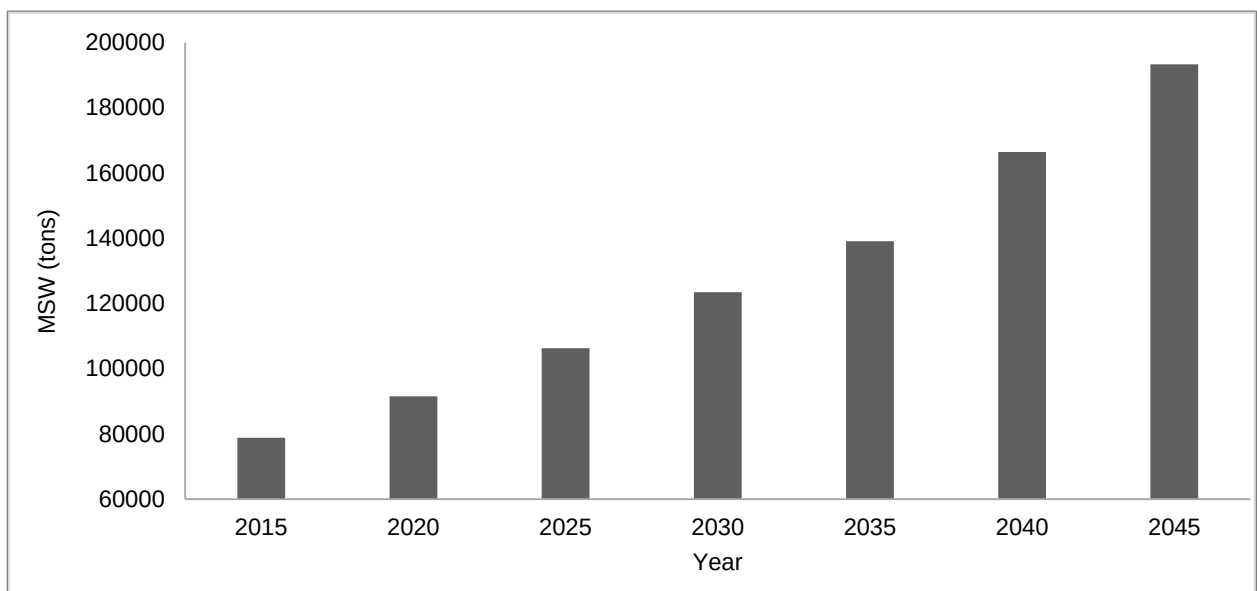


Figure 5.9 MSW generation projection for Tlokwe municipality (Potchefstroom)

5.10.3 Municipal solid waste management strategies

Landfill was identified as the dominant MSW management strategy for the small city of Potchefstroom. On average 98.3% of the waste generated is landfilled while 1.7% is recycled. Figure 5.10 shows the contribution of landfill and recycling to the overall waste management strategy of Tlokwe municipality (Potchefstroom).

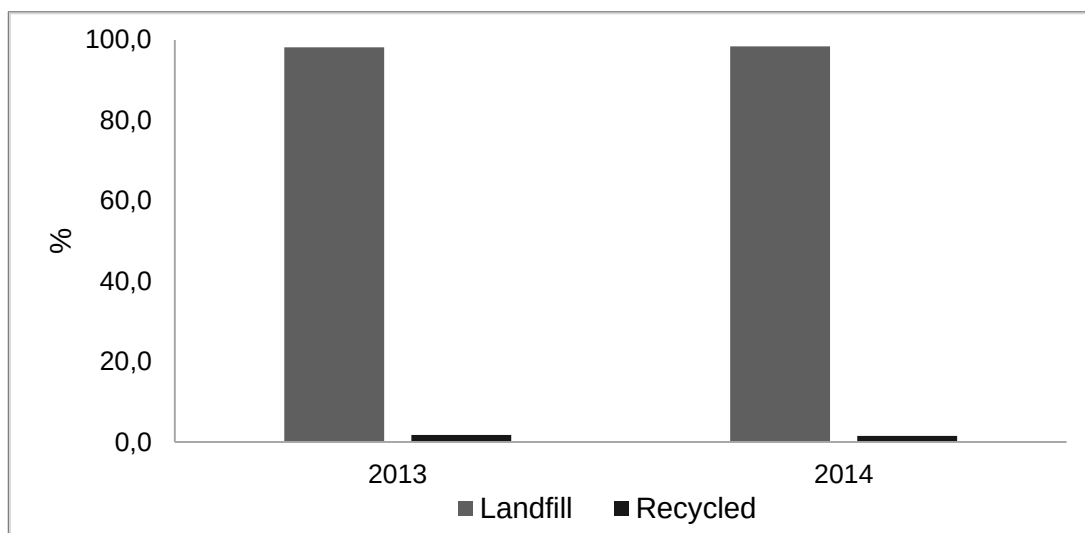


Figure 5.10: Contribution of landfill and recycling to the overall waste management strategy of Tlokwe municipality (Potchefstroom)

5.10.4 Municipal solid waste characterization

Table 5.7 shows MSW characterization for Tlokwe municipality (Potchefstroom). Plastic makes the highest percentage contribution to the composition of the waste, while builders' rubble makes the lowest percentage contribution. The LHV of MSW is estimated at 8.0 MJ/Kg.

Table 5.7: MSW characterization for Tlokwe municipality (Potchefstroom)

Waste Type	Percentage (%)
Builders rubble	2
Plastic	30
Paper	28
Organics, garden waste	8
Metals	6
Glass	13
Other (textile, disposable nappies, tyres, residue and miscellaneous)	13
TOTAL	100

5.10.5 Municipal solid waste dampness

Data analysis results showed that the small city has five dry months in a year. Figure 5.11 shows the rainfall patterns recorded at the landfill. Damp MSW dominates because of wet months recorded.

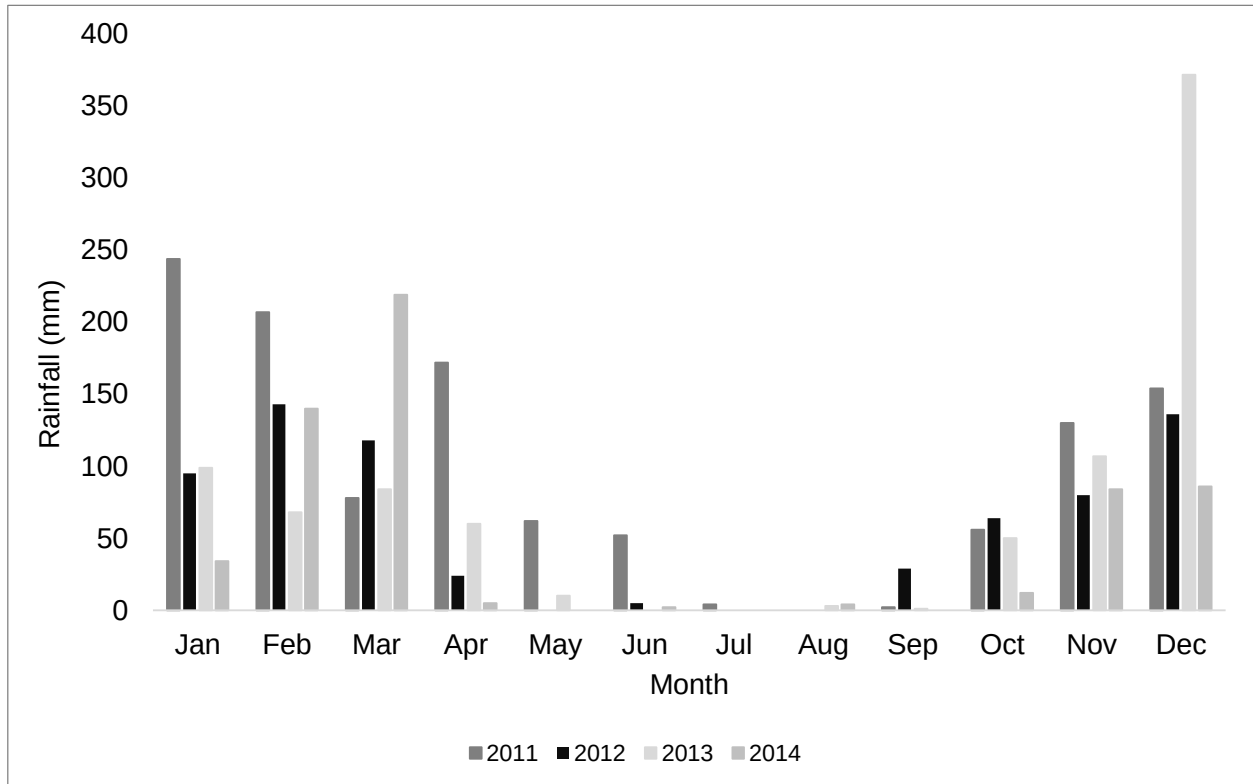


Figure 5.11: Monthly rainfall trends for Tlokwe municipality (Potchefstroom)

5.11 Conclusion

The purpose of this chapter was to perform a SWOT analysis for a WtE grate incineration power plant for a small South African city. The opportunities identified clearly support implementation of WtE thermal technologies in the city.

The drivers of WtE grate incineration power plant in South Africa include an average of 90% dominance of landfill over other MSW management strategies, average MSW generation growth rate of 3% per annum, national power shortages, the intermittent nature of solar and wind energy and non-energy recovery methods used in treating health care risk waste (HCRW).

However, obstacles to execution, such as the legislative framework, lack of landfill diversion measures, high capital investment involved and local culture were acknowledged. The objective of Chapter 6 is to perform a financial analysis of a WtE grate incineration power plant for a small

South African city. The financial analysis will use the case study data on Tlokwe municipality analyzed in this chapter.

CHAPTER 6

FINANCIAL ANALYSIS OF WASTE-TO-ENERGY GRATE INCINERATION POWER PLANT

6.1 Introduction

The aim of this research project is to perform a techno-economic evaluation of a WtE grate incineration power plant for a small South African city. Financial analysis of WtE grate incineration contributes to the study. This chapter focuses on financial analysis of WtE grate incineration for a small city in the North-West Province. Figure 6.1 shows the current position in the research roadmap.

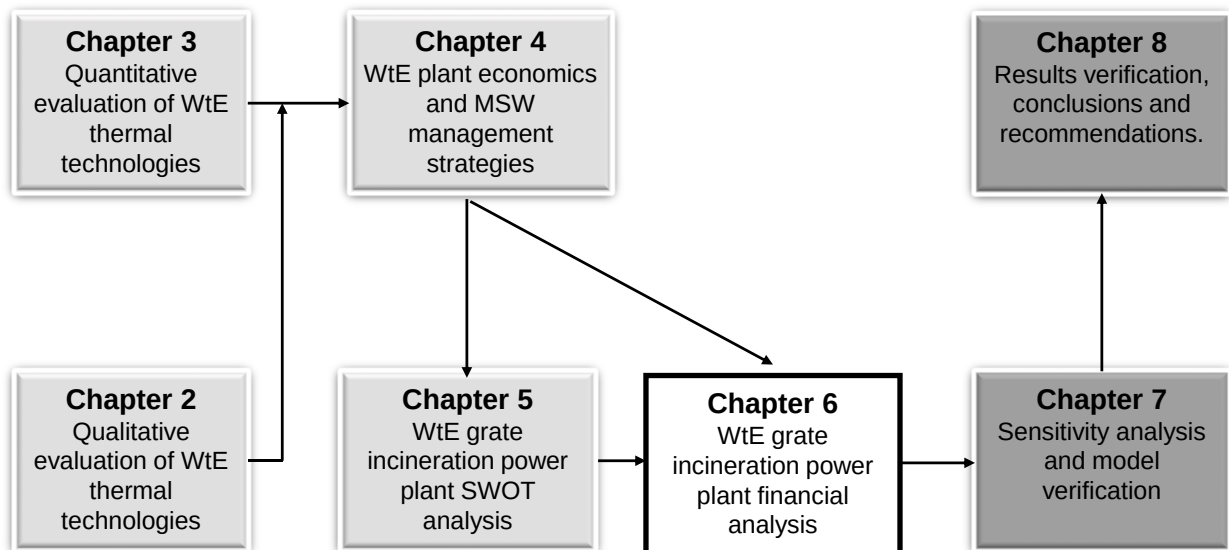


Figure 6.1: Research roadmap position 5

Part of the financial analysis results in this study was published in peer-reviewed conference proceedings of the ICUE 2015 (Appendix B). The contributions from the ICUE conference peer reviews were incorporated in this chapter.

This chapter is ordered as follows: Firstly, the financial analysis methodology is presented in section 6.2. This is followed by WtE grate incineration power plant model and financial model assumptions in section 6.3 and section 6.4 respectively. Financial analysis results are presented in section 6.5. A discussion of results (Section 6.6) and the chapter's conclusion (Section 6.7) are presented last.

6.2 Financial analysis methodology

A financial analysis model with four different scenarios was formulated as presented in the peer-reviewed conference paper of the ICUE 2015 by Maisiri. The purpose of the model was to determine the financial feasibility of a WtE grate incineration power plant for a small city in the North-West Province (Maisiri *et al.*, 2015:379).

The analysis begins by calculating the simple payback period (SPB) and return on investment (ROI) for each scenario. The two financial indicators are calculated from the capital cost and the project cash flow. SPB and ROI are simple and broad financial feasibility indicators used for preliminary assessment (School of Mechanical and Nuclear Engineering, 2014:1). SPB and ROI are calculated using equation 6.1 and equation 6.2 respectively.

$$SPB = \frac{\text{Capital Cost}}{\text{Annual Cash Flow}} \quad 6.1$$

$$ROI = \frac{\text{Annual Cash Flow}}{\text{Capital Cost}} \quad 6.2$$

The analysis narrows down to specific financial feasibility indicators, namely NPV and IRR. A positive NPV indicates a feasible project that will benefit society (Serfontein, 2014:1). The higher the NPV, the more attractive is the investment.

An IRR greater than the stated discount rate shows a feasible project (Serfontein, 2014:1). An IRR less than the discount rate will decrease shareholders' wealth, thus making the investment unfavorable.

NPV and IRR calculations were facilitated through performing WtE grate incineration power plant capital budgeting for a life span of 30 years. The capital budgeting was carried out for each scenario (Maisiri *et al.*, 2015:379).

In the ICUE conference paper, the author used electricity price and MSW accumulation in the sensitivity analysis (Maisiri *et al.*, 2015:379). To effect peer review comments and contributions, four major parameters, namely electricity price, power generation efficiency, MSW gate fees and medical waste gate fees, were incorporated in the sensitivity analysis.

The sensitivity analysis was carried out to identify how NPV and IRR are affected by varying electricity price, power generation efficiency, MSW gate fees and medical waste gate fees. An investment attractiveness scale was formulated for both NPV and IRR sensitivity analysis results (Maisiri *et al.*, 2015:379).

The financial and sensitivity analysis results for the four scenarios were evaluated and assessed. The scenarios were ranked according to performance in terms of SPB, ROI, NPV and IRR.

MSW generation trends, characteristics and management strategies data were gathered from a small city in the North-West Province with a population of approximately 300 000 people. This was achieved through an interview with representatives from the department of waste management (Maisiri *et al.*, 2015:379). Physical landfill site visits took place and observations were made.

A survey conducted for the Department of Environmental Affairs and Tourism (DEAT) on generation rates, treatment capacities and minimal costs of health care waste was used as reference for medical waste data. Medical waste treatment cost data were estimated from the DEAT data.

WtE grate incineration power plant capital cost data were obtained through interviews with representatives from one of the largest and most efficient WtE plants in the Netherlands. Plant operating cost and revenue streams data were also obtained in these interviews and through a literature review.

6.3 Waste-to-energy grate incineration power plant conceptual model.

A WtE grate incineration power plant conceptual model was developed for the small city of Potchefstroom in the North-West Province. This section presents the power plant conceptual model and is structured as follows: WtE grate incineration power plant schematic diagram (Section 6.3.1), plant model basic assumptions (Section 6.3.2) and plant power design capacity calculator (Section 6.3.3).

6.3.1 Plant schematic diagram

The WtE grate incineration power plant was modelled to operate with two lines, each line having its own incinerator, turbine and generator. The turbine and generator can be switched between lines to facilitate high availability and reliability percentages. The two lines use the same feedstock preparation bank and flue gas cleaning equipment. Figure 6.2 shows the schematic layout of the WtE grate incineration power plant.

6.3.2 Plant model basic information

The WtE grate incineration power plant design parameters are shown in Table 6.1. The plant's annual throughput is 200 000 tonnes of waste. This is calculated by factoring 90% availability on the plant design capacity.

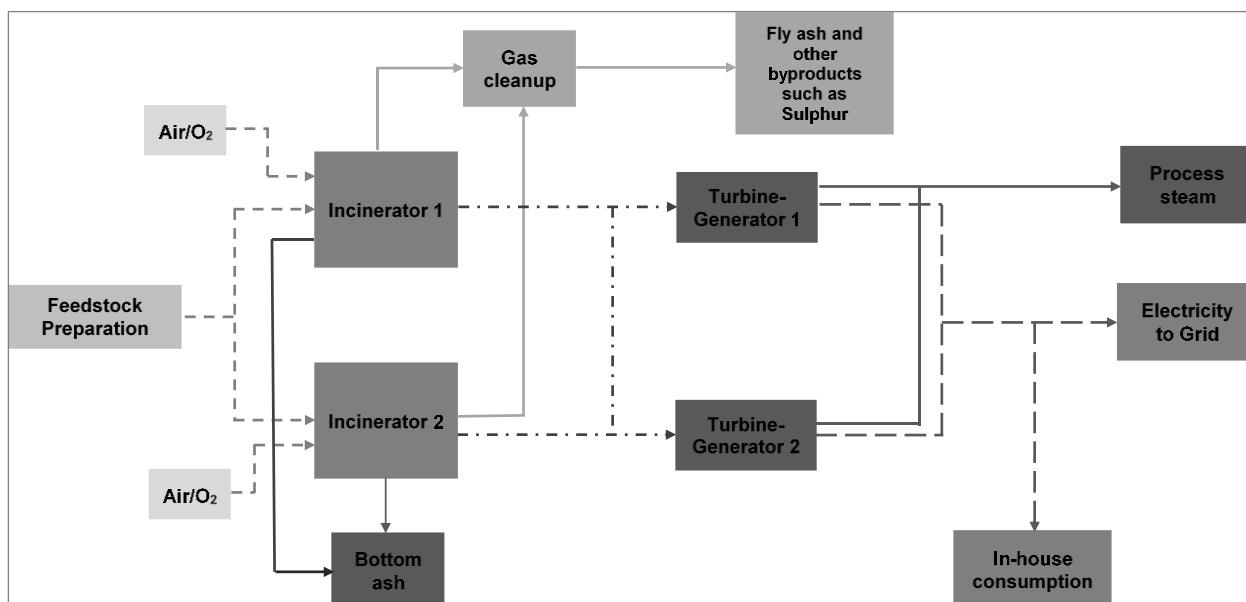


Figure 6.2: WtE grate incineration power plant schematic diagram for a small city

Table 6.1: WtE grate incineration power plant design parameters

Parameter	Quantity
Number of lines	2
Plant life	30 years
Construction period : line 1	3 years
: line 2	2 years
Processing design capacity	110 000 tonnes/year/line
Plant availability	90%
Plant annual throughput	200 000 tonnes
Average feedstock LHV	8 GJ/tonne
Electricity efficiency	30%
Processing steam efficiency	2.5%
Power plant design capacity	16.7 MW
Total power output	666.66 kWh/tonne
Plant consumption	66.66 kWh/tonne
Grid electricity	600 kWh/tonne
Total manpower	40 people

6.3.3 Plant power design capacity calculator

The WtE grate incineration power plant for a small city in the North-West Province was modelled to have a designed power capacity of 16.7 MW. Figure 6.3 shows the plant power design capacity calculator that was developed and used in this study.

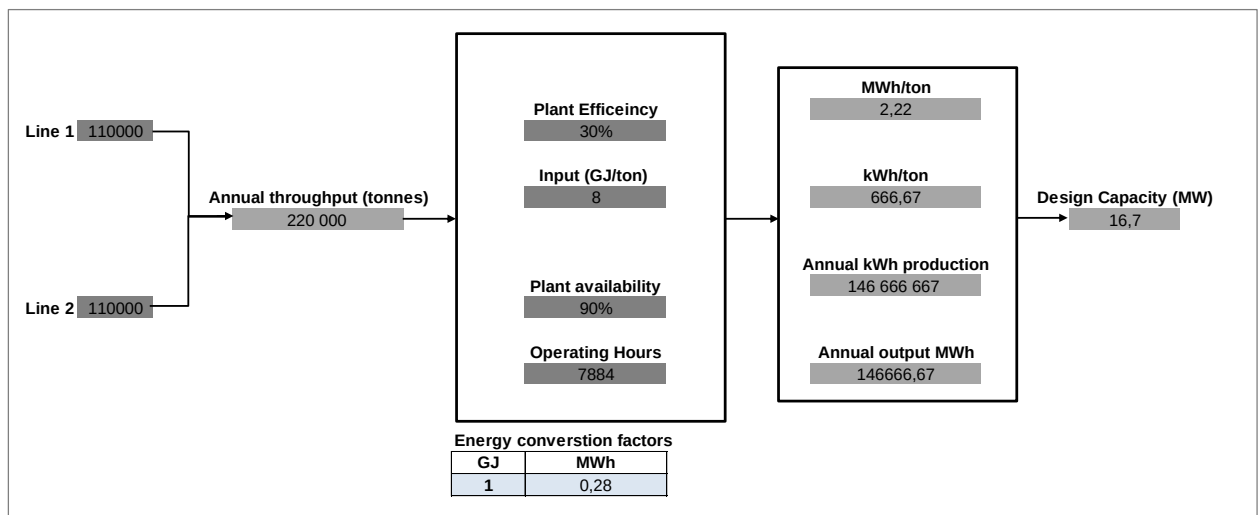


Figure 6.3: WtE grate incineration power plant design capacity calculator

6.4 Financial model assumptions

This section presents assumptions used in the financial analysis of a WtE grate incineration power plant for a small South African city in the North-West Province. The section is organized as follows: financial model scenarios (Section 6.4.1), financial model assumptions (Section 6.4.2), financial model scenarios capital cost (Section 6.4.3), annual income calculations assumptions (Section 6.4.4) and capital budgeting assumptions (Section 6.4.5).

6.4.1 Financial model scenarios

Financial analysis was modelled with four different scenarios shown in Table 6.2. The scenarios varied in terms of feedstock used and plant ownership (Maisiri *et al.*, 2015:379).

Table 6.2: Description of financial model scenarios for a small city in North-West Province, South Africa (Maisiri *et al.*, 2015:379)

Scenario	Feedstock type	Plant ownership
1	MSW	Investment company
2	MSW	IPP
3	MSW and Medical waste	Investment company
4	MSW and Medical waste	IPP

The assumption is that the IPP will merge with a foreign company with proven technology. This will entitle the IPP to an investment subsidy of 20%. According to Wentworth (2014:1), a financial subsidy can be accessed through the Green Energy Efficiency Fund administered by the

Industrial Development Corporation. Renewable energy subsidies can also be obtained from the Renewable Energy Finance Subsidy Office (Wentworth, 2014:1).

It is assumed that the investment company will fund and contract a company with proven WtE grate incineration technology to operate the plant. The investment company is to fund 100% of the plant's capital cost (Maisiri *et al.*, 2015:379).

6.4.2 Financial model assumptions

The WtE grate incineration power plant financial model basic assumptions are shown in Table 6.3. The assumptions are used as the base values for each scenario's financial analysis calculations.

Table 6.3: Financial model basic assumptions

Parameter	Base value	Assumption reference
Base design capacity	110 000 tonnes/year	Tlokwe municipality case study, Appendix D4
Base design capacity capital cost	R4500/tonne	E. Lichtenbelt (personal communication, August 14, 2014), (Whiting, 2013:24)
Additional MSW capacity capital cost	R3600/tonne	E. Lichtenbelt (personal communication, August 14, 2014), (Stantec, 2011:11)
Additional medical waste capacity capital cost	R5400/tonne	E. Lichtenbelt (personal communication, August 14, 2014)
Maintenance cost	3% of capital cost	(IEA Bioenergy, 2010:5; Rand <i>et al.</i> , 2000:118)
Electricity price	R1.25/kWh	(Rycroft, 2013:1; Rycroft, 2013:1)
MSW tipping fees	R50/tonne	Tlokwe municipality case study, Appendix D4
Medical waste tipping fees	R2500/tonne	(Otto & Clements, 2008:1)
Ferrous metals selling price	R10/kg	Service providers
Non-ferrous metals selling price	R1.5/kg	Service providers
Depreciation	5%	(EPRI, 2012:1)
Discount rate	10%	(EPRI, 2012:1)
Inflation	6%	(Investec, 2015)
Interest on loan	4%	(Wentworth, 2014:1)
Tax rate	28%	(EPRI, 2012:1)
IPP capital subsidy	20%	(Wentworth, 2014:1)

6.4.3 Financial model scenarios capital cost

The capital cost for each scenario is shown in Table 6.4. The capital cost was calculated on a design capacity of 220 000 tonnes of feedstock per year. The total design capacity is divided into

three categories, namely base design capacity, MSW additional design capacity and medical waste design capacity.

Table 6.4: Capital cost for the four financial model scenarios presented in the study

Scenario	Total capital cost (R million)
1	891.00
2	712.80
3	918.00
4	734.40

Each scenario has a base design capacity of 110 000 tonnes. Scenarios 3 and 4 each has a design capacity of 15 000 tonnes medical waste and MSW additional capacity of 95 000 tonnes. Scenarios 1 and 2 have medical waste design capacity of zero tonnes and MSW additional capacity of 110 000 tonnes.

6.4.4 Annual income calculations parameters

Table 6.5 shows parameters used to calculate the scenarios' annual income. An annual throughput of 200 000 tonnes is used in all scenarios' annual income calculations. Scenarios 3 and 4 assume 15 000 tonnes medical waste and the balance MSW (Maisiri *et al.*, 2015:379).

Table 6.5: Parameters used in calculating scenarios annual income (Maisiri *et al.*, 2015:379)

Parameter	Parameters
Average labour cost	R145 952.5/person/year
Overheads	50% of total labour cost
Chemicals cost	R1.8 per kg at rate of 13.55kg/tonne of waste
Water	R5 per kl at rate of 15 liters/tonne of waste
Maintenance cost	3% of the total investment cost
Interest	5% calculated on investor capital cost
Residue management cost	R570/tonne at production rate of 15kg/tonne of waste
Electricity sales	600 kWh/tonne of waste
Process steam sales	44.44 kWh/tonne of waste
Ferrous metal sales	10 kg/tonne of waste
Non-ferrous metal sales	8 kg/tonne of waste

Scenarios 1 and 2's annual waste tipping income was calculated by multiplying waste annual throughput by MSW tipping fee in Table 6.3. Annual waste tipping income for scenarios 3 and 4 was calculated by multiplying 15 000 tonnes by medical waste tipping fees in Table 6.3, and the balance with MSW tipping fees (Maisiri *et al.*, 2015:379).

The assumptions in Table 6.5 are based on a combination of information obtained from the biogenic report of the International Energy Agency, a WtE plant in the Netherlands, and experts' experience and knowledge.

6.4.5 Capital budgeting assumption

Capital budgeting was performed on the assumption that the plant will operate at 90% of the design capacity. The construction of the plant will be in two phases, namely construction of line 1 and construction of line 2. Line 1 construction is assumed to take three years before operation while line 2 construction starts in the fourth year of operation.

The plant is assumed to have an annual throughput of 100 000 tonnes of waste from the first year to the fifth year of operation. From the start of the sixth year to the 30th year of operation, annual throughput is expected to be 200 000 tonnes of waste.

To facilitate an annual throughput equivalent to 90% of the design capacity, the business case must consider contracting a company to provide MSW and medical waste for the plant. This will guarantee the availability of plant feedstock.

The WtE grate incineration power plant is assumed to experience a linear depreciation in value. The capital cost is divided by the expected number of years the plant will operate. This value is then assigned to every year of operation's cash flow analysis.

6.5 Financial analysis results

The financial analysis results are given in this section. The capital cost for each scenario is given in section 6.5.1. The financial analysis results for scenarios SPB and ROI (Section 6.5.2) and NPV and IRR (Section 6.5.3) are presented in this section.

6.5.1 Capital cost per megawatt

Table 6.6 shows the four scenarios' capital cost per MW. Scenario 3 has the highest capital cost of R50.72 million per MW while scenario 2 has the lowest capital cost of R39.38 million per MW.

Table 6.6: Scenarios' capital cost

Scenario	Capital cost (R million/MW)
1	49.22
2	39.38
3	50.72
4	40.57
Average	44.97

6.5.2 Scenarios' simple payback period and return on investment

SPB and ROI were used in the financial analysis preliminary stages. Table 6.7 shows the four scenarios' SPB and ROI results. Scenario 4 shows the best performance with an SPB of 10 years and 10% ROI. Scenario 1 yields the worst performance with an SPB of 25 years and 6% ROI.

Table 6.7: Scenarios' SPB and ROI

Scenario	SPB (years)	ROI (%)
1	25	4
2	17	6
3	13	7
4	10	10

6.5.3 Scenarios' net present value and internal rate of return

The four scenarios' NPV and IRR results are presented in Table 6.8. Scenario 4 shows the most favorable results with the highest NPV of R681.77 million and IRR of 21.21%. Scenario 1 has the lowest NPV of R375.50 million and IRR of 15.34%. NPV and IRR results for the four scenarios proved a feasible investment though varying in degree of attractiveness.

Table 6.8: Scenarios' NPV and IRR

Scenario	NPV (R million)	IRR (%)
1	375.50	15.34
2	531.69	19.13
3	524.03	17.10
4	681.77	21.21

6.6 Discussion of results

Financial performance based on SPB, ROI, NPV and IRR shows that scenario 4, characterised by MSW and medical waste as feedstock and owned by an IPP, is ranked number one, while scenario 2, marked by MSW as feedstock and owned by an IPP, is graded number two. Scenario 3, classified with MSW and medical waste as feedstock and owned by an investment company, is rated number three and scenario 1, characterized by MSW as feedstock and owned by an investment company, ranks number four.

The financial analysis results in Table 6.7 and Table 6.8 show that scenario 4 yields the best financial performance with SPB, ROI, NPV and IRR at 10 years, 10%, R681.77 million and 21.21% respectively. The worst financial performance is seen in scenario 1 with SPB, ROI, NPV and IRR at 25 years, 4%, R375.50 million and 15.34% respectively.

A comparison of the results of scenario 1 with those of scenario 3, which has an investment company as owner, proves that medical waste gate fees have a significant effect on financial performance. This is confirmed by comparing the results of scenario 2 and scenario 4 that have an IPP as owner.

Table 6.6 indicated that the capital costs of scenario 2 and 4 show an insignificant difference, while scenarios 1 and 3 follow the same pattern. Scenarios 2 and 4 have lower capital costs than scenarios 1 and 3 because of a 20% capital subsidy. The average WtE grate incineration power plant capital cost is R44.97 million per MW.

Table 6.9 shows a comparison of WtE grate incineration technology capital cost with other renewable energy technologies in the country. Solar energy has the lowest capital cost of R15 million per MW, while WtE grate incineration has the highest capital cost of R44.97 million per MW. This is when the average net capacity factor is not considered.

Table 6.9: Renewable energy capital costs comparison (DoE, 2011:1; DoE, 2015:1; EPRI, 2012:1)

Technology	Capital Cost (R million/MW)	Average net capacity factor	Weighted capital cost (R million /MW)
Wind	18.02	25%	72.80
Solar	15.00	20%	75.00
WtE grate incineration	44.97	>90%	49.97
Biomass	36.00	>85%	42.35

Weighted capital cost, which assumes a 100% capacity factor for all the technologies, was calculated as in Table 6.9. This results in WtE thermal technology having a lower capital cost than solar and wind energy. Though the capital cost per MW of both solar and wind generation seems to be small, their intermittent nature results in a significantly high weighted capital cost.

6.7 Conclusion

The aim of chapter six was to perform a WtE grate incineration power plant financial analysis for a small South African city. The chapter presented the methodology and assumptions used in the financial analysis.

The WtE grate incineration power plant and financial model results were presented with scenario 4, characterized by MSW and medical waste as feedstock and owned by an IPP, yielding the best performance. Scenario 1, distinguished by MSW as feedstock and owned by an investment company, offered the least favorable outcome.

The results obtained indicated that a WtE grate incineration power plant for a small South African city is financially viable and attractive on condition that medical waste is used as feedstock and that an investment subsidy is accessible.

The following chapter aims at performing NPV and IRR sensitivity analysis using four parameters that affect a WtE grate incineration power plant's financial viability.

CHAPTER 7

SENSITIVITY ANALYSIS AND MODEL VERIFICATION

7.1 Introduction

The aim of this study is to perform a techno-economic evaluation of a WtE grate incineration power plant for a small South African city. The purpose of this chapter is to carry out sensitivity analysis of the parameters that affect a WtE grate incineration power plant's financial viability as a means of verifying the financial model presented in chapter 6. Figure 7.1 highlights the current focus point in the research roadmap.

The work presented in this chapter is part of work published in the peer-reviewed conference proceedings of ICUE 2015 (Appendix B). In this chapter sensitivity analysis was performed on four parameters that affect financial viability, namely electricity price, power generation efficiency, MSW and medical waste gate fees.

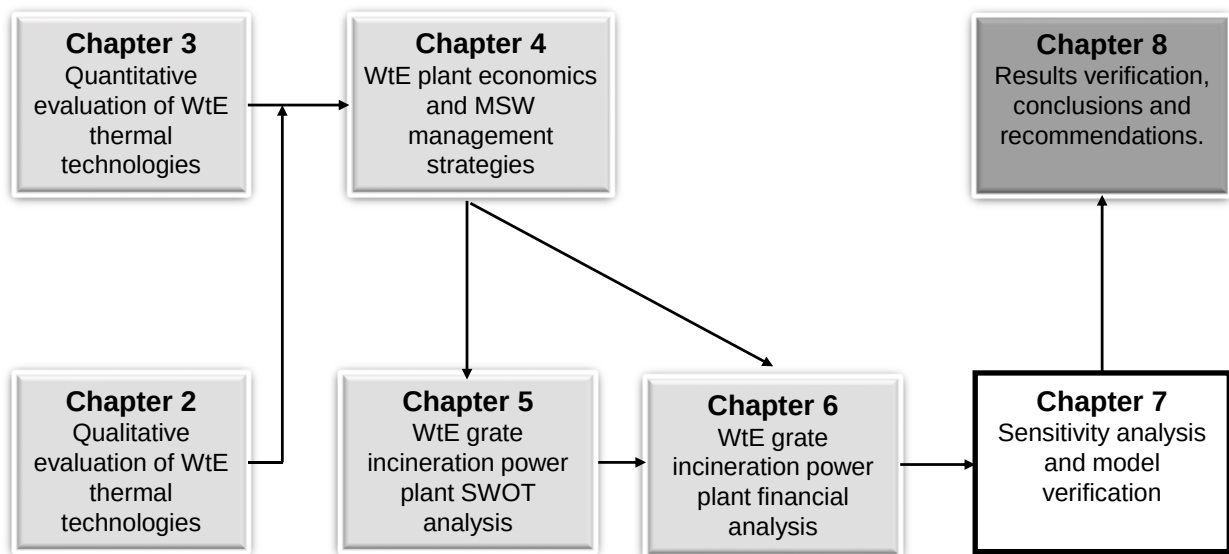


Figure 7.1: Research road map position 6

The chapter starts by discussing sensitivity analysis and affirm its role in model results verification in section 7.3. The sensitivity analysis results interpretation assumptions are presented in section 7.3. This is followed by single parameter (Section 7.4) and combination of parameters (Section 7.5) sensitivity analysis. Sensitivity analysis results are discussed in section 7.6. The conclusion of this chapter is given in section 7.7.

7.2 Discussion on sensitivity analysis and verification

Verification can be defined as the process of making sure that the model is doing what it is intended to do (Frey, 2001:1). According to Smith (2008:39), verification can mean ensuring that the model complies with the requirements and conforms to its design. Thus verification can be concluded to be a way of checking that a proposed solution to a problem is credible and robust.

The purpose of the financial model scenarios presented in chapter 6 is to perform a financial viability evaluation of WtE grate incineration power plant for a small South African city. The analysis further ranks the scenarios according to financial performance. This requires model verification tool that ascertain the credibility of chapter 6 results and findings.

According to Thabane (2013:1), sensitivity analysis can be defined as “a method to determine the robustness of an assessment by examining the extent to which results are affected by changes in methods, models, values of unmeasured variables or assumptions with the aim of identifying results that are most dependent on questionable or unsupported assumptions”. Thus sensitivity analysis is evaluation of a data set to verify whether altering any assumptions made leads to different final interpretations or conclusions (Thabane et al., 2013:1).

Sensitivity analysis can be used as a model verification and validation tool (Frey et al., Smith et al., 2008:39; Ekberg, 1999:1). Further to this sensitivity analysis can be used to provide insight into the robustness of model results when making decisions. Sensitivity analysis can be used to affirm if a model make sense. Results of sensitivity analysis can be used to point out the accuracy of calculated parameters (Smith et al., 2008:39).

Trucano (2006:1331) states that sensitivity analysis is required for understanding the extent to which a model is complicated enough to be credible. Sensitivity analysis can be used to strengthen the conclusions or credibility of the findings as well as assessing the robustness of the model (Thabane et al., 2013:1).

Sensitivity analysis poses a number of benefits which include: testing the correctness of expert predictions, revealing unimportant variables or unnecessary model complexity and ranking the input data with respect to their influence to the model (Ekberg, 1999:1). Using sensitivity analysis is highly recommended in exploring alternatives scenarios and uncertainty in cost-effective results (Thabane et al., 2013:1).

Sensitivity analysis methods can be applied in various fields such as engineering, economics, social sciences and medical decision making. Sensitivity analysis can be performed using partial derivatives or spreadsheet such as excel. Performing sensitivity analysis on spreadsheet is convenient for systems that are not described by equations (Smith et al., 2008:39).

To this end the verification of financial model presented in chapter 6 was achieved by performing a sensitivity analysis on major parameter that affect the model financial viability. In this study sensitivity analysis was performed on excel spread sheet as recommended by Smith (2008:39).

7.3 Sensitivity analysis results interpretation assumptions

To facilitate the sensitivity analysis results interpretation, an investment attractiveness scale for both NPV and IRR was formulated. Section 7.3.1 present the NPV investment attractiveness scale and section 7.3.2 gives the IRR investment attractiveness scale.

7.3.1 Net present value investment attractiveness scale

An investment attractiveness scale for the NPV is shown in Figure 7.2. This scale is used to interpret the NPV sensitivity analysis results for scenario 1 to 4.

	NPV ≤ 0 - investment not financially feasible
	$0 < \text{NPV} \leq 1/3$ of capital cost - feasible and not attractive
	$1/4 < \text{NPV} \leq 2/3$ of capital cost - feasible and attractive
	NPV $> 2/3$ of capital cost - feasible and most attractive

Figure 7.2: NPV investment attractiveness scale (Maisiri *et al.*, 2015:379)

An NPV value of less than or equal to zero ($\text{NPV} \leq 0$) is regarded as not financially feasible. An NPV value greater than zero and less than or equal to one third of the capital cost ($0 < \text{NPV} \leq 1/3$ of capital cost) is considered financially feasible but not attractive. A financially feasible and attractive NPV value is greater than one third and less than or equal to two thirds of the capital cost ($1/3 < \text{NPV} \leq 2/3$ of capital cost). The most attractive NPV is greater than two thirds of the capital cost ($\text{NPV} > 2/3$ of capital cost) (Maisiri *et al.*, 2015:379).

7.3.2 Internal rate of return investment attractiveness scale

The investment attractiveness scale used to interpret the IRR sensitivity analysis results for scenario 1 to 4 is shown in Figure 7.3.

An IRR less than or equal to the discount rate of 10% ($\text{IRR} < 10\%$) is considered not financially feasible. An IRR greater than 10% and less than or equal to 15% ($10\% < \text{IRR} \leq 15\%$) is considered financially feasible and attractive. An IRR value greater than 15% ($\text{IRR} > 15\%$) has the highest investment attractiveness (Maisiri *et al.*, 2015:379).

	IRR $\leq 10\%$ - project not financially feasible
	10% < IRR $\leq 15\%$ - feasible and less desirable
	IRR > 15% - feasible and most desirable

Figure 7.3: IRR investment attractiveness scale (Maisiri *et al.*, 2015:379)

7.4 Single parameter sensitivity analysis results

In this section, the results of varying a single parameter on NPV and IRR for the four scenarios are shown. The results are presented in the form of line graphs that compare the sensitivity analysis results of the four scenarios. NPV and IRR results are presented in sections 7.4.1 and 7.4.2 respectively.

7.4.1 Net present value sensitivity results

Figure 7.4 to Figure 7.6 compare the NPV sensitivity analysis results for the four scenarios on a single parameter. The results show that NPV is highly sensitive to electricity prices and least sensitive to power generation efficiency.

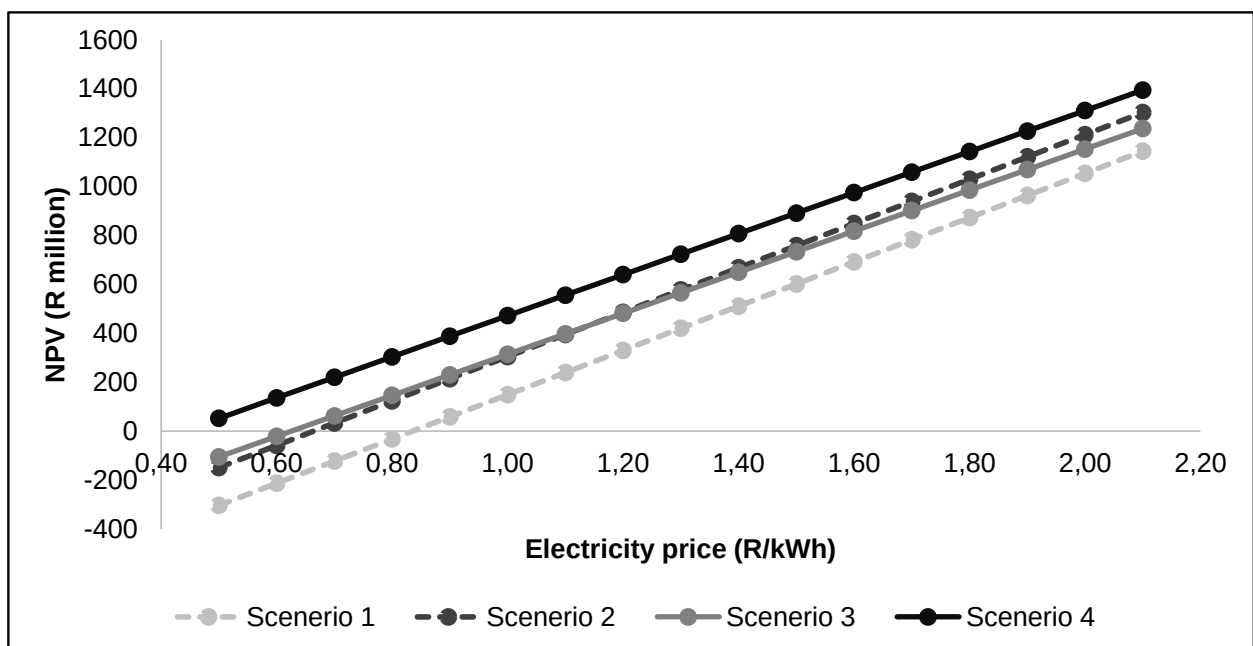


Figure 7.4: Impact of electricity price on NPV for scenarios 1 to 4

Figure 7.4 illustrates that scenario 4 registers positive NPV for an electricity price as low as R0.50/kWh and scenario 1 evidences positive NPV up to electricity price of R0.90/kWh. Scenarios 2 and 3 record a negative NPV for an electricity price lower than R0.70/kWh.

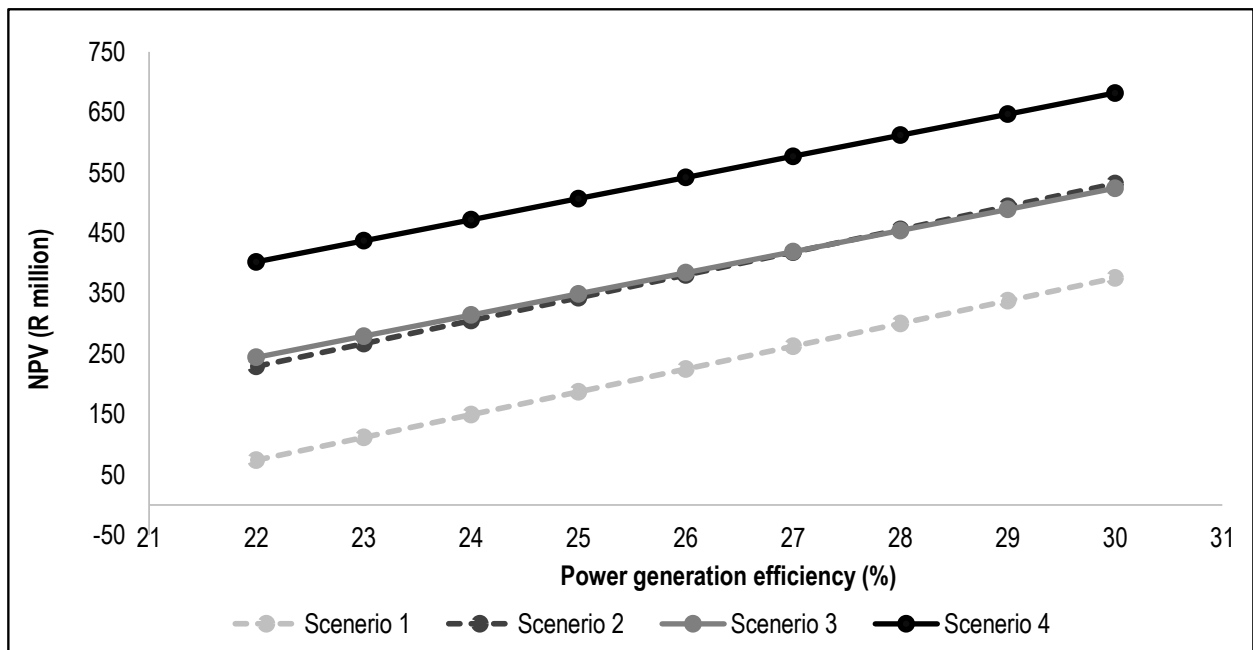


Figure 7.5: Effect of power generation efficiency on NPV for scenarios 1 to 4

Figure 7.5 shows a significant difference in the NPV for scenario 4 and 1 with variation in the power generation efficiency. Scenarios 2 and 3 show similarity in the NPV with changing power generation efficiency.

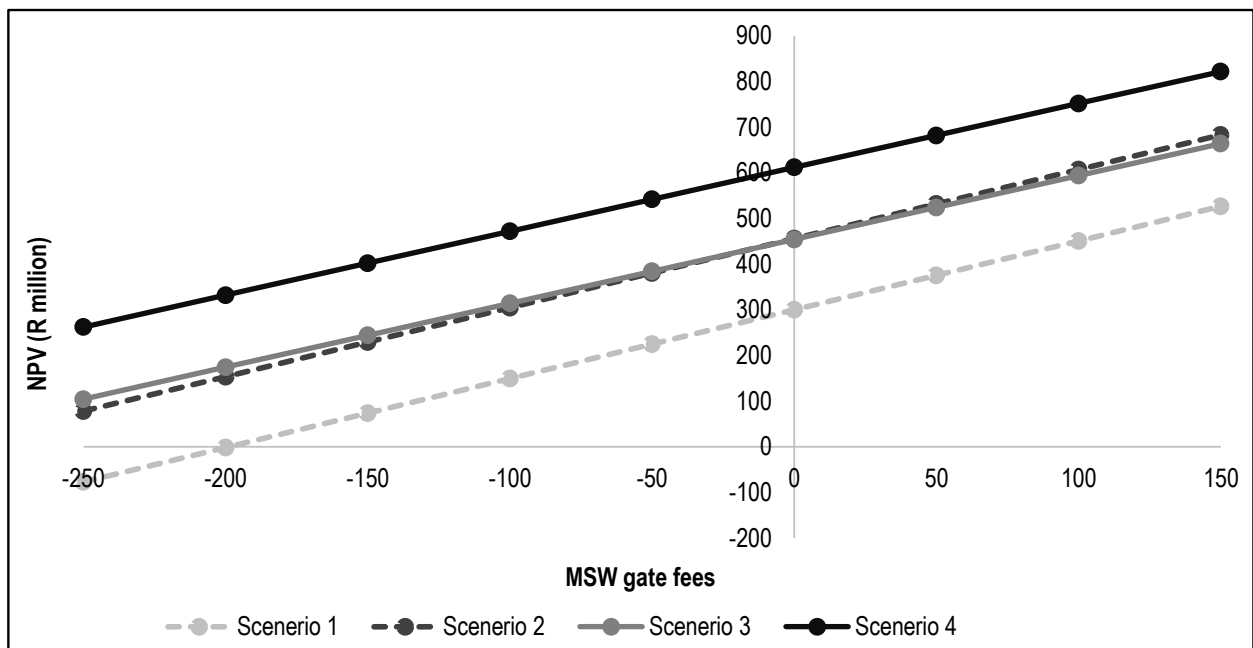


Figure 7.6: Influence of MSW gate fees on NPV for scenarios 1 to 4

Figure 7.6 proved that scenarios 4, 3 and 1 have positive NPV for an MSW gate fee of -R250/tonne of waste, while scenario 1 breaks even at gate fee of -R200/tonne. A negative gate fee implies that the plant operator will be paying waste generators for their waste to be processed.

7.4.2 Internal rate of return sensitivity results

Figure 7.7 to Figure 7.9 compare the IRR sensitivity analysis results for the four scenarios on a single variable. IRR sensitivity analysis results follows the same pattern of NPV sensitivity analysis results. IRR proves to be highly sensitive to electricity prices while least sensitive to power generation efficiency.

Figure 7.7 shows that an electricity price as low as R0.6/kWh results in an IRR greater than the discount rate for scenario 4. IRR values less than the discount rate are registered with an electricity price lower than R1.00/kWh for scenario 1. The IRR values for scenarios 3 and 2 are similar for an electricity price in the range of R0.60/kWh and R1.00/kWh, while significant divergence is observed for an electricity price in the range of R1.10/kWh upwards.

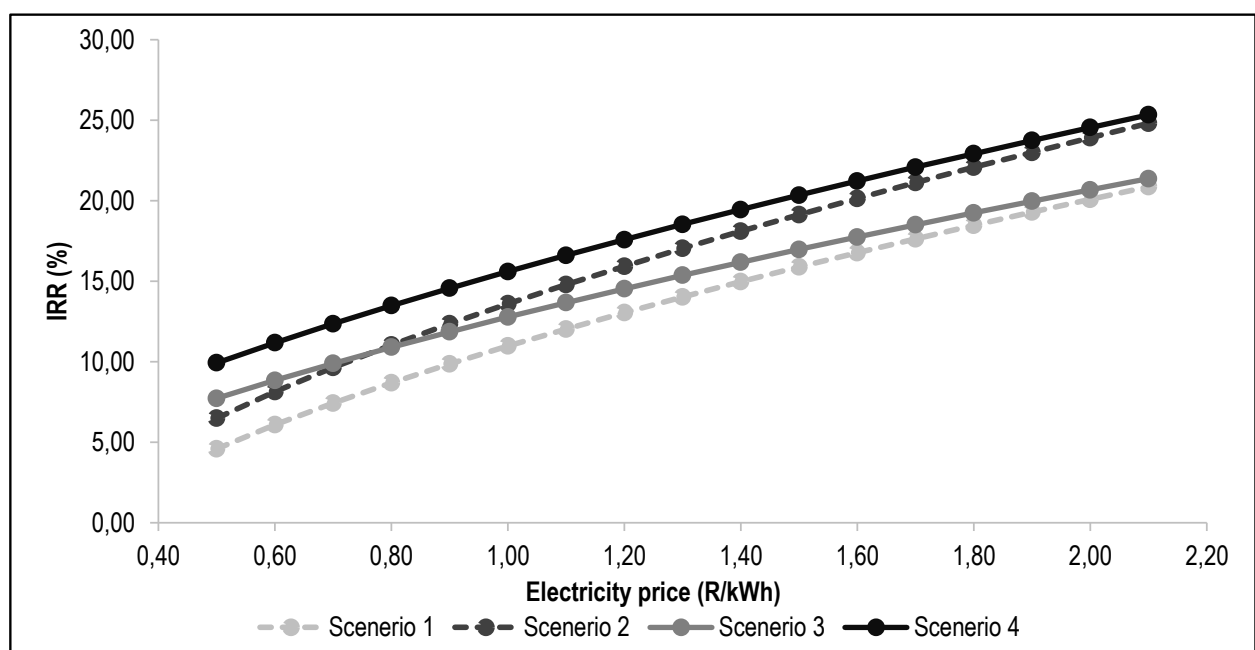


Figure 7.7: Impact of electricity price on IRR for scenarios 1 to 4

IRR has a linear relationship with power generation efficiency for scenarios 1 to 4. Figure 7.8 shows that power generation efficiency greater than or equal to 22% gives IRR values greater than the discount rate. IRR sensitivity to power generation efficiency is minimal, as portrayed by the near to horizontal linear graph in Figure 7.8.

Figure 7.9 shows variation of IRR with MSW gate fees for scenarios 1 to 4. IRR values greater than the discount rate are registered for MSW gate fees as low as –R250/tonne of waste for scenarios 2 to 4. MSW gate fees less than –R150 give IRR values less than the discount rate for scenario 1.

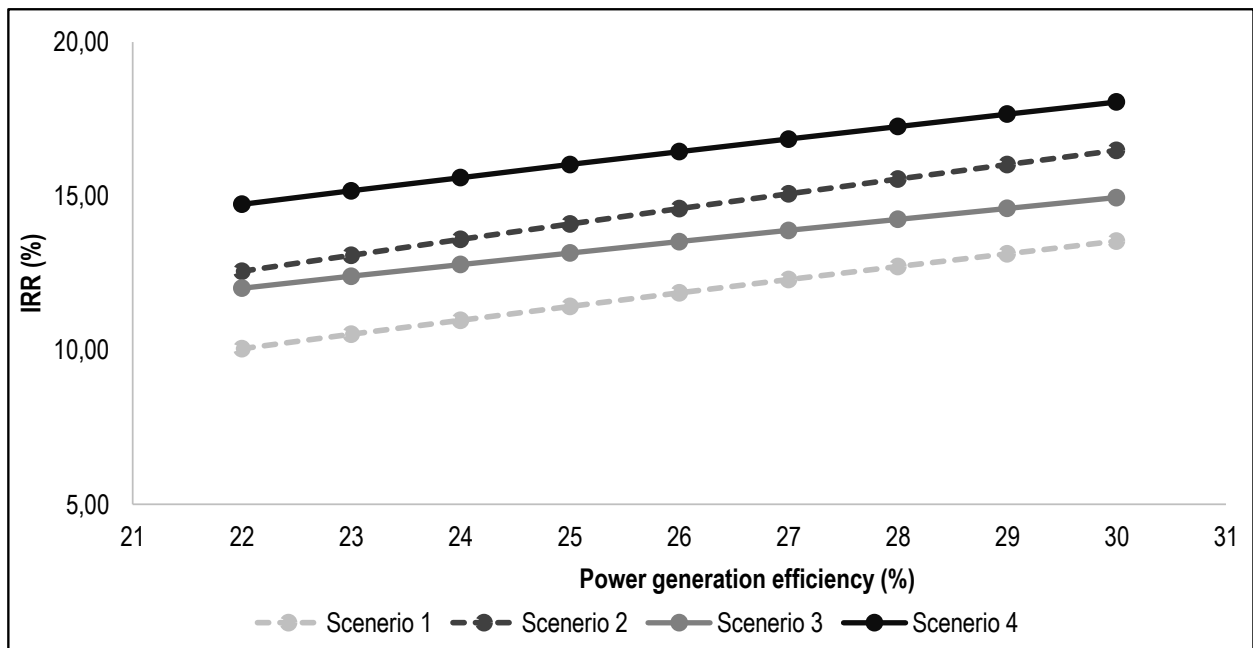


Figure 7.8: Effect of power generation efficiency on IRR for scenario 1 to 4

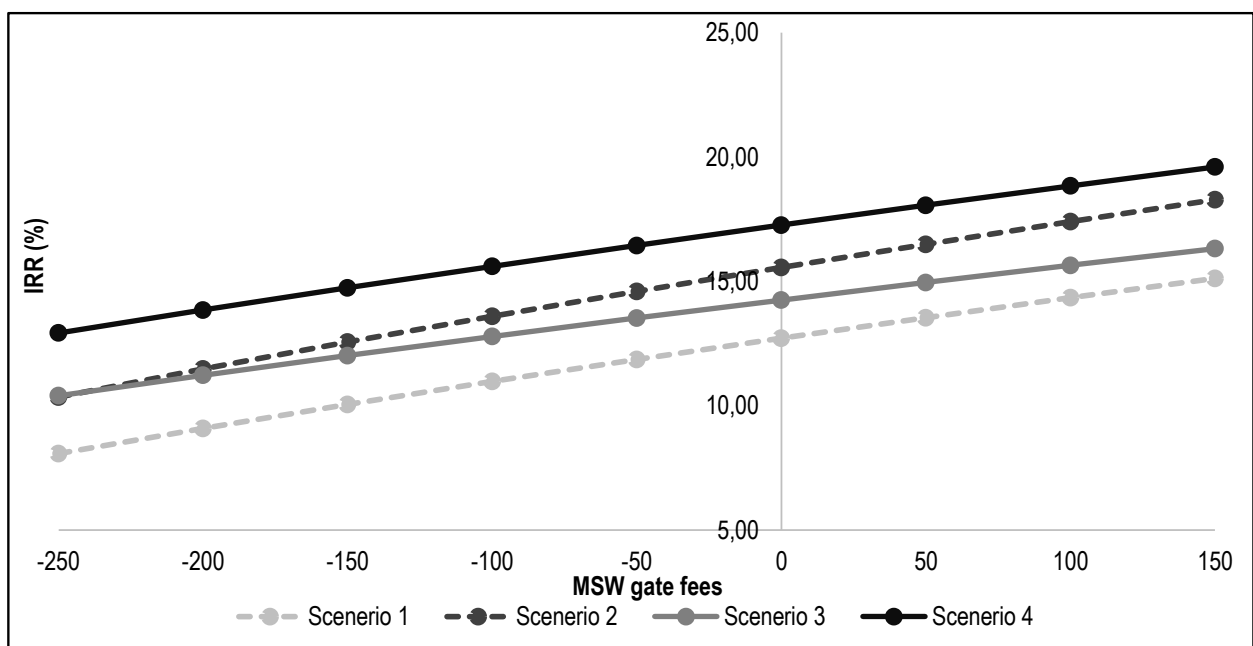


Figure 7.9: Influence of MSW gate fees on NPV for scenario 1 to 4

7.5 Combination of parameters' sensitivity analysis results

The results of varying a combination of parameters on NPV and IRR for the four scenarios are presented in this section. The NPV and IRR results matrices are presented in a tabular format for the four scenarios being considered. Section 7.5.1 presents NPV results while IRR results are shown in section 7.5.2.

7.5.1 Net present value sensitivity to combination of parameters

NPV sensitivity to a combination of electricity price and power generation efficiency, electricity price and MSW gate fees, electricity price and medical waste gate fees is presented in this section.

7.5.1.1 Scenario 1

Table 7.1 shows variation of NPV by changing the combination of electricity price and power generation efficiency. Options with $NPV \leq 0$ are dominant, followed by options with $NPV > 2/3$ of capital cost. Options with $0 < NPV \leq 1/3$ of capital cost and $1/3 < NPV \leq 2/3$ of capital cost have the same prevalence.

Table 7.1: Impact of electricity price and power generation efficiency on scenario 1 NPV

		Power generation efficiency								
NPV (R million)		22%	23%	24%	25%	26%	27%	28%	29%	30%
Electricity price	R 0,50	-424	-409	-393	-378	-363	-348	-333	-318	-303
	R 0,60	-357	-339	-321	-303	-285	-267	-249	-231	-213
	R 0,70	-291	-270	-249	-228	-206	-185	-164	-143	-122
	R 0,80	-225	-200	-176	-152	-128	-104	-80	-56	-32
	R 0,90	-158	-131	-104	-77	-50	-23	5	32	59
	R 1,00	-92	-62	-32	-1	29	59	89	119	149
	R 1,10	-26	8	41	74	107	140	173	207	240
	R 1,20	41	77	113	149	186	222	258	294	330
	R 1,30	107	146	186	225	264	303	342	382	421
	R 1,40	173	216	258	300	342	385	427	469	511
	R 1,50	240	285	330	376	421	466	511	556	602
	R 1,60	306	354	403	451	499	547	596	644	692
	R 1,70	372	424	475	526	578	629	680	731	783
	R 1,80	439	493	547	602	656	710	765	819	873
	R 1,90	505	562	620	677	734	792	849	906	964
	R 2,00	572	632	692	752	813	873	933	994	1054
	R 2,10	638	701	765	828	891	954	1018	1081	1144

Changing a combination of electricity price and MSW gate fees gives NPV shown in Table 7.2. The results follow the pattern of varying combinations of electricity price and power generation efficiency. There are more $NPV < 0$ options in Table 7.2 than in Table 7.1.

7.5.1.2 Scenario 2

Table 7.3 shows variation of NPV by changing the combination of electricity price and power generation efficiency. Options with $NPV > 2/3$ of capital cost lead over other options. Options with $NPV \leq 0$, $0 < NPV \leq 1/3$ of capital cost and $1/3 < NPV \leq 2/3$ of capital cost have the same occurrence.

Table 7.2: Impact of electricity price and MSW gate fees on scenario 1 NPV

NPV (R million)		MSW gate fees								
		-R 250	-R 200	-R 150	-R 100	-R 50	R 0	R 50	R 100	R 150
Electricity price	R 0,50	-756	-681	-605	-529	-454	-378	-303	-228	-152
	R 0,60	-666	-589	-514	-439	-363	-288	-213	-137	-62
	R 0,70	-574	-499	-424	-348	-273	-197	-122	-47	29
	R 0,80	-484	-409	-333	-258	-182	-107	-32	44	119
	R 0,90	-393	-318	-243	-167	-92	-17	59	134	210
	R 1,00	-303	-228	-152	-77	-1	74	149	225	300
	R 1,10	-213	-137	-62	14	89	164	240	315	391
	R 1,20	-122	-47	29	104	179	255	330	406	481
	R 1,30	-32	44	119	195	270	345	421	496	572
	R 1,40	59	134	210	285	360	436	511	587	662
	R 1,50	149	225	300	376	451	526	602	677	752
	R 1,60	240	315	391	466	541	617	692	768	843
	R 1,70	330	406	481	556	632	707	783	858	933
	R 1,80	421	496	572	647	722	798	873	948	1024
	R 1,90	511	587	662	737	813	888	964	1039	1114
	R 2,00	602	677	752	828	903	979	1054	1129	1205
	R 2,10	692	768	843	918	994	1069	1144	1220	1295

Table 7.3: Impact of electricity price and power generation efficiency on scenario 2 NPV

NPV (R million)		Power generation efficiency								
		22%	23%	24%	25%	26%	27%	28%	29%	30%
Electricity price	R 0,50	-270	-254	-239	-224	-209	-194	-179	-164	-149
	R 0,60	-203	-185	-167	-149	-130	-112	-94	-76	-58
	R 0,70	-137	-115	-94	-73	-52	-31	-10	12	33
	R 0,80	-70	-46	-22	3	27	51	75	99	123
	R 0,90	-3	24	51	78	105	133	160	187	214
	R 1,00	63	93	123	154	184	214	244	275	305
	R 1,10	130	163	196	229	263	296	329	362	396
	R 1,20	196	232	269	305	341	377	414	450	486
	R 1,30	263	302	341	381	420	459	498	538	577
	R 1,40	329	371	414	456	498	541	583	625	668
	R 1,50	396	441	486	532	577	622	668	713	758
	R 1,60	462	511	559	607	656	704	752	801	849
	R 1,70	529	580	631	683	734	786	837	888	940
	R 1,80	595	650	704	758	813	867	922	976	1 031
	R 1,90	662	719	777	834	892	949	1 006	1 064	1 121
	R 2,00	728	789	849	910	970	1 031	1 091	1 152	1 212
	R 2,10	795	858	922	985	1 049	1 112	1 176	1 239	1 303

The option with $1/3 < \text{NPV} \leq 2/3$ of capital cost is least dominant, while options with $\text{NPV} > 2/3$ of the capital cost dominate over other options in Table 7.4. There are more $\text{NPV} > 2/3$ options in Table 7.4 than in Table 7.3. There are fewer options with $\text{NPV} \leq 0$, $0 < \text{NPV} \leq 1/3$ of capital cost and $1/3 < \text{NPV} \leq 2/3$ of capital cost in Table 7.4 than in Table 7.3.

Table 7.4: Impact of electricity price and MSW gate fees on scenario 2 NPV

NPV (R million)		MSW gate fees								
		-R 250	-R 200	-R 150	-R 100	-R 50	R 0	R 50	R 100	R 150
Electricity price	R 0,50	-603	-527	-451	-375	-300	-224	-149	-73	3
	R 0,60	-511	-436	-360	-285	-209	-134	-58	18	93
	R 0,70	-421	-345	-270	-194	-118	-43	33	108	184
	R 0,80	-330	-254	-179	-103	-28	48	123	199	275
	R 0,90	-239	-164	-88	-13	63	139	214	290	365
	R 1,00	-149	-73	3	78	154	229	305	381	456
	R 1,10	-58	18	93	169	244	320	396	471	547
	R 1,20	33	108	184	260	335	411	486	562	638
	R 1,30	123	199	275	350	426	501	577	653	728
	R 1,40	214	290	365	441	517	592	668	743	819
	R 1,50	305	381	456	532	607	683	758	834	910
	R 1,60	396	471	547	622	698	774	849	925	1000
	R 1,70	486	562	638	713	789	864	940	1015	1091
	R 1,80	577	653	728	804	879	955	1031	1106	1182
	R 1,90	668	743	819	895	970	1046	1121	1197	1272
	R 2,00	758	834	910	985	1061	1136	1212	1288	1363
	R 2,10	849	925	1000	1076	1152	1227	1303	1378	1454

7.5.1.3 Scenario 3

NPV sensitivity to a combination of electricity price and power generation for scenario 3 is shown in Table 7.5. Options with $0 < \text{NPV} \leq 1/3$ and $1/3 < \text{NPV} \leq 2/3$ have the same prevalence. Options with $\text{NPV} > 2/3$ appear most in Table 7.5.

Table 7.5 Impact of electricity price and power generation efficiency on scenario 3 NPV

NPV (R million)		Power generation efficiency								
		22%	23%	24%	25%	26%	27%	28%	29%	30%
Electricity price	R 0,50	-217	-203	-189	-175	-161	-147	-133	-119	-105
	R 0,60	-156	-139	-122	-105	-88	-72	-55	-38	-21
	R 0,70	-94	-75	-55	-35	-16	4	23	43	63
	R 0,80	-33	-10	12	35	57	79	102	124	146
	R 0,90	29	54	79	104	130	155	180	205	230
	R 1,00	91	118	146	174	202	230	258	286	314
	R 1,10	152	183	214	244	275	306	337	367	398
	R 1,20	214	247	281	314	348	381	415	449	482
	R 1,30	275	311	348	384	421	457	493	530	566
	R 1,40	337	376	415	454	493	532	572	611	650
	R 1,50	398	440	482	524	566	608	650	692	734
	R 1,60	460	504	549	594	639	683	728	773	818
	R 1,70	521	569	616	664	711	759	807	854	902
	R 1,80	583	633	683	734	784	834	885	935	986
	R 1,90	644	697	751	804	857	910	963	1 016	1 069
	R 2,00	706	762	818	874	930	986	1 041	1 097	1 153
	R 2,10	767	826	885	944	1 002	1 061	1 120	1 179	1 237

Table 7.6 shows variation of NPV by altering a combination of electricity price and MSW gate fees. For a MSW gate fee of R150/tonne of waste, there are no NPV ≤ 0 options. Options with NPV $> 2/3$ of capital cost dominates over other options.

Table 7.6: Impact of electricity price and MSW gate fees on scenario 3 NPV

		MSW gate fees								
NPV (R million)		-R 250	-R 200	-R 150	-R 100	-R 50	R 0	R 50	R 100	R 150
Electricity price	R 0,50	-526	-456	-386	-315	-245	-175	-105	-35	35
	R 0,60	-442	-372	-301	-231	-161	-91	-21	49	118
	R 0,70	-358	-287	-217	-147	-77	-7	63	132	202
	R 0,80	-273	-203	-133	-63	7	77	146	216	286
	R 0,90	-189	-119	-49	21	91	160	230	300	370
	R 1,00	-105	-35	35	104	174	244	314	384	454
	R 1,10	-21	49	118	188	258	328	398	468	538
	R 1,20	63	132	202	272	342	412	482	552	622
	R 1,30	146	216	286	356	426	496	566	636	706
	R 1,40	230	300	370	440	510	580	650	720	790
	R 1,50	314	384	454	524	594	664	734	804	874
	R 1,60	398	468	538	608	678	748	818	888	958
	R 1,70	482	552	622	692	762	832	902	972	1041
	R 1,80	566	636	706	776	846	916	986	1055	1125
	R 1,90	650	720	790	860	930	1000	1069	1139	1209
	R 2,00	734	804	874	944	1013	1083	1153	1223	1293
R 2,10	818	888	958	1027	1097	1167	1237	1307	1377	

In Table 7.7, there is a significant reduction in options with NPV ≤ 0 . Distinct results are shown with options having NPV $> 2/3$ of capital cost representing close to half of the available options.

Table 7.7: Impact of electricity price and medical waste gate fees on scenario 3 NPV

		Medical waste gate fees								
NPV (R million)		R 500	R 1 000	R 1 500	R 2 000	R 2 500	R 3 000	R 3 500	R 4 000	R 4 500
Electricity price	R 0,50	-332	-275	-219	-162	-105	-49	8	65	122
	R 0,60	-248	-191	-135	-78	-21	35	92	149	205
	R 0,70	-164	-108	-51	6	63	119	176	233	289
	R 0,80	-80	-24	33	90	146	203	260	317	373
	R 0,90	4	60	117	174	230	287	344	400	457
	R 1,00	87	144	201	258	314	371	428	484	541
	R 1,10	171	228	285	341	398	455	512	568	625
	R 1,20	255	312	369	425	482	539	595	652	709
	R 1,30	339	396	453	509	566	623	679	736	793
	R 1,40	423	480	537	593	650	707	763	820	877
	R 1,50	507	564	620	677	734	790	847	904	961
	R 1,60	591	648	704	761	818	874	931	988	1044
	R 1,70	675	732	788	845	902	958	1015	1072	1128
	R 1,80	759	815	872	929	986	1042	1099	1156	1212
	R 1,90	843	899	956	1013	1069	1126	1183	1240	1296
	R 2,00	927	983	1040	1097	1153	1210	1267	1323	1380
	R 2,10	1010	1067	1124	1181	1237	1294	1351	1407	1464

7.5.1.4 Scenario 4

Table 7.8 to Table 7.10 show how NPV changes with different combinations of parameters for scenario 4. There is a distinct prevalence of options with NPV > 2/3 of capital cost in scenario 4.

Table 7.8: Impact of electricity price and power generation efficiency on scenario 4 NPV

		Power generation efficiency								
NPV (R million)		22%	23%	24%	25%	26%	27%	28%	29%	30%
Electricity price	R 0,50	-59	-45	-31	-17	-3	11	24	38	52
	R 0,60	2	19	36	52	69	86	103	120	136
	R 0,70	64	83	103	122	142	162	181	201	220
	R 0,80	125	148	170	192	215	237	259	282	304
	R 0,90	187	212	237	262	287	313	338	363	388
	R 1,00	248	276	304	332	360	388	416	444	472
	R 1,10	310	341	371	402	433	464	494	525	556
	R 1,20	371	405	438	472	506	539	573	606	640
	R 1,30	433	469	506	542	578	615	651	687	724
	R 1,40	494	534	573	612	651	690	729	768	808
	R 1,50	556	598	640	682	724	766	808	850	892
	R 1,60	617	662	707	752	796	841	886	931	975
	R 1,70	679	727	774	822	869	917	964	1 012	1 059
	R 1,80	741	791	841	892	942	992	1 043	1 093	1 143
	R 1,90	802	855	908	961	1 015	1 068	1 121	1 174	1 227
	R 2,00	864	920	975	1 031	1 087	1 143	1 199	1 255	1 311
R 2,10	925	984	1 043	1 101	1 160	1 219	1 278	1 336	1 395	

Table 7.9: Impact of electricity price and MSW gate fees on scenario 4 NPV

		MSW gate fees								
NPV (R million)		-R 250	-R 200	-R 150	-R 100	-R 50	R 0	R 50	R 100	R 150
Electricity price	R 0,50	-368	-298	-227	-157	-87	-17	52	122	192
	R 0,60	-283	-213	-143	-73	-3	66	136	206	276
	R 0,70	-199	-129	-59	11	80	150	220	290	360
	R 0,80	-115	-45	24	94	164	234	304	374	444
	R 0,90	-31	38	108	178	248	318	388	458	528
	R 1,00	52	122	192	262	332	402	472	542	612
	R 1,10	136	206	276	346	416	486	556	626	696
	R 1,20	220	290	360	430	500	570	640	710	780
	R 1,30	304	374	444	514	584	654	724	794	864
	R 1,40	388	458	528	598	668	738	808	878	947
	R 1,50	472	542	612	682	752	822	892	961	1031
	R 1,60	556	626	696	766	836	906	975	1045	1115
	R 1,70	640	710	780	850	920	989	1059	1129	1199
	R 1,80	724	794	864	933	1003	1073	1143	1213	1283
	R 1,90	808	878	947	1017	1087	1157	1227	1297	1367
	R 2,00	892	961	1031	1101	1171	1241	1311	1381	1451
	R 2,10	975	1045	1115	1185	1255	1325	1395	1465	1535

Table 7.8 presents NPV > 2/3 of capital cost options representing half of the available alternatives. A combination of electricity price and power generation efficiency in the range of 27% to 30% results in no NPV ≤ 0 options. Five out of 153 options have an NPV ≤ 0 in Table 7.8.

Options with NPV > 2/3 of capital cost occupy more than half of the area in Table 7.9. 0 < NPV ≤ 1/3 and 1/3 < NPV ≤ 2/3 options have the same prevalence. There is an insignificant increase in options with NPV ≤ 0 from Table 7.8 to Table 7.9.

Table 7.10: Impact of electricity price and medical waste gate fees on scenario 4 NPV

		Medical waste gate fees								
NPV (R million)		R 500	R 1 000	R 1 500	R 2 000	R 2 500	R 3 000	R 3 500	R 4 000	R 4 500
Electricity price	R 0,50	-174	-118	-61	-4	52	109	166	223	279
	R 0,60	-90	-34	23	80	136	193	250	306	363
	R 0,70	-6	50	107	164	220	277	334	390	447
	R 0,80	77	134	191	247	304	361	418	474	531
	R 0,90	161	218	275	331	388	445	501	558	615
	R 1,00	245	302	359	415	472	529	585	642	699
	R 1,10	329	386	443	499	556	613	669	726	783
	R 1,20	413	470	526	583	640	697	753	810	867
	R 1,30	497	554	610	667	724	780	837	894	951
	R 1,40	581	638	694	751	808	864	921	978	1034
	R 1,50	665	721	778	835	892	948	1005	1062	1118
	R 1,60	749	805	862	919	975	1032	1089	1146	1202
	R 1,70	833	889	946	1003	1059	1116	1173	1229	1286
	R 1,80	916	973	1030	1087	1143	1200	1257	1313	1370
	R 1,90	1000	1057	1114	1170	1227	1284	1341	1397	1454
	R 2,00	1084	1141	1198	1254	1311	1368	1424	1481	1538
	R 2,10	1168	1225	1282	1338	1395	1452	1508	1565	1622

In Table 7.10 options with NPV > 2/3 of capital cost occupy two thirds of the available options. Options with 1/3 < NPV ≤ 2/3 of capital cost prevail over NPV ≤ 0 and 0 < NPV ≤ 1/3 choices.

Scenario 4 results show that options with feasible and most attractive NPV are prevalent for a combination of electricity price and any other parameter.

7.5.2 Internal rate of return sensitivity to combination of parameters

The results of changing the combination of electricity price and power generation efficiency, electricity price and MSW gate fees or electricity price and medical waste gate fees on IRR are presented in this section.

7.5.2.1 Scenario 1

Table 7.11 shows variation of IRR by changing a combination of electricity price and power generation efficiency. Options with $IRR \leq 10\%$ are dominant, followed by options with $10\% < IRR \leq 15\%$.

Table 7.11: Impact of electricity price and power generation efficiency on scenario 1 IRR

Electricity price	Power generation efficiency									
	IRR (%)	22%	23%	24%	25%	26%	27%	28%	29%	30%
	R 0,50	2,32	2,63	2,93	3,23	3,51	3,79	4,07	4,34	4,60
	R 0,60	3,63	3,96	4,28	4,60	4,91	5,21	5,51	5,80	6,09
	R 0,70	4,81	5,16	5,51	5,85	6,18	6,50	6,82	7,13	7,44
	R 0,80	5,90	6,27	6,64	7,00	7,35	7,70	8,03	8,37	8,69
	R 0,90	6,91	7,31	7,70	8,08	8,45	8,81	9,17	9,52	9,87
	R 1,00	7,87	8,28	8,69	9,09	9,48	9,87	10,24	10,61	10,98
	R 1,10	8,77	9,21	9,64	10,06	10,47	10,87	11,26	11,65	12,04
	R 1,20	9,64	10,09	10,54	10,98	11,41	11,83	12,24	12,65	13,05
	R 1,30	10,47	10,94	11,41	11,86	12,31	12,75	13,18	13,61	14,03
	R 1,40	11,26	11,76	12,24	12,72	13,18	13,64	14,09	14,53	14,97
	R 1,50	12,04	12,55	13,05	13,54	14,03	14,50	14,97	15,43	15,88
	R 1,60	12,78	13,31	13,83	14,34	14,85	15,34	15,82	16,30	16,77
	R 1,70	13,51	14,06	14,60	15,12	15,64	16,15	16,65	17,15	17,63
	R 1,80	14,22	14,78	15,34	15,88	16,42	16,94	17,46	17,97	18,47
	R 1,90	14,91	15,49	16,06	16,62	17,17	17,72	18,25	18,77	19,29
	R 2,00	15,58	16,18	16,77	17,35	17,91	18,47	19,02	19,56	20,09
	R 2,10	16,24	16,86	17,46	18,05	18,64	19,21	19,78	20,33	20,88

Table 7.12: Impact of electricity price and MSW gate fees on scenario 1 IRR

Electricity price	MSW gate fees									
	IRR (%)	-R 250	-R 200	-R 150	-R 100	-R 50	R 0	R 50	R 100	R 150
	R 0,50		-5,84	-2,47	-0,16	1,67	3,23	4,60	5,85	7,00
	R 0,60	-5,02	-1,96	0,23	2,00	3,51	4,86	6,09	7,22	8,28
	R 0,70	-1,47	0,61	2,32	3,79	5,11	6,32	7,44	8,49	9,48
	R 0,80	0,98	2,63	4,07	5,36	6,55	7,65	8,69	9,68	10,61
	R 0,90	2,93	4,34	5,61	6,78	7,87	8,89	9,87	10,80	11,69
	R 1,00	4,60	5,85	7,00	8,08	9,09	10,06	10,98	11,86	12,72
	R 1,10	6,09	7,22	8,28	9,29	10,24	11,16	12,04	12,88	13,71
	R 1,20	7,44	8,49	9,48	10,43	11,34	12,21	13,05	13,87	14,66
R 1,30	8,69	9,68	10,61	11,51	12,38	13,22	14,03	14,81	15,58	
R 1,40	9,87	10,80	11,69	12,55	13,38	14,19	14,97	15,73	16,48	
R 1,50	10,98	11,86	12,72	13,54	14,34	15,12	15,88	16,62	17,35	
R 1,60	12,04	12,88	13,71	14,50	15,28	16,03	16,77	17,49	18,19	
R 1,70	13,05	13,87	14,66	15,43	16,18	16,91	17,63	18,33	19,02	
R 1,80	14,03	14,81	15,58	16,33	17,06	17,77	18,47	19,16	19,83	
R 1,90	14,97	15,73	16,48	17,20	17,91	18,61	19,29	19,96	20,62	
R 2,00	15,88	16,62	17,35	18,05	18,75	19,43	20,09	20,75	21,39	
R 2,10	16,77	17,49	18,19	18,88	19,56	20,23	20,88	21,52	22,15	

The results of varying a combination of electricity price and MSW gate fees on IRR are shown in Table 7.12. The options with $IRR \leq 10\%$ increase in number in Table 7.12 compared to results of Table 7.11, while the options with $10\% < IRR \leq 15\%$ decreased significantly.

7.5.2.2 Scenario 2

Table 7.13 shows variation of NPV by changing a combination of electricity price and power generation efficiency. Options with $IRR > 15\%$ of capital cost dominate over other options.

Table 7.13: Impact of electricity price and power generation efficiency on scenario 2 IRR

		Power generation efficiency								
	IRR (%)	22,00%	23,00%	24,00%	25,00%	26,00%	27,00%	28,00%	29,00%	30,00%
Electricity price	R 0,50	4,01	4,34	4,67	5,00	5,31	5,62	5,92	6,21	6,50
	R 0,60	5,43	5,80	6,15	6,50	6,84	7,18	7,50	7,82	8,14
	R 0,70	6,73	7,12	7,50	7,88	8,24	8,60	8,95	9,30	9,64
	R 0,80	7,93	8,35	8,75	9,15	9,54	9,93	10,30	10,67	11,04
	R 0,90	9,05	9,50	9,93	10,35	10,76	11,17	11,57	11,96	12,35
	R 1,00	10,12	10,58	11,04	11,48	11,92	12,35	12,77	13,19	13,60
	R 1,10	11,13	11,62	12,09	12,56	13,02	13,48	13,92	14,36	14,79
	R 1,20	12,09	12,61	13,11	13,60	14,08	14,56	15,02	15,48	15,94
	R 1,30	13,02	13,56	14,08	14,60	15,10	15,60	16,09	16,57	17,04
	R 1,40	13,92	14,48	15,02	15,56	16,09	16,60	17,11	17,61	18,11
	R 1,50	14,79	15,37	15,94	16,49	17,04	17,58	18,11	18,63	19,14
	R 1,60	15,64	16,23	16,82	17,40	17,97	18,52	19,07	19,61	20,14
	R 1,70	16,46	17,08	17,68	18,28	18,87	19,44	20,01	20,57	21,12
	R 1,80	17,26	17,90	18,52	19,14	19,75	20,34	20,93	21,51	22,08
	R 1,90	18,04	18,70	19,34	19,98	20,60	21,22	21,82	22,42	23,01
	R 2,00	18,80	19,48	20,14	20,80	21,44	22,08	22,70	23,31	23,91
	R 2,10	19,55	20,24	20,93	21,60	22,26	22,91	23,55	24,18	24,80

Options with $IRR \leq 10\%$ of capital cost are least dominant while options with $IRR > 15\%$ dominate over other options in Table 7.14. The incidence of $IRR > 15\%$ options in Table 7.14 is higher than in Table 7.13.

7.5.2.3 Scenario 3

A combination of electricity price and medical waste gate fee results is presented in addition to a combination of electricity price and power generation efficiency, electricity price and MSW gate fees for scenarios 3 and 4.

IRR sensitivity to a combination of electricity price and power generation for scenario 3 is shown in Table 7.15. Options with $IRR > 15\%$ occupy the largest area and are followed by options with $10\% < IRR \leq 15\%$. Options with $IRR \leq 10\%$ are least dominant.

Table 7.16 shows variation of IRR by altering a combination of electricity price and MSW gate fees. A gradual increase in IRR > 15% is noticed from Table 7.15 to Table 7.16. An MSW gate fee of less than –R150 significantly increases IRR ≤ 10% options.

Table 7.14: Impact of electricity price and MSW gate fees on scenario 2 IRR

Electricity price	MSW gate fees									
	IRR (%)	-R 250	-R 200	-R 150	-R 100	-R 50	R 0	R 50	R 100	R 150
	R 0,50		-4,67	-1,14	1,33	3,30	5,00	6,50	7,88	9,15
	R 0,60	-3,81	-0,59	1,75	3,66	5,31	6,79	8,14	9,40	10,58
	R 0,70	-0,07	2,16	4,01	5,62	7,07	8,40	9,64	10,81	11,92
	R 0,80	2,55	4,34	5,92	7,34	8,65	9,88	11,04	12,14	13,19
	R 0,90	4,67	6,21	7,61	8,90	10,12	11,26	12,35	13,40	14,40
	R 1,00	6,50	7,88	9,15	10,35	11,48	12,56	13,60	14,60	15,56
	R 1,10	8,14	9,40	10,58	11,70	12,77	13,80	14,79	15,75	16,68
	R 1,20	9,64	10,81	11,92	12,98	14,00	14,99	15,94	16,86	17,75
	R 1,30	11,04	12,14	13,19	14,20	15,18	16,12	17,04	17,93	18,80
	R 1,40	12,35	13,40	14,40	15,37	16,31	17,22	18,11	18,97	19,81
	R 1,50	13,60	14,60	15,56	16,49	17,40	18,28	19,14	19,98	20,80
	R 1,60	14,79	15,75	16,68	17,58	18,45	19,31	20,14	20,96	21,76
	R 1,70	15,94	16,86	17,75	18,63	19,48	20,31	21,12	21,92	22,70
	R 1,80	17,04	17,93	18,80	19,65	20,47	21,28	22,08	22,85	23,61
	R 1,90	18,11	18,97	19,81	20,64	21,44	22,23	23,01	23,76	24,51
	R 2,00	19,14	19,98	20,80	21,60	22,39	23,16	23,91	24,66	25,39
	R 2,10	20,14	20,96	21,76	22,54	23,31	24,06	24,80	25,53	26,24

Table 7.15: Impact of electricity price and power generation on scenario 3 IRR

		Power generation efficiency								
Electricity price	IRR (%)	22%	23%	24%	25%	26%	27%	28%	29%	30%
	R 0,50	6,12	6,33	6,54	6,75	6,95	7,15	7,34	7,54	7,73
	R 0,60	7,03	7,27	7,50	7,73	7,96	8,19	8,41	8,63	8,85
	R 0,70	7,89	8,15	8,41	8,67	8,92	9,17	9,42	9,66	9,90
	R 0,80	8,70	8,99	9,28	9,56	9,83	10,11	10,37	10,64	10,90
	R 0,90	9,49	9,80	10,11	10,41	10,71	11,00	11,29	11,58	11,86
	R 1,00	10,24	10,57	10,90	11,23	11,55	11,86	12,17	12,48	12,78
	R 1,10	10,97	11,32	11,67	12,02	12,36	12,69	13,02	13,35	13,67
	R 1,20	11,67	12,05	12,42	12,78	13,14	13,50	13,85	14,19	14,54
	R 1,30	12,36	12,75	13,14	13,53	13,91	14,28	14,65	15,01	15,37
	R 1,40	13,02	13,44	13,85	14,25	14,65	15,04	15,43	15,81	16,18
	R 1,50	13,67	14,11	14,54	14,96	15,37	15,78	16,18	16,58	16,98
	R 1,60	14,31	14,76	15,21	15,64	16,08	16,50	16,92	17,34	17,75
	R 1,70	14,93	15,40	15,86	16,32	16,77	17,21	17,65	18,08	18,50
	R 1,80	15,54	16,02	16,50	16,98	17,44	17,90	18,35	18,80	19,24
	R 1,90	16,13	16,64	17,13	17,62	18,10	18,58	19,05	19,51	19,97
	R 2,00	16,71	17,24	17,75	18,25	18,75	19,24	19,73	20,21	20,68
	R 2,10	17,29	17,83	18,35	18,88	19,39	19,90	20,39	20,89	21,37

Table 7.16: Impact of electricity price and MSW gate fees on scenario 3 IRR

IRR (%)	MSW gate fees								
	-R 250	-R 200	-R 150	-R 100	-R 50	R 0	R 50	R 100	R 150
Electricity price									
R 0,50	0,35	1,94	3,32	4,56	5,69	6,75	7,73	8,67	9,56
R 0,60	2,23	3,58	4,80	5,91	6,95	7,92	8,85	9,73	10,57
R 0,70	3,83	5,03	6,12	7,15	8,11	9,03	9,90	10,74	11,55
R 0,80	5,25	6,33	7,34	8,30	9,20	10,07	10,90	11,71	12,48
R 0,90	6,54	7,54	8,48	9,38	10,24	11,07	11,86	12,63	13,38
R 1,00	7,73	8,67	9,56	10,41	11,23	12,02	12,78	13,53	14,25
R 1,10	8,85	9,73	10,57	11,39	12,17	12,93	13,67	14,39	15,10
R 1,20	9,90	10,74	11,55	12,33	13,08	13,82	14,54	15,23	15,92
R 1,30	10,90	11,71	12,48	13,23	13,96	14,68	15,37	16,05	16,71
R 1,40	11,86	12,63	13,38	14,11	14,82	15,51	16,18	16,85	17,49
R 1,50	12,78	13,53	14,25	14,96	15,64	16,32	16,98	17,62	18,25
R 1,60	13,67	14,39	15,10	15,78	16,45	17,11	17,75	18,38	19,00
R 1,70	14,54	15,23	15,92	16,58	17,24	17,88	18,50	19,12	19,73
R 1,80	15,37	16,05	16,71	17,36	18,00	18,63	19,24	19,85	20,44
R 1,90	16,18	16,85	17,49	18,13	18,75	19,36	19,97	20,56	21,14
R 2,00	16,98	17,62	18,25	18,88	19,49	20,09	20,68	21,26	21,83
R 2,10	17,75	18,38	19,00	19,61	20,21	20,79	21,37	21,94	22,51

Medical waste gate fees of R4500/tonne result in no IRR ≤ 10% options in all combinations with electricity price, as shown in Table 7.17. Options with IRR > 15% represent more than half of all the options in Table 7.17.

Table 7.17: Impact of electricity price and medical waste gate fees on scenario 3 IRR

IRR (%)	Medical waste gate fees								
	R 500	R 1 000	R 1 500	R 2 000	R 2 500	R 3 000	R 3 500	R 4 000	R 4 500
Electricity price									
R 0,50	4,27	5,22	6,10	6,94	7,73	8,49	9,22	9,93	10,61
R 0,60	5,65	6,51	7,32	8,10	8,85	9,57	10,26	10,93	11,58
R 0,70	6,90	7,70	8,46	9,20	9,90	10,58	11,24	11,89	12,51
R 0,80	8,07	8,82	9,54	10,23	10,90	11,56	12,19	12,81	13,41
R 0,90	9,17	9,87	10,56	11,22	11,86	12,49	13,10	13,70	14,28
R 1,00	10,20	10,88	11,53	12,17	12,78	13,39	13,98	14,56	15,13
R 1,10	11,19	11,84	12,46	13,08	13,67	14,26	14,83	15,39	15,94
R 1,20	12,14	12,76	13,36	13,96	14,54	15,10	15,66	16,21	16,74
R 1,30	13,05	13,65	14,24	14,81	15,37	15,92	16,46	17,00	17,52
R 1,40	13,93	14,51	15,08	15,64	16,18	16,72	17,25	17,77	18,28
R 1,50	14,79	15,35	15,90	16,44	16,98	17,50	18,02	18,52	19,03
R 1,60	15,62	16,16	16,70	17,23	17,75	18,26	18,77	19,26	19,75
R 1,70	16,42	16,95	17,48	18,00	18,50	19,01	19,50	19,99	20,47
R 1,80	17,21	17,73	18,24	18,75	19,24	19,73	20,22	20,70	21,17
R 1,90	17,98	18,48	18,99	19,48	19,97	20,45	20,92	21,39	21,86
R 2,00	18,73	19,22	19,71	20,20	20,68	21,15	21,62	22,08	22,53
R 2,10	19,46	19,95	20,43	20,90	21,37	21,84	22,29	22,75	23,20

7.5.2.4 Scenario 4

Table 7.18 to Table 7.20 show how IRR varies with different combination of factors for scenario 4. IRR $\leq$ 10% options decrease significantly in all alternatives compared with other scenarios.

Table 7.18: Impact of electricity price and power generation efficiency on scenario 4 IRR

		Power generation efficiency								
Electricity price	IRR (%)	22%	23%	24%	25%	26%	27%	28%	29%	30%
	R 0,50	8,15	8,39	8,61	8,84	9,07	9,29	9,51	9,72	9,94
	R 0,60	9,15	9,42	9,68	9,94	10,19	10,44	10,69	10,94	11,18
	R 0,70	10,11	10,40	10,69	10,98	11,26	11,54	11,82	12,09	12,36
	R 0,80	11,02	11,34	11,66	11,97	12,28	12,59	12,89	13,19	13,49
	R 0,90	11,90	12,25	12,59	12,93	13,27	13,60	13,92	14,25	14,57
	R 1,00	12,74	13,12	13,49	13,85	14,21	14,57	14,92	15,26	15,61
	R 1,10	13,56	13,96	14,35	14,74	15,13	15,50	15,88	16,25	16,61
	R 1,20	14,35	14,78	15,19	15,61	16,01	16,41	16,81	17,20	17,59
	R 1,30	15,13	15,57	16,01	16,45	16,87	17,30	17,71	18,12	18,53
	R 1,40	15,88	16,35	16,81	17,26	17,71	18,16	18,59	19,03	19,45
	R 1,50	16,61	17,10	17,59	18,06	18,53	18,99	19,45	19,90	20,35
	R 1,60	17,33	17,84	18,34	18,84	19,33	19,81	20,29	20,76	21,23
	R 1,70	18,03	18,56	19,09	19,60	20,11	20,61	21,11	21,60	22,08
	R 1,80	18,72	19,27	19,81	20,35	20,88	21,40	21,91	22,42	22,92
	R 1,90	19,39	19,96	20,53	21,08	21,63	22,17	22,70	23,22	23,74
	R 2,00	20,05	20,64	21,23	21,80	22,36	22,92	23,47	24,01	24,55
R 2,10	20,70	21,31	21,91	22,50	23,09	23,66	24,23	24,78	25,33	

Table 7.19: Impact of electricity price and MSW gate fees on scenario 4 IRR

		MSW gate fees								
Electricity price	IRR (%)	-R 250	-R 200	-R 150	-R 100	-R 50	R 0	R 50	R 100	R 150
	R 0,50	1,86	3,57	5,08	6,43	7,68	8,84	9,94	10,98	11,97
	R 0,60	3,89	5,36	6,69	7,92	9,07	10,15	11,18	12,17	13,12
	R 0,70	5,63	6,94	8,15	9,29	10,36	11,38	12,36	13,30	14,21
	R 0,80	7,19	8,39	9,51	10,57	11,58	12,55	13,49	14,39	15,26
	R 0,90	8,61	9,72	10,77	11,78	12,74	13,67	14,57	15,44	16,28
	R 1,00	9,94	10,98	11,97	12,93	13,85	14,74	15,61	16,45	17,26
	R 1,10	11,18	12,17	13,12	14,03	14,92	15,78	16,61	17,42	18,22
	R 1,20	12,36	13,30	14,21	15,09	15,94	16,78	17,59	18,38	19,15
	R 1,30	13,49	14,39	15,26	16,11	16,94	17,74	18,53	19,30	20,05
	R 1,40	14,57	15,44	16,28	17,10	17,90	18,69	19,45	20,20	20,94
	R 1,50	15,61	16,45	17,26	18,06	18,84	19,60	20,35	21,08	21,80
	R 1,60	16,61	17,42	18,22	18,99	19,75	20,50	21,23	21,94	22,64
	R 1,70	17,59	18,38	19,15	19,90	20,64	21,37	22,08	22,78	23,47
	R 1,80	18,53	19,30	20,05	20,79	21,51	22,22	22,92	23,61	24,28
	R 1,90	19,45	20,20	20,94	21,66	22,36	23,06	23,74	24,41	25,07
	R 2,00	20,35	21,08	21,80	22,50	23,20	23,88	24,55	25,20	25,85
R 2,10	21,23	21,94	22,64	23,33	24,01	24,68	25,33	25,98	26,62	

Thirteen out of 153 options have $IRR \leq 10\%$ in Table 7.18. $IRR > 15\%$ options dominate the combination of $IRR \leq 10\%$ and $10\% < IRR \leq 15\%$ options.

Table 7.19 shows that an MSW gate fee of more than R100/tonne results in IRR greater than 10% in all combinations with electricity price. $IRR > 15\%$ options are dominant over other options in over half of the cases.

Medical waste gate fees of more than R3000/tonne result in no options with $IRR \leq 10\%$, as shown in Table 7.20. Options with $IRR > 15\%$ occupy two thirds of the total area in Table 7.20.

Table 7.20: Impact of electricity price and medical waste gate fees on scenario 4 IRR

Electricity price	Medical waste gate fees									
	IRR (%)	R 500	R 1 000	R 1 500	R 2 000	R 2 500	R 3 000	R 3 500	R 4 000	R 4 500
	R 0,50	6,11	7,15	8,13	9,05	9,94	10,79	11,60	12,39	13,16
	R 0,60	7,63	8,58	9,48	10,35	11,18	11,98	12,76	13,52	14,25
	R 0,70	9,02	9,90	10,75	11,57	12,36	13,13	13,87	14,59	15,30
	R 0,80	10,32	11,15	11,95	12,73	13,49	14,22	14,94	15,63	16,32
	R 0,90	11,54	12,33	13,10	13,84	14,57	15,27	15,96	16,64	17,30
	R 1,00	12,70	13,46	14,19	14,91	15,61	16,29	16,96	17,61	18,25
	R 1,10	13,81	14,54	15,24	15,94	16,61	17,27	17,92	18,56	19,18
	R 1,20	14,88	15,58	16,26	16,93	17,59	18,23	18,86	19,48	20,09
	R 1,30	15,91	16,58	17,25	17,89	18,53	19,16	19,77	20,37	20,97
	R 1,40	16,90	17,56	18,20	18,83	19,45	20,06	20,66	21,25	21,83
	R 1,50	17,87	18,51	19,13	19,75	20,35	20,94	21,53	22,10	22,67
	R 1,60	18,81	19,43	20,04	20,64	21,23	21,81	22,38	22,94	23,50
	R 1,70	19,72	20,33	20,92	21,51	22,08	22,65	23,21	23,76	24,31
	R 1,80	20,61	21,20	21,78	22,36	22,92	23,48	24,03	24,57	25,10
	R 1,90	21,48	22,06	22,63	23,19	23,74	24,29	24,82	25,36	25,88
	R 2,00	22,33	22,90	23,45	24,00	24,55	25,08	25,61	26,13	26,65
	R 2,10	23,17	23,72	24,26	24,80	25,33	25,86	26,38	26,89	27,40

7.6 Sensitivity analysis results discussion

Sensitivity analysis results proved that an increase in electricity price, power generation efficiency, MSW and medical waste gate fees results in an increase in NPV and IRR, thus an increase in investment attractiveness. This is in harmony with literature studied, which states that, increase in income with other factors constant result in increase in NPV and IRR (Serfontein, 2014:1; School of Mechanical and Nuclear Engineering, 2014:1). Thus the sensitivity analysis results show robustness of financial model.

Sensitivity analysis results indicate that varying the four parameters stated above show consistency in the ranking and performance of the financial model scenarios presented in chapter 6. Financial performance based on NPV and IRR shows that scenario 4, characterised by MSW and medical waste as feedstock and owned by an IPP, is ranked number one based on number

of feasible and most attractive investment options. Scenario 2 marked by MSW as feedstock and owned by an IPP, scenario 3 classified with MSW and medical waste as feedstock and owned by an investment company and scenario 1 characterized by MSW as feedstock and owned by an investment company are ranked number two, three and four respectively.

The consistency between financial model scenarios performance with the sensitivity analysis results verify that the financial model is credible and robust. Thus sensitivity analysis plays the role of model verification in this study and the conclusions of chapter 6 can be accounted dependable.

Comparing Figure 7.4 to Figure 7.6 and Figure 7.7 to Figure 7.9 shows that NPV and IRR are more sensitive to electricity price variation and least susceptible to power generation efficiency. This is relative to the four sensitivity parameters considered in this analysis.

Figure 7.4 to Figure 7.9 indicate that scenario 4 has the highest NPV and IRR. Scenario 1 registers the lowest NPV and IRR values. In Figure 7.4 to Figure 7.6, there is an insignificant difference in the variation of NPV with the enlisted parameters for scenarios 2 and 3.

Figure 7.6 and Figure 7.9 show that the financial model developed supports a business case where waste producers are paid for bringing waste to the plant. Scenarios 4, 3 and 2 indicate that waste producers can be paid up to R250 per tonne of waste sent to the plant.

Evaluating Table 7.1 to Table 7.10 and Table 7.11 to Table 7.20 shows that scenario 4 has the highest number of options with NPV and IRR results that indicate the most attractive investment. The same comparisons prove that scenario 1 is dominated by options that are not financially feasible.

Table 7.7 and Table 7.10 show that a combination of electricity price and medical waste gate fees has the highest impact on NPV compared to a combination with other factors. The same results are portrayed for the IRR as indicated in Table 7.17 and Table 7.20.

WtE grate incineration thermal and power generation efficiency can significantly be improved by waste energy recovery. Instead of condensing the low pressure steam to water and loss energy to the surrounding, energy can be recovered as district heating and process heat for industries. Combined heat and power WtE plants has the best environment performance (European Commission, 2006:19; IEA Bioenergy, 2010:5).

Power generation efficiency can be raised in order of 5% to 10% through utilizing low pressure steam in industrial processes and district heating, rather than discarding energy into the environment (IEA Bioenergy, 2010:5). District heating does not apply to the context of South

African cities, hence energy is recovered as process steam. Considering an improvement of power generation efficiency of 5% will results in increase of feasible and most attractive investment in Table 7.1, Table 7.3, Table 7.5, Table 7.8, Table 7.11, Table 7.13, Table 7.15 and Table 7.18.

An improvement in power generation efficiency of 5% will shift sensitivity analysis results of combination of electricity price and power generation efficiency five steps up. This means that, for example, the sensitivity results at 22% power generation efficiency will shift to 27%. Therefore there is significant improvement in the financial performance of the WtE grate incineration power plant.

7.7 Conclusion

The purpose of this chapter was to perform sensitivity analysis of the parameters that affect a WtE grate incineration power plant's financial viability as a means of verifying the credibility of the financial model of chapter 6. Four parameters were considered in the sensitivity analysis, namely electricity price, power generation efficiency, MSW and medical waste gate fees.

NPV and IRR are highly sensitive to a variation in electricity prices and least sensitive to power generation efficiency. Scenario 4, characterized by MSW and medical waste as feedstock and IPP-owned, registers a significant number of feasible and most attractive investment options. Scenario 1, marked by MSW and owned by an investment company, records a noticeable number of investment options that are not financially feasible.

The next chapter aims at presenting the verification of the results, research conclusions and study recommendations.

CHAPTER 8

VERIFICATION OF RESULTS, CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

The research aimed at performing a techno-economic evaluation of a WtE grate incineration power plant for a small South African city. The purpose of this chapter is to carry out verification of results and to present conclusions and recommendations drawn from the study. Figure 8.1 shows the research roadmap with the final stage highlighted.

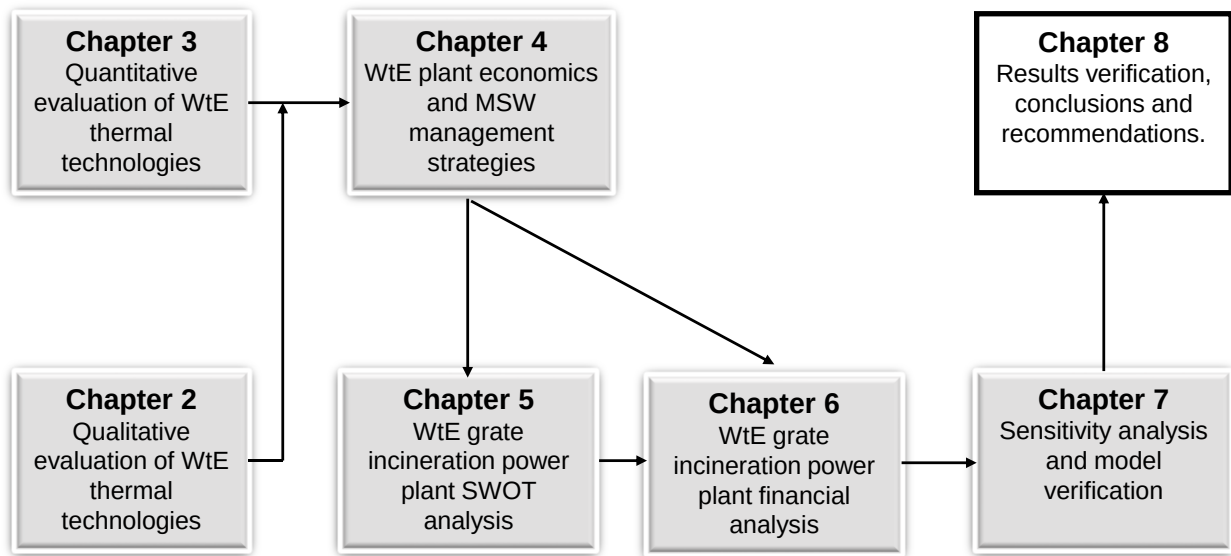


Figure 8.1: Research roadmap position 7

The chapter is ordered as follows: Firstly, the verification of results is presented in section 8.2. The conclusions drawn from the techno-economic evaluation of a WtE grate incineration power plant are discussed in section 8.3. This is followed by a list of recommendations on future work derived from the study in section 8.4. The chapter is concluded in section 8.5.

8.2 Verification of results

The research project results were verified by performing a sensitivity analysis, surveys and consultation with experts on WtE grate incineration power plants and publication of the results in two peer-reviewed conference proceedings. The model capital cost and operating cost was compared with figures of existing WtE power plant. This section includes verification of

technological and performance qualitative (Section 8.2.1) and quantitative (Section 8.2.2) evaluation results, financial and sensitivity analysis (Section 8.2.3) results and comparison of model capital and operating cost with existing WtE plant data (Section 8.2.4).

8.2.1 Technological and performance qualitative evaluation results

A technological and performance evaluation of WtE thermal technologies was performed and the results are presented in chapter two. The qualitative evaluation of WtE technologies was carried out using published journals and other trusted sources as referenced. With reference to chapter two, section 2.5, the four technologies are ranked as grate incineration, fluidized bed incineration, gasification and pyrolysis.

To verify the results of chapter two, AHP, which is a multi-criteria decision-making tool, was used to verify the qualitative results of chapter two as discussed in section 8.2.2.

Further to the results verification by AHP, technological and performance evaluations results were published in the peer-reviewed conference proceedings of SAUPEC 2015, where the author made a presentation. Peer- reviews confirmed that the results were realistic and credible.

8.2.2 Technological and performance quantitative evaluation results

The technological and performance quantitative evaluation was performed as a means to verify the results of qualitative analysis performed in chapter two. The quantitative analysis was performed using AHP.

The WtE technological and performance quantitative evaluation results are given in chapter three. AHP comparison matrix results must have a $CR < 0.1$. The results obtained in this study showed that all the comparison matrices have a CR in the range of $0.0021 < CR < 0.03$. The accuracy of the results is significantly above the expected CR. The technological and performance quantitative results are consequently regarded as rational.

The technological and performance qualitative and quantitative evaluations results of the WtE thermal technologies are expected to concur. Qualitative results showed that grate incineration performed best and pyrolysis worst. The same performance hierarchy was displayed with quantitative analysis. There is coherence between qualitative and quantitative analysis results, thus the results are realistic.

8.2.3 Financial analysis results

Financial and sensitivity analyses were performed and presented in chapters six and seven respectively. Analysis assumptions were programmed on one worksheet linked to the four

scenarios' analysis. This was to avoid variance due to data input errors. The financial analysis results were verified through interviews with scholars and industrial experts (Section 8.2.3.1), publication of the results in a peer-reviewed paper (Section 8.2.3.2) and results pattern analysis (Section 8.2.3.3).

8.2.3.1 Results verification interviews

Interviews were conducted with three experts whose biographies are shown in Table 8.1. Table 8.2 displays the results verification interview questions that were employed in the results verification process. The interviewee responses are presented in Table 8.3.

Table 8.1: Results verification interviewee bibliography

Interviewee N ^o	Bibliography
1	He is an actuarial scientist with an honours degree in business mathematics and master's degree in mechanical engineering. He is currently employed as a lecturer at the School for Mechanical and Nuclear Engineering at the NWU. He is well experienced in financial modelling and his research interests include mathematical and statistical modelling.
2	He is a finance, administration and economic development specialist with nine years' experience, five of which were spent in the international economic development sector. He is currently in his second year of MBA studies at the North West University PBS (NWU).
3	An economist, working for AEB Amsterdam as a strategic advisor to the board. He is responsible for the international co-operation of AEB Amsterdam. Among others he is responsible for identifying countries/locations that could be suitable for WtE from an environmental, economic and technical point of view.

Table 8.2: Results verification interview questions

Question N ^o	Content
1	The first worksheet in the excel calculations shows all the assumptions used in the economic model. Do you think the assumptions made for the analysis are realistic?
2	The objective of the economic analysis is to assist investors to make investment decision on a waste-to-energy grate incineration power plant for a small South African city. Do the financial viability indicators (NPV and IRR) used assist in making this decision?
3	Are the variables used in the sensitivity analysis appropriate for this study?
4	What future work do you think should be considered as a follow-up to this study?

Table 8.3: Interviewee responses to the interview

Question No	Number positive response	Number of negative response
1	3	0
2	3	0
3	3	0

All the interviewees responded positively to the first three questions. The responses show that the interviewees agreed that the assumptions used in the economic model were realistic and the sensitivity analysis parameters used in this study were credible. The interviewees' answers also proved that the financial indicators used in this study can assist investors to make an investment decision on a WtE grate incineration power plant for a small South African city. Appendix F2, F3 and F4 give the interviewees' complete response.

The interviewees suggested that a pre-feasibility study for a prospective investor to determine the most feasible technology, scope and location be conducted. It was recommended that physical values measurement over an average time for a complete case study should be carried out.

AEB Amsterdam operates one of the largest and cleanest WtE grate incineration power plants in the world. The financial analysis was sent to them for verification. They confirmed that the financial model was convincing and credible. See Appendix E5.

8.2.3.2 Publication of the results

The financial analysis methodology and results were published in the peer-reviewed conference proceedings of the ICUE 2015 (Appendix B). A presentation by the author at the ICUE conference exposed the financial analysis to further review to ensure that the results were realistic and credible. Recommendations from the peer review were incorporated in the results presented in this work.

8.2.3.3 Results pattern analysis

Sensitivity analysis can be employed as model verification tool (Frey et al., Smith et al., 2008:39; Ekberg, 1999:1). The model's stability and consistency were tested by performing a sensitivity analysis using four parameters, namely electricity price, power generation efficiency, MSW gate fees and medical waste gate fees.

Literature that was studied indicate that as income increases and other factors remain constant, the IRR and NPV must in turn increase in value (Serfontein, 2014:1; School of Mechanical and Nuclear Engineering, 2014:1). Thus the investment becomes more attractive. The sensitivity analysis showed that increasing the electricity price, power generation efficiency, MSW and medical waste gate fees resulted in a significant increase in value of the NPV and IRR. Sensitivity analysis results portrayed the expected results from the literature studied, confirming that the results were credible.

8.2.4 Comparison of model capital and operating cost with existing WtE plants data

The major parameters of the financial model in this study are WtE plant operating cost and capital cost. To verify that the used capital cost and operating cost in the model is credible, a comparison with capital cost of the exiting WtE power plant in other countries was performed. Data from four existing WtE plants is used as comparison references as well as technical report by Stantec consultants and assessment by Jacobs Babbie.

8.2.4.1 Capital cost

The capital cost for a WtE power plant varies from region to region. Table 8.4 show the capital cost for WtE grate incineration power plant in different regions. The difference in capital cost can be attributed to size of the plant, configuration, architectural design, air pollution control system design, availability of local structure among other (Stantec Consulting Ltd, 2011:7.1). Low price in land and infrastructure contribute to the low capital cost of WtE power plant in South Africa.

The variance in the capital cost in Table 8.4 is justified since the WtE plants being compared are of different sizes and are located in different locations. Comparing WtE power plant capital cost data in different regions is uncertain practise and can lead to evaluation discrepancies (Whiting, 2013:24)

Table 8.4: Model capital cost comparison with exiting plant capital costs (Stantec Consulting Ltd, 2011:7.1; Whiting et al., 2013:51; Jacobs Babbie, 2006:12)

Description	Capacity (t/hr)	Capital cost (R/ton)	Reference
Scenario 1	25	4550	Chapter 6 , Table 6.8
Scenario 2	25	3564	Chapter 6, Table 6.8
Scenario 3	25	4590	Chapter 6, Table 6.8
Scenario 4	25	3672	Chapter 6, Table 6.8
Stantec (medium)	23	6168	(Stantec Consulting Ltd, 2011:7.1)
Stantec (low)	23	5120	(Stantec Consulting Ltd, 2011:7.1)
Jacobs Babbie (250K)	29	5425	(Jacobs Babbie, 2006:12)
Jacobs Babbie (200K)	23	5276	(Jacobs Babbie, 2006:12)
Lakeside London, UK	47	7844	(Whiting et al., 2013:51)
Allington, Kent, UK	57	6030	(Whiting et al., 2013:70)
Brescia, Italy	100	7236	(Whiting et al., 2013:109)
Riverside London	90	8212	(Whiting et al., 2013:117)
Average	42.2	6040	N/A

8.2.4.2 Operating cost

According to Whiting et al. (2013:24), obtaining cost data from plant owners and operators is challenging. Table 8.5 show that no operating data could be obtained from the listed exiting WtE grate incineration power plants. Only data from Stantec consultants and Jacobs Babbie was used for the comparisons.

Comparing WtE power plant cost data in different regions is unreliable practise. Whiting et al. (2013:28), further states that the major contributor to WtE plant operating cost is labour cost and the larger the plant the lower the labour cost per tonne of processed MSW. The comparison of the operating cost in Table 8.5 show the correlation between operating cost and size of the plant. The operating cost variations in Table 8.5 are therefore justified and accounted credible since there is variation in plant capacity.

Table 8.5: Model operating cost comparison with exiting plant operating cost (Stantec Consulting Ltd, 2011:7.1; Whiting et al., 2013:51; Jacobs Babbie, 2006:12)

Description	Capacity (t/hr)	Operating cost (R/ton)	Reference
Scenario 1&2	25	692	Chapter 6 of this study
Scenario 3&4	25	711	Chapter 6 of this study
Stantec (medium)	23	513	(Stantec Consulting Ltd, 2011:7.1)
Stantec (low)	23	311	(Stantec Consulting Ltd, 2011:7.1)
Jacobs Babbie (250K)	29	492	(Jacobs Babbie, 2006:12)
Jacobs Babbie (200K)	23	409	(Jacobs Babbie, 2006:12)
Lakeside London, UK	47	-	(Whiting et al., 2013:51)
Allington, Kent, UK	57	-	(Whiting et al., 2013:70)
Brescia, Italy	100	-	(Whiting et al., 2013:109)
Riverside London	90	-	(Whiting et al., 2013:117)
Average	42.2	6040	N/A

8.3 Research conclusions

The conclusions drawn from the research are listed in this section. The aim of the research was to perform a techno-economic evaluation of a WtE grate incineration power plant for a small South African city. To accomplish this, the following objectives were set:

- identify and evaluate possible WtE thermal technologies that can be implemented in South African cities;

- b. identify and organize factors that have an impact on WtE grate incineration power plants in South Africa, using strengths, weakness, opportunities and threats (SWOT) analysis;
- c. investigate MSW generation trends and management strategies for a small South African city in the North-West Province, Potchefstroom;
- d. develop a WtE grate incineration power plant conceptual model for the city of Potchefstroom; and
- e. perform financial evaluation and sensitivity analyses of a WtE grate incineration power plant for the small city.

To identify and evaluate possible WtE thermal technologies that can be implemented in South African cities (Objective a), a technological and performance qualitative and quantitative evaluation was performed in this study.

The qualitative and quantitative evaluations proved that grate incineration technology remains the preferred WtE thermal technology over fluidized bed, gasification and pyrolysis. This is because of its reliability, capability to incinerate assorted waste, lower operational complexity and higher power efficiency.

WtE grate incineration significantly supports material recycling initiatives, as confirmed by countries that implemented this technology. This is achieved through recovery of metals from the bottom ash and APC residue. Recyclable materials can be recovered from the feedstock preparation stage.

Factors that would have an impact on a WtE grate incineration power plant in South Africa were listed using SWOT analysis (Objective b). Tlokwe municipality, incorporating the small city of Potchefstroom, was used as a case study and its MSW generation and management data were gathered and analyzed (Objective c).

The identified WtE grate incineration opportunities in South Africa included MSW, characterized by 80% combustible material, an average of 90% dominance of landfill over other waste management strategies, an average MSW generation growth rate of 3% per annum, national power shortages, the intermittent nature of solar and wind energy, non-energy recovery methods used in treating HCRW and accumulation of WT, among others.

The possibility of implementing WtE grate incineration is substantial in countries that have landfill dominating other waste management strategies. This study is thus of significance in the South African context, because landfill is the governing MSW management strategy in the country.

A WtE grate incineration power plant can be classified among renewable energy sources. This is because 50% to 70% of energy recovered in a WtE grate incineration power plant is biogenic. Grate incineration technology has a lower weighted capital cost compared to wind and solar technologies.

There is noteworthy potential of WtE grate incineration contributing to the country's renewable energy mix. Approximately 1255 MW power generation capacity can be realized in South Africa by implementing WtE grate incineration technology.

High capital cost is a serious hindrance in implementing WtE grate incineration technology, regardless of its positive financial performance. Lack of enforcement of environmental legislation in the country, such as landfill diversion, adds to WtE grate incineration implementation obstacles. Another constant implementation challenge is the local culture of non-payment for service, especially in the African and colored communities.

A WtE grate incineration power plant conceptual model for the small South African city was developed and financial evaluation and sensitivity analysis performed (Objectives d and e). It was concluded that investment in a WtE grate incineration power plant is feasible and attractive, on condition that medical waste is diverted to the plant and an investment subsidy is accessible.

An investment scenario characterized by MSW and medical waste as feedstock and IPP-owned is regarded as a feasible and most attractive investment option. An investment scenario marked by MSW and owned by an investment company is the least attractive investment option.

Electricity sales and medical waste gate fees contribute greatly to WtE grate incineration power plant revenue streams. Thus a favorable electricity price and medical waste gate fees are of importance in achieving financial viability.

The financial feasibility of a WtE grate incineration power plant is considerably influenced by the plant's processing capacity. A plant capacity of greater than or equal to 200 000 tonnes per annum proved to be financially feasible.

Investment in a WtE grate incineration power plant is feasible and more attractive as the plant capacity increases ($\geq 200\,000$ tonnes). Therefore the results of this study can be used to predict WtE grate incineration power plant feasibility for medium to large South African cities, which generates large amount of MSW.

It was identified that among the four sensitivity analysis parameters considered in this study, NPV and IRR are highly sensitive to variation in electricity price and least susceptible to power generation efficiency.

8.4 Recommendations on future work

Investigations showed that WtE grate incineration can contribute significantly to the mitigation of power shortages, MSW management problems and unemployment in South Africa. With regard to the findings and conclusions reached in this study, the following recommendations are made:

- WtE grate incineration must be listed among the renewable energy sources in the REIPPP. This will arouse interest among investors and lead to further investigations into WtE grate incineration technology implementation in South Africa.
- The government must initiate landfill diversion incentives and enforce environmental protection legislations. This will promote alternative and sustainable waste management strategies, such as WtE grate incineration.
- A detailed WtE grate incineration power plant equipment and material cost calculation must be carried out in order to determine the actual WtE grate incineration capital cost. This will facilitate accuracy in the financial viability study.
- A feasibility study on WtE grate incineration for a small city must be carried out to ascertain the applicability of the technology in South Africa. This must include a life cycle assessment for the plant.

8.5 Conclusion

South Africa is faced with electrical power shortages and the country is promoting renewable energy through participation in IPP programs. Moreover, the country is faced with MSW management problems, with landfill and illegal dumping dominating other strategies. In addition, the unemployment rate in South Africa is on the rise.

The results of the study show that WtE grate incineration technology has the potential of simultaneously mitigating MSW generation and management challenges, power shortages and unemployment problems. Investment in such technologies can assist the country in alleviating the problems currently faced. Thus a techno-economic evaluation of a WtE grate incineration power plant for a small city is a relevant study in the South African context and if similar studies and initiatives can be pursued in future, it will significantly contribute to the economic growth in South Africa.

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APPENDIX A: QUALITATIVE EVALUATION SAUPEC PUBLICATION

A TECHNOLOGICAL AND PERFORMANCE COMPARISON OF WASTE-TO-ENERGY THERMAL TECHNOLOGIES

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Abstract: Economic growth and rapid population growth are a combination of factors that causes an increase in electric energy demand and municipal solid waste (MSW) generation. Interest in MSW as an alternative source of renewable energy has been growing and the global focus has shifted to waste management strategies that are harmonized with the goal of sustainable development through electrical power generation and minimization of adverse effects of landfill. Waste-to-energy (WtE) is proving to be a sustainable and successful alternative technology to treat residual MSW. The purpose of this study is to carry out a technological and performance comparison of proven WtE thermal technologies. The paper presents a comparison of four WtE technologies in the field of waste treatment, the thermal process and energy recovery options.

Keywords: Municipal Solid Waste (MSW), Waste-to-energy (WtE), Incineration, Gasification, Pyrolysis.

1. INTRODUCTION

Economic growth and rapid population growth are a combination of factors that are bound to increase the demand for electric energy and the generation of municipal solid waste (MSW). Strategies to de-couple economic growth from an increase in the rate of MSW generation have met with little success in developed countries, resulting in MSW management becoming a growing problem. Globally, the focus has shifted to waste management strategies that are harmonized with the goal of sustainable development through electrical power generation and minimization of adverse effects of landfill [1,2].

South Africa has been hit with a shortfall in electrical energy generation capacity due to an increase in demand and failure to invest in additional capacity since the onset of 2008 [3]. It has furthermore been projected that South Africa will experience a great risk of electrical energy supply interruptions between 2018 and 2024, fostering the need to moderate the anticipated supply interruptions by increasing the generation capacity [4].

Renewable energy is the fastest growing technology in the global energy mix, with a growing rate estimated at 8.2% by 2010 [4]. In a bid to align with global development, South Africa has adopted a policy that advocates renewable energy in mitigating the adverse impacts associated with its dependence on coal to meet the country's energy requirements [5]. South Africa is set to achieve a greener energy mix by 2030 through the contribution of independent power producers [6].

South Africa's renewable energy sources mix includes solar energy, biomass, wind and small-scale hydro generation. MSW is listed among the renewable energy

sources and it is estimated that the equivalent of 11 000 GWh per annum of MSW is sent to landfill sites [7]. This wasted energy can be harnessed through WtE thermal technologies and/or methane gas.

In South Africa, municipalities are regarded as the major consumers of electricity; their consumption percentage ranges roughly from 40 to 42% [8]. This can be supplemented by taking advantage of MSW as a source of energy.

WtE incineration technologies have been implemented in developed countries with overwhelming success to harness energy from MSW. In 2012, 472 European and 86 American WtE plants were in operation [9]. AEB, Amsterdam's WtE plant, the world's largest and cleanest plant, produces 1 million MWh/year of electricity and 300 million MJ/year of district heating through the incineration of 1.4 million tonnes of MSW [1].

The work presented in this paper forms part of an ongoing research project into technological and financial factors that influence the implementation of WtE thermal technologies in South Africa.

The paper presents a technological and performance evaluation of WtE thermal technologies. In this study four WtE thermal processes are compared in respect of classification, waste pre-treatment requirements and energy recovery options. The paper investigates technological performance in terms of capacity and scalability, energy production potential, flue gas and residual production and technological reliability.

This paper is organized as follows: a WtE overview, technological evaluation, comparison of technological

performance, technological cost evaluation and conclusion.

2. WASTE-TO-ENERGY OVERVIEW

WtE facilities convert MSW into gaseous, liquid and solid conversion products, simultaneously releasing heat energy, which is recovered through boilers. The recovered heat can be converted into electricity or directly exported to district heating systems [10].

About 50%-70% of the MSW stream sent to landfill sites as residual waste is of biogenic origin, such as food and garden waste, wood, paper and textiles. Therefore 50% of energy recovered from WtE incineration is regarded to be biogenic energy, hence contributing to renewable energy [1].

The efficiency of energy recovery in a WtE plant is influenced by factors such as the calorific value of the feedstock, losses in the combustion chamber and steam-water cycle, steam parameters and energy recovery process, which can be in the form of heat, power generation and combined heat and power generation (CHP) [11].

WtE thermal processes are classified as conventional and advanced technologies. Table 1 shows technologies discussed in this paper and their classification.

Table 1: WtE thermal technologies classification

Classification	Technology
Conventional	Grate incineration
	Fluidized bed incineration
Advanced	Gasification
	Pyrolysis

Figure 1 is a comparison of worldwide application of the WtE technologies mentioned in Table 1. Grate incineration is a commercially proven technology, with 90% of the WtE incinerators in Europe and more than 500 WtE plants worldwide using this technology. Fluidized bed incineration is commonly used for small throughput plants in Japan, with 50 plants operating on this technology worldwide [1,10].

Gasification is widely used in Japan, with 95 WtE plants using this technology. Pyrolysis is less proven on commercial scale with only 11 plants in Germany operating with this technology [1].

The process flow of conventional technologies, grate and fluidized bed incineration is shown in Figure 2. Figure 3 illustrates gasification and pyrolysis process flow.

In countries where WtE incineration has been implemented, it has been proved that WtE is compatible with high recycling rates [1, 12]. European countries such as Sweden, Denmark and the Netherlands make the highest

contributions to WtE, and concurrently show the highest recycling rates [13, 14]

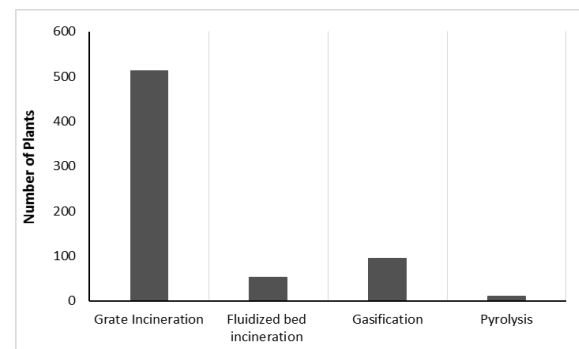


Figure 1: Worldwide operating WtE plants [1]

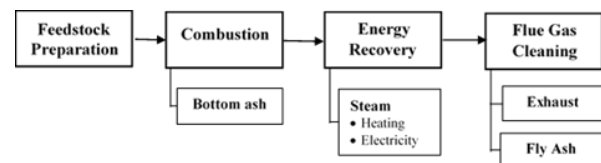


Figure 2: Conventional WtE overview [10]

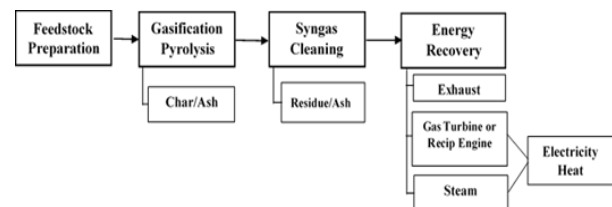


Figure 3: Advanced thermal treatment WtE [10]

Successful implementation of WtE has been driven by the desire to achieve sustainable development through elimination of landfill and improve on material and energy recovery. Countries that rely on landfill thus have greater potential to implement WtE [1].

3. WASTE-TO-ENERGY TECHNOLOGIES

This section evaluates four WtE thermal technologies namely grate incineration, fluidized bed incineration, gasification and pyrolysis. The technologies are evaluated on the basis of waste pre-treatment, the thermal process, energy recovery and management of residual waste from the processes. Table 2 is a summarized comparison of the above-mentioned four technologies.

3.1 Pre-treatment process

The first stage in a WtE plant is the storage and pre-treatment of the feedstock. Each technology has different feedstock quality and characteristics requirements, hence the objective of pre-treatment MSW is to ensure that waste is in an appropriate form for the combustion process [1, 10, 11, 15, 16].

Grate incineration processes MSW with minimum pre-treatment, such as the removal of recyclables, reusable material and bulky materials. Waste fuel is mixed and

homogenized with overhead cranes before being transferred into the incinerator hopper [1, 15, 16].

Fluidized bed incineration, gasification and pyrolysis handle waste fuel/feedstock of limited particle size and specific characteristics. These technologies are limited to

homogenous waste streams, hence effort is required in the waste pre-treatment process. Waste pre-treatment involves size reduction combined with removal of metallic species [1, 10, 11, 15, 16].

Table 1: Comparison of WtE thermal technologies

Parameter	Grate	Fluidized bed	Gasification	Pyrolysis
Waste type	Mixed waste from waste streams with no pre-treatment, LHV of 6 MJ/kg to 12 MJ/kg [1, 10]	Homogenized and pre-treated waste, specific particle size required, LHV of < 5 MJ/kg to >20 MJ/kg [1, 10].	Homogenized and pre-treated waste [1, 10].	Homogenized and pre-treated waste [1, 10].
Thermal process	Complete combustion in excess air [1, 10, 11, 16]	Complete combustion in excess air [1, 10, 11, 16]	Partial thermal degradation in limited oxygen [1, 11, 16].	Decomposition of organic substances in the absence of oxygen [1, 11, 16].
Operating parameters	Temperature – 800 °C to 1450 °C, pressure – 1 bar [1].	Temperature – 800 °C to 1450 °C, pressure – 1 bar [1].	Temperature – 500 °C to 1000 °C, pressure – 1 bar to 50 bar [1].	Temperature – 250 °C to 700 °C, pressure – 1 bar [1].
Energy recovery	Heat energy in off-gas of a combustion process is recovered in a boiler as process steam, heat and electricity [1, 11, 15, 16].	Heat energy in off-gas of a combustion process is recovered in a boiler as process steam, heat and electricity [1, 11, 15, 16].	Syngas either directly combusted and heat recovered in a boiler as process steam, and electricity or syngas processed into other fuels [1].	Syngas directly combusted and heat recovered in a boiler as process steam, and electricity or syngas processed into other fuels [1].

3.2 Thermal process

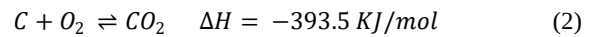
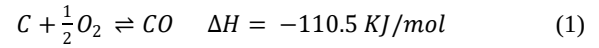
WtE thermal technologies are distinguished through the thermal process applied. Thermal processes are classified into three categories, namely combustion/incineration, pyrolysis and gasification. The principal distinguishing feature of these processes is the oxygen content in the process atmosphere and operating temperature range [1, 11, 16].

The pyrolysis process is the thermal decomposition or fragmentation of organic matter in a strictly inert atmosphere. The reaction temperature affects the proportion of gaseous, liquid and solid products. The temperature varies directly with the amount of gaseous products, whereas solid residues vary inversely with temperature. The pyrolysis gas produced is directly combusted to recover energy because of its complex composition, which requires extensive gas cleaning to remove sulphur compounds and other impurities [1, 11, 16].

The gasification process is the partial decomposition of feedstock in the presence of insufficient oxygen to oxidize the fuel. The main product of this process is synthetic gas, commonly referred to as syngas. Syngas from gasification of MSW is commonly used in a combustion chamber for energy recovery [1, 11, 16].

Grate incineration and fluidized bed incineration recover heat through complete combustion of waste fuel, an exothermic chemical process with the main energy

releasing chemical reactions, shown in equations (1) and (2) [1,10,11,16].



3.3 Energy recovery

Thermal process technologies that use MSW as feedstock are designed so that the chemical energy in the fuel is finally released into the off-gas of a combustion process and the energy is recovered in a boiler. The energy from waste, auxiliary fuels and pre-heated air is converted during the combustion process and transferred to a water steam circle [1, 11].

Gasification and pyrolysis of waste and waste-derived fuels are in principle two-stage processes designed to allow direct combustion of process products [1].

Recovered heat from the boiler can be used in three alternatives, namely direct export for district heating, conversion to electricity using turbines and combined heat and power. Figure 4 and Figure 5 show the hot water boiler circuit and the Rankine circuit used for heat recovery options [1, 11, 15, 16].

Factors that affect the choice of an energy cycle/circuit include the quality and quantity of waste, possibility of energy sales, water sources availability, acceptable noise levels and space available.

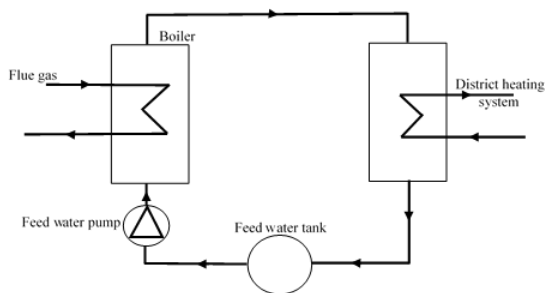


Figure 1: Hot water boiler circuit [15]

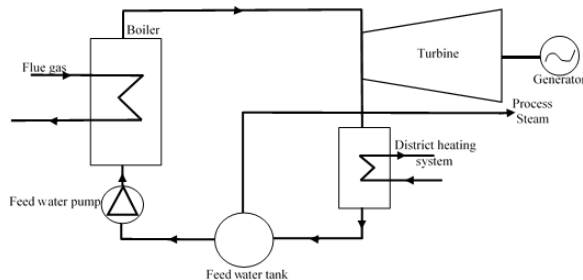


Figure 2: Rankine circuit [15]

3.4 Air pollution control

The removal of pollutants from the flue gas is one of the most important and most expensive process stages in a WtE plant. The design and operation of the air pollution control system technology is highly influenced by the required reduction in emissions to meet regulations, the compatibility of system components with one another, and investment, operation and maintenance costs [1, 10].

The air pollution control systems' components are classified according to their functions, namely removal of fly ash, removal of acid gases and removal of specific contaminants such as mercury and nitrogen oxides [1].

Combination of air pollution control components is determined by the system component to clean acidic gases, such as sulphur dioxide (SO_2), hydrogen chloride (HCl) and hydrogen fluoride (HF). Hence these components are selected first, then the selection of compatible and appropriate components to remove particulate matter, dioxins, mercury and NO_x follows [10].

Flue gas acidic compounds are cleaned using three options, namely dry/semi-dry scrubbing, wet scrubbing and semi-wet scrubbing systems. In this regard, there are three possible combinations of air pollution control system components [1, 10, 16].

Fly ash can be removed using cyclones; electrostatic precipitators (ESP) and fabric filters or bag house systems [1, 10, 16]. Cyclones have limited removal efficiency for fine particles and are not commonly used in modern WtE plants. ESP is the technique mostly applied owing to its design simplicity, low pressure loss and easy operation. The Morden ESP system can achieve dust removal efficiencies greater than 99% for particle sizes between

0.01 and $>100 \mu\text{m}$. The lowest emission, in a range of less than 1 mg/m^3 , is achieved through a fabric filter system [1].

Nitrogen oxide control is achieved through either non-catalytic removal (NSCR) or selective catalytic removal (SCR). NSCR uses the principle of injecting ammonia or another nitrogen-containing compound into the hot flue gases in the first flue of the boiler. SCR is done at the end of the gas-cleaning system at a temperature level of 250°C to 300°C [1].

3.5 Residue management

WtE facilities generate three categories of residue, namely bottom ash, fly ash and APC residues. Fly ash and APC residue are deposited into the landfill. Ferrous and non-ferrous metal can be separated from raw bottom ash for a further recycling process. Gravel size fractions of the bottom ash can be sieved and used in the construction industry, mainly road construction and brick pavement manufacturing [1, 15]

4. WTE TECHNOLOGIES PERFORMANCE

This section will evaluate the performance of four WtE technologies in terms of plant capacity and scalability, energy production, flue gas production, residual waste production and technological reliability. An analysis of potential revenue streams from each technology is carried out in this section.

Table 3 summarizes WtE thermal technologies' performance evaluation.

4.1 Plant capacity and scalability

WtE thermal technologies' capacity is measured in terms of the amount of waste that can be processed at any given time per individual line. A single installation can have a number of lines and the number of lines installed is directly proportional to overall size per installation.

Grate incineration records the highest capacities because of its ability to treat unprocessed waste. Single-line capacity ranges from 3 tonnes to 40 tonnes per hour. The technology can process waste with calorific values in the range 6 MJ/tonne to 12 MJ/tonne [1]. Grate incinerators can be scaled to various sizes, with a capability of multiple lines installation. However, only large installations of greater than 100 000 tonne/year can be economically viable.

Fluidized bed incinerators' single-line capacity ranges from 3 tonnes to 15 tonnes per hour. The technology can process waste with a calorific value of 5 MJ/tonne to 20 MJ/tonne [1].

Gasification has a processing capacity of 1 tonnes to 11 tonnes per hour for each single line. Gasification reactors

can have modularized designs, which are suitable for small installations [1, 10].

Pyrolysis thermal processing technology has the lowest capacity of 2.5 tonnes to 8.3 tonnes per hour. Annual installed capacity ranges from 28 000 tonnes to 140 000 tonnes [1].

Table 1: Technologies' performance evaluation

Parameter	Grate	Fluidized bed	Gasification	Pyrolysis
Capacity	3 tonnes to 40 tonnes/hr for a single-line, compatible with multiple lines [1].	3 tonnes to 15 tonnes/hr for a single line [1].	1 tonne to 11 tonnes/hr for each single line [1].	2.5 tonnes to 8.3 tonnes/hour [1].
Scalability	Various sizes, large installations of greater than 100 000 tonne/year can be economically viable [10].	Small installation [10]	Small installation with modularized designs [10]	Small installation [10]
Boiler efficiency	75% to 85%> [1].	75% to 85%> [1].	>80% [1].	75% to 85%> [1].
Power efficiency	Power only – 31 %, CHP - >70 % [1,10]	Power only – 25%, CHP - >70% [1,10]	Power – 20% to 22% [1,10]	Power – 15% [1,10]
Raw bottom ash	20% to 25% [10]	20% to 25% [10]	10% to 20% [10]	more than 30% [10]
Potential revenue streams	Electricity, heat and process steam, construction material, ferrous and non-ferrous metals [1, 10, 11, 15, 16].	Electricity, heat and process steam [1, 10, 11, 15, 16].	Combustion – process steam and electricity. Catalytic conversion – alcohols, chemicals, and synthetic diesel [1,10].	Combustion – process steam and electricity. Catalytic conversion – Pyrolysis oil, transportation fuel [1,10]

4.2 Energy production

The choice of a WtE thermal technology is influenced by the energy efficiency of a plant. Energy can be recovered as heat and/or electricity.

Grate technology has primary boiler efficiency in a range of 75% to greater than 85%. Modern facilities have power efficiencies that can reach as high as 31% and for heat only or combined power efficiency reach more than 70% [1]. Where grate incinerator plants are operated in combination with power plants, an efficiency of more than 40% can be reached.

Gasification in different types of reactors has boiler efficiency of more than 80%. Depending on plant size and waste, power efficiencies are found to be in the range of 22 % to 33% [1].

Fluidized bed incinerator boilers have primary efficiency of 80 % to more than 85%. The overall power efficiency reaches up to 25% and for heat and combined power it can surpass 70% [1].

Pyrolysis boiler efficiency can reach as high as that of grate incineration and the fluidized bed process. Power efficiency can be as low as 15% [1].

4.3 Flue gas production

The performance of a WtE plant can be measured in terms of the composition of the raw flue gas from the thermal process. The production of acidic substances, heavy metals and dust particulate are the best indicators in measuring the performance of a WtE plant.

Gasification and pyrolysis produce synthetic gases that are used in direct combustion for energy recovery or can be further cleaned and processed to be used in other applications. Pollutants of concern in these processes are HCl and SO₂ [1,10]. Gasification and pyrolysis aim to minimize gas cleaning obligations by lowering flue-gas volumes [16].

Grate and fluidized bed incineration produce raw flue gases that have a high margin of deviation from the minimum emission requirements. Conventional thermal process must be equipped with efficient air pollution control systems to meet emission requirements [1, 10].

4.4 Residual waste production

Grate and fluidized incineration produce bottom ash amounting to 20 % to 25% by weight of the incinerated waste. The bottom ash can be used in other applications, which can reduce residue disposed into the landfill to about 5% by weight of the incinerated waste. Grate and fluidized bed incineration conserve landfill capacity up to 90 % to 95% [10].

The gasification process is capable of minimizing bottom ash to about 10 % to 20% by weight of the incinerated waste. The bottom ash for gasification is highly marketable for other applications and residual disposal to the landfill can be minimized to 1% by weight of the incinerated waste. Gasification has the potential of reducing landfill capacity consumption by 90 % to 95% [10].

Pyrolysis produces residue of more than 30% by weight of the incinerated waste. However, if the residue can be treated, landfill disposal is reduced from 30 % to 10% by weight of the incinerated waste. Pyrolysis has the capability of conserving landfill capacity up to 90% [10].

4.5 Potential revenue streams

Potential revenue streams of a WtE thermal plant vary with applied technology. The common revenue stream is the sale of process steam, heat and electricity. Other streams of revenue include construction aggregate recovered from bottom ash, recyclable ferrous and non-ferrous metals recovered from bottom ash, syngas and pyrolysis oil [10].

Morden plants on grate incineration technology have electricity production rates of between 0.75 MWh and 0.85 MWh/annual tonne of MSW. Gasification and pyrolysis energy production is in the range 0.4 MWh to 0.8 MWh/annual tonne of MSW and 0.5 MWh to 0.8 MWh/annual tonne of MSW respectively [10].

Raw bottom ash from the incineration of mixed MSW contains huge amounts of ferrous and non-ferrous metals, amounting to about 10% by weight of the input incinerated waste. Post-processing of bottom ash, disposal and utilization depend on the total organic carbon of the ash [1].

4.6 Technological reliability

Grate technology is the oldest technology used in more than 500 plants worldwide, with proven operational success. The technology is commercially proven, operating with minimum challenges, with some plants having been in operation for 15 years to 30 years. Grate technology is reported to have both scheduled and unscheduled downtime of less than 10% of operating time. The technology is less complex in comparison with other thermal processes [1, 10]

Though commercially proven, fluidized bed incineration is faced with operational challenges with MSW as feedstock. About 50 plants worldwide use this technology, with many plants found in Japan for smaller throughputs [10].

Gasification has been used for more than a century with other fuels and recently MSW has been used as feedstock. The technology operates with scheduled and unscheduled downtime at approximately 20% [1,10]

Pyrolysis of waste is applied in only a few commercial-scale plants, hence there is limited information on the reliability of the process. The technology has limited capability to process MSW.

5. COST EVALUATION

WtE technology system component cost can be distributed as indicated in Table 1. Thermal processing equipment makes the highest contribution to the capital cost of a WtE thermal processing plant.

Table 2 is a comparison of estimated capital cost per installed tonne capacity and operating cost of a WtE thermal technology.

Table 1: Total WtE capital cost distribution of WtE [10]

System Component	Capital Cost % contribution
Thermal processing equipment (incinerator/boiler)	40%
Energy production equipment (turbines and generators)	10%
APC system (flue gas treatment)	15%
Building (civil works)	25%
Miscellaneous (approvals, general site works, ash processing, electrical transmission and interconnect etc.)	10%

Table 2: WtE facilities capital and operating Costs [10]

Technology	Capital Cost (\$/ton)	Operating Cost (\$/ton)
Conventional	775 +/- 50%	65 +/- 30%
Gasification	800 +/- 40%	60 +/- 45%
Pyrolysis	926	105

The capital cost per ton of installed capacity for gasification and pyrolysis is high owing to a front-end waste pre-processing system to achieve homogeneity, higher electrical energy and/or fossil fuel consumption to operate the facilities and decreased reliability of the technologies [10].

6. CONCLUSION

WtE thermal technologies stand to be a valuable alternative source of energy and a solution to ever-increasing MSW and other waste streams, such as medical waste and waste vehicle tyres. Experience from countries that have implemented WtE technologies proved that WtE it is compatible with high recycling rates.

The comparison of WtE thermal technologies indicates that grate incineration remains the preferred and economical thermal technology in view of its reliability, capability to incinerate assorted waste, lower operational complexity and higher power efficiency.

Advanced thermal technologies face both operational and economic drawbacks. Gasification and pyrolysis continue to experience certain limitations due to their complexity, difficulty in treating waste of various streams and lower net energy recovery.

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Financial analysis of waste-to-energy grate incineration power plant for a small city.

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Abstract — Grate incineration is a widely used waste-to-energy (WtE) technology, which has the potential of contributing significantly to clean energy production and sustainable waste management systems. Various research studies have shown that WtE grate incineration in developed countries has contributed to the goal of economic, social and environmentally sustainable development.

The purpose of this study is to carry out a financial analysis of a WtE grate incineration power plant for a small South African city of North-West Province. Municipal solid waste (MSW) data used in this study was collected from a small municipality in North-West Province.

A financial model with four different scenarios was formulated. Net present value and internal rate of return were used as financial feasibility indicators. Sensitivity analysis was performed to see how electricity price and MSW accumulation rate affected the financial feasibility of the model. The results proved that the major revenue stream of a WtE plant is electricity sales and medical waste gate fees. High capital cost is the main drawback in implementing a WtE grate incineration power plant.

A WtE grate incineration power plant also makes a significant contribution to the goal of recycling. The conclusion reached is that WtE could be economically viable if medical waste is diverted to the grate incineration power plant and 150 000 tonnes to 220 000 tonnes of residual MSW is generated annually.

Keywords — Grate incineration, Municipal solid waste, Medical waste, Waste-to-Energy, Waste-to-Energy plant economics.

1. INTRODUCTION

Waste management systems that are environmentally and economically sound contributes to sustainable development [1][2]. Investigations attest that waste-to-energy (WtE) technologies contribute significantly to clean energy production and sustainable waste management systems [3].

Globally, the focus has shifted to view municipal solid waste (MSW) as a useful resource. MSW has been used as the major feedstock in WtE plants across the world [4][5].

Grate incineration, a commercially proven technology, has been in use for more than 130 years. This technology is widely used over other WtE thermal technologies [2]. In Europe, 90% of WtE plants use grate incineration, and there are more than 800 WtE plant installations across the world [2].

WtE has contributed significantly to renewable energy in European countries such as the Netherlands, Denmark and Sweden [6]. International Energy Agency statistics point out that residual MSW has the potential of replacing 2% of fossil fuel in South Africa (SA) [2], thus WtE can make a significant contribution to the country's renewable energy mix.

According to Yokesesh [7], renewable energy must have a share of 26% in SA's energy mix by 2030. This is to ensure alignment with global renewable energy trends growing at 8.2% per annum by 2010.

In SA, the total consumption of municipalities and their customer's is 40% to 42% of the total power used in SA [6]. This presents an opportunity for WtE to contribute to meeting the electrical power demand for municipalities. To assist with this engagement, the purpose of this study is to carry out a financial analysis of a WtE grate incineration power plant for a small South African city.

Maisiri [6], performed technological and performance evaluation of four WtE thermal technologies. This paper is a continuation of this work and focuses on financial analysis of a WtE grate incineration power plant. The work is part of an ongoing research project on technological and financial factors that influence the implementation of WtE thermal technologies in SA.

This paper is organised as follows: WtE overview, WtE plant economics, methodology for financial analysis, MSW generation and management for a small municipality in SA, financial analysis, discussion of results, conclusion and references.

2. WASTE-TO-ENERGY OVERVIEW

This section gives an overview of the role of WtE in sustainable energy generation and waste management strategies. Grate incineration technology is outlined in this section.

2.1 Waste-to-energy

The WtE thermal process, grate incineration included, plays a crucial role in green energy production. The ratio

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of biogenic to fossil carbon in MSW is in the range 50% to 70% [6]. Thus more than 50% of energy recovered from waste is classified as biogenic. Accordingly WtE promotes the goal of renewable energy strategies [2].

Approximately 19% of renewable energy share in the EU-27 countries is from waste and biomass [8]. Fig. 1 shows the contribution of WtE to renewable energy in the leading EU countries.

The share of energy from waste in the world energy mix is approximated at 0.4% [10]. In 2009, WtE had a capacity of 3425 MW and 6280 MW of electricity and heat respectively [11]. The contribution of WtE in Europe is estimated at 5822 MW and 9475 MW electricity and heat respectively [3].

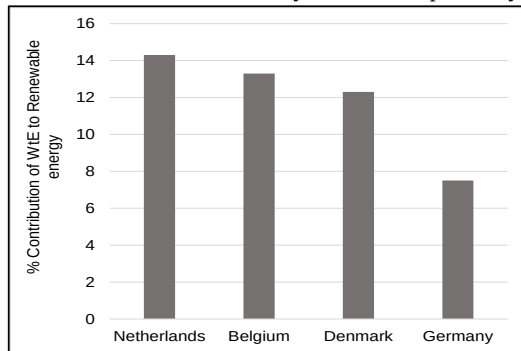


Fig. 1. WtE percentage contribution to renewable energy by leading EU countries [9].

The goal of waste management is to protect man and the environment and conserve resources [12]. This is in line with the goals of sustainable development. Investigations indicated that WtE has made a positive contribution to this goal in developed countries.

WtE incineration facilities achieve complete destruction of hazardous organic waste. This results in minimising risks of pathogenic and virus infections.

Waste incineration has the potential to reduce waste volume and mass by 80% to 90% and 70% to 80% respectively [13][14], reducing land usage for residual waste disposal. WtE promotes divergence of waste from the landfill, thus decreasing the adverse effects of landfill.

WtE facilities have become recycling facilities through recovery of materials. Metals can be recovered from air pollution control and bottom ash residue [12]. Fig. 2 shows the percentage contribution of WtE incineration, recycling and landfill in managing MSW in Europe. Countries that have used WtE show high recycling ratios [8]. This can serve as a proof that WtE is compatible with recycling.

Modern WtE plants have managed to achieve the goal of sustainable waste management. Resources such as energy, material and land have been conserved through WtE initiatives. Implementation of WtE has significantly contributed to protection of the environment.

2.2 WtE grate incineration

WtE grate incineration, also known as mass burn, is a commercially proven technology. The technology has proven to be dominant among other thermal treatment technologies [13][15][16].

A WtE grate incineration power plant consists of a waste tipping and storage area, incinerator charging equipment, a

combustion chamber, energy recovery, an air pollution control system and a bottom ash removal system [16]. Fig. 3 summarises the process flow in a WtE grate incineration power plant.

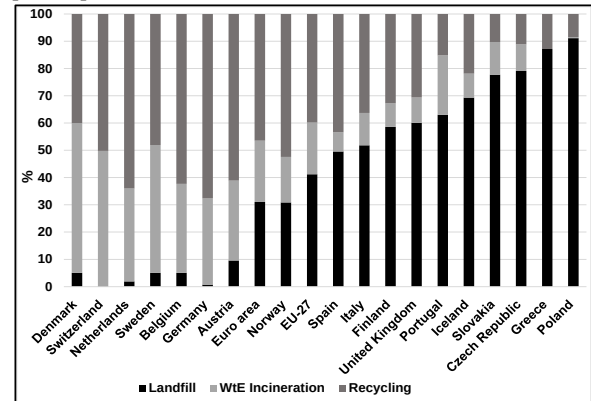


Fig. 2. Percentage contribution of WtE incineration, recycling and landfill in managing MSW in EU [8].

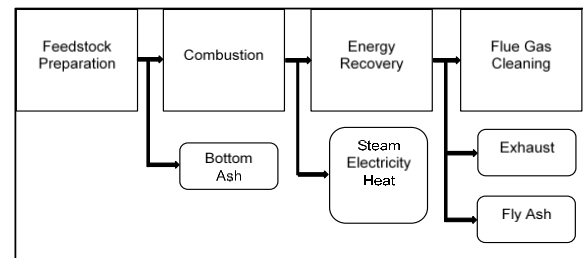


Fig. 3. WtE grate incineration process flow [6] [16].

The combustion chamber, referred to as the incinerator, is the core of a WtE plant. Modern incinerators are designed to operate in a temperature range of 800°C to 1400°C [17].

Grate incineration is capable of processing waste ranging from general to hazardous and infectious waste. The feedstock requires minimum pre-processing, such as removal of recyclables, reusable material and bulky materials [6].

Recent grate incineration boiler designs have been using nickel base alloys. This results in high steam temperatures and pressure, thus power efficiency of more than 30% is achieved [2][13].

3. WtE PLANT ECONOMICS

WtE grate incineration involves high capital investment, operation and maintenance cost. Plant economics are influenced by factors such as the size and design of the facility, legal aspects, labour cost, the cost of consumables, potential for heat utilisation, and the market price for energy, among others [18][19].

Capital investment cost can be split into components, as shown in Table I. Thermal processing equipment makes the highest contribution to the total capital investment cost.

The cost of machinery is influenced by the type of energy recovered. Energy can be recovered as heat, electricity or combined heat and power [6]. The flue gas treatment system cost is determined by the quality of the pollution to be achieved [19].

Table I. WtE capital investment cost components [6]

System Component	Capital Cost contribution (%)
Thermal processing equipment (incinerator/boiler)	40
Energy production equipment (turbines and generators)	10
APC system (flue gas treatment)	15
Building (civil works)	25
Miscellaneous (approvals, general site works, ash processing, electrical transmission and interconnect etc.)	10

WtE plant operating cost comprises fixed and variable operating costs and maintenance cost. Table II is an overview of operating cost in a WtE plant.

Table II. Operating cost overview [19]

Category	Cost component
Fixed cost	- Administration - Salaries
Variable cost	- Flue gas cleaning chemical - Water and handling waste water - Residue disposal
Maintenance cost	- Machinery maintenance - Building maintenance

The fixed costs are highly influenced by the number of employees, ratio of skilled to unskilled employees and local salary levels. Variable cost depends on the flue gas system in use. The total maintenance cost is estimated to be 3.5% of the total investment cost [19].

The WtE revenue stream ranges from gate fees to energy sales. Fig. 4 shows the major revenue stream of a WtE plant.

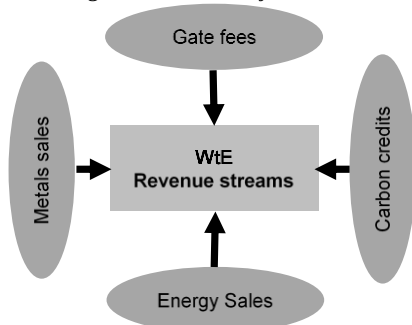


Fig. 1. WtE main revenue streams [6] [19]

Energy sales are a significant revenue stream of a WtE plant. Income from energy sales has the potential of covering up to 80% of the total capital and operating cost. Energy can be sold as heat, electricity, or process steam [19].

The lower heating value (LHV) of waste significantly affects the amount of electricity generated and thus has an impact on energy sales. Fig. 5 shows the variation of energy output with lower heating value of a WtE plant.

Gate fees make a noticeable contribution to the revenue stream in countries where a ban on landfill is the major driver of WtE. Countries with successful WtE have managed to achieve a negative market price of waste. This means that waste producers have to pay for their waste to be processed [2].

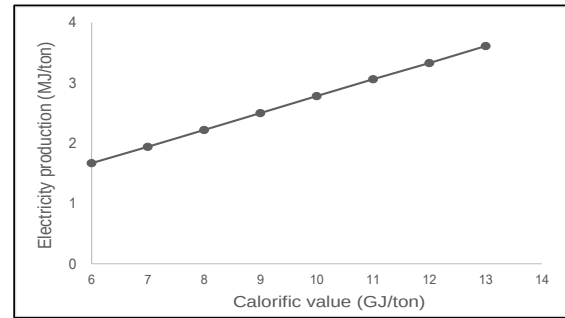


Fig. 2. Variation of electricity production with calorific value for a plant operating at 30% efficient electricity production [19].

4. METHODOLOGY FOR FINANCIAL ANALYSIS

A financial analysis model with four different scenarios was formulated. The purpose of the model was to determine the financial feasibility of a WtE grate incineration power plant for a small city in the South African context.

The analysis begins by calculating the simple payback period (SPB) and return on investment (ROI). These are simple and broad financial feasibility indicators used for preliminary assessment [20].

The analysis narrows down to specific financial feasibility indicators, namely: net present value (NPV) and internal rate of return (IRR). A positive NPV indicates a feasible project and a higher NPV generally indicates a more attractive investment. An IRR greater than the stated discount rate shows a feasible project [20].

WtE grate incineration power plant capital budgeting for a life span of 30 years was carried out. This facilitated calculations of the NPV and IRR.

Two major variables that affect project financial performance were identified. NPV and IRR sensitivity analysis was then performed. An investment attractiveness scale was formulated for both NPV and IRR sensitivity analysis results.

An NPV value of less than zero is regarded as not financially feasible. An NPV value between zero and a quarter of the capital cost is considered financially feasible but not attractive. A financially feasible and attractive NPV value is in the range greater than a quarter and less than half of the capital cost. The most attractive NPV is greater than half of the capital cost [20].

An IRR less than the discount rate, 10%, is not considered financially feasible. An IRR between 10% and 15% is considered financially feasible and attractive. An IRR value greater than 15% has the highest investment attractiveness [20].

Financial analysis results for the four scenarios were compared. The scenarios were ranked according to performance in terms of NPV and IRR.

MSW generation trends, characteristics and management strategies data was gathered from a city in North-West Province with a population of 300 000 people. This was achieved through interviews with representatives from the department of waste management.

A survey conducted for the Department of Environmental Affairs and Tourism on generation rates, treatment capacities and minimal costs of health care waste was used as reference for medical waste data. Medical waste treatment cost data was obtained from a private local health provider facility.

The WtE grate incineration power plant capital cost data was obtained through interviews with representatives from one of the largest and most efficient WtE plant in the Netherlands. Plant operating cost and revenue streams data was also obtained in these interviews and through a literature review.

5. MSW GENERATION AND MANAGEMENT FOR A SMALL MUNICIPALITY IN SOUTH AFRICA

SA uses landfill as the major MSW management strategy [21]. It is approximated that 11000GWh equivalent of waste is dumped into the landfill annually [22]. The amount of energy dumped is significant and can be converted to useful energy.

MSW data from a small city in North-West Province, SA, was collected and analysed. This section presents MSW data analysis results.

5.1 MSW generation trends

Fig. 6 shows MSW generation trends for a small South African city of North-West province. The average growth rate was calculated at 3.04% per year.

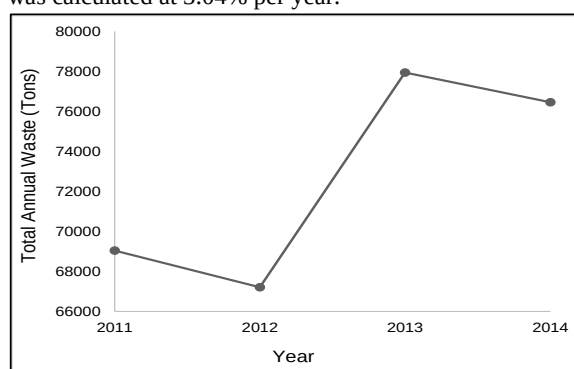


Fig. 1. MSW generation trends for a small city in North-West Province, South Africa.

5.2 Management strategies

Landfill was identified as the dominant MSW management strategy. On average 98.3% of the waste generated is landfilled while 1.7% is recycled. This is illustrated in Fig. 7.

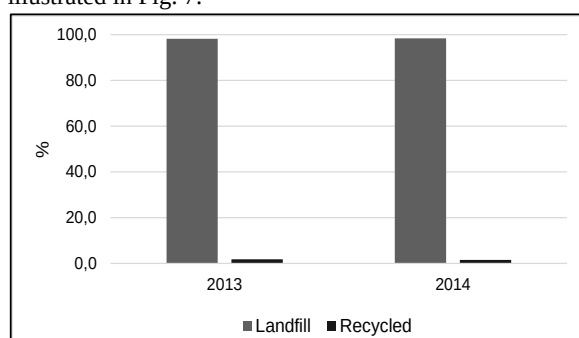


Fig. 2. Contribution of landfill and recycling to the overall waste management strategy of a small city in North-West Province, South Africa.

5.3 MSW characterization

Table III shows MSW characterisation for the small city investigated. Plastic makes the highest percentage contribution to the composition of the waste. The LHV of MSW is estimated at 8.0 MJ/Kg.

Table I. MSW characterisation for a small city in North-West Province, South Africa.

Waste Type	Percentage (%)
Builders Rubble	2
Plastic	30
Paper	28
Organics, garden waste	8
Metals	6
Glass	13
Other (textile, disposable nappies, tyres, residue and miscellaneous)	13
TOTAL	100

5.4 Projected MSW generation trends

Projected MSW annual tonnage was calculated using the current generation growth rate of 3.04% per year Fig. 8 shows the projected MSW yearly tonnage up to 2045.

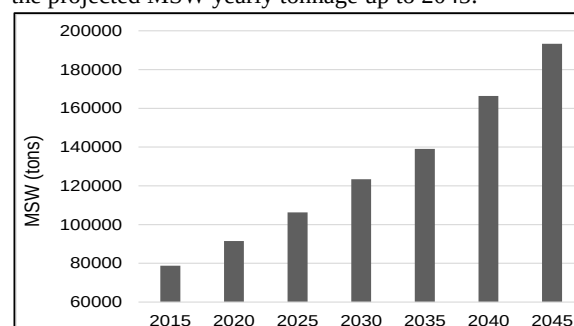


Fig. 3. MSW generation projection for a small municipality investigated.

6. FINANCIAL ANALYSIS

6.1 Plant model basic information

The WtE grate incineration power plant design parameters are shown in Table IV. The plant was designed to operate with two lines to facilitate its availability and reliability.

Table I: WtE grate incineration power plant design parameters

Parameter	Quantity
Number of lines	2
Plant life	30 years
Construction period: line 1	3 years
: line 2	2 years
Processing design capacity	110 000 tonne/year/line
Plant availability	90%
Plant annual throughput	200 000 tonnes
Average feedstock LHV	8 GJ/tonne
Electricity efficiency	30%
Processing steam efficiency	2.5%
Power plant design capacity	16.7 MW
Total power output	666.66 kWh/tonne
Plant consumption	66.66 kWh/tonne
Grid electricity	600 kWh/tonne
Total manpower	40 people

6.2 Financial model assumptions

Financial analysis was modelled with four different scenarios shown in Table V. The scenarios varied in terms of feedstock used and plant ownership.

Table II: Financial model scenarios description.

Scenario	Feedstock type	Plant Ownership
1	MSW	Investment Company
2	MSW	IPP
3	MSW and medical waste	Investment Company
4	MSW and medical waste	IPP

The assumption made is that the independent power producer (IPP) will merge with a foreign company with proven technology. This will entitle the IPP to an investment subsidy of 20%. It is assumed that the investment company will fund and contract a company to run the WtE plant. The investment company is to fund 100% of the plant capital cost.

Basic assumptions for a WtE grate incineration power plant financial model are shown in Table VI. These assumptions are used as the base values for financial analysis.

Table VII shows the capital cost for each scenario. The capital cost was calculated on a design capacity of 220 000 tonnes of feedstock per year. The total design capacity is divided into three categories namely: base design capacity, MSW additional design capacity and medical waste design capacity.

Each scenario has a base design capacity of 110 000 tonnes. Scenario 3 and 4 each has medical waste design capacity of 15 000 tonnes.

Table III: Financial model assumptions

Parameter	Base value
Base design capacity	110 000 tonne/year
Base design capacity capital cost	R4500/tonne
Additional capital cost: MSW	R3600/tonne
: Medical waste	R5400/tonne

Maintenance cost	3% of Capital cost
Electricity price	R1.25/kWh
Tipping fees: MSW	R50/tonne
: Medical waste	R2500/tonne
Metal sales : Ferrous metals	R10/kg
: Non-ferrous metals	R1.5/kg
Depreciation	5%
Discount rate	10%
Inflation	6%
Tax rate	28%
IPP capital subsidy	20%

Table IV: Capital cost for the four scenarios presented in the study.

Scenario	Total capital cost (R million)
1	891.00
2	712.80
3	918.00
4	734.40

Table VIII shows assumptions used to calculate the scenario's annual income. Annual throughput of 200 000 tonnes is used in all scenario's annual income calculations. Scenario 3 and 4 assumes 15 000 tonnes medical waste and the balance MSW.

Scenario 1 and 2 annual waste tipping income was calculated by multiplying waste annual throughput by MSW tipping fee in Table VI. Annual waste tipping income for scenario 3 and 4 was calculated by multiplying 15 000 tonnes by medical waste tipping fees in Table VI, and the balance with MSW tipping fees.

The assumptions in Table VIII are based on a combination of information obtained from one of the most efficient WtE plant in the Netherlands, International Energy Agency biogenic report, and expects experience knowledge.

Table V: Assumptions used in calculating scenarios annual income.

Parameter	Assumption
Average Labour cost	R145 952.5/person/year
Overheads	50% of total labour cost
Chemicals cost	R1.8 per kg at rate of 13.55kg/tonne of waste
Water	R5 per kl at rate of 15 litres/tonne of waste
Maintenance cost	3 % of the total investment cost
Interest	5% calculated on investor capital cost
Residue management cost	R570/tonne at production rate of 15kg/tonne of waste
Electricity sales	600 kWh/tonne of waste
Process steam sales	55.56kWh/tonne of waste
Ferrous metal sales	10 kg/tonne of waste
Non-ferrous metal sales	8 kg/tonne of waste

6.3 Financial analysis results

Table IX shows the SPB and ROI results for the four scenarios. Scenario 4 shows the best performance with an SPB of eight years and 13% ROI. Scenario 1 yields the worst performance with an SPB of 17 years and 6% ROI.

Table I: Scenarios SPB and ROI

Scenario	SPB (years)	ROI (%)
1	17	6
2	9	11
3	11	9
4	8	13

Capital budgeting was performed and NPV and IRR were used as financial indicators. The NPV and IRR for each scenario are shown in Table X.

Table II: Scenarios NPV and IRR.

Scenario	NPV (R million)	IRR (%)
1	63.56	10.99
2	212.45	14.05
3	237.03	13.63
4	390.44	17.39

Scenario 4 has the highest NPV of R390.44 million and IRR of 17.39%. Scenario 1 has the lowest NPV of R63.56 million and IRR of 10.99%.

7. SENSITIVITY ANALYSIS

7.1 NPV sensitivity analysis

The sensitivity analysis was performed for varying average MSW percentage increase and electricity prices. Fig. 9 shows the NPV sensitivity analysis results interpretation key.

	NPV ≤ 0 - investment not financially feasible
	0 < NPV ≤ ¼ of Capital cost - feasible and not attractive
	¼ < NPV ≤ ½ of Capital cost - feasible and attractive
	½ of capital cost < NPV - feasible and most attractive

Fig. 1. Key used to interpret NPV sensitivity analysis results for different options.

7.1.1 Scenario 1

Fig. 10 shows that options with $NPV \leq 0$ are dominant, followed by options with $0 < NPV \leq \frac{1}{4}$ of capital cost.

7.1.2 Scenario 2

Options with half of capital cost < NPV are prevalent as shown in Fig. 11. Regardless of this, options with $NPV \leq 0$ are substantial.

7.1.3 Scenario 3

Fig. 12 shows unique results with options with $NPV \leq 0$ and half of capital cost < NPV having an equal share. The same result is displayed for options with $0 < NPV \leq \frac{1}{4}$ of capital cost and $\frac{1}{4} < NPV \leq \frac{1}{2}$.

		Average MSW % increase								
NPV(R million)		0,50%	1,00%	1,50%	2,00%	2,50%	3,00%	3,50%	4,00%	4,50%
Electricity price	R 0,50	-484	-473	-460	-447	-433	-418	-404	-390	-379
	R 0,60	-433	-419	-405	-389	-372	-354	-337	-321	-307
	R 0,70	-382	-366	-349	-331	-311	-290	-270	-252	-235
	R 0,80	-331	-313	-294	-273	-251	-227	-204	-183	-164
	R 0,90	-280	-260	-238	-215	-190	-163	-137	-114	-92
	R 1,00	-229	-207	-183	-157	-129	-99	-70	-44	-21
	R 1,10	-178	-153	-127	-99	-68	-35	-4	25	51
	R 1,20	-127	-100	-71	-40	-7	29	63	94	122
	R 1,30	-76	-47	-16	18	54	92	130	163	194
	R 1,40	-25	6	40	76	115	156	196	233	265
	R 1,50	26	59	95	134	176	220	263	302	337
	R 1,60	77	112	151	192	236	284	330	371	409
	R 1,70	128	166	206	250	297	348	396	440	480
	R 1,80	178	219	262	308	358	412	463	509	552
	R 1,90	229	272	318	366	419	475	530	579	623
	R 2,00	280	325	373	425	480	539	596	648	695
	R 2,10	331	378	429	483	541	603	663	717	766

Fig. 2. Scenario 1 NPV sensitivity analysis results.

		Average MSW % increase								
NPV(R million)		0,50%	1,00%	1,50%	2,00%	2,50%	3,00%	3,50%	4,00%	4,50%
Electricity price	R 0,50	-335	-324	-311	-298	-284	-269	-255	-242	-230
	R 0,60	-284	-270	-256	-240	-223	-205	-188	-172	-158
	R 0,70	-233	-217	-200	-182	-163	-142	-121	-103	-87
	R 0,80	-182	-164	-145	-124	-102	-78	-55	-34	-15
	R 0,90	-131	-111	-89	-66	-41	-14	12	35	57
	R 1,00	-80	-58	-34	-8	20	50	79	105	128
	R 1,10	-29	-5	22	50	81	114	145	174	200
	R 1,20	22	49	77	109	142	178	212	243	271
	R 1,30	73	102	133	167	203	241	279	312	343
	R 1,40	124	155	189	225	264	305	345	381	414
	R 1,50	175	208	244	283	324	369	412	451	486
	R 1,60	225	261	300	341	385	433	478	520	557
	R 1,70	276	314	355	399	446	497	545	589	629
	R 1,80	327	368	411	457	507	560	612	658	701
	R 1,90	378	421	466	515	568	624	678	728	772
	R 2,00	429	474	522	573	629	688	745	797	844
	R 2,10	480	527	578	632	690	752	812	866	915

Fig. 3. Scenario 2 NPV sensitivity analysis results.

		Average MSW % increase								
NPV(R million)		0,50%	1,00%	1,50%	2,00%	2,50%	3,00%	3,50%	4,00%	4,50%
Electricity price	R 0,50	-309	-298	-286	-273	-259	-244	-230	-218	-206
	R 0,60	-258	-245	-230	-215	-198	-180	-164	-149	-135
	R 0,70	-207	-192	-175	-157	-137	-116	-97	-80	-64
	R 0,80	-156	-138	-119	-99	-77	-53	-31	-11	7
	R 0,90	-106	-85	-64	-41	-16	11	36	58	78
	R 1,00	-55	-32	-8	17	45	75	102	127	149
	R 1,10	-4	21	47	75	106	138	169	196	220
	R 1,20	47	74	102	133	166	202	235	265	292
	R 1,30	98	127	158	191	227	266	302	334	363
	R 1,40	149	180	213	249	288	330	368	402	434
	R 1,50	199	233	269	307	349	393	435	471	505
	R 1,60	250	286	324	365	409	457	501	540	576
	R 1,70	301	339	380	423	470	521	567	609	647
	R 1,80	352	392	435	481	531	584	634	678	718
	R 1,90	403	445	491	539	592	648	700	747	790
	R 2,00	454	498	546	597	652	712	767	816	861
	R 2,10	504	551	601	655	713	775	833	885	932

Fig. 4. Scenario 3 NPV sensitivity analysis results.

7.1.4 Scenario 4

Fig. 13 displays a distinct pattern, with options with half of capital cost < NPV filling more than half of the available options.

		Average MSW % increase								
NPV (R million)		0,50%	1,00%	1,50%	2,00%	2,50%	3,00%	3,50%	4,00%	4,50%
Electricity price	R 0,50	-155	-144	-132	-119	-105	-90	-77	-64	-53
	R 0,60	-105	-91	-77	-61	-45	-27	-10	5	18
	R 0,70	-54	-38	-21	-3	16	37	56	74	89
	R 0,80	-3	15	34	55	77	101	123	142	160
	R 0,90	48	68	90	113	138	164	189	211	232
	R 1,00	99	121	145	171	198	228	256	280	303
	R 1,10	150	174	200	229	259	292	322	349	374
	R 1,20	200	227	256	287	320	355	389	418	445
	R 1,30	251	280	311	345	381	419	455	487	516
	R 1,40	302	333	367	403	441	483	521	556	587
	R 1,50	353	386	422	461	502	547	588	625	658
	R 1,60	404	439	478	519	563	610	654	694	730
R 1,70	455	492	533	577	624	674	721	763	801	
R 1,80	505	546	589	635	684	738	787	832	872	
R 1,90	556	599	644	693	745	801	854	900	943	
R 2,00	607	652	699	751	806	865	920	969	1 014	
R 2,10	658	705	755	809	867	929	987	1 038	1 085	

Fig. 1. Scenario 4 NPV sensitivity analysis results.

7.2 IRR sensitivity analysis results.

An average MSW percentage increase and electricity price were used as variable in the sensitivity analysis. Fig. 14 shows the IRR sensitivity analysis results interpretation key.

IRR ≤ 10% - investment not financially feasible
10% < IRR ≤ 15% - feasible and less desirable
IRR > 15% - feasible and most desirable

Fig. 2. Key used to interpret the variation of IRR with average MSW percentage increase and electricity price.

7.2.1 Scenario 1

Fig. 15 presents options with $IRR \leq 10\%$ occupying the largest area of the available option. Options with $IRR > 15\%$ are insignificant.

		Average MSW % increase								
IRR (%)	0,50%	1,00%	1,50%	2,00%	2,50%	3,00%	3,50%	4,00%	4,50%	
R 0,50	-0,22	0,29	0,80	1,30	1,81	2,31	2,71	3,01	3,26	
R 0,60	1,04	1,55	2,06	2,57	3,08	3,58	3,99	4,31	4,57	
R 0,70	2,18	2,69	3,20	3,71	4,22	4,73	5,15	5,48	5,76	
R 0,80	3,23	3,75	4,26	4,77	5,28	5,79	6,21	6,56	6,86	
R 0,90	4,22	4,74	5,25	5,76	6,27	6,78	7,21	7,57	7,88	
R 1,00	5,16	5,67	6,19	6,70	7,21	7,71	8,16	8,53	8,85	
R 1,10	6,05	6,57	7,08	7,59	8,10	8,61	9,05	9,44	9,77	
R 1,20	6,91	7,43	7,94	8,45	8,96	9,47	9,92	10,31	10,65	
R 1,30	7,74	8,26	8,77	9,28	9,79	10,29	10,75	11,14	11,50	
R 1,40	8,55	9,07	9,58	10,09	10,59	11,10	11,55	11,96	12,32	
R 1,50	9,34	9,85	10,36	10,87	11,37	11,88	12,34	12,75	13,11	
R 1,60	10,11	10,62	11,13	11,63	12,14	12,64	13,10	13,51	13,89	
R 1,70	10,86	11,37	11,87	12,38	12,88	13,38	13,84	14,26	14,64	
R 1,80	11,59	12,10	12,61	13,11	13,61	14,11	14,57	15,00	15,38	
R 1,90	12,32	12,83	13,33	13,83	14,33	14,82	15,29	15,72	16,11	
R 2,00	13,03	13,54	14,04	14,54	15,03	15,53	15,99	16,42	16,82	
R 2,10	13,73	14,24	14,73	15,23	15,73	16,22	16,68	17,12	17,51	

Fig. 3. Scenario 1 IRR sensitivity analysis results.

7.2.2 Scenario 2

Options with $IRR > 15\%$ show a significant increase in number in Fig. 16 compared with Fig. 15.

		Average MSW % increase								
Electricity price	IRR (%)	0,50%	1,00%	1,50%	2,00%	2,50%	3,00%	3,50%	4,00%	4,50%
	R 0,50	1,37	1,88	2,39	2,90	3,41	3,91	4,32	4,65	4,91
	R 0,60	2,74	3,26	3,77	4,28	4,79	5,30	5,72	6,06	6,35
	R 0,70	4,01	4,52	5,04	5,55	6,06	6,56	7,00	7,35	7,66
	R 0,80	5,18	5,70	6,21	6,73	7,24	7,74	8,18	8,55	8,87
	R 0,90	6,30	6,81	7,33	7,84	8,35	8,85	9,30	9,68	10,02
	R 1,00	7,36	7,87	8,38	8,89	9,40	9,91	10,36	10,75	11,10
	R 1,10	8,37	8,89	9,40	9,91	10,42	10,92	11,38	11,78	12,14
	R 1,20	9,36	9,87	10,38	10,89	11,40	11,90	12,36	12,77	13,13
	R 1,30	10,32	10,83	11,34	11,84	12,35	12,85	13,31	13,72	14,10
	R 1,40	11,25	11,76	12,26	12,77	13,27	13,77	14,23	14,65	15,04
	R 1,50	12,16	12,67	13,17	13,67	14,17	14,67	15,13	15,56	15,95
	R 1,60	13,05	13,56	14,06	14,56	15,05	15,55	16,01	16,44	16,84
	R 1,70	13,93	14,43	14,93	15,42	15,92	16,41	16,87	17,31	17,71
R 1,80	14,79	15,29	15,78	16,27	16,77	17,25	17,72	18,15	18,56	
R 1,90	15,63	16,13	16,62	17,11	17,60	18,08	18,55	18,99	19,39	
R 2,00	16,47	16,96	17,45	17,93	18,42	18,90	19,37	19,80	20,21	
R 2,10	17,29	17,78	18,26	18,75	19,23	19,71	20,17	20,61	21,02	

Fig. 4. Scenario 2 IRR sensitivity analysis results.

7.2.3 Scenario 3

Fig. 17 has a different pattern, having options with $10\% < IRR \leq 15\%$ appearing most often.

		Average MSW % increase								
IRR (%)	0,50%	1,00%	1,50%	2,00%	2,50%	3,00%	3,50%	4,00%	4,50%	
R 0,50	3,90	4,19	4,49	4,80	5,12	5,45	5,72	5,94	6,12	
R 0,60	4,81	5,13	5,45	5,78	6,12	6,47	6,76	7,00	7,21	
R 0,70	5,69	6,02	6,36	6,71	7,07	7,43	7,74	8,00	8,22	
R 0,80	6,53	6,88	7,23	7,60	7,97	8,34	8,67	8,94	9,18	
R 0,90	7,34	7,70	8,07	8,45	8,83	9,21	9,55	9,84	10,09	
R 1,00	8,13	8,51	8,88	9,27	9,66	10,05	10,40	10,70	10,97	
R 1,10	8,90	9,28	9,67	10,06	10,46	10,86	11,22	11,53	11,81	
R 1,20	9,65	10,04	10,44	10,84	11,24	11,64	12,01	12,33	12,62	
R 1,30	10,39	10,79	11,19	11,59	12,00	12,41	12,78	13,11	13,41	
R 1,40	11,11	11,51	11,92	12,33	12,74	13,15	13,53	13,87	14,18	
R 1,50	11,82	12,23	12,64	13,05	13,46	13,88	14,26	14,61	14,93	
R 1,60	12,52	12,93	13,34	13,76	14,17	14,59	14,98	15,33	15,66	
R 1,70	13,21	13,62	14,04	14,45	14,87	15,29	15,68	16,04	16,38	
R 1,80	13,89	14,30	14,72	15,14	15,56	15,98	16,38	16,74	17,08	
R 1,90	14,56	14,97	15,39	15,81	16,23	16,66	17,05	17,42	17,77	
R 2,00	15,22	15,64	16,05	16,48	16,90	17,32	17,72	18,10	18,45	
R 2,10	15,87	16,29	16,71	17,13	17,55	17,98	18,38	18,76	19,11	

Fig. 5. Scenario 3 IRR sensitivity analysis results.

7.2.4 Scenario 4

Fig. 18 displays options with $IRR \geq 15\%$ dominating in number and options with $IRR \leq 10\%$ being the fewest.

		Average MSW % increase								
Electricity price	IRR (%)	0,50%	1,00%	1,50%	2,00%	2,50%	3,00%	3,50%	4,00%	4,50%
	R 0,50	5,91	6,21	6,51	6,82	7,13	7,46	7,74	7,97	8,18
	R 0,60	6,95	7,26	7,59	7,92	8,26	8,60	8,90	9,16	9,38
	R 0,70	7,94	8,28	8,62	8,96	9,32	9,68	10,00	10,27	10,51
	R 0,80	8,91	9,25	9,61	9,97	10,34	10,71	11,04	11,33	11,59
	R 0,90	9,84	10,20	10,57	10,94	11,31	11,70	12,04	12,34	12,62
	R 1,00	10,76	11,12	11,50	11,88	12,26	12,65	13,00	13,32	13,61
	R 1,10	11,65	12,02	12,41	12,79	13,18	13,58	13,94	14,26	14,57
	R 1,20	12,52	12,90	13,29	13,68	14,08	14,48	14,85	15,18	15,49
	R 1,30	13,38	13,77	14,16	14,55	14,95	15,36	15,73	16,07	16,40
	R 1,40	14,22	14,61	15,01	15,41	15,81	16,21	16,59	16,95	17,27
	R 1,50	15,05	15,44	15,84	16,25	16,65	17,06	17,44	17,80	18,13
	R 1,60	15,87	16,26	16,66	17,07	17,47	17,88	18,27	18,63	18,98
	R 1,70	16,67	17,07	17,47	17,88	18,28	18,69	19,08	19,45	19,80
R 1,80	17,46	17,86	18,27	18,67	19,08	19,49	19,88	20,26	20,61	
R 1,90	18,25	18,65	19,05	19,46	19,87	20,28	20,67	21,05	21,40	
R 2,00	19,02	19,42	19,83	20,23	20,64	21,05	21,44	21,82	22,18	
R 2,10	19,78	20,18	20,59	20,99	21,40	21,81	22,21	22,59	22,95	

Fig. 6. Scenario 4 IRR sensitivity analysis results.

8. DISCUSSION OF RESULTS

The base result in Table IX and Table X shows that scenario 4 yields the best financial performance with SPB, ROI, NPV and IRR at eight years, 13%, R390.44 million and 17.39% respectively. The worst financial performance is seen in scenario 1 with SPB, ROI, NPV and IRR at 17 years, 6%, R63.56 million and 10.99% respectively.

A comparison of Scenario 1 with Scenario 3, results proves that medical waste gate fees have a significant effect on financial performance. This is confirmed by comparing Scenario 2 and Scenario 3 results.

Sensitivity analysis results proved that an increase in electricity price and average MSW percentage increase results in an increase in NPV and IRR, thus an increase in investment attractiveness.

Comparing Fig. 10 to Fig. 13 and Fig. 15 to Fig. 18 shows that scenario 4 has the highest number of options with NPV and IRR results that indicate the most attractive investment. The same comparisons proves that scenario 1 is dominated by options that are not financially feasible.

Evaluation of the financial analysis results indicates the ranking in order of desirability as: scenario 4, scenario 2, scenario 3 and scenario 1. This is confirmed by financial performance indicators and sensitivity analysis results.

Financial performance and sensitivity analysis results prove that WtE grate incineration is more attractive on condition that medical waste is diverted to the WtE plant and an investment subsidy is accessible.

The results obtained proved that the major revenue stream of a WtE plant is electricity sales and medical waste gate fees. High capital cost stand is a major hindrance in implementing a WtE grate incineration power plant, regardless of positive financial performance.

The financial feasibility of a WtE grate incineration power plant is significantly influenced by the plant processing capacity. A plant capacity of 150 000 tonnes to 200 000 tonnes per annum proved to be financially feasible.

9. CONCLUSION

A financial analysis of a WtE grate incineration power plant, with four scenarios, was accomplished. Scenario 4, which is characterised by MSW and medical waste as feedstock and IPP owned, exhibited the best financial performance and is economically viable. Scenario 1 characterised by MSW and investment Company owned has low investment attractiveness.

The potential of implementing WtE grate incineration is significant in countries that have landfill dominating other waste management strategies. Thus this study is of significance in the South African context, since landfill is the dominant MSW management strategy in the country.

South Africa is currently faced with electrical power shortages and the country is promoting participation in IPP. The results of the study show that the potential of WtE grate incineration can support the country's IPP initiatives.

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Dieter Krueger has an M.Eng degree from UCT and is a Pr Eng as well as CEM. He has a wealth of experience in the energy industry. He served as director of the CSIR's *Division of Energy Technology* (Enertek) from 1983 and as Secretary of the *SA Association of Energy Services Companies* from 2006 to 2014. Since April 2012 he has been retained by BBEnergy as Consultant on a part-time basis.

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APPENDIX C: AHP ANALYSIS

C1: CRITERIA, SUB-CRITERIA AND GLOBAL WEIGHTS CALCULATIONS

Goal:	Choosing the best WtE thermal technology for Potchefstroom						
Alternative:	Grate Incineration (GI), Fluidized bed incineration (FBI), Gasification (G), and Pyrolysis (P)						
Criteria:	Waste processed (WP), Capacity (C), Scalability (S), Potential revenue streams (PRS), and Operating temperatures (OT)						
Criteria Matrix, (A_1)	WP	OT	C	S	PRS		
WP	1,00	3,00	2,00	2,00	4,00		
OT	0,33	1,00	2,00	2,00	2,00		
C	0,50	0,50	1,00	1,00	2,00		
S	0,50	0,50	1,00	1,00	2,00		
PRS	0,25	0,50	0,50	0,50	1,00		
Normalized matrix	WP	OT	C	S	PRS	Weights	
WP	0,39	0,55	0,31	0,31	0,36	0,39	$= w_1^T$
OT	0,13	0,18	0,31	0,31	0,18	0,23	
C	0,19	0,09	0,15	0,15	0,18	0,15	
S	0,19	0,09	0,15	0,15	0,18	0,15	
PR	0,10	0,09	0,08	0,08	0,09	0,09	
Checking consistence							
$A_1 w_1^T =$	2,02	$A_1 w_1^T$ average=	5,15	CR =	0,03		
	1,12	CI =	0,04	Results =	Valid		
	0,78	RI =	1,12				
	0,78						
	0,45						
Sub-criteria matrix₁, (A_2)	MMSW	Mw	WT				
MMSW	1,00	2,00	5,00				
Mw	0,50	1,00	3,00				
WT	0,20	0,33	1,00				
Normalized matrix₁	MMSW	Ms	WT	Weights			
MMSW	0,59	0,60	0,56	0,58	$= w_2^T$		
Ms	0,29	0,30	0,33	0,31			
WT	0,12	0,10	0,11	0,11			
Checking consistence							
$A_2 w_2^T =$	1,74749	$A_2 w_2^T$ average=	3,003696	CR =	0,0031863		
	0,92854	CI =	0,001848	Results =	Valid		
	0,32889	RI =	0,58				
Global Weight for WP							
MMSW	0,22						
MD	0,12						
WT	0,04						
Sub-criteria matrix₂, (A_3)	E	H	PS	FNFM	SD		
E	1,00	3,00	3,00	7,00	8,00		
H	0,33	1,00	1,00	2,00	2,00		
PS	0,33	1,00	1,00	2,00	2,00		
FNFM	0,14	0,50	0,50	1,00	1,00		
SD	0,13	0,50	0,50	1,00	1,00		

Normalized matrix ₂	E	H	PS	FNFM	SD	Weights	
E	0,52	0,50	0,50	0,54	0,57	0,53	
H	0,17	0,17	0,17	0,15	0,14	0,16	
PS	0,17	0,17	0,17	0,15	0,14	0,16	$=W_3^T$
FNFM	0,07	0,08	0,08	0,08	0,07	0,08	
SD	0,06	0,08	0,08	0,08	0,07	0,08	
Checking consistence							
$A_3 W_3^T =$	2,64	$A_2 W_2^T$ average=	5,009251	CR =	0,002065		
	0,80346	CI =	0,002313	Results =	Valid		
	0,80346	RI =	1,12				
	0,38922						
	0,37984						
Global Weight for PR							
E	0,04						
H	0,01						
PS	0,01						
FNFM	0,01						
SD	0,01						

C2: PAIRWISE COMPARISON AND SYNTHESISING

Alternative matrix ₁ (MMSW)	GI	FBI	G	P			
GI	1		5	7	7		
FBI	0,2	1	2	2	2		
G	0,14286		0,5	1	1		
P	0,14286		0,5	1	1		
Normalized matrix ₃	GI	FBI	G	P	Weights		
GI	0,67308	0,714285714	0,636364	0,6363636	0,6650225		
FBI	0,13462	0,142857143	0,181818	0,1818182	0,1602772	= w ₁	
G	0,09615	0,071428571	0,090909	0,0909091	0,0873501		
P	0,09615	0,071428571	0,090909	0,0909091	0,0873501		
Checking consistence							
B ₁ w ₁ =	2,68931	Bw ₁ average=	4,015966	CR =	0,0059135		
	0,64268	CI =	0,005322	Results =	Valid		
	0,34984	RI =	0,9				
	0,34984						
Alternative matrix ₂ (Mw)	GI	FBI	G	P			
GI	1	4	2	2			
FBI	0,25	1	2	2			
G	0,5	0,5	1	1			
P	0,5	0,5	1	1			
Normalized matrix ₄	GI	FBI	G	P	Weights		
GI	0,44444	0,666666667	0,333333	0,3333333	0,4444444		
FBI	0,11111	0,166666667	0,333333	0,3333333	0,2361111	= w ₂	
G	0,22222	0,083333333	0,166667	0,1666667	0,1597222		
P	0,22222	0,083333333	0,166667	0,1666667	0,1597222		
Checking consistence							
B ₂ w ₂ =	2,02778	B ₂ w ₂ average=	4,24996	CR =	0,0925778		
	0,98611	CI =	0,08332	Results =	Valid		
	0,65972	RI =	0,9				
	0,65972						
Alternative matrix ₃ (WT)	GI	FBI	G	P			
GI	1	3	3	3			
FBI	0,33333	1	1	1			
G	0,33333	1	1	1			
P	0,33333	1	1	1			
Normalized matrix ₅	GI	FBI	G	P	Weights		
GI	0,5	0,5	0,5	0,5	0,5		
FBI	0,16667	0,166666667	0,166667	0,1666667	0,1666667	= w ₃	
G	0,16667	0,166666667	0,166667	0,1666667	0,1666667		
P	0,16667	0,166666667	0,166667	0,1666667	0,1666667		
Checking consistence							
B ₃ w ₃ =	2	B ₂ w ₂ average=	4	CR =	0		
	0,66667	CI =	0	Results =	Valid		
	0,66667	RI =	0,9				
	0,66667						

Alternative matrix₄ (OT)	GI	FBI	G	P			
GI	1	2	4	5			
FBI	0,5	1	2	2			
G	0,25	0,5	1	1			
P	0,2	0,5	1	1			
Normalized matrix₆	GI	FBI	G	P	Weights		
GI	0,51282	0,5	0,5	0,5555556	0,517094	= w ₄	
FBI	0,25641	0,25	0,25	0,2222222	0,2446581		
G	0,12821	0,125	0,125	0,1111111	0,1223291		
P	0,10256	0,125	0,125	0,1111111	0,1159188		
Checking consistence							
B ₄ w ₄ =	2,07532	B ₄ w ₄ average=	4,006232	CR =	0,0023082		
	0,9797	CI =	0,002077	Results =	Valid		
	0,48985	RI =	0,9				
	0,464						
Alternative matrix₅ (C)	GI	FBI	G	P			
GI	1	3	4	5			
FBI	0,33333	1	2	3			
G	0,25	0,5	1	2			
P	0,2	0,33333333	0,5	1			
Normalized matrix₇	GI	FBI	G	P	Weights		
GI	0,56075	0,620689655	0,533333	0,4545455	0,542329	= w ₅	
FBI	0,18692	0,206896552	0,266667	0,2727273	0,2333016		
G	0,14019	0,103448276	0,133333	0,1818182	0,1396967		
P	0,11215	0,068965517	0,066667	0,0909091	0,0846727		
Checking consistence							
B ₅ w ₅ =	2,22438	B ₅ w ₅ average=	4,051235	CR =	0,018976		
	0,94749	CI =	0,017078	Results =	Valid		
	0,56128	RI =	0,9				
	0,34075						
Alternative matrix₆ (S)	GI	FBI	G	P			
GI	1	0,5	0,25	0,5			
FBI	2	1	0,5	1			
G	4	2	1	0,5			
P	2	1	2	1			
Normalized matrix₈	GI	FBI	G	P	Weights		
GI	0,11111	0,11111111	0,066667	0,1666667	0,1138889	= w ₆	
FBI	0,22222	0,22222222	0,133333	0,3333333	0,2277778		
G	0,44444	0,44444444	0,266667	0,1666667	0,3305556		
P	0,22222	0,22222222	0,533333	0,3333333	0,3277778		
Checking consistence							
B ₆ w ₆ =	0,47431	B ₆ w ₆ average=	4,247037	CR =	0,0914953		
	0,94861	CI =	0,082346	Results =	Valid		
	1,40556	RI =	0,9				
	1,44444						

Alternative matrix₇ (E)	GI	FBI	G	P			
GI	1		2	2	3		
FBI	0,5		1	1	2		
G	0,5		1	1	2		
P	0,33333		0,5	0,5	1		
Normalized matrix₉	GI	FBI	G	P	Weights		
GI	0,42857	0,444444444	0,444444	0,375	0,4231151	= w ₇	
FBI	0,21429	0,222222222	0,222222	0,25	0,2271825		
G	0,21429	0,222222222	0,222222	0,25	0,2271825		
P	0,14286	0,111111111	0,111111	0,125	0,1225198		
Checking consistence							
B ₇ w ₇ =	1,6994	B ₇ w ₇ average=	4,010365	CR =	0,003839		
	0,91096	CI =	0,003455	Results =	Valid		
	0,91096	RI =	0,9				
	0,49074						
Alternative matrix₈ (H)	GI	FBI	G	P			
GI	1		1	3	3		
FBI	1		1	3	3		
G	0,33333	0,333333333		1	1		
P	0,33333	0,333333333		1	1		
Normalized matrix₁₀	GI	FBI	G	P	Weights		
GI	0,375	0,375	0,375	0,375	0,375	= w ₈	
FBI	0,375	0,375	0,375	0,375	0,375		
G	0,125	0,125	0,125	0,125	0,125		
P	0,125	0,125	0,125	0,125	0,125		
Checking consistence							
B ₈ w ₈ =	1,5	B ₈ w ₈ average=	4	CR =	0		
	1,5	CI =	0	Results =	Valid		
	0,5	RI =	0,9				
	0,5						
Alternative matrix₉ (PS)	GI	FBI	G	P			
GI	1		1	3	3		
FBI	1		1	3	3		
G	0,33333	0,333333333		1	1		
P	0,33333	0,333333333		1	1		
Normalized matrix₁₁	GI	FBI	G	P	Weights		
GI	0,375	0,375	0,375	0,375	0,375	= w ₉	
FBI	0,375	0,375	0,375	0,375	0,375		
G	0,125	0,125	0,125	0,125	0,125		
P	0,125	0,125	0,125	0,125	0,125		
Checking consistence							
B ₉ w ₉ =	1,5	B ₉ w ₉ average=	4	CR =	0		
	1,5	CI =	0	Results =	Valid		
	0,5	RI =	0,9				
	0,5						
Alternative matrix₁₀ (FNFM)	GI	FBI	G	P			
GI	1		5	5	5		
FBI	0,2		1	1	1		
G	0,2		1	1	1		
P	0,2		1	1	1		
Normalized matrix₁₂	GI	FBI	G	P	Weights		
GI	0,625	0,625	0,625	0,625	0,625	= w ₁₀	
FBI	0,125	0,125	0,125	0,125	0,125		
G	0,125	0,125	0,125	0,125	0,125		
P	0,125	0,125	0,125	0,125	0,125		
Checking consistence							
B ₁₀ w ₁₀ =	2,5	B ₁₀ w ₁₀ average=	4	CR =	0		
	0,5	CI =	0	Results =	Valid		
	0,5	RI =	0,9				
	0,5						

Alternative matrix ₁₁ (SD)																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
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APPENDIX D: TLOKWE MUNICIPALITY CASE STUDY

D1: INTRODUCTION LETTER 1



NORTH-WEST UNIVERSITY
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2520
5 May 2014

Programme Manager: Industrial Engineering
Faculty of Engineering
North-West University
Tel: +27(0)18 299 1524
liezl.vandyk@nwu.ac.za

To whom it may concern

Masters of Engineering Research Project: A Techno-economic evaluation of a Waste-to-Energy Incineration Power Plant in Tlokwe

This letter serves to confirm that Whisper Maisiri (Student Number – 25727265) is a registered student at the NWU in the School for Mechanical and Nuclear Engineering. Currently he is in his first year Masters in Mechanical Engineering.

He presented on 2 April 2014 a research proposal on the above mentioned topic to the satisfaction of the research panel of the Faculty. This research proposal can be made available upon request. His research will have both economic and environmental benefits to the community of Tlokwe if successfully completed.

To this end, he requires information pertaining Municipal Solid Waste management in Tlokwe, which I believe you can assist with. May you please assist him with the information he requires to successfully pursue his research. All information will be used for academic purposes only, according to the strict ethical and confidential guidelines provided by the NWU.

It will be appreciated if you could assist him in meeting his research objectives.

Yours sincerely

Dr Liezl van Dyk, Pr.Eng

Original details: Whisper Maisiri(25727265) C:\Users\24827533\Dropbox\Whisper\Whisper Letter 4 municipality.docm
30 April 2014 File reference: MEng 25727265



D2: INTRODUCTION LETTER 2



NORTH-WEST UNIVERSITY
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19 May 2014

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To whom it may concern

Masters of Engineering Research Project: A Techno-economic evaluation of a Waste-to-Energy Incineration Power Plant in Tlokwe

This letter serves to confirm that Whisper Maisiri (Student Number – 25727265) is a registered student at the NWU in the School for Mechanical and Nuclear Engineering under my supervision. Currently he is in his first year Masters in Mechanical Engineering.

He presented in April 2014 a research proposal on the above mentioned topic to the satisfaction of the research panel of the Faculty of Engineering. This research proposal can be made available upon request. His research will have both economic and environmental benefits to the community of Tlokwe if successfully completed.

His research project includes a feasibility study of incorporating Medical Waste in the incineration process. To this end, he requires information pertaining current Medical Waste management in Potchefstroom, which I believe you can assist with. May you please assist him with the information he requires to successfully pursue his research. All information will be used for academic purposes only, according to the strict ethical and confidential guidelines provided by the NWU.

It will be appreciated if you could assist him in meeting his research objectives.

Yours sincerely



Dr Liezl van Dyk, Pr.Eng

Original details: Whisper Maisiri(25727265) C:\Users\24827533\Dropbox\Whisper\Whisper Letter 4 municipality.docx
30 April 2014 File reference: MEng 25727265



D3: INTRODUCTION LETTER 3



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To whom it may concern

Masters of Engineering Research Project: A Techno-economic evaluation of a Waste-to-Energy Incineration Power Plant in Tlokwe

This letter serves to confirm that Whisper Maisiri (Student Number – 25727265) is a registered student at the NWU in the School for Mechanical and Nuclear Engineering. Currently he is in his final year Masters in Mechanical Engineering.

He presented a conference paper on 29 January 2015 on technological and performance comparison of waste-to-energy thermal technologies. The research proposal and conference paper can be made available upon request. His research will have both economic and environmental benefits to the community of Tlokwe if successfully completed.

Now he is carrying an economic and financial evaluation of waste-to-energy power plant. To this end, he requires information pertaining electricity demand and cost and other related issues on energy management in the Municipality of Tlokwe, which I believe you can assist with. May you please assist him with the information he requires to successfully pursue his research. All information will be used for academic purposes only, according to the strict ethical and confidential guidelines provided by the NWU.

It will be appreciated if you could assist him in meeting his research objectives.

Yours sincerely

Prof Liezl van Dyk, Pr.Eng



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D4: TLOKWE MUNICIPAL WASTE MANAGEMENT DEPARTMENT

INTERVIEW QUESTIONS AND RESPONSES

Purpose of the Interviews.

The purpose of this interview is to determine municipal solid waste (MSW) generation trends and the management strategies being used by a small South African city in the North-West Province, Potchefstroom. The interview also seeks to discover problems encountered with managing MSW and plans in place to implement an integrated MSW management system that will mitigate environmental challenges of landfilling and meet energy demand in the city.

Introduction

My name is Whisper Maisiri (Student Number – 25727265) and I am a registered student at the NWU in the School for Mechanical and Nuclear Engineering. Currently I am in my first year of study for a Masters' degree in Mechanical Engineering. I am pursuing a research project titled "A techno-economic evaluation of a waste-to-energy grate incineration power plant for a small South African city", that is meant to meet the economic, environmental and energy challenges being faced by many municipalities today.

I presented my research proposal on 2 April 2014 to the satisfaction of the research panel of the faculty. This research proposal can be made available upon request. If successfully completed, my research is meant to have both economic and environmental benefits for the community of Tlokwe and other cities in South Africa.

In brief, a waste-to-energy incineration power plant is an alternative MSW management strategy that seeks to minimize problems of landfill while at the same time meeting the energy demand of municipalities. It can successfully co-exist with recycling and re-use and other MSW management strategies.

Structure of the Interview

- A. General information
- B. MSW generation statistics
- C. MSW management policies
- D. MSW management strategies in operation
- E. Environmental impacts of landfills
- F. Small city plans to meet ever increasing MSW

Statement of confidentiality

Before we start, I would like to assure you that this interview is confidential and completely voluntary. If we should come to any question that you do not want to answer, feel free to leave it blank. All information will be used for academic purposes only, according to the strict ethical and confidential guidelines provided by the NWU.

Section A: General Questions

1. Approximately how many people reside in Potchefstroom?	
<i>Currently there are about 300 000 residents in Potchefstroom</i>	
2. Do you face MSW management challenges as a growing city in a developing country?	
<i>Yes, generally the challenge concerns resources. Waste management is not receiving the same priority during planning as other basic services and has therefore become poorly</i>	

<i>resourced. As the city grows, all other services are budgeted for, but waste is considered last and gets the lowest allocation.</i>	
3. How is the public's response and participation in maintaining sanitation in the small city?	<i>N/A</i>
4. How do you meet MSW management costs as a small city?	
<i>Revenue is collected according to an annually reviewed tariff. More than 80% payment for services is collected monthly.</i>	
5. Are residents charged for generating waste?	
<i>Yes. There is tariff set for refuse removal only.</i>	
6. If yes, how much are they charged and how are they charged?	
<i>The charges differ according to the services rendered, either for residential or business purposes; for example the minimum is R52 per household and R194 per business.</i>	
7. Is any economic benefit realized from management of MSW in the small city?	
<i>Yes, there are several recycling activities of solid waste that the municipality encourages, which are economically viable. There is no direct benefit to the Waste Section, the revenue collected goes straight into the municipal account.</i>	
8. Is a private company engaged by the municipality to handle MSW?	
<i>Yes, both the consulting engineer and the landfill operator are private companies. The landfill operation is the only portion outsourced. Refuse removal is solely managed by the municipality.</i>	

Section B: MSW generation statistics

1. Does the city council record the amount of waste collected in the city?	
<i>Yes. The main source of the statistics is waste captured on entry to the landfill. Monthly statistics are provided to the city council by the landfill operator.</i>	
2. If yes, what is the current rate of MSW generation per day in the city?	
<i>It fluctuates but is estimated at ± 200 tons per day, including rubble and organic waste.</i>	
3. How much waste is collected, transported and disposed of per year in the city?	
<i>A total of $\pm 80\,000$ is disposed of at the landfill annually.</i>	
4. Has there been an increasing trend in the generation of MSW over the past years?	
<i>The amount has increased by more than 10 000 tonnes annually.</i>	
5. How can you characterize the composition of MSW in the city?	
<i>Because of the city's growth the amount of commercial and industrial waste is higher than domestic waste. This is also influenced by new development around the university area. Demolition and a high rate of construction has picked up greatly in recent years.</i>	
6. Which segment of society is the main contributor to MSW?	
<i>Commercial and industrial waste, though it may be temporary, but in competition with domestic waste.</i>	
7. Is the capacity of disposal facilities meeting the MSW amounts produced daily?	

<i>Yes, the landfill in Potchefstroom is capable of handling the current production, though it is not a sustainable measure.</i>	
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C: MSW management policies

1. Are there by-laws that standardize the management and handling of MSW in the city?	
<i>Draft by-laws are in circulation for approval, though it has been a lengthy process since 2012.</i>	
2. Is there any policy regulating private investors in the field of MSW management and treatment?	
<i>No.</i>	
3. Are there any regulations in SA on the establishment of waste-to-energy incineration plants?	
<i>Several proposals are anticipated by the national DEA and private companies constantly present projects, though none has gone beyond presentation.</i>	
4. How effective are the local regulations and policies in maintaining proper management of MSW?	
<i>There are currently insufficient resources to formulate and execute local policies and regulations to maintain MSW effectively, though there are systems to ensure service delivery is not compromised.</i>	
5. Is there any policy that regulates uncontrolled burning of MSW and is it being enforced?	
<i>The function lies with the Dr KK District and Environmental Management office.</i>	

D: MSW management strategies in operation

1. What is the most accepted and practiced waste disposal method in the city?	
<i>Landfill.</i>	
2. What is the MSW management strategy mix adopted in the city?	
<i>Landfill and recycling.</i>	
3. How do you manage MSW (the collection, transportation and final disposal of MSW)?	
<i>The municipality provides basic waste receptacles to residents, conducts daily/weekly refuse collection and transports domestic and business waste with compactor trucks to the landfill. The private recycling companies collect recyclables directly or through waste reclaimers from kerbsides and process these at their centers. Forty-five re-claimers recycle material at the landfill through a controlled arrangement with the site operator. There is an operational drop-off facility for green waste that is accessible to the community but contracted to the landfill operator. The waste is collected by skip loader and disposed of at the landfill site. Private contractors use trucks and hire skips to transport and dispose of their construction waste at the landfill.</i>	
4. Is most of the waste coming from household, commercial and non-commercial establishments dumped in a mixed state without segregation?	
<i>Yes, though the city council encourages recycling and allows the recyclers and re-claimers to operate, less than 10% of waste is saved from landfilling</i>	
5. Is there official recycling and re-use of MSW in the city?	

<i>Yes, though not operated by the city council; it is driven by private recycling companies.</i>	
6. Approximately how many tonnes MSW are recycled per year in the city?	
<i>No official statistics are available in this regard, only recycling statistics for waste re-claimed at the landfill is captured. About 1400 tonnes is recovered from the landfill per year.</i>	
7. At the current recycling rate, can recycling and re-use manage to mitigate environmental challenges of landfill?	
<i>Not at the current rate.</i>	
8. Does the municipality operate non-energy recovery incinerators?	
<i>No.</i>	
9. What alternative strategies to landfilling are practiced?	
<i>A composting initiative was successfully piloted in partnership with the local university and has potential for growth. Currently funding is a challenge and the project is on hold. The city council supports and encourages recycling.</i>	
10. Can you conclude that there is an integrated approach to MSW management in the city?	
<i>Yes, though on a small scale; all plans and strategies require resources.</i>	

E: Environmental impacts of landfills

1. How many landfill sites are being operated by the city?	
<i>Only one.</i>	
2. What type of landfill (sanitary or simple) do you operate?	
<i>The sanitary cell system; ISO 14001 standard</i>	
3. Approximately how much land is covered by landfills?	<i>N/A</i>
4. Are there MSW management strategies in operation with the aim of reducing the burden on landfill?	
<i>Yes, but not compatible with resources available for this purpose</i>	
5. Are you aware of environmental impacts of landfill? If possible, highlight some of them.	
<i>Yes, potential for ground water and land contamination, hazardous chemical formation (methane) and air pollution.</i>	
6. As a municipality, have you experienced challenges from the landfills you are operating?	
<i>Yes, in the form of mortar recovery and shortage of cover material.</i>	
7. At the current rate at which MSW is produced, can landfill sustain MSW management in the future?	
<i>No.</i>	
8. What is the expected life of the landfill site, and is it filling up at the expected rate?	
<i>Estimated 20 years and no, it is not filling up at the expected rate.</i>	

F: City council plans to meet the ever increasing MSW

1. What is your MSW generation forecast per year, for say the next five years?	
<i>80 000 tonnes per year.</i>	
2. Is the Tlokwe municipality looking forward to conducting integrated MSW management as an alternative to the concept of just dumping all the waste generated?	
<i>Yes.</i>	
3. What other MSW management strategies do you plan to implement in the future?	
<i>Composting, recycling at source and establishment of an MRF</i>	
4. Are there current plans to implement of waste-to-energy technologies in the city?	
<i>Yes, review the methane recovery plant at the waste treatment facility.</i>	
5. Will you welcome waste-to-energy incineration power plant as an alternative strategy to MSW management?	
<i>Yes.</i>	

D5: SMALL CITY 2011 MSW TONNAGE

2011	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Totals	AVERAGE
Dry Mix-Industrial	1986,54	2759,47	2748,17	1622,79	2004,09	2419,12	1683,45	2096,82	2051,74	2338,72	3141,53	2985,75	27838,19	2319,85
Domestic Waste	1757,23	1389,05	2790,77	2452,41	2736,69	1181,55	1965,59	1723,38	1325,60	1266,13	1460,12	1363,96	21412,48	1784,37
Cover Material	371,86	138,12	309,00	100,00	80,00	296,92	55,30	136,24	100,54	101,00	278,44	271,34	2238,76	186,56
Building Material	602,40	533,50	1055,00	818,00	1038,00	487,26	1240,20	409,84	1029,97	1371,62	464,61	437,34	9487,74	790,65
Garden Materials	1142,72	761,28	1052,98	1082,62	1118,06	686,52	937,34	804,55	671,64	676,00	739,29	625,30	10298,30	858,19
Totals Tons	5860,75	5581,42	7955,92	6075,82	6976,84	5071,37	5881,88	5170,83	5179,49	5753,47	6083,99	5683,69	71275,47	5939,62
Cover Material Deducted	371,86	138,12	309,00	100,00	80,00	296,92	55,30	136,24	100,54	101,00	278,44	271,34	2238,76	186,56
Total Tons Invoiced	5488,89	5443,30	7646,92	5975,82	6896,84	4774,45	5826,58	5034,59	5078,95	5652,47	5805,55	5412,35	69036,71	5753,06
Rainfall	244,00	207,00	78,00	172,00	62,00	52,00	4,00	0,00	2,00	56,00	130,00	154,00	1161,00	96,75
Site Users	2810,00	2659,00	3102,00	2391,00	2607,00	2354,00	2349,00	2817,00	2809,00	3039,00	3210,00	2780,00	32927,00	2743,92

D6: SMALL CITY 2012 MSW TONNAGE

2012	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Totals	Average
Contractors Mix Waste	6421,21	1999,63	1585,62	1570,25	2349,61	1822,04	1378,56	7339,80	2172,22	2882,70	1975,88	2020,64	33518,16	2793,18
Domestic Waste	1541,59	1650,08	1767,78	1437,13	1440,97	1267,98	2041,73	1402,16	1344,98	1660,24	1404,19	1510,71	18469,54	1539,13
Cover Material	446,52	97,66	168,00	170,36	131,22	798,54	0,00	208,20	161,46	207,56	583,30	419,37	3392,19	282,68
Building Material	133,71	248,30	425,10	483,78	392,18	515,00	997,55	372,18	453,30	782,73	860,56	993,05	6657,44	554,79
Garden Material	892,53	797,27	859,90	705,56	745,75	554,52	846,96	465,34	545,32	729,76	748,09	664,12	8555,12	712,93
Total Tons	9435,56	4792,94	4806,40	4367,08	5059,73	4958,08	5264,80	9787,68	4677,28	6262,99	5572,02	5607,89	70592,45	5882,70
Cover Material Deducted	446,52	97,66	168,00	170,36	131,22	798,54	0,00	208,20	161,46	207,56	583,30	419,37	3392,19	282,68
Total Tons Invoiced	8989,04	4695,28	4638,40	4196,72	4928,51	4159,54	5264,80	9579,48	4515,82	6055,43	4988,72	5188,52	67200,26	5600,02
Rainfall	95,00	143,00	118,00	24,00	0,00	5,00	0,00	0,00	29,00	64,00	80,00	136,00	694,00	57,83
Site Users	3542,00	2528,00	2691,00	2263,00	2696,00	2684,00	3279,00	2485,00	2500,00	3271,00	2930,00	2718,00	33587,00	2798,92

D7: SMALL CITY 2013 MSW TONNAGE

2013															
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Totals	Average	
Contractors Mix Waste	2908,14	2017,51	1626,11	1554,58	2173,52	4929,08	2567,00	2818,00	2008,28	2081,69	2307,49	1242,81	28234,21	2352,85	
Domestic Waste	1634,74	1510,00	1544,07	1836,87	1757,62	1758,33	1715,47	1708,20	1391,62	1600,85	1878,72	1509,48	19845,97	1653,83	
Cover Material	480,94	248,04	288,48	1308,70	122,16	79,98	29,32	39,00	43,30	3,20	35,74	43,68	2722,54	226,88	
Building Material	958,45	2081,47	1327,47	1909,66	1521,52	590,09	641,92	3391,92	2214,86	1539,84	2336,37	1605,31	20118,88	1676,57	
Garden Material	884,98	820,61	627,09	872,40	779,55	1049,97	590,31	1553,14	654,48	603,01	1408,97	917,74	10762,25	896,85	
Total Tons	6867,25	6677,63	5413,22	7482,21	6354,37	8407,45	5544,02	9510,26	6312,54	5828,59	7967,29	5319,02	81683,85	6806,99	
Cover Material Deducted	480,94	248,04	288,48	1308,70	122,16	79,98	29,32	1056,58	43,30	3,20	35,74	43,68	3740,12	311,68	
Total Invoiced	6386,31	6429,59	5124,74	6173,51	6232,21	8327,47	5514,70	8453,68	6269,24	5825,39	7931,55	5275,34	77943,73	6495,31	
Recycling Volume	82,54	165,88	110,94	168,34	146,18	65,29	140,80	91,74	90,70	120,70	134,40	99,20	1416,71	118,06	
Rainfall	99,00	68,00	84,00	60,00	10,00	0,00	0,00	3,00	1,00	50,00	107,00	372,00	854,00	71,17	
Site Users	3206,00	2949,00	2761,00	2923,00	3105,00	3169,00	2849,00	2910,00	2683,00	2823,00	3340,14	2519,00	35237,14	2936,43	

D8: SMALL CITY 2014 MSW TONNAGE

2014															
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Totals	Average	
Commercial & Industrial	5404,70	1722,30	1886,14	4630,53	2032,96	0,00	0,00	0,00	0,00	0,00	0,00	0,00	15676,63	3135,33	
Municipal - Domestic Waste	1718,60	1922,26	1645,12	1623,78	1554,48	0,00	0,00	0,00	0,00	0,00	0,00	0,00	8464,24	1692,85	
Cover Material	424,22	335,26	141,66	4264,31	70,98	0,00	0,00	0,00	0,00	0,00	0,00	0,00	5236,43	1047,29	
Building Material	1135,84	869,02	360,79	628,43	930,94	0,00	0,00	0,00	0,00	0,00	0,00	0,00	3925,02	785,00	
Garden Material	1022,72	962,14	1034,06	818,90	789,25	0,00	0,00	0,00	0,00	0,00	0,00	0,00	4627,07	925,41	
Organic Food	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	
Total Tons	9706,08	5810,98	5067,77	11965,95	5378,61	0,00	0,00	0,00	0,00	0,00	0,00	0,00	37929,39	7585,88	
Cover Material Deducted	424,22	335,26	141,66	4264,31	70,98	0,00	0,00	0,00	0,00	0,00	0,00	0,00	5236,43	1047,29	
Total Invoiced	9281,86	5475,72	4926,11	7701,64	5307,63	0,00	0,00	0,00	0,00	0,00	0,00	0,00	32692,96	6538,59	
Recycling Volume	128,58	183,96	140,92	150,92	59,72	0,00	0,00	0,00	0,00	0,00	0,00	0,00	664,10	132,82	
Rainfall	34,00	140,00	219,00	5,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	398,00	79,60	
Site Users	3738,00	3291,00	2541,00	3550,00	2886,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	16006,00	3201,20	

APPENDIX E: AEB WTE GRATE INCINERATION POWER PLANT CORRESPONDENCE

E1: AEB CORRESPONDENCE 1

Date: 04 July 2014

Time: 13:34

Minutes on Skype conversation between Whisper Maisiri and Evert Lichtenbelt.

Evert is the Strategic Advisor at AEB Amsterdam. His contact details are: e-mail: Evert.Lichtenbelt@aebamsterdam.nl, Tel: +31 20 5876234, Cell: +31 6 52 00 88 25

Introduction

The conversation took place from 13:34 to 13:56. It was a follow-up on an e-mail conversation between Whisper and Evert regarding to Whisper's research project titled "A techno-economic evaluation of a waste-to-energy grate incineration power plant for a small South African city".

Summary of discussion

Whisper explained the research intentions, which were to do a technical and economic evaluation of a WtE grate incineration plant for a small South African city. He proceeded by asking about factors to be considered in implementing and running a waste-to-energy plant.

In response Evert highlighted that he had looked into Potchefstroom and asked, on the basis of approximations, about the number of people living in Potchefstroom and the amount of waste generated. The response was that approximately 300 000 people live in Potchefstroom and about 80 000 tonnes of waste is collected in the landfill per year.

Evert highlighted the factors to be regarded for a WTE plant to be economically viable:

- Waste volumes: It was highlighted that AEB incinerates about 1.5 million tons per year.
- Waste composition: This affects the calorific values of the waste. Waste handled by AEB has a calorific value of 10 GJ/tonne.
- Logistics: It is very important to have a stable and sufficient flow of waste because the incinerator has to operate at full capacity to maintain efficiency.
- Regulations: For example, in the Netherlands the fee for landfill is so high that people opt to bring waste to AEB and pay a gate fee/tipping fee.
- Electricity price
- Wages
- Building cost
- Interest
- Cost of land: In most countries this is borne by the government, so the WtE facility incurs no cost. One can thus assume zero cost, but this assumption needs to be considered.
- Subsidies and tax breaks for environmentally friendly techniques and companies.

Whisper inquired about the feasibility of burning medical waste and waste vehicle tyres. The response was that AEB incinerates medical waste and sends waste vehicle tyres for recycling.

On inquiry, Evert highlighted that they have a current capacity of 130 MW and run high and normal efficiency lines. AEB uses a grate technology and has a very high advanced flue gas cleaning system.

Whisper's initial inquiry was on the possibility of visiting AEB, to which Evert said the idea would be welcomed. Evert inquired about the visit and Whisper responded that he still had to discuss the idea with his academic supervisors.

Action plans

Whisper was to gather data about Potchefstroom to be discussed in the next conversation in two weeks' time.

Evert stated that he had a lot of data and he was willing to share it to ensure the success of the research.

Evert agreed to get in touch with Whisper's academic supervisors and said they could contact him at any time.

E2: AEB CORRESPONDENCE 2

Date: 14 August 2014

Time: 17:00

Skype conversation between Whisper Maisiri and Evert Lichtenbelt

Introduction

The conversation lasted from 17:00 to 17:30. The scheduled meeting was a feedback meeting from the previous minutes dated 04 July 2014. The meeting scheduled in the previous conversation could not take place since Evert was not in the office (gone on holiday). The conversation was comprehensive and productive, with both parties noting progress.

Summary of discussion

Evert inquired about the aim of the research project Whisper was carrying out.

In response Whisper highlighted that he was to carry out a technical and economic evaluation of a WtE grate incineration power plant for a small South Africa city.

As agreed in the previous conversation, Whisper presented summarized data for Potchefstroom. It was agreed that Whisper had to prepare and send a work sheet with the summarized data for Potchefstroom to Evert through mail.

This is the discussion that arose from the data for Potchefstroom presented by Whisper:

- EU landfill charges are very high as 100 Euro/tonne and makes WtE more favourable compared to Potchefstroom landfill charges of \$0.00/tonne. Evert highlighted that his family spends about 1000 Euro/year to dump waste.
- The way forward is to assess proven available WtE technologies, the capital investment required and operating expenses that will suit the Potchefstroom scenario.
- There is a need to assess the income that can be realized from managing waste and selling electrical energy and to determine whether it can match capital investment and operating expenses.
- In Europe land charges and wages are very high and this raises the costs of establishing and running a WtE plant. It is necessary to establish land charges and average wages in Potchefstroom.

Evert said that he had six technical workers in the Advisory Department who would assist Whisper with information on about five proven WtE technologies.

Evert highlighted that waste in Europe has a calorific value of about 10 MJ/tonne and he asked what the waste calorific value in Potchefstroom was. Whisper did not have the data at hand.

Evert indicated that they had a lot of data for South Africa that they could access from a worldwide association database, of which they were a member.

Beside the waste that is recorded at the landfill, Whisper pointed out that a lot of waste is unaccounted for through dumping activities. Evert highlighted that for a WtE plant to be economically viable, there must be a lot of waste. Whisper suggested that waste could be imported from others towns around Potchefstroom to obtain an economic amount of waste to run a WtE incineration plant.

Action plans

Whisper should prepare and send a work sheet with summarized Potchefstroom statistics to Evert as soon as possible.

Whisper is to read and gather literature on WtE technologies, to complement the information he will get from Evert.

Evert is going to download data on South Africa and send it to Whisper before the next meeting.

Evert is to provide data of WtE proven technologies and send it to Whisper before the next skype conversation.

Whisper is to provide the contact details of Prof Jan de Kock and Prof Liezl van Dyk.

Evert is to reach out to Whisper's academic supervisors, Prof Liezl van Dyk and Prof Jan de Kock.

The next skype conversation will be on 25 August 2014 at 17:00 CET.

E3: AEB CORRESPONDENCE 3

Date: 27 August 2014

Time: 17:00

Skype conversation between Whisper Maisiri and Evert Lichtenbelt

Introduction

The conversation took place from 17:00 to 17:30. The scheduled meeting was a feedback meeting from the previous minutes dated 14 August 2014.

Summary of discussion

We discussed the minutes of the last meeting. All the action plans were completed and we agreed that we were progressing well.

Evert said that he had discussed the available technologies with Jörn Wandschneider, highly regarded WtE designer from Germany. He highlighted that for a WtE incineration plant to operate profitably, the current minimum capacity had to be 100 000 tonnes/year.

Evert also stated that there was little information on South Africa on the ISWA website, and that the NWU group might be one of the frontrunners in such research work.

Evert provided contact details for Nicolien Legtenberg, one of the researchers on WtE, since he anticipated that she might provide information on South Africa.

Action plans

To discuss proven technologies in the next meeting, which must involve Whisper, Evert, Technical personnel working with Evert and Whisper's supervisors.

Whisper is to communicate with Nicolien on information on WtE in South Africa.

To formulate unanswered questions and send them to ISWA.

To identify technology that might suit the Potchefstroom scenario.

The next skype conversation is to be scheduled by Evert after he has discussed it with his technical team.

E4: AEB CORRESPONDENCE 4

Date: 01 October 2014

Time: 10:57

Skype conversation between Whisper Maisiri and Evert Lichtenbelt

Introduction

The conversation took place from 10:57 to 11:49. The discussion was scheduled with the aim of reviewing alternative proven technologies mentioned in the document Evert sent Whisper. The discussion was an eye-opener about possible technologies that may be applicable in Potchefstroom, South Africa.

Summary of discussion

Whisper mentioned four technologies that were listed in the document, IEA Task 36 report, namely grate incineration, fluidized bed incineration, gasification and pyrolysis.

Evert commented on the highlighted technologies as follows:

- Pyrolysis is a good technology though it is not a proven WtE technology. The main challenge is that it operates on a specific waste stream, meaning it is highly dependent on the type of waste, hence pre-treatment required.
- Gasification is an excellent technology and is widely used in Japan at more than 42 installations. The main advantage is that it is a scalable technology and might be suitable for Potchefstroom, taking into consideration the amount of waste generated. Evert indicated that gasification is a robust technology.
- Grate incineration is the best proven technology, which is suitable for large installations of not less than 150 000 tonnes per year for it to be economically viable.
- Fluidized bed is not widely applied in WtE plants because of technological challenges.

The operation of this technology is dependent on waste type and more effort is required in the pre-treatment process.

Evert highlighted that he could not get information on South Africa from Nicolien. Whisper also indicated that Nicolien did not respond to his e-mails.

Whisper posed a question on the capital investment per tonne of waste for the technologies. Evert said that he could not get the information for fluidized bed incineration and pyrolysis and that for grate incineration and gasification it could be worked out. For grate incineration one can estimate the capital investment using the AEB plant model and for gasification Evert's Japanese friend from Nipple Steel could assist the researchers.

Whisper enquired about ways to produce a model and the requirements to achieve this. Evert pointed out the need to consider design parameters and potential revenue streams.

Evert also stated that the capital cost was estimated at €365 per tonnes of waste, which translated to R4500 per tonne of waste at the current euro-to-rand rate.

Action plans

Whisper is to send design input parameters of the model to Evert before the next meeting

Evert is to provide Whisper with contact details for the Japanese person from Nipple Steel and contacts details for a tyre recycling company in the Netherlands.

The next Skype conversation was scheduled for Wednesday, 08 October 2014 at 09:00.

E5: AEB CORRESPONDENCE 5



REF: ECONOMIC MODEL RESULTS VERIFICATION

I hereby take time to confirm that the Waste-to-energy (WtE) grate incineration economic model by Whisper Maisiri is convincing and credible. I have gone through the excel model and it make economic sense.

AEB Amsterdam operates one of the largest and clean WtE grate incineration power plant in the world. And with the experience we have in our economic models, assumptions made in this model appears sound. To single out some of the assumptions, capital costs, maintenance cost, overheads and plant availability are realistic. The variables used in the sensitivity analysis are appropriate for this study.

To this end, I verify that the economic evaluation results can be used for reference and further study.

Also it was a great pleasure working with Whisper Maisiri

Yours faithfully

A handwritten signature in blue ink, appearing to be 'E. Lichtenbelt', with a long horizontal flourish extending to the right.

Evert Lichtenbelt
Strategic Advisor
AEB Amsterdam

APPENDIX F: RESULTS VERIFICATION INTERVIEW

F1: RESULTS VERIFICATION INTERVIEW QUESTIONS

Techno-economic evaluation of waste-to-energy grate incineration power plant

Introduction

My name is Whisper Maisiri (Student Number – 25727265) and I am a registered student at the NWU in the School for Mechanical and Nuclear Engineering. Currently I am in my final year of studies for the degree of Masters in Mechanical Engineering.

I am pursuing a research project titled “A techno-economic evaluation of a waste-to-energy incineration power plant for a small South African city”, which is meant to meet the economic, environmental and energy challenges being faced by many municipalities today.

I have performed techno-economic evaluations and managed to publish two academic peer-reviewed papers from my research. The current stage in my research roadmap is to verify the results of the economic model.

Purpose of the interviews

The purpose of this interview is to carry out results verification for economic evaluations performed by the researcher. The interview also seeks to discover future work that can be carried out.

Question 1
The first worksheet in the excel calculations shows all the assumptions used in the economic model. Do you think the assumptions made for the analysis are realistic?
Question 2
The objective of the economic analysis is to assist investors to make decisions on investment in a waste-to-energy grate incineration power plant for a small South African city. Do the financial viability indicators (NPV and IRR) used assist in making this decision?
Question 3
Are the variables used in the sensitivity analysis appropriate for this study?
Question 4
What future work do you think should be considered as a follow-up to this study?

Thank you for your input.

F2: INTERVIEWEE 1 RESPONSE

Question 1

The first worksheet in the excel calculations shows all the assumptions used in the economic model. Do you think the assumptions made for the analysis are realistic?

Answer : Yes

Question 2

The objective of the economic analysis is to assist investors to make decisions on investment in a waste-to-energy grate incineration power plant for a small South African city. Do the financial viability indicators (NPV and IRR) used assist in making this decision?

Answer : Yes

Question 3

Are the parameters used in the sensitivity analysis appropriate for this study?

Answer : Yes

Question 4

What future work do you think should be considered as a follow-up to this study?

Answer: Perform physical values and measurements over an average span of time for a complete case study.

F3: INTERVIEWEE 2 RESPONSE

Question 1

The first worksheet in the excel calculations shows all the assumptions used in the economic model. Do you think the assumptions made for the analysis are realistic?

Answer: Yes I do, especially considering the current economic performance. The discount rate, inflation rate, and corporate taxes are key in this project.

Question 2

The objective of the economic analysis is to assist investors to make decisions on investment in a waste-to-energy grate incineration power plant for a small South African city. Do the financial viability indicators (NPV and IRR) used assist in making this decision?

Answer: Yes, the IRR helps investors to pitch their investment commitment to the project. If the IRR had been lower than the discount rate then the investment would have been discouraging for investors, as it lowers their returns. A higher IRR also indicate a positive NPV.

Question 3

Are the variables used in the sensitivity analysis appropriate for this study?

Answer: Yes

Question 4

What future work do you think should be considered as a follow-up to this study?

Answer: I have general comments on the economic model.

- *The discount rate, which is also referred to as the hurdle rate, is a rate that is market-based. In other words, a project should set its discount rate at a level that reflects market returns (Megginson et al, 2010). The discount rate used in this model is realistic.*
- *Scenario 4, which is the best case, offers a high IRR at 21.21%. If the IRR is less than the discount rate this will decrease the shareholders' wealth, making the investment unfavorable. Because in scenario 4 IRR is higher than the discount rate, it will create more wealth for shareholders on assumption. The effect of this is also a positive NPV, as already indicated on the scenario 4 cash flow analyses.*
- *As indicated above, the discount rate reflects the current market's rates of return but we have to factor in inflation rate assumption when forecasting project cash flow. This helps to maintain the real rate or value of the money at a particular time.*
- *The taxes indication is an important aspect on this capital budget. Shareholders are interested in seeing the value of cash generation, therefore it is critical to consider corporate taxes to the government. This will avoid distortions and present the cash flows in a favorable position for investors to make decisions.*

F4: INTERVIEWEE 3 RESPONSE

Question 1

The first worksheet in the excel calculations shows all the assumptions used in the economic model. Do you think the assumptions made for the analysis are realistic?

Answer: Yes, I do, we have jointly gone through these assumptions.

Question 2

The objective of the economic analysis is to assist investors to make decisions on investment in a waste-to-energy grate incineration power plant for a small South African city. Do the financial viability indicators (NPV and IRR) used assist in making this decision?

Answer: Those indicators are very important. The economic model gives a strong starting point for investors for further determination of these indicators. Follow-up studies would be more and more granular up to detailed design, which would limit uncertainty to 5%.

Question 3

Are the variables used in the sensitivity analysis appropriate for this study?

Answer: They are.

Question 4

What future work do you think should be considered as a follow-up to this study?

Answer: The next step could be a "scoping mission", or pre-feasibility study, which would be conducted for a prospective investor (or government) to define the most feasible technology, scope and location. Usually this kind of study is executed by a consultant like Royal Haskoning DHV, or Ramboll, just to name two that I am familiar with.