ANALYSIS OF A MUNICIPAL SOLID WASTE BIOREFINERY FOR JOHANNESBURG EAST MUNICIPALITIES

by

Tshepiso Mapotle Matlala (45857547)

submitted in accordance with the requirements

for the degree of

Magister of Technology

in the subject

Chemical Engineering

at the

UNIVERSITY OF SOUTH AFRICA

Supervisor: Professor Bilal Patel

February 2022

DECLARATION

I declare that **Analysis of a Municipal Solid Waste biorefinery for Johannesburg East Municipalities** is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

I further declare that I submitted the dissertation to originality checking software. The result summary is attached.

I further declare that I have not previously submitted this work, or part of it, for examination at UNISA for another qualification or at any other higher education institution.

TM Matlala..

Tshepiso Matlala (45857547)

...08th.........day of...February......2022

ACKNOWLEDGEMENTS

I would like to give the outmost gratitude to my Lord and Saviour for carrying me till thus far. I went through some of the toughest periods of my life while busy with this Masters, but He always gave me the strength to carry on. The glory belongs to Him for letting me not give up. Thank you, Jesus.

To my husband and son, you guys have been my pillars. Your understanding and positive contribution to my studies and life during this period really means the world to me. It is a blessing to have a husband who encouraged me and supported me whole-heartedly. I love you guys.

To my supervisor Prof Bilal Patel, where do I even begin? You have been there for me every step of the way. Your patience, guidance, level of professionalism, encouragement and work ethics have carried me through this journey. Thank you.

To the University of South Africa, thank you for the bursary I received for my studies. It assisted me so much and I truly appreciate it.

My sincere gratitude goes to Mr Lunghile Ntsemi Ndleve of Swaka Ntsemi (Pty) Ltd for his assistance and guidance. You were truly God-sent.

To the staff at Ekurhuleni Metropolitan Municipality: Mr Nhlanhla Khumalo, Mr Flip Viljoen, Mrs Cecilia Rakgoale and Mr Jabulani Chavalala. This project would not have been possible without your assistance. Thank you for opening up your doors for me and availing yourselves amidst the COVID-19 pandemic.

To my late dad, mom and siblings; thank you for the encouragement, support and listening to me when the going got tough. I dedicate this Master’s degree to my late dad who passed on a few months before my submission. Dad I did it, I hope you are proud!

To myself – I am so proud of you. You did it.

ABSTRACT

The purpose of this study was to analyse the amount of municipal solid waste disposed at various landfill sites in the east of Johannesburg. As a resident residing in the east of Johannesburg, it was of interest to me to understand the monetary implications involved in the disposal of waste by the City of Ekurhuleni (CoE) municipality which was formerly known as Ekurhuleni Metropolitan Municipality (EMM). The east of Johannesburg has five operational landfill sites with the Rietfontein Landfill Site being one of them. The Rietfontein Landfill Site is located in Springs, Johannesburg. The Rietfontein Landfill Site is a special landfill site as it is the only one that accepts lower hazardous waste and at the time of research had a 20 year lifespan remaining compared to the others. It was on this basis that the municipal solid waste disposal data from the Rietfontein Landfill Site was utilised to determine whether any valuable products could be recovered from the waste using a biorefinery technology called fast pyrolysis.

The objectives of the study were: (i) To assess the different challenges faced by the landfills in the East of Johannesburg (ii) Identifying useful products which can be recovered from municipal solid waste (iii) Model a process to derive value from the municipal solid waste based on a chosen biorefinery technology and (iv) Apply the combined economic value and environmental impact method to measure the economic and margins and environmental impact saving margins of each product produced.

A theoretical approach was used for this study. Data collection was conducted through a site visit to the Rietfontein Landfill Site. Data was available for the different waste categories used by Rietfontein Landfill Site, namely: Ash Cover Material, Clean Building Rubble (for less than and more than 300mm), General Public and Contractors – Clean Compost/Garden Refuse, Delisted Solids, General Domestic Refuse, Industrial Refuse (For inside and outside Ekurhuleni Metropolitan Municipality), Mixed Waste, Soil, Treated Liquid Foodstuffs, Lesedi Waste, Nigel Waste and Paper Pulp >40%. However, the fast pyrolysis process which was used to determine the amount of valuable products to be recovered; required only the data for Clean Compost/Garden Refuse and not any other waste type.

This data was then collated and analysed to determine data inputs and operating conditions required for the COCO (CAPE-OPEN to CAPE-OPEN) simulation software. The feed flowrate of 40 kg/hr of pine wood biomass provided a yield of 13% flue gas, 18% biochar and 69% bio-oil. The energy balances conducted around the process units found that the coolers and flash separator had a negative change in enthalpy. The capital cost of the process was also determined. The total delivered cost of equipment amounted to 1.29 million Rands. The reactor accounts for 83.92% of the CAPEX. On the other hand, the total annual cost of the process units was found to be 2.20 million Rands. A combined economic value and environmental impact (EVEI) method was utilized to measure the economic margins and environmental impact saving margins of recovered products. The EVEI results indicated that the flue gas product would be uneconomical to produce whilst the biochar and bio-oil products would be economical to produce. The results for the environmental aspects highlighted that 75% of the streams would result in a higher environmental impact. This meant that the streams with negative environmental impact margin savings will be expensive to produce. The first sensitivity analysis for the effect of conversion rates on the yield of products revealed that at low conversion rates, there is less bio-oil and flue gas generated. At high conversion rates, there is more bio-oil generated but less biochar and flue gas generated. A second sensitivity analysis was conducted to determine the effect of the feed flowrate on the quantity of pyrolysis products produced. It was observed that an increase in the feed flowrate resulted in a proportional increase in the flue gas, bio-oil and biochar quantities produced. It can be summed from the EVEI profiles of the recovered products that the bio-oil stream was the only stream that had a negative EI saving margin and a positive economic margin unlike other product streams.

Keywords: biorefinery, sensitivity analysis, fast pyrolysis, flue gas, bio-oil, biochar, landfill, Economic Value and Environmental Impact (EVEI)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Waste is defined as any substance, whether that substance can be re-used, reduced, recovered and recycled-

(a) that is surplus, unwanted, rejected, discarded, abandoned or disposed of;

(b) which the generator has no further use of for the purposes of production;

(c) that must be treated or disposed of; or

(d) that is identified as a waste by the Minister by notice in the Gazette, and includes waste generated by the mining, medical or other sector; but –

(i) a by-product is not considered waste; and

(ii) any portion of waste, once re-used, recycled and recovered, ceases to be waste;

(Department of Environmental Affairs, 2011)

Generally, waste is created by the industries that produce the items that are utilized in daily life and through human activities. This waste then accumulates and must be discarded. Waste is then collected and transported by waste collection service providers to be taken to various stations. It is either taken to be compacted at landfills or taken to material recovery facilities (MRF) where it will be sorted for composting or recycling. Other than that, it can go for treatment using the relevant waste-to-energy technologies but in most instances, the route taken is landfilling the waste (Mmereki, Baldwin & Li, 2016). A landfill is described as a site for disposing waste material by burying the waste. Landfilling is the oldest and most popular method of treating waste (Hlongwane, 2013).

Rubbish that households and businesses discard is called general waste. This general waste cannot be recycled and is therefore taken for landfilling. There are different types of general waste which are generated, namely: Municipal Waste, Commercial and Industrial Waste, Organic Waste, Construction and Demolition Waste, Paper, Plastic, Glass, Metals, Tyres and Other (Department of Environmental Affairs, 2018).

Only a few waste types that are discussed in this chapter will be defined. Industrial waste refers to waste generated by manufacturing or industrial processes. Municipal solid waste (MSW) is produced from shops, homes, offices, hotels, educational institutions and other facilities. The main elements are food waste, paper, plastic, rags, metal and glass, but often include demolition and construction waste. It is found not only in collected waste, but also in small amounts of hazardous waste such as light bulbs, batteries, car components, medicines that have thrown away and chemicals (United Nations Economic and Social Commission for Asia and the Pacific, 2002).

The types of solid wastes as well as their sources are provided in Table 1.1 below.

Table 1.1: Types of solid wastes and sources (United Nations Economic and Social Commission for Asia and the Pacific, 2002)

Types of Solid Wastes	Source	Typical Waste Generator
✓ Food wastes ✓ Paper ✓ Cardboard ✓ Plastics ✓ Textiles ✓ Leather ✓ Yard wastes ✓ Wood ✓ Glass ✓ Metals ✓ Ashes ✓ Special wastes (e.g. bulky items, consumer electronics, white goods, batteries, oil, tires) ✓ Household hazardous wastes	Residential	Single and multifamily houses

Types of Solid Wastes	**Source**	**Typical Waste Generator**
✓ Housekeeping wastes ✓ Packaging ✓ Food wastes ✓ Construction and demolition materials ✓ Hazardous wastes ✓ Ashes ✓ Special wastes	Industrial	✓ Light and heavy manufacturing ✓ Fabrication ✓ Construction sites ✓ Power and chemical plants
✓ Paper ✓ Cardboard ✓ Plastics ✓ Wood ✓ Food wastes ✓ Glass ✓ Metals ✓ Special wastes	Commercial	✓ Stores ✓ Hotels ✓ Restaurants ✓ Markets ✓ Office buildings, etc.

Types of Solid Wastes	Source	Typical Waste Generator
✓ Hazardous wastes		
Same as commercial	Institutional	✓ Schools ✓ Hospitals ✓ Prisons ✓ Government centres
✓ Wood ✓ Steel ✓ Concrete ✓ Dirt, etc.	Construction and demolition	✓ New construction sites ✓ Road repair ✓ Renovation sites ✓ Demolition of buildings
✓ Street sweepings ✓ Landscape and tree trimmings ✓ General wastes from parks, beaches and other recreational area ✓ Sludge	Municipal services	✓ Street cleaning ✓ Landscaping ✓ Parks ✓ Beaches ✓ Other recreational areas ✓ Water and wastewater treatment plants

Types of Solid Wastes	Source	Typical Waste Generator
✓ Industrial process wastes ✓ Scrap materials ✓ Off-specification products ✓ Slag ✓ Tailings	Process	✓ Heavy and light manufacturing ✓ Refineries ✓ Chemical plants ✓ Power plants ✓ Mineral extraction and processing
All of the above should be included as “municipal solid waste.”		
✓ Spoiled food wastes ✓ Agricultural wastes ✓ Hazardous wastes (e.g. pesticides)	Agriculture	✓ Crops ✓ Orchards ✓ Vineyards ✓ Dairies ✓ Feedlots ✓ Farms

There has been a significant increase in the population over the years in South Africa. From the total South African population, the Gauteng Province's population is the largest. By the middle of 2019, there were approximately 15.2 million people residing within the province. This constitutes 25.8% of the total population of South Africa. The Gauteng province's population contribution to the total South African population has increased by a total of 1% over a 4-year period. In comparing year-on-year growth; by the middle of 2019 there was already a 0.2% increase from 2018. In 2018, there was a 0.3% increase from 2017; whereas in 2016 the increase was 0.2% from 2015 (Statistics South Africa, 2019). Luke & Jason (2015) advocate the view that a rise in population impacts the amount of waste generated. However, this is not applicable for Gauteng. In Gauteng, there has been a slight decrease in general waste generation over the last 4 years irrespective of the 1% increase in population over the same period. In 2015, the general waste produced was 14.6 million tonnes. The quantity of general waste production decreased to 8.7 million tonnes in 2019. This indicates a 5.9 million tonnes decrease of general waste over a 4-year period (GWIS - Gauteng Waste Information System, 2020). In spite of the fact that this is viewed as a reduction, the quantity of waste being created is substantial. Given the volume of general waste generated, a portion of the waste was collected for recycling. In 2016, the amount of general waste recycled decreased by 26% from the year 2015. For the next two years in 2017 and 2018; the waste recycled increased by 6% and 14% respectively. However, in 2019, the recycling rate declined by 45% (GWIS - Gauteng Waste Information System, 2020). Recycling is an attempt to divert waste from being landfilled.

Although the above waste generation statistics create an impression that there is not a lot of general waste produced, the actual waste generation quantities are actually significant and have been increasing over the years. The increasing quantity of municipal solid waste (MSW) being generated poses huge issues for urban areas which do not have sufficient landfill capacity. The landfill capacity in South Africa is rapidly decreasing and with the tremendous quantity of waste being generated through virtue of the growing population, this is becoming an ongoing issue that needs a solution-driven approach to address the issue. It needs to be determined what needs to be done when landfills are close to reaching their filling capacity or once they are filled to capacity as this is one of the biggest challenges. Not only does landfilling pose environmental and health concerns due to the leachate produced; but it also brings no economic value as nothing valuable is gained or recovered from it. In addition to this, there is the issue of landfill fires which are quite frequent. Proper management of these landfill sites is necessary by the landfill operators to prevent these hazardous fires from taking place (Aderemi & Otitoloju, 2012).

Therefore, waste management programs were developed in an effort to minimize and regulate the quantity of waste generated. Nonetheless, waste management programs driven by the Hierarchy of Waste Management are not entirely effective. The Hierarchy of Waste Management stresses waste control, elimination, re-using waste, recycle, regeneration, treatment and proper disposal of waste if all else fails (Department of Environmental Affairs, 2011).

From July 2017 to June 2019, quantities between 1.3 and 1.4 million tons of waste were still being taken to landfill in the East Rand (F Viljoen 2019, personal communication, 6 November). The total waste taken to the Johannesburg East (also referred to as the East Rand) municipal landfills between July 2017 - June 2018 was 1.36 million tons; whereas from July 2016 – June 2017, the total waste landfilled was 1.16 million tons. This represents a 17% increase in the total waste landfilled. Subsequently between July 2018 – June 2019, 1.41 million tons of waste was landfilled which is a 4% increase from the 1.36 million tons which was landfilled from July 2017 – June 2018 (F Viljoen 2019, personal communication, 6 November). The total increase over the 2-year period was 21% and this is likely to increase with time.

The large amount of waste that is still being landfilled in the East Rand indicates a deficiency in the waste management system design.

1.2 PROBLEM STATEMENT

1.2.1 Existing Waste Management System

Not only is there an issue of landfills running out of space or the lack of recovery of materials from the waste but South Africa faces challenges of having ineffective processes for managing waste (Santibañez-Aguilar et al., 2013).

In South Africa, the waste control approach revolves around the waste hierarchy. This hierarchy is an international model for classifying waste management options. It provides a complete system to managing waste materials during the waste lifespan. The hierarchy has several tiers. It covers waste prevention as a high priority first tier all the way to the low priority last tier which allows responsible waste disposal if all else fails (Department of Environmental Affairs, 2011).

To date, the method that is commonly utilized is the disposal of waste at landfills. The East Rand in Johannesburg has five operational landfill sites (Hlongwane, 2013) which are battling to meet this high demand of waste disposal I am aware that by now the Simmer and Jack landfill site is probably now at the end life as according to the data provided by Hlongwane (2013). On the other hand, other four landfills have a minimum of 20 years plus before they are filled to capacity. This issue of high waste disposal which compromises the landfill capacities cannot be ignored.

According to Nizami et al., (2017), if controlled sensibly, waste generated in industrialized economies signifies a substantial power source, reusable products, biomass and cashflow. For certain biorefinery processes such as anaerobic processing (AD), burning, fermenting, gasifying and pyrolyzing; this waste may even be used as raw material.. Hoornweg and Bhada-Tata (2012) together with Cardoen et al., (2015) indicate that common trend amongst Africa and elsewhere in the world is solid waste high in organic waste. In Africa, the solid waste composition consists of 57% organic waste. This confirms that the organic waste can actually be used in a biorefinery to recover materials.

The disposal of waste in general falls under what is regarded as a linear economy. A closed loop system guided by what is called a circular economy is essentially what is required to mitigate the high volumes of solid waste that end up being disposed. The difference between a linear and circular economy will be discussed in more detail below.

1.2.2 Circular economy

For many years, a linear economy has been widely used in many countries including South Africa. The linear economy is built on the 'create - use - discard' concept. This simply means that products are manufactured from raw materials, consumers use the products and throw away any waste such as packaging afterwards. This has proved to be rather unsustainable due to resource losses incurred and environmental impacts as explained by Michelini *et al*., (2017).

The approach that can be used for a sustainable economy is the circular economy concept. There are several definitions attached to the circular economy (Korhonen et al., 2018). However, Morseletto (2020) explains a circular economy as an economic concept aiming at the productive usage of energy by eliminating waste, maintaining long-term efficiency, growing primary capital and closed commodity chains, component sections and components within boundaries of the environment and socio-economic gains. This simply means that it is a concept aimed at turning waste into valuable materials that can be re-used through recovery or regeneration for as long as possible. Wainaina *et al*., (2020) observes that re-using and recycling is the significant guideline for structuring and improvement of products in a circular economy. While countries and governments across the globe increasingly adopt the idea of a circular economy and strive to bring it into action, waste disposal in an established and sustainable manner could concurrently encourage productive economic development with minimal environmental effects (Yadav & Samadder, 2018).

Through a biorefinery solution, the recovery process aligns with the circular economy concept. Essentially, through this circular economy concept, waste disposal ought to be eliminated altogether. In addition to this, the biorefinery concept is a direct link to achieving a circular economy. The waste that would normally be disposed off at landfill, would now be used as a raw material or input towards the the conversion of garden waste (biomass) into value-added products.

This study will be carried out to identify how much economic and environmental value is present in the organic waste from Rietfontein Landfill Site through a biorefinery approach.

1.3 AIM AND OBJECTIVES

The study seeks to recognize obstacles experienced by landfill sites in the East of Johannesburg and to identify methods by which maximum value can be retrieved or derived from municipal solid waste. This will be achieved through the biorefinery concepts in order to encourage the zero-to-landfill initiative that the country would like to achieve.

The objectives of the study are:

- Assess the different challenges faced by the landfills in the East Rand of Johannesburg.
- Identifying useful products which can be recovered from municipal solid waste
- Model a process to derive value from the municipal solid waste based on a chosen biorefinery technology
- Apply the combined economic value and environmental impact method to measure the economic margins and environmental impact saving margins of each product produced.

1.4 STRUCTURE OF DISSERTATION

Chapter 1 - Introduction

This chapter looks at the concept of waste and gives a brief overview of the Johannesburg East operational landfills and their increasing waste disposal quantities. The Gauteng province's biggest contribution and year-to-year increase to the overall South African population growth is indicated. It also offers a summary of the present system for managing waste. This is then followed by mentioning a strategy for upgrading the present waste system to a circular economy. The potential benefits of waste in developing counties are discussed. Subsequently, it mentions the common trend in Africa and the rest of the world pertaining to organic waste content. The impact of surging waste and the ineffectiveness of the existing waste management programs are stated. In addition to the above, it also presents the research objectives and the value of the study.

Chapter 2 - Literature Review

The chapter begins with a discussion indicating the statistics regarding the consumption of coal, natural gas and oil at a global level and within South Africa. It proceeds to touch on waste definition and classification, waste generation (waste disposal tonnages for various landfill sites in the east of Johannesburg) and the landfilling criteria used in South Africa. It also highlights the current issues associated with landfilling as well as the current solid waste management practices. Furthermore, it discusses the circular economy concept. The diverse types of biorefineries and Waste-To-Energy technologies are described in detail. In addition to this, the status of Waste-To-Energy technologies is reviewed. The last section focuses on the gaps identified in areas such as waste management, circular economy and the modelling of biorefineries.

Chapter 3 – Methodology

The chapter provides a comprehensive summary of the research methods and procedures that were followed to gather the data and results for this study. The data collection methods and data inputs were highlighted. Furthermore, the data collection process looked at the composition of the municipal waste material and the different waste categories available at the chosen landfill site. The chosen Waste-to-Energy (WtE) technology and process flow diagram of the chosen WTE technology are also discussed in detail. . The simulation model setup is explained together with data description of the operating conditions and process units. In addition to this, a method for measuring the economic margins and environmental impact saving margins of the products produced is examined. Under this value analysis concept, the capital costs of the plant and their formulas are covered. Lastly, the expected simulation output is listed.

Chapter 4 - Results and discussions

This chapter presents the results obtained from the CAPE-OPEN to CAPE-OPEN (COCO) simulation software which aids in answering the objectives of this research. In addition to the simulation software results, the findings for the challenges faced by landfills in Johannesburg East are included in this chapter. It also covers the validation of the simulation results and investigates the material and energy balances of the study. The mass and energy balances for the process units have been included in this chapter. In addition to the above, a sensitivity analysis has been conducted to analyse the effect of certain variables on the output from the simulation. A combined economic value and environmental impact method was used to measure the economic margins and environmental impact saving margins of products produced. On top of this, the economic and environmental profiles were generated for the recovered products to determine whether they are economical and sustainable. Each one of these elements of the key findings are discussed in this chapter.

Chapter 5 - Conclusion and Recommendations

The chapter ends the study by summing up the findings obtained and also provides an overall conclusion in relation to the aims and objectives that were set for this study. It also highlights any recommendations for future work.

REFERENCES

Aderemi, A.O. & Otitoloju, A.A. 2012. An assessment of landfill fires and their potential health effects-A case study of a municipal solid waste landfill in Lagos, Nigeria. Air Pollution Monitoring Around Residential and Transportation Sector Locations in Lagos Mainland View project Agro-chem. *International Journal of Environmental Protection IJEP IJEP*. 2(2):22–26. Available: https://www.researchgate.net/publication/255179339.

Cardoen, D., Joshi, P., Diels, L., Sarma, P.M. & Pant, D. 2015. Agriculture biomass in India: Part 1. Estimation and characterization. *Resources, Conservation and Recycling*. 102:39–48.

Department of Environmental Affairs. 2011. National Waste Management Strategy. *National Waste Management Strategy*. (November):75. Available: https://www.environment.gov.za/sites/default/files/docs/nationalwaste_management_strategy.pdf.

Department of Environmental Affairs. 2018. South Africa State of Waste Report. *Government of South Africa*. 68. Available: http://sawic.environment.gov.za/documents/8635.pdf.

GWIS - Gauteng Waste Information System. 2020. Available: https://www.gwis.gpg.gov.za/reports (Accessed on 04/08/2020)

Hlongwane, E. 2013. Ekurhuleni Metro Municipality Waste Management Services. *4thWaste Management Officers Khoro 2013*. 32.

Korhonen, J., Nuur, C., Feldmann, A. & Birkie, S.E. 2018. Circular economy as an essentially contested concept. *Journal of Cleaner Production*. 175:544–552.

Luke, C. & Jason, O. 2015. Leading the way: Direction in municipal solid waste management in South Africa. *Future Directions of Municipal Solid Waste Management in Africa*. 176–201.

Michelini, G., Moraes, R.N., Cunha, R.N., Costa, J.M.H. & Ometto, A.R. 2017. From Linear to Circular Economy: PSS Conducting the Transition. *Procedia CIRP*. 64:2–6.

Mmereki, D., Baldwin, A. & Li, B. 2016. A comparative analysis of solid waste management in developed, developing and lesser developed countries. *Environmental Technology Reviews*. 5(1):120–141.

Morseletto, P. 2020. Targets for a circular economy. *Resources, Conservation and Recycling*. 153(October 2018):104553.

Nizami, A.S., Rehan, M., Waqas, M., Naqvi, M., Ouda, O.K.M., Shahzad, K., Miandad, R., Khan, M.Z., Syamsiro, M., Ismail, I. M. I., & Pant, D. (2017). Waste biorefineries: Enabling circular economies in developing countries. Bioresource Technology. 241:1101–1117.

Santibañez-Aguilar, J.E., Ponce-Ortega, J.M., Betzabe González-Campos, J., Serna-González, M. & El-Halwagi, M.M. 2013. Optimal planning for the sustainable utilization of municipal solid waste. *Waste Management*. 33(12):2607–2622.

Statistics South Africa. 2019. Midyear Population Estimate 2019. *Statistics South Africa*. (July):24.

United Nations Economic and Social Commission for Asia and the Pacific. 2002. Chapter 8 Types of wastes. *United Nations ESCAP Library*. 170–194. Available: http://www.unescap.org/sites/default/files/CH08.PDF.

Wainaina, S., Awasthi, M.K., Sarsaiya, S., Chen, H., Singh, E., Kumar, A., Ravindran, B., Awasthi, S.K., Liu, T., Duan, Y., Kumar, S., Zhang, Z., Taherzadeh, M.J. 2020. Resource recovery and circular economy from organic solid waste using aerobic and anaerobic digestion technologies. *Bioresource Technology*. 301(November 2019):122778.

Yadav, P. & Samadder, S.R. 2018. A critical review of the life cycle assessment studies on solid waste management in Asian countries. *Journal of Cleaner Production*. 185:492–515.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

One of the greatest challenges to date is the world's heavy reliance on fossil fuels such as natural gas, crude oil and coal. The issue with these fossil fuels is that they are not renewable. A report by BP revealed that the consumption of coal in 2019 has dropped globally by 0.6%. However, South Africa has a 1.4% growth rate in coal consumption for 2019. The global natural gas consumption (in billion cubic metres) increased to 2% while the South African consumption decreased by 4.2% in 2019. However, the global oil consumption (in thousands of barrels per day) grew by 0.9% while the South African oil consumption had a 2.3% growth rate for 2019 (BP, 2020). Lastly, the global renewable energy electricity generation for 2019 increased by 6.5% (IEA, 2020). While South Africa had a renewable energy increase for electricity generation of 4.9% in 2019 (Statistics South Africa, 2021). These statistics give an overview of whether South Africa is well on the way from shifting from fossil fuels to renewable energy or not as compared to the rest of the world. Based on the above statistics, it is visible that South Africa still relies heavily on coal and crude oil compared to natural gas. Energy from garbage which can also be referred to as municipal solid waste (MSW) is largely made up of organic matter which comes from plants and trees. These plants and trees are also renewable resources and essential components of the natural ecosystem. This makes MSW a renewable resource. By burning the garbage or dumping it in landfills and extracting gas, energy is produced. This energy is then transformed into electrical energy and is referred to as renewable energy (Gumbo, 2014). This renewable energy concept is an approach that is worth exploring. Once the renewable energy concept is fully utilised, it should ultimately eliminate the huge waste quantities that end up at landfill sites. For instance, through the renewable energy concept, municipal solid waste that normally gets landfilled can be used for power generation.

Looking at the link between the renewable energy concept and the positive impact that it can have on the reduction of landfilled waste, it is vital to delve deeper into the issue of landfilling. The issue of landfilling, the oldest and frequently used waste management method, is an ongoing challenge globally. Municipalities prefer to landfill waste as it is the cheapest method. However, it is not an effective solution to waste disposal due to various reasons. Some of these reasons include landfills running out of space, new legislations and policies, landfills being a source of methane; which is a greenhouse gas (GHG), emissions that have an impact on climate change, and landfills producing leachate which has health and environmental implications. The growing population in urban areas is putting a strain on landfills due to increased waste quantities (Hoornweg & Bhada-Tata, 2012). Moreover, very little is being done to obtain valuable products from the municipal waste. This is a huge loss to the economy. The transformation of municipal solid waste into valuable products will generate some income and boost the South African economy. South Africa is still in the infancy stage and experiencing challenges when coming to transforming solid waste into valuable products. Not only is the transformation of municipal waste into valuable products a challenge, but landfill sites experience other unknown challenges which are not easily spotted. These unknown landfill site challenges form part of the objectives this study aims to reveal at the end of the research period.

In the previous chapter, the objectives of this study were stated. In this chapter, various aspects that link to the objectives will be discussed in more detail. These concepts will be covered in this literature review:

- Waste definition and classification
- Landfilling criteria used in South Africa
- Current issues associated with landfilling
- Waste generation
- Waste management: Current solid waste management practices
- Circular Economy
- Biorefineries (Definitions & Types of Biorefineries)

- Waste to Energy Technologies (Types and the Status of Waste to Energy Technologies)
- Gaps identified in literature

2.2 WASTE

2.2.1 Waste Definition and Classification

There is no single definition of waste. Muzenda (2014) sets out the general concept of waste as an ***unavoidable*** side-effect of most human action. To guarantee that the waste is managed and discarded in a safe and lawfully consistent way, it must be classified to decide the nature and danger posed by the waste. Regardless of whether it presents a slight danger to the environment or it represents a high risk, the category the waste falls under must be known. A suitable disposal method can then be identified (South African Waste Information Centre, 2020).

There are generally two categories for classifying waste in accordance with the risk it poses:

i. General Waste
ii. Hazardous Waste

General waste is waste that does not pose an immediate hazard or threat to health or to the environment. General waste includes domestic waste, construction and demolition waste, commercial waste and inert waste like sand. On the other hand, hazardous waste is any waste that contains organic or inorganic elements or compounds that may, owing to the inherent physical, chemical or toxicological characteristics of that waste, have a detrimental impact on health and the environment (Department of Water Affairs and Forestry, 2008).

The National Norms and Standards (Department of Environmental Affairs, 2013a) have stipulated a methodology for classifying waste prior to disposal. All waste must be classified within 90 days. If there is a change of a process or an input material, re-classification needs to take place. A Material Safety Data Sheet (MSDS) must always be generated and must accompany the waste. The classification of the waste is noted on the MSDS. If waste is appropriate for disposal, it must be discarded as per the waste removal guidelines (Department of Environmental Affairs, 2008).

The following activities must be carried out in order to assess the level of risk related to the disposal of waste at the landfill (Department of Environmental Affairs, 2008):

- Establish the chemical compounds that could be entrained in the waste
- Collect a sample and assess it to determine the total concentration (TC) and leachable concentration (LC)
- TC to be established for all potential compounds in the waste
- An authorized laboratory must conduct analysis
- Analysis to be carried out using local or global analytical techniques

Once the waste type has been determined using the procedure stipulated by the Department of Environmental Affairs (2013a), Table 2.1 is used to determine the risk level for landfilling. Two additional provisions exist in relation to the above. Firstly, it must be expected that waste is Type 1 if an agent test of dangerous waste cannot be gathered for appropriate leachable concentration (LC) and total concentration (TC) examination. Examples of this is personal protective equipment, oily rags etc. Secondly, if a specific contaminant is not recorded and the waste has been delegated unsafe then the waste must be viewed as Type 1 waste. This implies that the waste must be disposed at a Class A landfill.

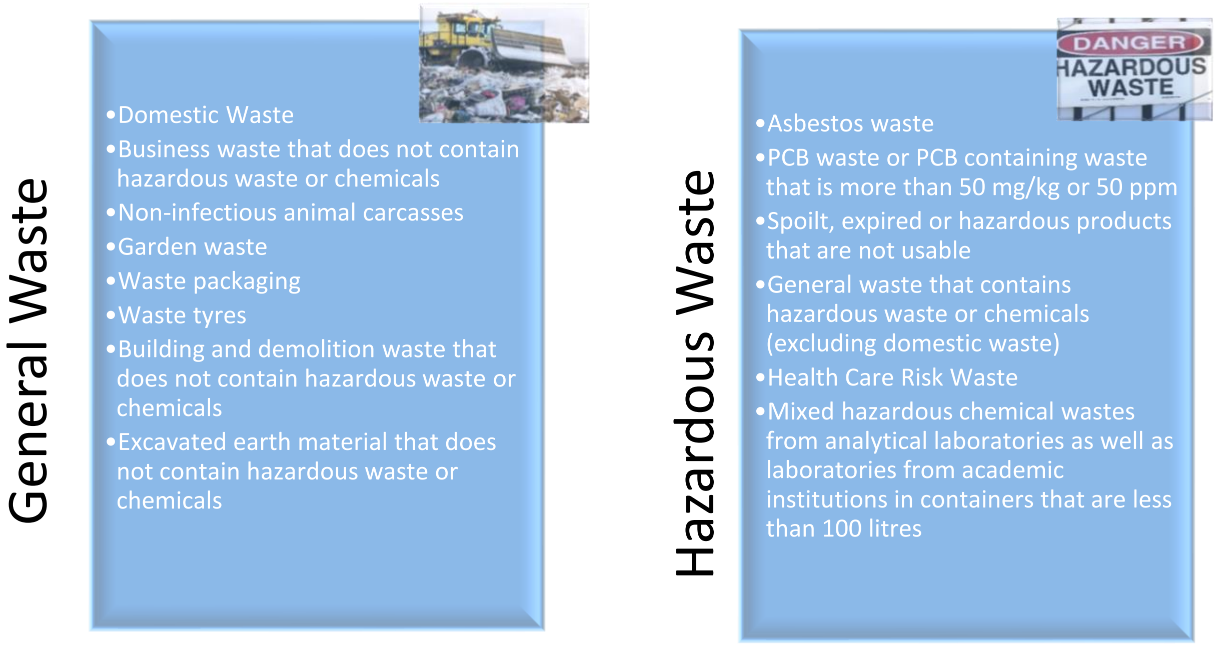
Table 2.1: Landfill Acceptance Criteria for Waste Types (Department of Environmental Affairs, 2008)

Waste Risk	Disposal Requirements	Examples of Waste Types
Type 0: Very High Risk	**No disposal permitted.** To assess the risk profile for disposal, the waste must first be treated and then re-tested.	• Waste that may be corrosive, explosive, oxidizing or flammable • Waste that has a pH of <6 or >12 • Flammable waste with closed cup flashpoint which is lower than 61°C • Waste that may react with acids, water, air or that could create intolerable quantities of toxic gases

Waste Risk	Disposal Requirements	Examples of Waste Types
Type 1: High Risk	Disposal is only permitted at a landfill with a **Class A** or **Hh/HH** containment barrier design.	• Asbestos waste • Expired, spoilt or unusable hazardous products • PCBs or PCB containing waste which is >50ppm • General waste, excluding domestic waste, that contains hazardous waste or hazardous chemicals • Mixed, hazardous chemical wastes from analytical laboratories and laboratories from academic institutions in containers <100 litres
Type 2: Moderate Risk	Disposal is only permitted at a landfill with a **Class B** or **GLB+** containment barrier design (or Class A).	• Domestic waste • Business waste that does not contain hazardous waste or hazardous chemicals • Animal carcasses that are not infectious • Garden waste
Type 3: Low Risk	Disposal is only permitted at a landfill with a **Class C** or **GLB+** containment barrier design (or Class B or A).	• Post-consumer packaging • Waste tyres

Waste Risk	Disposal Requirements	Examples of Waste Types
Type 4: Inert Waste	Disposal is only permitted at a landfill with a **Class D** or **GSB-** containment barrier design.	• Building and demolition waste that does not contain hazardous waste or hazardous chemicals • Earth material that is excavated and does not contain hazardous waste or hazardous chemicals
Non-hazardous Waste (Pre-classified)	Disposal is only permitted at a landfill with a **Class B** or **G S/M/L B-/B+** containment barrier design.	• General waste

There are, however, some waste specified in the legislation (Figure 2.1) that do not need classification and are regarded as pre-classified waste. The below are examples only as the list is not exhaustive.



General Waste

- Domestic Waste
- Business waste that does not contain hazardous waste or chemicals
- Non-infectious animal carcasses
- Garden waste
- Waste packaging
- Waste tyres
- Building and demolition waste that does not contain hazardous waste or chemicals
- Excavated earth material that does not contain hazardous waste or chemicals

Hazardous Waste

- Asbestos waste
- PCB waste or PCB containing waste that is more than 50 mg/kg or 50 ppm
- Spoilt, expired or hazardous products that are not usable
- General waste that contains hazardous waste or chemicals (excluding domestic waste)
- Health Care Risk Waste
- Mixed hazardous chemical wastes from analytical laboratories as well as laboratories from academic institutions in containers that are less than 100 litres

Figure 2.1: Pre-classified waste - Waste that do not require classification (Department of Environmental Affairs, 2018)

2.2.2 Waste Generation

Waste generation is a global issue as waste is inevitably created. The generation of waste in most developing countries has increased greatly due to the population growth and urbanization rate in cities. A population growth means that there are more natural resources consumed and proportionally there is an increase in the waste volumes produced. In mid-2019, the global population was 7.7 billion, this is an increase of 1 billion since 2007. Although the growth rate has been reduced by half for the past 5 years, the population growth is estimated to hit 8.5 billion in 2030 (United Nations, 2019). Predictions indicate that for the next 15 years, the urbanization rate will increase yearly by 1.5% (GHO, 2014). In theory, this will lead to an expansion in the creation of waste over the next couple of years. A correlation exists between population growth, urbanization and the generation of waste.

The world's metropolitan cities create roughly 1.3 billion tons of solid waste annually. This is equivalent to 1.2 kg/capita/day. This is the reality of a global challenge that affects every nation. These global statistics are an indication that there is no current system that prevents waste from being created altogether. This is contradictory to the statement provided by (Morseletto, 2020) that implies that there is no waste generation in a flawless system. Such a system does not exist currently. Urban dwellers generate double the amount of waste as compared to rural dwellers (Hoornweg & Bhada-Tata, 2012). This generation rate by the world's metropolitan cities is anticipated to rise to 2.2 billion tons each year by 2025 (Moya et al., 2017).

South Africa is no exception to the growing population and high urbanization rate. In 2018 the South African population was 57.73 million (Statistics South Africa, 2018). The population had already grown to 58.78 million the following year (Statistics South Africa, 2019). The population size is currently estimated at 59.62 million, suggesting a rise of 0.84 million people (Statistics South Africa, 2020). South Africa is approximated to have produced 42 million tonnes of general waste in 2017. The estimate is that just 11% of general waste was recycled in that year (Department of Environmental Affairs, 2018).

The population and economic growth apply to the East of Johannesburg (East Rand) which is highly urbanized. The downside of population and economic growth is the amount of pressure this puts on waste treatment facilities, which are already in shortage. There are only five licensed waste disposal facilities that are owned by the Ekurhuleni Metropolitan Municipality (EMM). In addition to this, waste is directed to two private landfill sites which also operate from under the EMM. The private landfills namely, Interwaste FG and Enviroserve, receive municipal waste from the EMM. However, the Interwaste FG landfill has since been shut down by the Department of Environmental Affairs (DEA). From July 2017 to June 2019 the waste disposed of at the Johannesburg East landfills increased from 1 360 718 tons to 1 413 911 tons (F Viljoen 2019, personal communication, 6 November). Large quantities of waste end up being disposed of annually at the various landfill sites as indicated below by Table 2.2.

Table 2.2: Waste disposal tonnages for each landfill site

Landfill Site Name	July 2014 - June 2015 (Tons)	July 2015 - June 2016 (Tons)	July 2016 - June 2017 (Tons)	July 2017 - June 2018 (Tons)	July 2018 - June 2019 (Tons)	July 2019 - Sept 2019 (Tons)
Weltevreden	238,83	236,74	222,74	356,91	347,03	88,28
Interwaste FG	140,36	151,11	124,92	51,24	17	0
Enviroserve	0	0	0	0	128,89	34,427
Platkop	111,73	107,21	135,98	142,36	126,25	30,42
Rietfontein	242,94	217,12	179,51	224,95	224,65	48,85
Rooikraal	295,22	236,75	229,08	248,16	300,66	71,35
Simmer & Jack	284,83	315,29	271,87	287,07	284,11	72,82

The overall graphical waste quantities representation across all municipal landfills in the Johannesburg East landfills is indicated by Figure 2.2 (F Viljoen 2019, personal communication, 6 November).

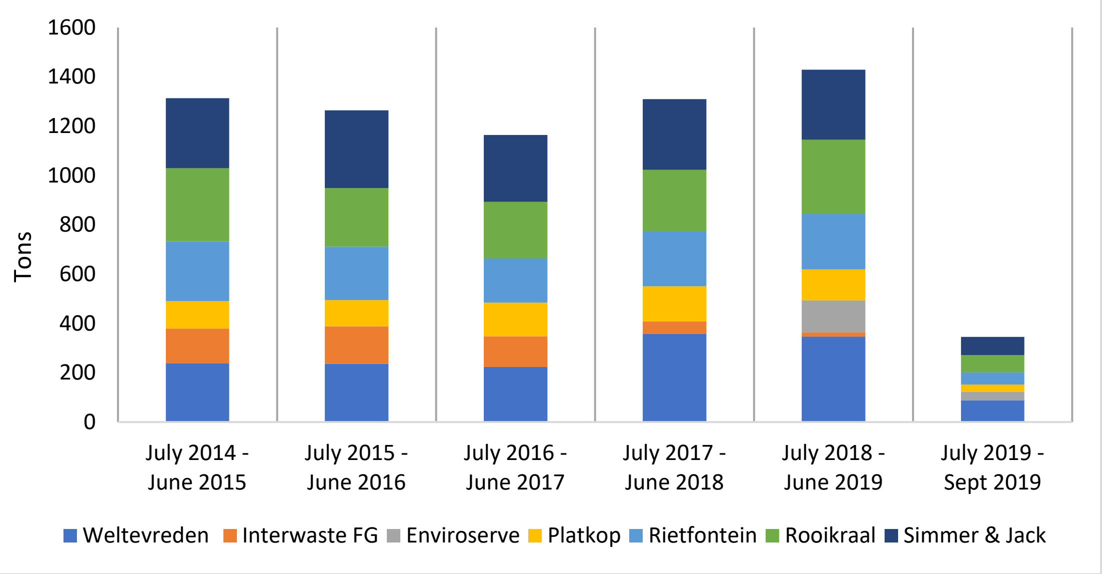


Figure 2.2: Waste Disposal Tonnages of Johannesburg East Landfills (F Viljoen 2019, personal communication, 6 November)

The above waste quantities across all landfill sites indicate a decrease in waste from July 2014 to June 2017. However as from July 2017 there has been an increase in waste volumes despite the use of the hierarchy for managing waste. The hierarchy of waste management advocates and promotes waste avoidance, reduction, reuse, recycling, recovery, and safe disposal as the final resort. The expected outcome of the waste management hierarchy is to avoid large waste quantities being taken for landfilling. However, looking at the above waste quantities from Figure 2.2, it can be seen that large volumes of waste are still being taken to landfill.

2.2.3 Landfilling criteria used in South Africa

Landfilling is a method that involves burying waste deep into the ground. The Department of Environmental Affairs has taken environmental factors into account regarding landfilling. Requirements which include the containment barrier designs have been set for licensed landfill sites. This is to avoid leakages into the ground which will result in environmental and health issues. Prior to the operation of a landfill site, authorization must be sought. The landfill engineering design must be according to the National Norms and Standards for Disposal of Waste to Landfill. The design drawings must be approved by the Regional Director of Department of Water Affairs. Leakage rates must be established in order to calculate the seepage. Seepage pipes must be installed in all drainage layers (Department of Environmental Affairs, 2008). Figures 2.3 to Figures 2.6 indicate the four acceptable Landfill Containment Barrier Designs (Class A – Class D).

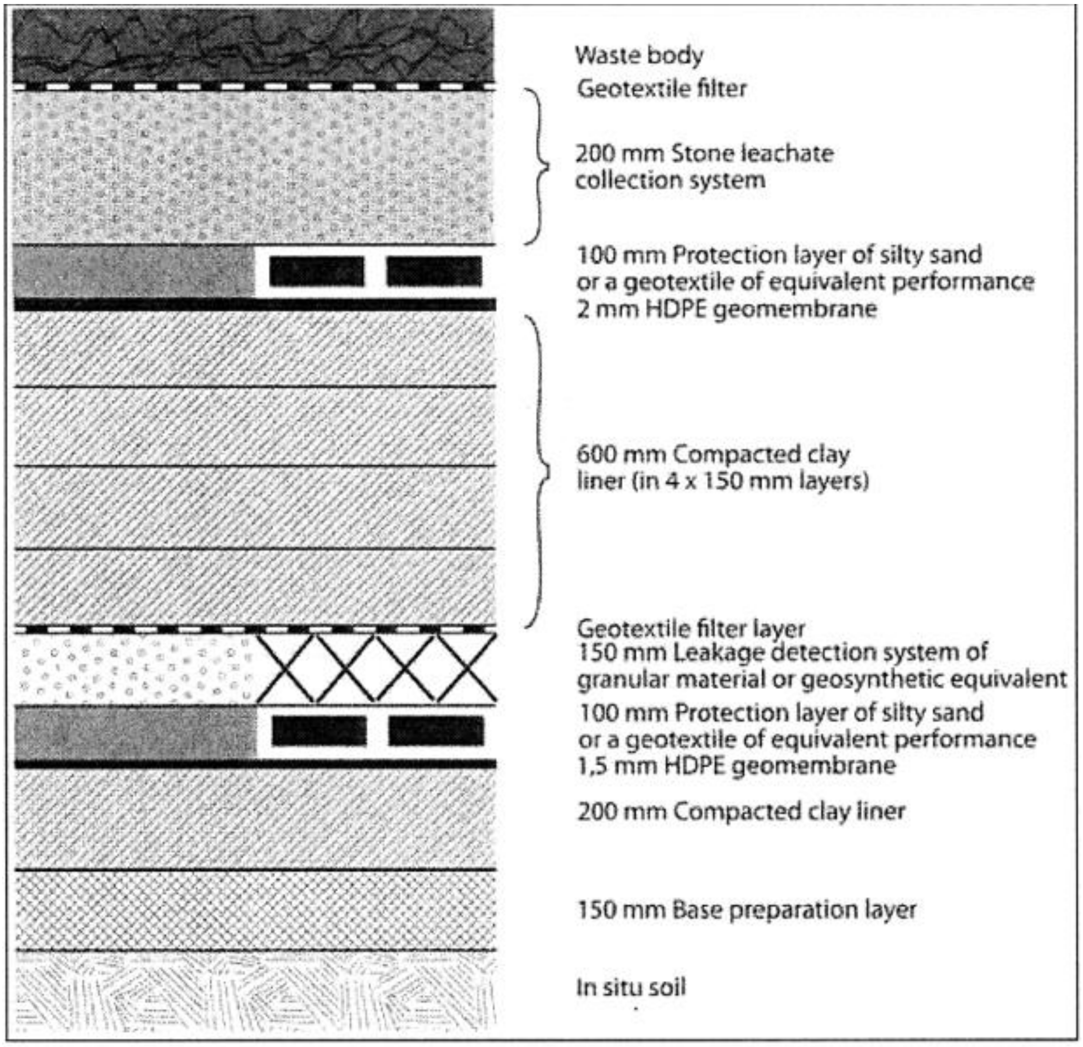


Figure 2.3: Class A Containment Barrier Design (Department of Environmental Affairs, 2013b)

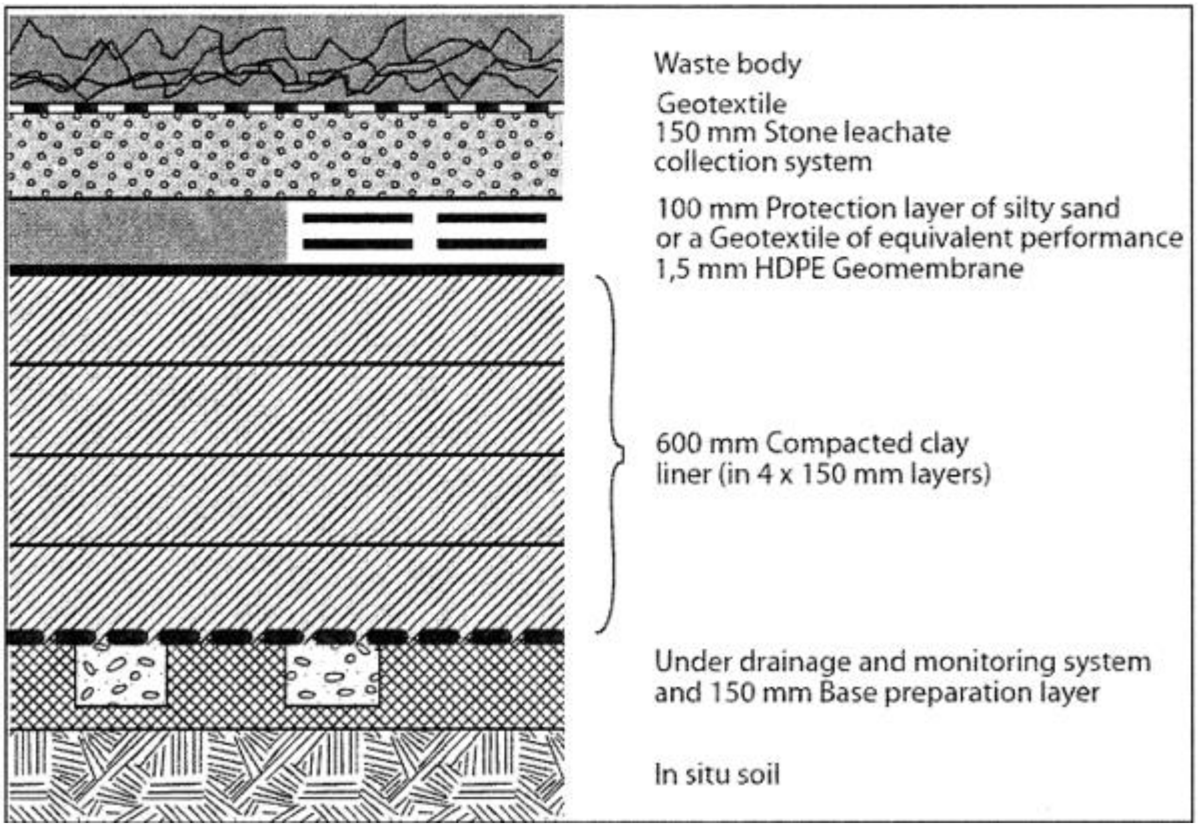


Figure 2.4: Class B Containment Barrier Design (Department of Environmental Affairs, 2013b)

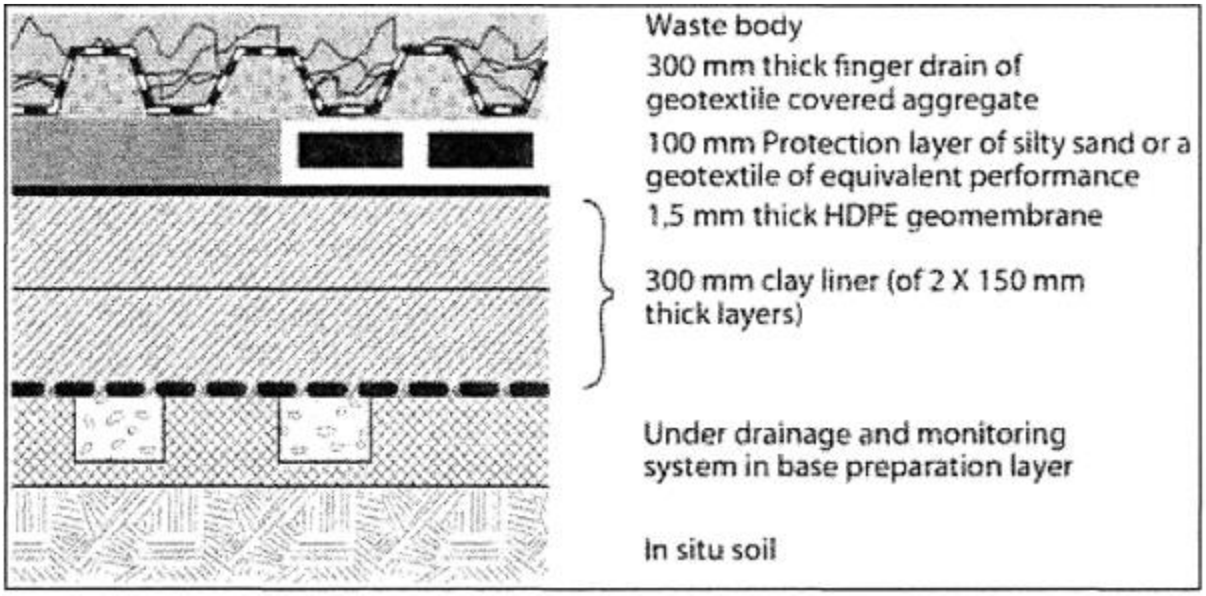


Figure 2.5: Class C Containment Barrier Design (Department of Environmental Affairs, 2013b)

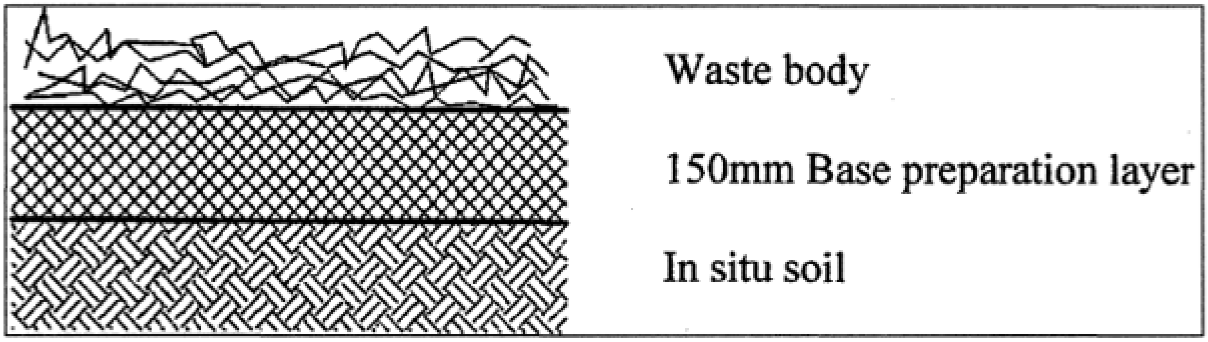


Figure 2.6: Class D Containment Barrier Design (Department of Environmental Affairs, 2013b)

Waste was historically treated by landfills as either general or hazardous waste. In recent years, however, a risk-based approach has been adopted to address waste according to either Class A – High Risk Waste, Class B – Moderate Risk Waste, Class C – Low Risk Waste or Class D – Inert Waste.

The landfill sites owned by the City of Ekurhuleni Metropolitan Municipality (EMM) are: Weltevreden Landfill Site, Platkop Landfill Site, Simmer & Jack Landfill Site, Rietfontein Landfill Site and Rooikraal Landfill Site. As of 2016, all the landfill sites in the City of Ekurhuleni Metropolitan Municipality have been classified as Class B landfill sites. This is as per the Waste Classification and Management Regulations that came into effect in 2013. The landfill sites were licensed as GLB- landfill sites, excluding Rietfontein Landfill Site, meaning that it is a huge facility that collects 500 tons and more of general waste every day and has a negative water balance. The negative water balance was meant to suggest that the site did not produce substantial quantities of leachate and thus no leachate collection system was needed and thus no leachate collection system was installed in the first cell at most of the landfill sites. However, except for Simmer and Jack Landfill Site, all the sites have installed leachate disposal systems in the new waste cells, as well as leachate dams or sumps. The Rietfontein Landfill Site was graded as a GLB+ facility with a positive water balance and leachate collection systems had to be used in the waste cells. Rietfontein Landfill Site is licensed to accept delisted waste. (Pienaar et al., 2016).

2.2.4 Current issues associated with landfilling

Landfilling is becoming an issue for most countries globally. According to Kumar et al., (2023), landfills are the world's most cost-effective method of disposing of municipal solid waste. In the Asia-Pacific region, solid waste disposal in semi-technical or fully sanitary landfills has been adopted as the most attractive disposal option in cities in both low-income and high-income countries. Bandung, Singapore, Hong Kong, China, Seoul, Chennai and Tokyo have well-designed and well-operated regulated landfills, while other cities in Australia, the People's Republic of China, Japan, South Korea, Malaysia and Thailand have well-managed landfill sites. A landfill or regulated solid waste disposal site is in place (United Nations Economic and Social Commission for Asia and the Pacific, 2002). However, there are several issues with landfilling hence the reason it is the least favourable method of waste disposal. Firstly, there is limited capacity or airspace left of the existing landfill sites. The term landfill airspace refers to the amount of space on a landfill site which is allowed for disposing solid waste. Initially, this area is filled by air that will ultimately be consumed by the waste disposed of, hence referred to as landfill airspace. To prolong the lifespan of these landfills, there is an immediate need to redirect waste from existing municipalities in South Africa. An estimate of some of the biggest municipalities in South Africa is reflected in Figure 2.7 for 2014. It is evident from the represented graph below that the City of Johannesburg and City of Cape Town are in a crisis as they only have 8 years and 5 years remaining of landfill airspace, respectively. This is likely to have reduced even further by now.

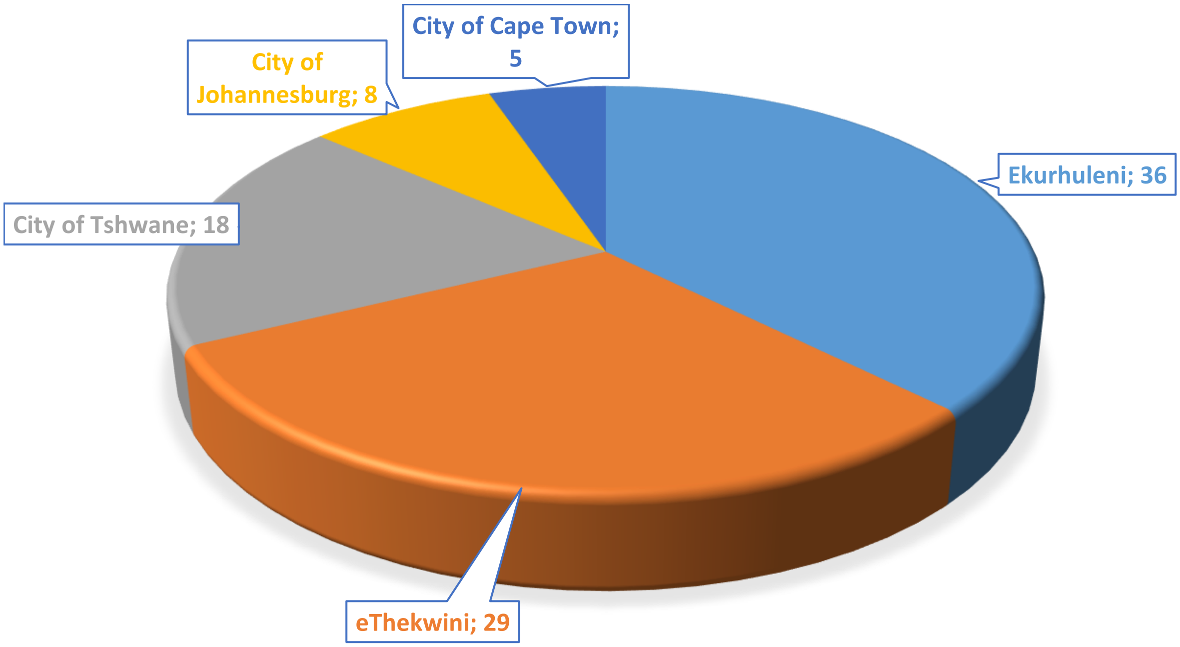


Figure 2.7: Estimated remaining landfill airspace of South Africa's biggest municipalities (South African Cities Network (SACN), 2014)

It is also clear from Section 24 of the Constitution of the Republic of South Africa (Act 108 of 1996) that every South African resident has a right to an atmosphere which is not detrimental to his or her health and well-being. It goes on to say that, for current people and generations to come, this atmosphere or ecosystem should be preserved.

In addition to these points, that there must be policies and other mechanisms in place to:

- Prevent contamination and environmental destruction
- Encourage saving and protecting the environment
- Safe environmentally sustainable growth and use of natural resources while fostering socio - economic development that is justifiable
  (The Constitution of the Republic of South Africa, 1996)

Failure to uphold the requirements of this Act on citizens will be contravening the constitution. The landfilling process produces a leachate which if not managed properly, can compromise the health of citizens.

Several other serious issues related with landfilling include (Muzenda, 2014):

- Foul scents from the landfill site
- Wind scattering particles
- Sudden ignition danger
- Rats, creepy crawly and winged creature pervasion which can convey infections
- Contamination of surface and ground water

2.2.5 Waste Management: Current solid waste management practices

It is essential for waste to be managed and controlled correctly. Brunner & Rechberger (2015) explain that the objective of waste management is to keep the environment and humans safe. The waste management process entails waste collection, transportation of waste, treatment of waste and the safe disposal of waste. A successful waste management system requires having policies in place and most importantly, implementation of those policies.

The municipal waste policy in South Africa draws on the principles of the waste management hierarchy system as represented in Figure 2.8 (Department of Environmental Affairs, 2011) . The objective is to decrease the amount of waste disposed of in landfills as the bulk of the waste is landfilled. The South African strategy is driven by the key components of the waste program hierarchy. This waste hierarchy controls the overarching waste management plan. With the waste management strategy, the following key features are highlighted (Department of Environmental Affairs, 2011):

- **Avoidance & Reduction:** Products and goods are to be engineered in a context that minimizes their potential harmfulness of waste produced during and after production; and decreases the quantity of natural raw material.

- **Re-use:** Components can be used for different or related uses without modifying the structure or characteristics of that material. The aim is to re-use an item once it completes its life expectancy. It will therefore become an input for new materials and products.

- **Recycle:** This ensures that the materials are isolated from waste and utilized as resources or goods. The waste materials are converted into new materials so they can be utilized for a purpose that is not identical to the initial purpose.

- **Recovery:** The objective is to retrieve other parts or products or use the waste as a fuel.

- **Treatment and disposal:** In the hierarchy of waste this is the last choice. To treat the waste pertains to the use of a method aimed at reducing waste's effect on the environment. This is achieved by modifying or removing the physical characteristics of the waste and getting rid of hazardous waste elements. Waste disposal relates to burying or storing waste into the ground which we refer to as landfilling.

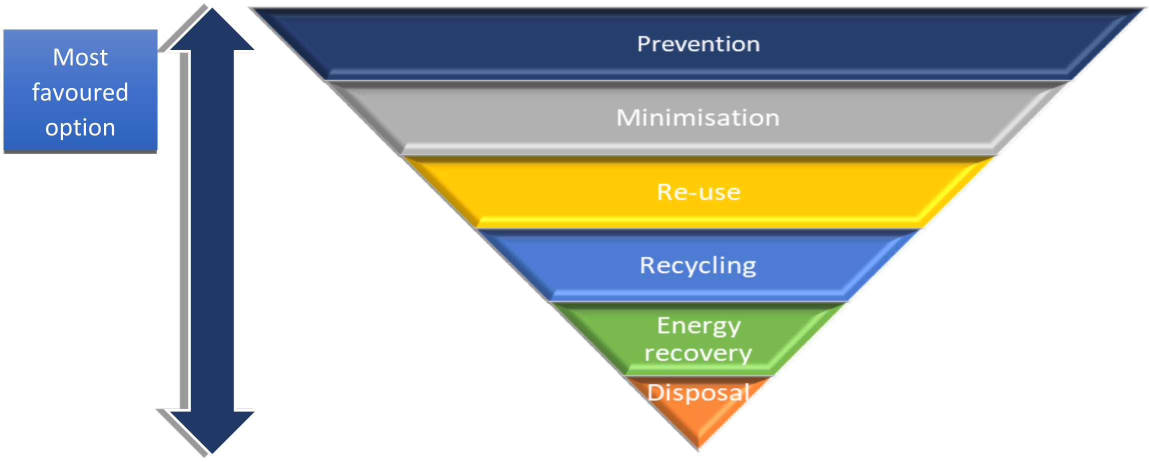


Figure 2.8: Hierarchy of Waste Management (Adapted from Department of Environmental Affairs, 2012)

The top four levels of the waste management hierarchy promote the cradle-to-cradle concept to waste management in which, as it reaches the end of its life period, the item is reused or recycled and therefore becomes an input for new goods or materials (Department of Environmental Affairs, 2018). Although the four top levels of the Waste Management Hierarchy are meant to promote the cradle-to-cradle concept, this is not what is actually happening in reality. However, the waste management hierarchy has since been revised to rather focus on the following three crucial principles of the 2020 National Waste Management Strategy (NWMS): waste minimisation, waste prevention and waste as a resource. It is yet to be observed as to whether these new three principles of the 2020 NWMS will have a positive impact as per the intended purpose of the strategy.

A duty is placed on the state by the National Waste Act to place standardized measures in place that aim to minimize the quantity of waste generated. In cases where the waste is produced, to guarantee the re-use, recycling and recycling of waste before being disposed in an environmentally sound way. The Act allows the Minister to hold the manufacturer accountable for specified goods or product groups, specify the steps to be taken and define the measures to be taken. Individuals who must implement these measures for waste management strategies for industry; set targets for waste minimization and for re-use, recycling and regeneration. It will allow, or mandate, municipalities to collect general recyclable waste materials (separation) and type (at source), and this is assisted by a recycling process. Looking at the required obligation above by the Waste Act, South Africa is still lacking proper implementation to manage waste as indicated by the large waste quantities still being taken to landfills in Figure 2.2.

In 2017, 4.9 million tonnes of general waste are reported to have been recycled. This amounts to a figure of 11% of the general waste recycled. In addition to that, the rate of recycling was estimated to be 34%. It must be noted that this is based on the common recyclable materials like glass, plastic, metal and paper. This overall recycling rate is quite low for a country like South Africa that needs to ease the burden on landfills. Furthermore, the total municipal, commercial and industrial waste generated were completely landfilled in 2017. Organic waste which is the second largest contributor (17%) to the total general waste quantity, only had 12% of it recovered/recycled. This indicates 5% of the organic waste being landfilled. The waste type with the highest recycling/recovery rate is metals (48%), followed by paper (39%), Tyres (29%), Glass (23%), Plastic (15%), Organic Waste (12%) and lastly Construction & Demolition Waste (6%) (Department of Environmental Affairs, 2018).

Table 2.3 provides a detailed breakdown of the 2017 general waste quantities produced together with the indication of how much of the waste went to landfill as well as how much was recycled or recovered.

Table 2.3: General waste by management option in 2017 (Department of Environmental Affairs, 2018)

Waste Type		Generated	Recovered / Recycled	Landfilled	Percentage Recovered / Recycled
GW01	Municipal waste	1 770 009	-	1 770 009	0%
GW10	Commercial and industrial waste	3 179 157	-	3 179 157	0%
GW20	Organic waste	6 656 234	812 206	5 844 028	12%
GW30	Construction and demolition waste	5 360 556	305 761	5 054 795	6%
GW50	Paper	3 635 825	1 414 378	2 221 447	39%
GW51	Plastic	2 247 323	332 713	1 914 610	15%
GW52	Glass	1 395 103	320 000	1 075 103	23%
GW53	Metals	3 345 565	1 622 059	1 723 506	48%
GW54	Tyres	221 751	64 061	157 690	29%
GW99	Other	14 868 997	-	14 868 997	0%
Total general waste (t)		42 680 520	4 871 178	37 809 341	11%

Other challenges also present themselves in our waste management system. However, these challenges can be visible from an implementation and/or monitoring level and not from a citizen level. A report by the South African Cities Network (SACN) has highlighted the challenges as follows (South African Cities Network (SACN), 2014) :

- There is no specific concept of institutional and governance frameworks for waste management systems in some cities.
- Lack of waste management metropolitan policies and governance systems.
- Limited distributions of budgets and waste management financial tools.
- The lack of appropriate national government support tools, structures and services for the waste hierarchy has had a negative effect on the capacity of a town to create, reuse and minimize waste recycling programs.
- Lack of support structures at national level, including funding for the restoration of old landfill sites, though compliance with landfill licensing conditions and standards is still a challenge at municipal level.
- The exponential expansion of cities.
- Lack of sufficient city monitoring, documentation and knowledge on programs for waste management.
- Dumping illegally.
- Lack of cooperation in relation to processes and mutual monitoring structures between a town and private waste service providers (South African Cities Network (SACN), 2014)

2.3 CIRCULAR ECONOMY

For many decades, the economy has been based on a linear model. This is a one-way model where products are produced using raw materials, sold, utilized and afterwards burned or disposed of as waste (Wautelet & Impakt, 2018). This model is better illustrated in Figure

2.9. This is not sustainable and is putting pressure on natural resources. There is considerable public interest to achieve a more sustainable solution for manufacturing methods. The solution to this requires the extensive use of raw materials that are renewable which in turn requires new production processes (Dimian, 2007).

Figure 2.9: Linear economy (Olabi, 2019)

A Circular Economy (CE) can be described as an economic system targeted at effective use of resources by waste minimisation, long-term conservation of value, elimination of primary resources and closed loops within the limits of environmental and socio-economic benefits for goods, component parts and materials (Morseletto, 2020). This implies that the value of goods, materials and capital in the economy must be retained for the longest period (Merli, Preziosi & Acampora, 2018). The concept is better explained in Figure 2.10 below.

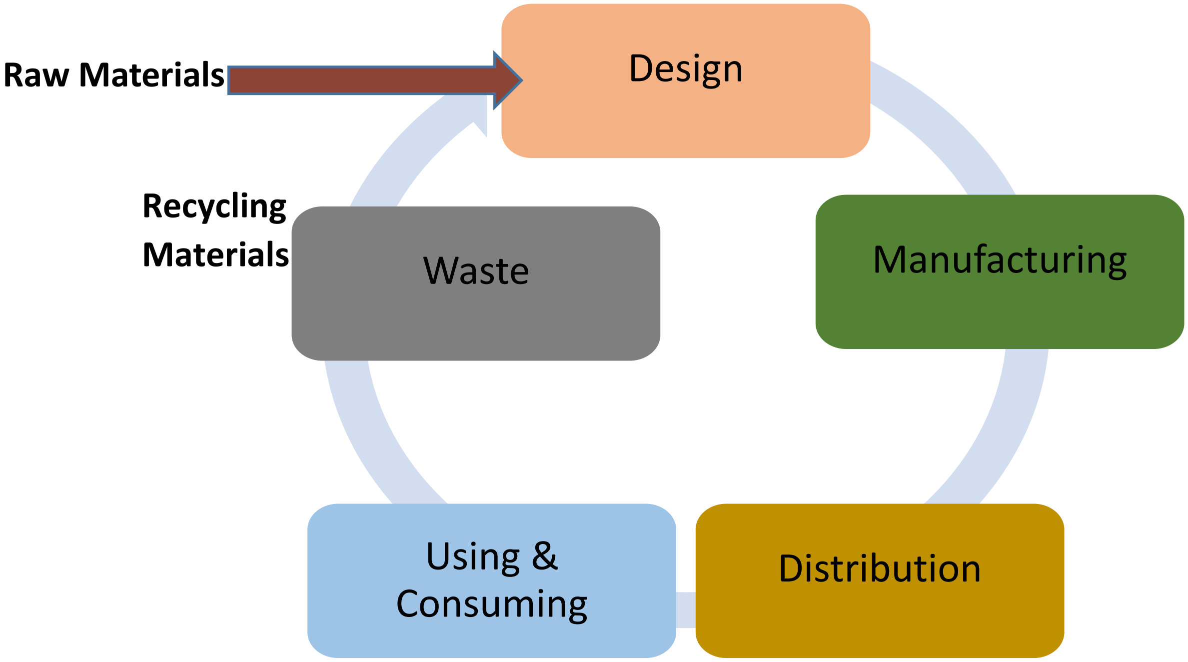


Figure 2.10: Circular economy (Olabi, 2019)

While the practice of a circular economy has been explored since the 1970s (Wautelet & Impakt, 2018), it has only gained momentum in recent years. The circular economy has emerged as a method to reduce the strain on resource consumption and has attracted attention globally. According to World Bank Group (2019), the Chinese originally interpreted the idea of the circular economy in China as a substitute model of growth to respond to resource scarcity and the complexities of pollution. However, the perception has changed over the years as currently, the development of sustainable economic activities is deemed a significant measure of the green economy. Furthermore, the implementation of a circular economy requires stringent enforcement measures to be in place. A green economy goes together with what is called a waste-to-energy concept which is linked to a biorefinery. The definition of a biorefinery as well as the types of biorefineries are discussed in more detail in the next section.

2.4 BIOREFINERIES

2.4.1 Definition

In order to better understand the concept of waste-to-energy using biorefineries, it is crucial to understand the meaning of a biorefinery. A biorefinery is a plant that combines the production of fuels, electricity, and value-added chemicals by utilizing processes that convert biomass (Dimian, 2007). The term biomass is a general term applied to all products produced from plants and animals. Biomass from plants is grown to produce food and animal feed, bio-based products and burned for renewable energy (Sherwood, 2020). It is an alternative organic option to fossil fuels which are mainly oil and natural gas. The biorefinery model revolves around four conversion processes which are biological conversion, chemical conversion, mechanical conversion and thermochemical conversion.

A typical biorefinery plant consists of an input system using the following sustainable waste or recycled materials:

- Oils from vegetables and fats from animals which are called lipids.
- Timber, crop deposits, hay, bagasse from sugarcane and so forth. These fall under the lignocellulose category.
- Glucose biomass which consists of sugarcane, starch from potatoes and sugar-beet.
- Municipal solid waste
- Starchy and corn grains (Dimian, 2007)

In the initial step, the biomass is subjected to a pre-processing step for direct extraction of essential products by effective techniques. The pyrolysis of wood is an example. Important synthetic compounds such as phenols, alcohols and esters are acquired. Complex natural particles like guaiacol or syringol, which in any case would require complex natural blend processes, are also obtained. However, in limited concentrations, the isolation of specimens might not be economic in any way. An option is the transformation to oil by hydro-deoxygenation, and handling of the oil in regular oil processing plants. The biorefinery concept is represented in Figure 2.11.

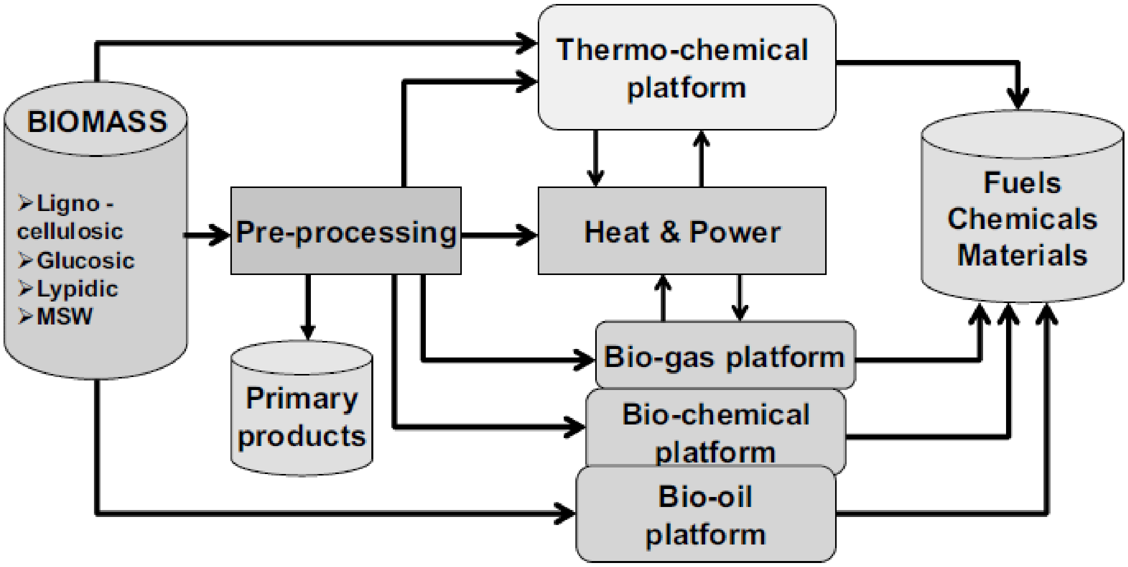


Figure 2.11: The Biorefinery Concept (Dimian, 2007)

2.4.2 Types of Biorefineries

2.4.2.1 Waste Biorefinery

This type of biorefinery uses various types of waste. Ubando, Felix & Chen (2020) points out that a crucial element of the circular bioeconomy is waste. This is mainly due to the fact that possibilities for remanufacturing, re-using and recycling are feasible since many technologies for conversions and methods are established and readily accessible. Previous research has been conducted on waste types such as lignocellulosic materials (Singh et al., 2019), foodstuffs (Bastidas-Oyanedel & Schmidt, 2018), paper waste (Adu, Jolly & Kumar, 2018), manure (Chen et al., 2005) and municipal solid waste (Barampouti et al., 2019). Waste classification by Skaggs et al., (2018) was carried out along with the construction of waste-to-energy facilities by Chandak, Chari & Memon (2015) to allow an effective and competitive conversion from waste-to-bioenergy. In the context of a circular economy, Nizami et al., (2017) carried out an assessment of various waste biorefinery routes in developing countries as a solution to current waste disposal problems and as facilities to produce fuels, power, heat, and value-added products. From the assessment conducted by Nizami et al., (2017), it was found that waste biorefineries if developed in developing countries could provide energy generation, land savings, new businesses and consequent job creation, savings of landfills costs, GHG emissions reduction. This also includes savings of natural resources of land, soil, and groundwater. By using the biorefinery principle, a sustainable bioenergy output from waste can be achieved by obtaining value-adding products.

2.4.2.2 Lignocellulosic Biorefinery

Considering the wide range of plant choices and high availability in tropical climates, lignocellulosic biomass is an attractive biomass feedstock. Lignocellulosic biomass is primarily obtained from hay wheat, coir, grain stove, rice, sugarcane molasses, straw, sorghum stems, wheat, and timber (Ubando, Felix & Chen, 2020). Approximately 1.3 billion tons of lignocellulosic biomass are produced worldwide annually, in which only 3% is consumed for energy, chemicals and bio-products connected to non-food products according to Baruah et al., (2018). On the other hand, (Zhang, 2008) iterates that it comprises of hemicellulose, lignin and cellulose which, through the lignocellulosic fractionation process in a biorefinery, can be transformed to various products. De Bhowmick, Sarmah & Sen (2018) suggested the use of lignocellulosic biorefinery, along with biofuel processing, as a forum to tackle the long-term growth of valuable organic products. They stressed that the recycling of biomass and its waste, as well as the integration by process integration of various conversion technologies, are feasible routes for sustainable bio-product development.

2.4.2.3 Algal Biorefinery

As opposed to lignocellulosic biomass, algal biomass is regarded to be developed biomass feedstocks that have certain advantages. These advantages are lower land requirements and increased productivity and output of biomass. Two major groups, such as microalgae according to Chew et al., (2017) and macroalgae according to Torres, Kraan & Dominguez (2019) can be classified into algal biomass. Leu & Boussiba (2014) describe microalgae as photoautotrophs that use energy from the sun efficiently to accumulate biomass made up of basic biomolecules. A variety of reactor setups can be utilised to cultivate the growth of microalgae, including bioreactors made for cultivating microalgae. They can be built upright and manufactured with less space than traditional cultivation methods (Ubando et al., 2016). To sustainably generate numerous microalgal-based products, several routes for biorefineries, particularly for microalgal biomasses, have been proposed by researchers namely, Chew et al., (2017) and López et al., (2014). However, seaweeds or macroalgae are ocean organisms that are mostly cultivated by the shore side and are prevalent along seashores by the coast (Lehahn, Ingle & Goldberg, 2016). They provide a renewable supply of biological compounds, such as biofuels and biochemicals, that can be transformed to food and valuable products (Jiang, Ingle & Golberg, 2016). A macroalgae biorefinery had been implemented for the manufacturing of highly valuable seaweed bio-products by Ingle et al., (2018) and Sadhukhan, Ng & Martinez-Hernandez (2016). Microbes are microorganisms that reside as singular cells or survive in a multi cellular setting that promote the degradation of lignocellulosic biomass (lignin and hemicellulose) into biological compounds that are necessary to get them fermented (Jin et al., 2015). Almeida, Fávaro & Quirino (2012) together with Jiang et al., (2017) propose that biofuels can be produced by fermentation using microbial biorefinery systems. Hasunuma et al., (2013) has carried out a comprehensive analysis of different microbes used from a biorefinery perspective for the development of biofuel from lignocellulosic biomass.

Figure 2.12 provides more insight of the role of a biorefinery in the circular bioeconomy. This looks at the different biorefinery platforms available, the conversion processes, primary bio-products and secondary bio-products. Primary bio-products are formed by the direct photosynthetic use of solar energy. Substances such as plant mass are created. However, secondary bio-products are formed as a result of the transformation or decomposition of organic matter such as by other users or animals.

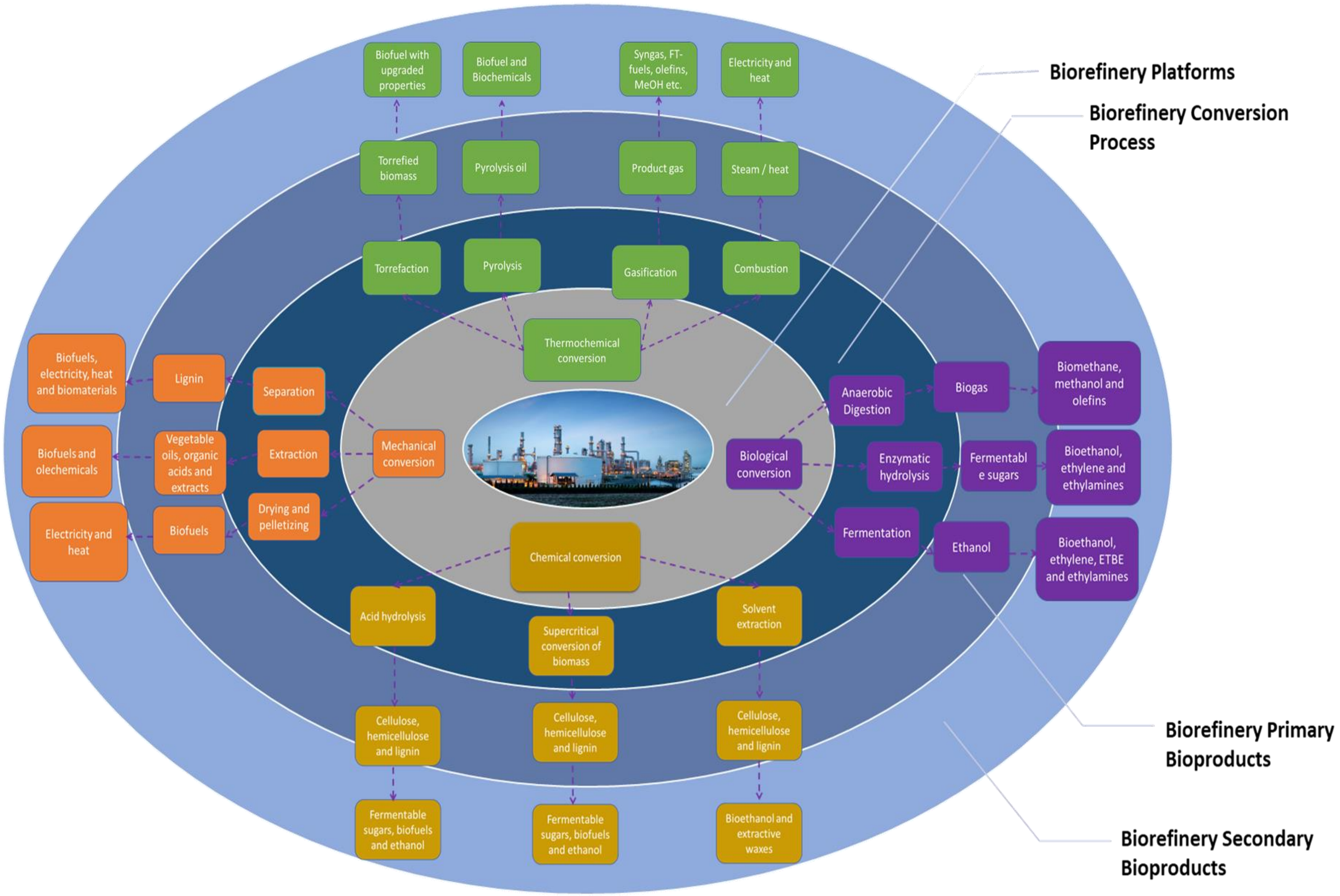


Figure 2.12 : The role of biorefinery in circular bioeconomy (Ubando, Felix & Chen, 2020)

2.5 WASTE-TO-ENERGY TECHNOLOGIES

2.5.1 Types of Waste-To-Energy Technologies

2.5.1.1 Biological Treatment Technologies

Biodegradable MSW fractions have a high potential of being converted to electricity. Biological treatment systems are intended for natural bioprocesses that involve the organically rich fraction of MSW. The treatment of MSW is divided into various methods relating to the circumstances under which they occur: composting or aerobic (where oxygen is present) method and anaerobic (where oxygen is absent) processes. The main product of the anaerobic process is a gas that is a mixture of carbon dioxide and methane (Moya et al., 2017). The method requires less energy compared to the aerobic cycle and generates less heat. The biogas is then burnt to create either heat or electrical energy.

Biogas production methods are comprised of wet and dry techniques. Dry technologies process dry materials and wet technologies process material that has high moisture content (Moya et al., 2017). Dry anaerobic technologies function with high content of solids and generate a large amount of heat according to (Andriamanohiarisoamanana et al., 2017). The production of biogas decreases the waste quantity, which in turn has an effect on the waste volume which is taken to landfills for disposal. Biogas normally has two functions: generating electricity and generating heat for various processes (Bayard et al., 2010).

2.5.1.2 Thermal Treatment Technologies

A. <u>Pyrolysis</u>

The process involves the degradation of MSW at high temperatures in the absence of oxygen. The waste is initially pre-treated. The inert materials, glass and metals are separated mechanically. The thermal decomposition of organic material occurs at 300°C (Agarwal, Tardio & Venkata Mohan, 2013). The temperature is then increased in an atmosphere that does not react and the bioproducts created are liquids (bio-oil), gases and solid biochar (Moya et al., 2017). According to Yang et al., (2018), pyrolysis is the thermal breakdown of organic compounds at high temperatures (about 500 °C) without oxygen. The feedstock is transformed in varied ratios into liquid, gaseous, and solid products with potential for biofuel applications.

There are three types of pyrolysis processes, namely: Conventional Pyrolysis (Slow), Fast Pyrolysis and Flash Pyrolysis (Tangsathitkulchai, Punsuwan & Weerachanchai, 2019).

- **Conventional Pyrolysis:** Slow pyrolysis is another name for conventional pyrolysis. Charcoal has traditionally been produced using this form of pyrolysis. The slow heating rate (less than 10 C/s) and prolonged residence periods of gases and solids at temperatures of about 450˚C are the defining characteristics of slow pyrolysis. In comparison to quick pyrolysis, there is a slower release of vapor products. As a result, elements in the vapor phase continue to interact with one another, producing char and other liquids (Tangsathitkulchai, Punsuwan & Weerachanchai, 2019).
- **Fast Pyrolysis:** In a high-temperature procedure known as fast pyrolysis, biomass is heated quickly to a temperature of around 500 °C without the presence of oxygen. When biomass breaks down, fumes, aerosols, and some char that resembles charcoal are produced. Rapid pyrolysis heating rates can reach 10,000 C/s or even 100 C/s, and the typical vapor residence time is under 2 s. The main result of rapid pyrolysis at higher temperatures is gas. The liquid products of pyrolysis are maximized by quick heating and quenching, which condense out before additional processes break down the higher molecular-weight species into gaseous products. Once the vapors cool and condense, a dark brown liquid forms. This liquid's heating value is roughly half that of regular fuel oil. Depending on the feedstock utilized, fast pyrolysis operations generate 60–75 weight % of liquid bio-oil, 15–25 weight % of solid char, and 10–20 weight % of non-condensable gases (Tangsathitkulchai, Punsuwan & Weerachanchai, 2019).
- **Flash Pyrolysis:** The temperature range for flash pyrolysis is 700–1000°C, with a substantially quicker heating rate of more than 500°C/s and a brief residence duration of less than 0.5 s. The efficiency of biomass conversion to bio-oil during the

> flash pyrolysis process can reach 80%. Because it can be transported easily, burned directly in thermal power plants, and utilized as a chemical feedstock to create a variety of valuable chemical products, the liquid product is seen as a very promising fuel. Nevertheless, bio-oils' high oxygen content (35–50%) results in high acidity (pH as low as 2) and their high acidity. Moreover, bio-oils have a high solid residue concentration (up to 40%) and are viscous (20-1000 cP at 40°C) (Tangsathitkulchai, Punsuwan & Weerachanchai, 2019).

Pyrolysis is a process that is being introduced worldwide. Some fast pyrolysis studies that been done, include the study by Winjobi (2017) where loblolly pine chips and torrefied pine chips were modelled in ASPEN Plus using a yield reactor at 530˚C and 1 bar with recycled inert gas to eliminate oxygen from the reactor. For a one-step pyrolysis process using raw pine the results obtained were 28 wt% gas, 59 wt% liquid and 10wt% char.

Another pyrolysis simulation includes the simulation of Batch Slow Pyrolysis of Biomass Materials Using the Process-Flow-Diagram COCO Simulator (Tangsathitkulchai, Punsuwan & Weerachanchai, 2019). However, this is a slow pyrolysis process that produced 12.3%, 10.6%, and 27.5% for the solid, liquid, and gas products. This produced less liquid than the study by Winjobi (2017).

In addition to the above, a simulation that used the catalytic and thermal pyrolysis routes to convert waste pinewood chips into biofuel via pyrolysis with production of hydrogen, electricity, steam, and ash as co-products was undertaken (Patel et al., 2020) . This simulation was modelled using ASPEN Plus. All these simulations discussed above are an indication of the initiatives that have been taken using pyrolysis processes. The above reflect only a few of the studies done as there is more to what is indicated here.

In South Africa, there are a few pyrolysis plants that have been built to address various challenges. One of the biggest challenges in South Africa is addressing the issue of waste tyres which are not biodegradable and therefore pose an environmental concern. There are a number of pyrolysis organizations in South Africa namely, The IRR Manufacturing facility processes waste tyres, waste wood, and waste polyolefin plastics in a 1000 kg/hour pyrolysis plant in Rosslyn, Pretoria, to produce pyrolytic gas, oil, and carbon black. Recor-Waste to Energy Solutions is a South-Gauteng-based pyrolysis plant that converts a variety of wastes such as municipal solids, agricultural, medical, abattoir, and sawdust, converting them to energy. Additionally, waste tyres are converted to energy, oil, and char, while plastic and waste oils are processed to yield a variety of diesel grades. Lastly, Trident Fuels Pty Ltd., located in Germiston, Gauteng, processes waste tyres to produce crumb rubber and carbon black.

B. Gasification

This process has evolved during the past 30 years to generate energy from MSW (Thakare & Nandi, 2016). The process entails partial oxidation and fuel gas (syngas) is the main product. The waste is subjected to elevated temperatures in a gasifier ranging between 600°C to 1000°C (Gasification Technologies Council, 2014). The chemical energy contained in those gases can be utilized in different manners. Firstly, it can be burned in a gas engine or gas turbine to produce power. On the other hand, the chemical energy can be transformed to transportation fuels, substitute natural gas or chemicals, again at greater efficiency (Department for Environment Food & Rural Affairs, 2014). The weight of the waste can be decreased by 70% and over 90% of the waste volume through gasification (Moya et al., 2017). A recent analysis revealed that thermally processed waste is a feasible option to transform waste, decreasing the amount of waste to landfill and reducing greenhouse emissions (Arena, 2012).

C. Incineration

Moya et al., (2017) states that Incineration involves burning the waste inside a combustion chamber at a temperature of 900°C to 950°C by utilizing the combustion exhaust gas and pre-heated air. Tan et al., (2014) mentions that once the incineration process is complete, steam gas is generated and used inside a combined heat and power (CHP) system to create heat and energy. Heat is generated by a district heating system. Whereas a turbine coupled with a generator produces electricity. Ashworth, Elliott & Toledano (2014) describes the generation of greenhouse gas emissions as a serious concern of municipal solid waste incineration in terms of public health. However, some complex technologies have been generated to decrease these effects.

2.5.2 Status of Waste-To-Energy (WtE) Technologies

Samun et al., (2017) states that solid waste can be best utilised by producing high- value products and energy from it. Ryu & Shin (2013) mention that just by making use of suitable WtE methods, the production of biogas for combined heat and power (CHP) can be achieved through using a high-value resource like MSW which is renewable. Korai, Mahar & Uqaili (2016) claim that an assessment on the waste composition and finances must be conducted first in order to choose the most suitable technology to use. Choosing the relevant WtE method is a difficult task as the recurrence and the socio-economic level of producers affect the solid waste generation (Alam et al., 2008). Landfill gas usage technologies (Yechiel & Shevah, 2016) as well as biorefineries, are regarded as WtE techniques as stated by Sanchez et al., (2017) and Stamatelatou et al., (2014). This involves the recovery of waste by incineration, recycling of landfill gas and anaerobic digestion of the relevant biodegradable portion of waste (Al-Salem, Evangelisti & Lettieri, 2014). Based on this observation by Dlamini, Simatele & Serge Kubanza (2019) an incineration process can be used for recovering non-recyclable waste. It can also be used for the recovery of landfill gas for producing gas on the operational landfills and anaerobic digestion for biodegradable waste that has been separated. Dlamini, Simatele & Serge Kubanza (2019) maintain that Waste-To-Energy (WtE) technologies can be used to improve the MSW crisis facing the country through waste recovery and the generation of energy. WtE technologies remove usable energy that is contained inside the organic component of MSW for power or heat production through processes which are biological and thermal as according to Brunner & Rechberger (2015).

Despite the fact that Waste-to-Energy technologies are still leaning toward renewable energy as an alternative, some countries have begun implementing these technologies. Johari et al. (2012) together with Tan et al., (2015) and Tozlu, Özahi & Abuşoğlu (2016) indicate that there is an estimation of almost 800 Waste-To-Energy projects being functional in about 40 countries worldwide. As such, 11% percent of the treated municipal solid waste produces a maximum of 429 Terawatt hours of electricity.

A variety of companies in Scotland use organic waste materials through the anaerobic digestion process to produce biogas. There are also other heat recovery projects, through the use of waste heat for the production of thermal or electrical energy (Olabi, 2019).

A Spanish company called Endesa Generacion SA identified that landfill gas recovery is not a popular procedure in South Africa. Therefore, an Ekurhuleni Landfill Gas Recovery Project was proposed in 2007 to recover landfill gas through flaring at the four landfill sites namely: Simmer & Jack Landfill Site, Weltevreden Landfill Site, Rietfontein Landfill Site and Rooikraal Landfill Site. Some of the objectives of the project include: using a renewable energy source to produce heat or electricity, reducing environmental impacts (ie. odours, minimising the pollution of air, improving the health and safety of the community and landfill employees, minimising explosion and fire hazards) (Ekurhuleni Metropolitan Municipality, 2007). The landfill gas recovery is currently being carried out on all four operational landfill sites however the gas is not being used to generate electricity; instead it is flared and released into the atmosphere. In 2014 a pilot project for generating 1 MW of electricity from landfill gas commenced. The pilot project was conducted on the Simmer & Jack Landfill Site. Within the first month, 594 MWh of electricity was produced. However, this energy is only used within the municipality and was exported to the municipality grid. There have been no new developments with the pilot project.

Dlamini, Simatele & Serge Kubanza (2019) report that the City of Johannesburg has made attempts regarding WtE projects. The City of Johannesburg and EnerG Systems Joburg (Pty) Ltd had an agreement in place to build and ensure the functioning of WtE initiatives. This is free of charge for 20 years. By implementing the Clean Development Mechanism (CDM) project, The City of Johannesburg is playing a role in the Kyoto Protocol commitments that the country has now established. This also creates income from electricity trading and Certified Emission Reductions (CERs). The project's electricity will fuel approximately 12500 middle class families (Baker & Letsoela, 2016). 3 megawatts (MW) of renewable electricity in 2016 generated by the Robinson Deep initiative for recovering landfill gas; supplied more than 5500 homes (Dlamini, Simatele & Serge Kubanza, 2019).

Baker & Letsoela (2016) explain that the gas accumulated by the landfill facilities of Goudkoppies and Marie Louise is being burned and that the fitting of a gas storage system and a turbine is in progress. Every facility will produce 3 MW of electricity supplying the City Power network (Baker & Letsoela, 2016). As according to Baker & Letsoela (2016), the Marie Louise facility has retrieved and burned about 1756 cubic meters per hour of landfill gas since May 2011 and May 2012. Such gas would have been discharged as a toxic greenhouse gas (GHG) to the environment. For gas accumulation, much of the reservoirs have already been fitted in order to prepare for the energy production. Therefore, there is a rise in toxic GHGs expected (Baker & Letsoela, 2016). The project has gathered certified emission reductions (carbon offsets) of about 243 859. Both Mbuli (2015) and Baker & Letsoela (2016) are of the opinion that this should decrease emissions by GHG by 60% to 70% during its operation.

2.6 GAPS IDENTIFIED IN LITERATURE

2.6.1 Waste Management

An analysis of the report by (South African Cities Network (SACN), 2014) has pointed out the following gaps in the current waste management process: The issue at landfill sites is with the informal recycling activities done by reclaimers. The health and safety of the reclaimers is compromised. This puts municipalities in a tough position as they will be held accountable should anything occur to the reclaimers. Therefore, support needs to be given to the reclaimers so that the municipalities work together with the reclaimers. Another point to consider is the implementation of standard procedures and manufacturing material recovery systems. Policies are there, but actioning the policies and procedures is still in the infancy stage. There is also a gap in promoting resource recovery systems and processing. Another challenge to note is in the development of strategies which will assist in the financing of activities relating to waste management (South African Cities Network (SACN), 2014). These challenges are an indication of internal issues faced by landfill sites that tend to be overlooked or that the public is not aware of. This study therefore needs to bring these landfill site challenges to the forefront.

2.6.2 Circular Economy

Literature reveals that certain research initiatives have been undertaken towards the building of a circular economy. Hidalgo, Martín-Marroquín & Corona (2019) have piloted a circular economy model by building a multi-waste plant to generate energy. On the other hand, the composting of food waste is one identified opportunity by Awasthi et al., (2020). The drawback of this composting, however, is the odour generation caused by the process which will have health implications on the surrounding community.

Ellen MacArthur Foundation (2016) has already identified initiatives for a variety of enterprises and sectors to be creative and innovative. One of these initiatives is with the digital connectivity of smart devices. It looks at how electronics and specialized equipment are produced and used, how the energy infrastructure is built, how to construct and develop houses, and how food is made. It evaluates how intelligent cities will develop to become a central focus for the transformations to follow. There are opportunities for corporations to compete for profit, but maybe more significantly, there is a chance for society to clearly define its relationship with capital.

The above initiatives indicate that globally there is progress with regards to adopting and implementing a circular economy approach. However, in South Africa, the circular economy concept is a new concept with regards to municipal solid waste. In 2017, the Department of Environmental Affairs (2017) was strategizing on how to maximise the circular waste economy in South Africa. This is the reason why there was a need for the researcher to quantify its value. South Africa has not yet reached that level of implementing the circular economy let alone in the Fourth Industrial Revolution segment.

2.6.3 Modelling of biorefineries

Although a study by Satchatippavarn et al., (2016) has indicated that it is possible to implement a biorefinery concept that is integrated with a number of systems for the recycling of material, it has not considered other upcoming technologies such as Waste-To-Energy technology modelling. A study conducted by Dunmade, Akinlabi & Daramola (2020) revealed the factors why biorefinery production in the West African Region has been delayed. Particularly when there is an opportunity to boost the manufacturing of liquid fuels from biomass in West Africa. The enforcement of energy regulations, for instance, is still lacking (Dunmade, Akinlabi & Daramola, 2020). Implementation and enforcement of regulations is a huge factor to the success of a sustainable future. To date there has been modelling of waste to products such as through biorefineries based on South African waste composition. However, the focus is more on utilizing incineration and anaerobic digestion technologies to transform waste to energy (Dlamini, Simatele & Serge Kubanza, 2019). In view of this, opportunities arise to model biorefineries using other waste-to-energy technologies such as gasification and pyrolysis. This is where this study fits in; by exploring an alternative waste-to-energy technology in South Africa.

REFERENCES

Adu, C., Jolly, M. & Kumar, V. 2018. ScienceDirect Exploring new horizons for paper recycling : A review of biomaterials and biorefinery feedstocks derived from wastepaper. *Current Opinion in Green and Sustainable Chemistry*. 13:21–26.

Agarwal, M., Tardio, J. & Venkata Mohan, S. 2013. Critical analysis of pyrolysis process with cellulosic based municipal waste as renewable source in energy and technical perspective. *Bioresource Technology*. 147:361–368.

Almeida, J.R.M., Fávaro, L.C.L. & Quirino, B.F. 2012. Biodiesel biorefinery : opportunities and challenges for microbial production of fuels and chemicals from glycerol waste. 1–16.

Andriamanohiarisoamanana, F.J., Matsunami, N., Yamashiro, T., Iwasaki, M., Ihara, I. & Umetsu, K. 2017. High-solids anaerobic mono-digestion of riverbank grass under thermophilic conditions. *Journal of Environmental Sciences (China)*. 52:29–38.

Arena, U. 2012. Process and technological aspects of municipal solid waste gasification . A review. *Waste Management*. 32(4):625–639.

Ashworth, D.C., Elliott, P. & Toledano, M.B. 2014. Waste incineration and adverse birth and neonatal outcomes: A systematic review. *Environment International*. 69:120–132.

Awasthi, S.K., Sarsaiya, S., Awasthi, M.K., Liu, T., Zhao, J., Kumar, S. & Zhang, Z. 2020. Changes in global trends in food waste composting: Research challenges and opportunities. *Bioresource Technology*. 299(December 2019):122555.

Barampouti, E.M., Mai, S., Malamis, D., Moustakas, K. & Loizidou, M. 2019. Liquid biofuels from the organic fraction of municipal solid waste : A review. *Renewable and Sustainable Energy Reviews*. 110(November 2018):298–314.

Baruah, J., Nath, B.K., Sharma, R. & Kumar, S. 2018. Recent Trends in the Pretreatment of Lignocellulosic Biomass for Value-Added Products. 6(December):1–19.

Bastidas-Oyanedel, J. & Schmidt, J. 2018. Increasing profits in food waste biorefinery- a techno-economic analysis.

Bayard, R., de Araújo Morais, J., Ducom, G., Achour, F., Rouez, M. & Gourdon, R. 2010. Assessment of the effectiveness of an industrial unit of mechanical-biological treatment of municipal solid waste. *Journal of Hazardous Materials*. 175(1–3):23–32.

BP. 2020. Statistical Review of World Energy.

Brunner, P.H. & Rechberger, H. 2015. Waste to energy - key element for sustainable waste management. *Waste Management*. 37:3–12.

Chandak, S., Chari, K. & Memon, M. 2015. Converting waste agricultural biomass into energy: experiences and lessons learnt from a capacity building and technology demonstration project in india. (December 2016).

Chew, K., Yap, J., Show, P., Suan, N., Juan, J., Ling, T., Lee, D. & Chang, J. 2017. Microalgae biorefinery : High value products perspectives. *Bioresource Technology*. 229:53–62.

De Bhowmick, G., Sarmah, A. & Sen, R. 2018. Lignocellulosic biorefinery as a model for sustainable development of biofuels and value added products. *Bioresource Technology*. 247(June 2017):1144–1154.

Department for Environment Food & Rural Affairs. 2014. Energy from waste. 2014(February):1–70.

Department of Environmental Affairs. 2008. Waste Classification and Management Regulations and Supporting Standards. In *Waste Management*. 38.

Department of Environmental Affairs. 2011. National Waste Management Strategy. *National Waste Management Strategy*. (November):75. Available: https://www.environment.gov.za/sites/default/files/docs/nationalwaste_management_strategy.pdf.

Department of Environmental Affairs. 2012. Municipal Solid Waste Tariff Strategy. (May):1–31. Available: http://sawic.environment.gov.za/documents/1352.pdf.

Department of Environmental Affairs. 2013a. National Norms and Standards For The Assessment of Waste For Landfill Disposal. 7(10505):22–33.

Department of Environmental Affairs. 2013b. National Norms And Standards For Disposal Of Waste To Landfill. 7(August 2013):34–45.

Department of Environmental Affairs. 2017. Maximising the circular waste economy in South Africa.

Department of Environmental Affairs. 2018. South Africa State of Waste Report. *Government of South Africa*. 68. Available: http://sawic.environment.gov.za/documents/8635.pdf.

Department of Water Affairs and Forestry. 2008. *Minimum requirements for the Handling, Classification and Disposal of Hazardous Waste*. Second ed.

Dimian, A.C. 2007. Renewable Raw Materials : chance and challenge for Computer-Aided Process Engineering. 309–318.

Dlamini, S., Simatele, M.D. & Serge Kubanza, N. 2019. Municipal solid waste management in South Africa: from waste to energy recovery through waste-to-energy technologies in Johannesburg. *Local Environment*. 24(3):249–257.

Dunmade, I.S., Akinlabi, E. & Daramola, M. 2020. A sustainable approach to boosting liquid biofuels production from second generation biomass resources in West Africa. *Agronomy Research*. 18(Special Issue 2):1220–1234.

Ekurhuleni Metropolitan Municipality. 2007. Ekurhuleni Landfill Gas Recovery Project - South Africa. 1–40.

Ellen MacArthur Foundation. 2016. Intelligent Assets : Unlocking The Circular Economy.

Gasification Technologies Council. 2014. *The waste-to-energy solution*.

Gumbo, T. 2014. Scaling Up Sustainable Renewable Energy Generation from Municipal Solid Waste in the African Continent: Lessons from eThekwini, South Africa. *Consilience: The Journal of Sustainable Development*. 12(1):46–62.

Hasunuma, T., Okazaki, F., Okai, N., Hara, K.Y., Ishii, J. & Kondo, A. 2013. Bioresource Technology A review of enzymes and microbes for lignocellulosic biorefinery and the possibility of their application to consolidated bioprocessing technology. *Bioresource Technology*. 135:513–522.

Hidalgo, D., Martín-Marroquín, J.M. & Corona, F. 2019. A multi-waste management concept as a basis towards a circular economy model. *Renewable and Sustainable Energy Reviews*. 111(May):481–489.

Hoornweg, D. & Bhada-Tata, P. 2012. A Global Review of Solid Waste Management. 116.

IEA. 2020. Global Energy Review 2019 - The latest trends in energy and emissions in 2019. *Global Energy Trends*. 1–50. Available: https://webstore.iea.org/download/direct/2994.

Ingle, K., Vitkin, E., Robin, A., Yakhini, Z., Mishori, D. & Golberg, A. 2018. Macroalgae Biorefinery from Kappaphycus alvarezii : Conversion Modeling and Performance Prediction for India and Philippines as Examples. *Bioenergy Resources*. 1(11):22–32.

Jiang, L.L., Zhou, J.J., Quan, C.S. & Xiu, Z.L. 2017. Advances in industrial microbiome based on microbial consortium for biorefinery. *Bioresources and Bioprocessing*.

Jiang, R., Ingle, K.N. & Golberg, A. 2016. Macroalgae (seaweed) for liquid transportation biofuel production: what is next ? *Algal Research*. 14:48–57.

Jin, M., Slininger, P.J., Dien, B.S., Waghmode, S., Moser, B.R., Orjuela, A., Sousa, C. & Balan, V. 2015. Microbial lipid-based lignocellulosic biorefinery : feasibility and challenges. *Trends in Biotechnology*. 33(1):43–54.

Kumar, S.S., Kumar, A., Malyan, S.K., Ghosh, P., Kumar, M., Kapoor, R., Kumar, A., Kumar, S., Kumar, V., Singh, L. 2023. Landfill leachate valorization: A potential alternative to burden off resources and support energy systems. *Fuel*. 331(P2):125911.

Lehahn, Y., Ingle, K. & Goldberg, A. 2016. Global potential of offshore and shallow waters macroalgal biorefineries to provide for food, chemicals and energy : feasibility and sustainability. *Algal Research*. 17:150–160.

Leu, S. & Boussiba, S. 2014. Advances in the production of High Value Products by Microalgae: Current Status and Future Prospectives. *Industrial Biotechnology*. 3(10):169–183. Available: http://www.moag.gov.il/yhidotmisrad/fishery/Mariculture/Documents/Prof. Sammy Boussiba-Advances in the production of High Value Products by Microalgae.compressed.pdf.

López, D., Samorì, C., Terranella, G., Hornung, U., Kruse, A. & Prins, W. 2014. Assessing microalgae biorefinery routes for the production of biofuels via hydrothermal liquefaction. *Bioresource Technology*. 174:256–265.

Merli, R., Preziosi, M. & Acampora, A. 2018. How do scholars approach the circular economy? A systematic literature review. *Journal of Cleaner Production*. 178:703–722.

Morseletto, P. 2020. Targets for a circular economy. *Resources, Conservation and Recycling*. 153(October 2018):104553.

Moya, D., Aldás, C., López, G. & Kaparaju, P. 2017. Municipal solid waste as a valuable renewable energy resource: A worldwide opportunity of energy recovery by using Waste-To-Energy Technologies. *Energy Procedia*. 134:286–295.

Muzenda, E. 2014. A discussion on waste generation and management trends in South Africa. *International Journal of Chemical, Environmental & Biological Sciences*. 2(2):105–112. Available: https://152.106.6.200/handle/10210/11871.

Nizami, A.S., Rehan, M., Waqas, M., Naqvi, M., Ouda, O.K.M., Shahzad, K., Miandad, R., Khan, M.Z., Syamsiro, M., Ismail, I. M. I., & Pant, D. 2017. Waste biorefineries: Enabling circular economies in developing countries. *Bioresource Technology*. 241:1101–1117.

Olabi, A.G. 2019. Circular economy and renewable energy. *Energy*. 181:450–454.

Patel, A.D., Zabeti, M., Seshan, K. & Patel, M.K. 2020. Economic and Environmental Assessment of Catalytic and Thermal Pyrolysis Routes for Fuel Production from Lignocellulosic Biomass. *Processes*. 8(12):1–18.

Pienaar, R.A., Bhailall, S., Coetser, Z. & Gcwensa, Q. 2016. Long Term Waste Management Master Planning for the Ekurhuleni Metropolitan Municipality. *Proceedings of the 23rd WasteCon Conference 17-21 October 2016, Emperors Palace, Johannesburg, South Africa*. (October):446–455.

Sadhukhan, J., Ng, K.S. & Martinez-Hernandez, E. 2016. Novel integrated mechanical biological chemical treatment (MBCT) systems for the production of levulinic acid from fraction of municipal solid waste: A comprehensive techno-economic analysis. *Bioresource Technology*. 215:131–143.

Satchatippavarn, S., Martinez-Hernandez, E., Leung Pah Hang, M.Y., Leach, M. & Yang, A. 2016. Urban biorefinery for waste processing. *Chemical Engineering Research and Design*. 107:81–90.

Sherwood, J. 2020. The significance of biomass in a circular economy. *Bioresource Technology*. 300(November 2019).

Singh, A., Jasso, R.M.R., Gonzalez-gloria, K.D., Rosales, M., Belmares, R., Aguilar, C.N., Rani, R. & Ruiz, H.A. 2019. Bioresource Technology Reports The enzyme biore fi nery platform for advanced biofuels production. *Bioresource Technology Reports*. 7(June):100257.

Skaggs, R.L., Coleman, A.M., Seiple, T.E. & Milbrandt, A.R. 2018. Waste-to-Energy biofuel production potential for selected feedstocks in the conterminous United States. *Renewable and Sustainable Energy Reviews*. 82(July 2017):2640–2651.

South African Cities Network (SACN). 2014. *State of Waste Management in Cities – Phase 2: Modelling the Effects of Landfilling As A Disposal Method*. Braamfontein.

Statistics South Africa. 2019. Midyear Population Estimate 2019. *Statistics South Africa*. (July):24.

Statistics South Africa. 2021. *Five facts about the electricity, gas & water supply industry (2019)*. Available: https://www.statssa.gov.za/?p=14643 [2022, September 19].

Tan, S., Hashim, H., Lee, C., Taib, M. & Yan, J. 2014. Economical and environmental impact of waste-to-energy (WTE) alternatives for waste incineration, landfill and anaerobic digestion. *Energy Procedia*. 61:704–708.

Tangsathitkulchai, C., Punsuwan, N. & Weerachanchai, P. 2019. Simulation of Batch Slow Pyrolysis of Biomass Materials Using the Process-Flow-Diagram COCO Simulator. *Processes*. 7(775):20.

Thakare, S. & Nandi, S. 2016. Study on Potential of Gasification Technology for Municipal Solid Waste (MSW) in Pune City. *Energy Procedia*. 90(December 2015):509–517.

The Constitution of the Republic of South Africa. 1996. *Constitution of The Republic of South Africa (No. 108 of 1996)*. Pretoria: Government Printers, South Africa.

Ubando, A., Felix, C. & Chen, W. 2020. Biorefineries in circular bioeconomy: A comprehensive review. *Bioresource Technology*. 299(December 2019).

Ubando, A.T., El-halwagi, J.L.C.M.M., Culaba, A.B., Promentilla, M.A.B. & Tan, R.R. 2016. Application of stochastic analytic hierarchy process for evaluating algal cultivation systems for sustainable biofuel production. *Clean Technologies and Environmental Policy*. 18(5):1281–1294.

United Nations. 2019. *World Population Prospects 2019*.

United Nations Economic and Social Commission for Asia and the Pacific. 2002. Chapter 8 Types of wastes. *United Nations ESCAP Library*. 170–194. Available: http://www.unescap.org/sites/default/files/CH08.PDF.

Wautelet, T. & Impakt, P. 2018. The Concept of Circular Economy : its Origins and its Evolution. (January).

Winjobi, O. 2017. Techno-Economic and Life Cycle Assessments of Biofuel Production From Woody Biomass Through Torrefaction-Fast Pyrolysis and Catalytic Upgrading. Michigan Technological University.

World Bank Group. 2019. Urban And Rural Municipal Solid Waste In China And The Circular Economy. (April):1–23.

Yang, Y., Wang, J., Chong, K. & Bridgwater, A. V. 2018. A techno-economic analysis of energy recovery from organic fraction of municipal solid waste (MSW) by an integrated intermediate pyrolysis and combined heat and power (CHP) plant. *Energy Conversion and Management*. 174:406–416.

Zhang, Y. 2008. Reviving the carbohydrate economy via multi-product lignocellulose biorefineries. *Journal of Industrial Microbiology Biotechnology*. (May 2008):367–375.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter provides a comprehensive summary of the research methods and procedures followed to obtain data and results for this study. This methodology section is centred around three main categories: The data input, data processing and data output expected from the study. Firstly, the data collection methods and data inputs are highlighted. The chosen Waste-to-Energy (WtE) technology and process flow diagram of the chosen WTE technology are also discussed in detail. Furthermore, the simulation model setup is explained. The purpose of the simulation model is to determine how much products can be recovered from the chosen WtE technology using the waste quantities obtained from the data collection. The data for the process units chosen for the simulator together with the operating conditions are supplied. Later in the chapter, the value analysis method for measuring the economic margins of recovered products is considered. This will cover the capital costs required and how to obtain the Cost of Production (COP), Value on Processing (VOP) as well as the economic margins of the recovered products. The chapter ends off with the expected data output being listed. It must be noted that a theoretical approach was used for this study.

The simulation software used in this study is the CAPE-OPEN to CAPE-OPEN (COCO) simulator and it was obtained online from the COCO simulator website ("COCO Simulator", 2020). The input data used for the simulation process was based on the data from the Rietfontein Landfill Site for January to October 2019 (Figure 3.1). The Rietfontein Landfill Site is located in Springs in the Eastern Part of Johannesburg. The landfill accepts all types of waste excluding medical waste. However, it differs from other municipal landfill sites in Ekurhuleni as it is licensed to accept lower hazardous waste. The chosen Waste-to-Energy

(WtE) technology chosen for this study is fast pyrolysis. Fast pyrolysis was chosen since it yields more bio-oil as a main product and is also easy to simulate.

3.2 INPUT / DATA COLLECTION

3.2.1 Site Visit Data Collection

A site visit was scheduled at Rietfontein Landfill Site in the Springs area. Firstly, the intention of the site visit was to familiarise the researcher with the site and to understand the waste disposal process that took place at landfills. It was also easy to identify some of the landfill site challenges through site observation. The data collection process involved having a discussion with one of the experts. Subsequently, the other collection processes included site reports and taking a tour of the landfill site.

3.2.2 Flow rate and waste disposal tonnages of municipal waste material

The problem statement has highlighted the issue of landfills running out of space in South Africa. Therefore, obtaining the waste disposal tonnages was an integral part of this study. The waste disposal tonnages support the problem statement regarding the increased waste quantities taken to landfill as the consequences of a growing population and the increasing urbanisation rate as indicated in Chapter 1. However, these tonnages ultimately affect the landfill site capacities, and this is a challenge for the municipalities.

In this instance, the flowrate is required for this research solely for the feedstock input to the simulation software. The feed stream of the simulation software will take into account the solid waste composition. The flowrate is the main input. It is assumed that the solid waste has already been dried. It is important for the solid waste to be thoroughly dry for the fast pyrolysis process. This is due to the fact that the amount and nature of the bio-oil will be negatively impacted if the moisture content is high (Hu, Bassi & Xu, 2020) . The lower the moisture content, the better the quality of the bio-oil will be. According to Antal & Gronli, (2003), the moisture content range for a wood feedstock is generally 15% to 20%. However, the moisture content for this study was assumed to be 10% after drying. For a fast pyrolysis process, Zaman et al., (2017) states that the moisture content should approximately be 10%. Therefore, the drying section will not be simulated as the 10% moisture content after drying has already been assumed for this process.

3.2.3 Composition of municipal waste material

Municipal solid waste consists of different waste types. Therefore, the waste has to be categorised first to ensure that only the correct type of waste is landfilled. However, biorefinery processes involve using organic waste as raw material. This implied that only the information for garden waste could be extracted for the purpose of this study. The information was extracted from the Monthly Operations Reports (personal communication, 13 February 2020) for the period indicated in the Introduction of this chapter. The General Public compost/Garden Refuse and Contractors Clean Compost/Garden Refuse tonnages were combined to give a total value of 264 tons of garden waste over a nine-month period.

The waste classification used by Rietfontein Landfill Site is given below:

I. Commercial and Industrial Waste
II. Organic Waste – Garden Waste
III. Organic Waste – Food Waste
IV. Municipal Waste
V. Other Type 2 and/or 3 Solids

The detailed information of the waste composition and quantities for the overall site is illustrated in Figure 3.1.

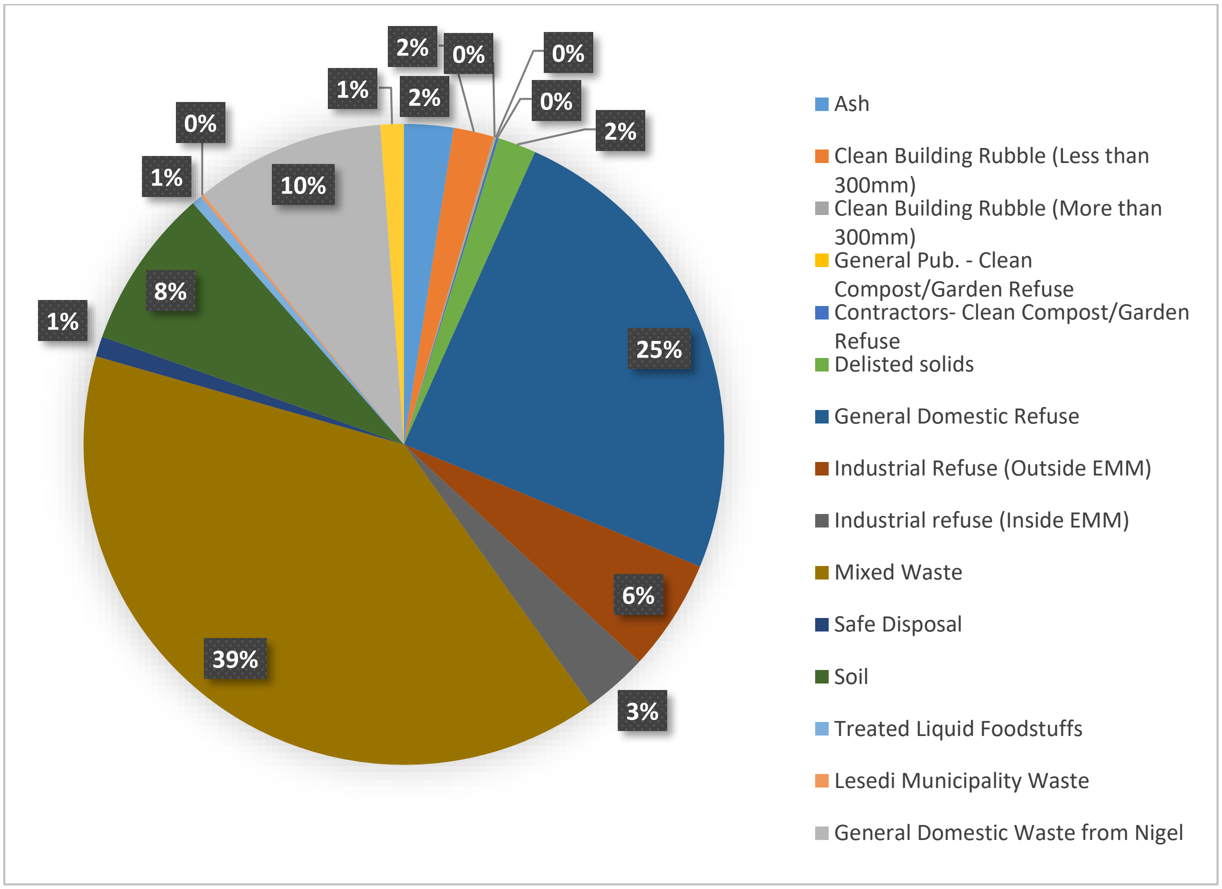


Figure 3.1: Waste Disposal Tonnages for Rietfontein Landfill Site for the period January to October 2019 (personal communication, 13 February 2020)

The explanation of the legend in Figure 3.1 above is as follows (personal communication, 13 February 2020):

- **Ash**: This refers to the ash received from industrial companies.
- **Clean Building Rubble (Less than & more than 300mm)**: This is construction waste such as leftover bricks, broken concrete etc. The 300mm refers to the size of the bricks or concrete rubble.
- **General Pub - Clean Compost/Garden Refuse**: This is organic waste that is not contaminated with any other waste type that is disposed by citizens.
- **Contractors - Clean Compost/Garden Refuse**: This is organic waste that is not contaminated with any other waste type that is disposed by contracting companies.

- **Delisted Solids**: This is hazardous waste that has been treated to lower its dangerous properties so that it can be disposed of as general waste.
- **General Domestic Refuse**: This is waste generated by households.
- **Industrial Refuse (Inside & Outside EMM)**: This is waste produced by industrial or manufacturing activities inside and outside the vicinity of the Ekurhuleni Metropolitan Municipality (EMM).
- **Mixed Waste**: This is a combination of different waste types.
- **Safe Disposal**: This refers to sewer waste that consists of sludge. The waste is analysed at the laboratory beforehand before being disposed into a trench.
- **Soil**: This is soil that is usable as cover material for covering the buried waste during landfilling.
- **Treated Liquid Foodstuffs**: This is contaminated food waste that has been treated to lower its dangerous properties so that it can be disposed of as general waste.
- **Lesedi Municipality Waste**: This is general domestic waste received from a different municipality called Lesedi Municipality.
- **General Domestic Waste from Nigel**: This is general domestic received from an area called Nigel in the East Rand region.

3.2.4 Simulation Input

I. Chosen simulation model and WTE technology

Bio-oil, bio-gas and bio-char are formed by pyrolysis technology. Compared to other thermochemical processes for the conversion of waste, it is also regarded as the most effective technology option (Jahirul et al., 2012). According to Yang, Yao & Chen (2014), pyrolysis is considered an ***advanced technique*** for the processing of liquid oil. It is therefore a technology worth exploring.

The simulation model used in this research project was based on the property packages and compositions from a model used by a company called Biomass Technology Group (BTG) based in The Netherlands. The component selection of the compounds used in the simulation were as a result of the reaction and property packages installed by the BTG company. This model was originally adapted from (Venderbosch, 2019). The original model was obtained in an existing simulation entitled Biomass Pyrolysis on the COCO simulator website ("COCO Simulator", 2020). A detailed description of how the researcher modified and built the pyrolysis process relevant to this study will be discussed in section 3.3.1.2. It must be noted that the Bio-Oil, Biochar and Flue Gas compositions were selected based on the available COCO software compounds installed by Biomass Technology Group and may not share similar properties as other pyrolysis processes. A comprehensive composition of the pyrolysis products from this model is shown in Table 3.1. This fast pyrolysis method is unique to the Biomass Technology Group and University of Twente.

Table 3.1 Composition of pyrolysis products

Flue Gas
Nitrogen
Carbon Dioxide
Oxygen
Biochar
Char
Bio-Oil
Water
High MW lig A
High MW lig B
Benzaldehyde, 3-hydroxy-4-methoxy
2-Butenoic acid, (E)-
Dehydroabietic acid
Isoeugenol
Levoglucosan
Maltose
P-hydroquinone
Nitrogen
Hydroxy acetone

II. <u>Feed material data</u>

- The Reference State = 100 KPa and 25ºC

- To maintain the basis of calculation for the energy balance, the inputs are fed at 25 ºC. The products are also cooled to 25 ºC.
- Assumption: The solid waste has already been dried therefore no dryer is necessary.

The feedstock chosen for the pyrolysis process is organic waste consisting of garden waste. The quantity of garden waste obtained through the data collection amounts to 264 tons over a nine-month period. The ultimate analysis of waste describes the elemental composition of the waste. The proximate analysis describes the ash, moisture content, fixed carbon content, volatile matter and total solid content that is in the waste (Disco, Mahanta & Bora, 2017). There is no data in terms of the ultimate and proximate analysis for this particular landfill site. An assumption had to be made based on South African literature. The proximate and ultimate chemical analysis of the South African municipal solid waste is shown in Table 3.2. It is a reasonable assumption that the solid waste is within these ranges as there is not much South African literature available on the particular feed material for this pyrolysis process. However, a comparison of the ultimate analysis for the South African context and non-South African context is provided in Table 3.3.

For the purpose of this study, pine wood will be used as the feed material for the simulation as was the case for the BTG process. A comparison of the ultimate analysis of pine wood (used by the BTG process) and South African wood, has indicated that they are similar (Table 3.3). Furthermore, the ultimate analysis data for the BTG process and South African wood fall within the acceptable ranges as shown in Table 3.2.

The property package used is an adaptation of the SRK Thermodynamic Package by BTG company. This model is suitable for this system as it is designed specifically for the pyrolysis method and it also utilises garden waste as feedstock. The Pyrolysis Reaction package was utilized in this instance. The information can be validated by the fact that the model adapted from Venderbosch (2019) is quite recent. Therefore, the information used is updated.

Table 3.2 Proximate and ultimate chemical analysis of municipal waste (UNISA, 2005)

PROXIMATE ANALYSIS		
	Range (mass %)	***Typical (mass %)***
Volatile matter	40 - 60	53
Moisture	15 - 40	20
Non-combustible	15 - 30	20
Fixed carbon	5 - 12	7

ULTIMATE ANALYSIS OF COMBUSTIBLE COMPONENTS		
	Range (mass %)	***Typical (mass %)***
Carbon	40 - 60	47
Hydrogen	4 - 8	6
Oxygen	30 - 50	40
Nitrogen	0,2 -10	0,8
Sulphur	0,05 - 0,3	0,2
Ash	1 - 10	6

Table 3.3 Comparison of the ultimate analysis of the combustible components in municipal solid waste for outside South Africa and within South Africa (Vigouroux, 2001; UNISA, 2005)

OUTSIDE SOUTH AFRICA						
Component	**Carbon**	**Hydrogen**	**Oxygen**	**Nitrogen**	**Sulphur**	**Ash**
	(mass %, dry basis)	(mass %, dry basis)	(mass %, dry basis)	(mass %, dry basis)	(mass %, dry basis)	(mass %, dry basis)
Pine Wood	49.3	6.0	44.2	0.5	0.01	0.5

WITHIN SOUTH AFRICA						
Component	**Carbon**	**Hydrogen**	**Oxygen**	**Nitrogen**	**Sulphur**	**Ash**
	(mass %, dry basis)	(mass %, dry basis)	(mass %, dry basis)	(mass %, dry basis)	(mass %, dry basis)	(mass %, dry basis)
Wood	49.5	6.0	42.7	0.2	0.1	1.5

The higher heating value (HHV) refers to the heat emitted in a condensed state from fuel combustion with the initial and produced water. On the other hand, the lower heating value(LHV) is centred on gaseous water as the product (Sheng & Azevedo, 2005). However, for this research, no calculations of HHV and LHV are necessary. This is due to the fact that both the HHV and LHV values are calculated automatically by the COCO simulator using a built-in chemical formula.

A calculation provided by (Jahirul et al., 2012) indicates a typical calculation of the HHV as below, however it was not necessary for the researcher to incorporate this formula into the simulation:

$$\text{HHV (kJ/kg)} = 354.68\,C + 1376.29\,H - 15.92\,\text{Ash} - 124.69\,(O+N) + 71.26$$

It must be noted that the amounts of C, H, O, N and ash for the above calculation are expressed as mass %.

To obtain HHV values: The pure compound values needed to calculate this parameter were automatically identified by the Pure Compound Data (PCD) files since there was a match found. Once compounds have been loaded from a PCD file, they are then stored in the configuration data of the property package.

To obtain LHV values: The chemical formula for calculating the compounds such as C, H, O etc is also built into the simulator. Therefore, the LHV values were automatically determined and calculated at reference conditions of 25°C and 100 KPa.

III. Process Flowsheet and tables

In order to better simulate and illustrate information about a process, process flowsheets are created. A schematic diagram of the pyrolysis process for the COCO simulator and process conditions for the main process units are illustrated in Figure 3.2. The pyrolysis simulation for this research was based entirely on this specific process flowsheet. The feed flowrate was calculated based on 264 tons of garden waste collected over a 9-month period. The plant will be operating on a 24-hour basis for 365 days.

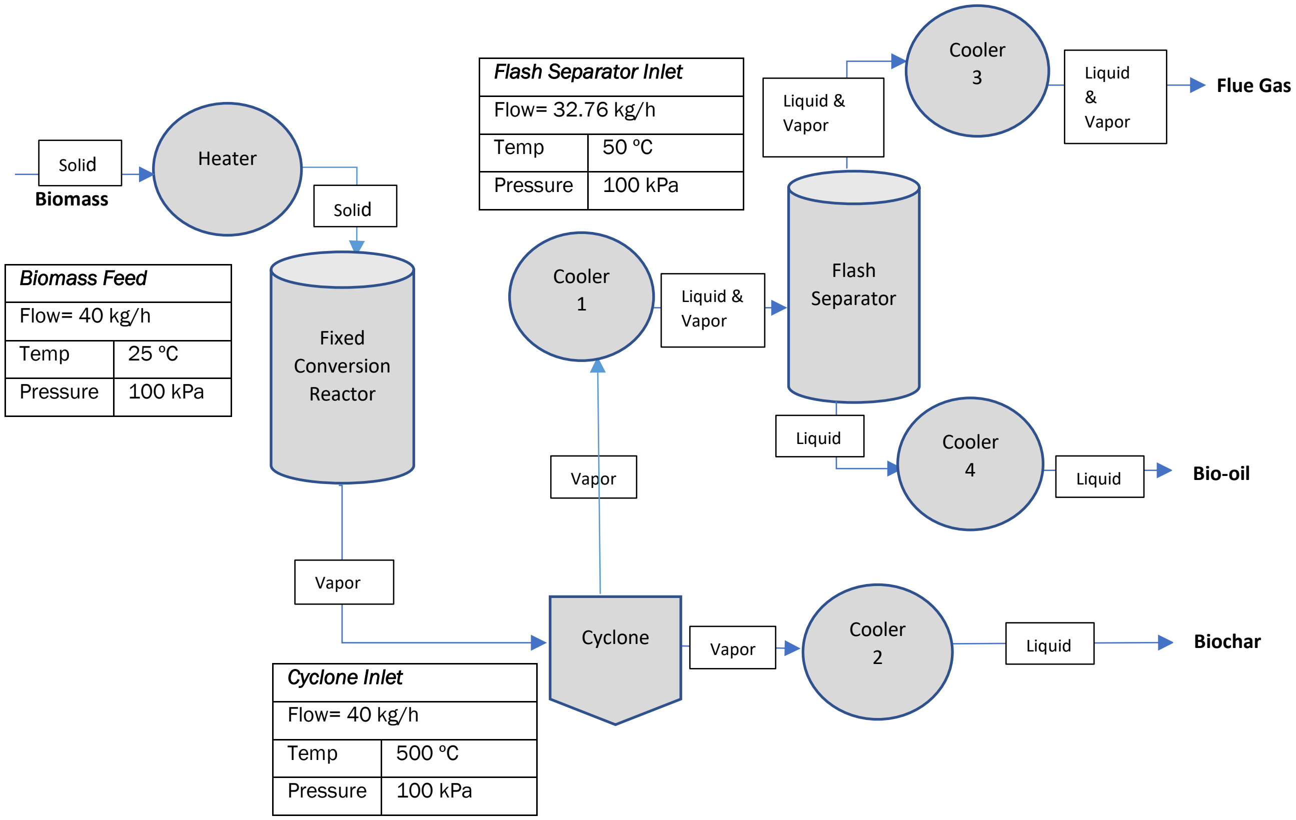


Figure 3.2: Schematic diagram of the researcher's pyrolysis process used for COCO

A description of the various process units used in the COCO simulator and their respective functions and operating conditions are outlined below in Table 3.4:

Table 3.4 Process unit data and operating conditions used for COCO simulation

Process Unit Name	**Function**	**Type**	**Temperature (°C)**	**Pressure (kPa)**	**Conversion (%)**
Reactor	It is used to perform reactions using a specified conversion.	Fixed Conversion Reactor	500 °C	100 kPa	100% (dry pine wood)
Cyclone	It is used to split compounds into pre-defined fractions.	Compound Splitter	500 °C	100 kPa	-
Heat Exchangers	They are used to heat a stream specifying heat duty or outlet temperature.	-	25°C	-	-

Process Unit Name	Function	Type	Temperature (°C)	Pressure (kPa)	Conversion (%)
Coolers	They are used to cool a stream specifying heat duty or outlet temperature.	-	25°C & 50°C	-	-
Separator	It is used to separate input stream into vapour and remaining phases.	Flash	50°C	100 kPa	-

3.2.5 Literature Consulted

Journals were used to obtain data for the cost of equipment, capital costs formulas (Sadhukhan & Martinez-Hernandez, 2017), process unit specifications (Wright et al., 2010; Yang et al., 2018), market cost of woody biomass feedstock (Dutta et al., 2015). Literature books assisted with determining equipment types and sizes (Towler & Sinnott, 2008), economic evaluations, equipment cost estimations (Peters, Timmerhaus & West, 2003). It is imperative to note that this is a provisional list of journals and technical books utilised for the study.

3.2.6 Data from public domain

The data from the public domain and government agencies were utilised for this research. This included data from the following sources (however, this list is not complete):

Department of Environmental Affairs, Statistics South Africa, Gauteng Waste Information System (GWIS), Department of Water Affairs and Forestry, Ekurhuleni Metropolitan Municipality, Department for Environment Food & Rural Affairs, South African Waste Information etc.

3.3 DATA PROCESSING

3.3.1 COCO (CAPE-OPEN to CAPE-OPEN) Simulation Program

3.3.1.1 Elements in COCO

COCO (CAPE-OPEN to CAPE-OPEN) is a CAPE-OPEN steady-state simulation software compatible with Windows XP or higher. It is a free software that consists of the elements stated in Appendix C.

3.3.1.2 Modifying and building the flowsheet using COFE

- As a starting point, an existing simulation called 'Biomass Pyrolysis' was used ("COCO Simulator", 2020). All that was needed from that existing simulation was the property and reaction packages. The existing simulation was modified to the specific circumstances in this particular study using that 'BTG Pyrolysis' property package and reaction package.

- A stream was inserted for the Biomass Feed using the 'Insert' tab. The pressure was set to 100 kPa and the temperature set to 25°C. The flow was set to 40 kg/h after a manual calculation; using the 264 tons of garden waste collected over a nine-month period. The mass fraction of dry pine wood was set to 1 while the mass fractions for all the other components were set to 0. The volume and enthalpy of the stream were calculated by the simulator based on the reaction package installed.

- A heater was then inserted using the ‘Insert unit operation’ icon. An outlet stream was drawn from the heater.

  Using the ‘Insert unit operation’ icon, a fixed conversion reactor was inserted. The reaction package was assigned by right-clicking the reactor. The chosen reaction package was the ‘pyrolysis reaction’. Afterwards, the reaction temperature was set to 500°C. According to Boateng (2020), operating the reactor at temperature of 500°C -550°C will provide the highest liquid yields of bio-oil. The pressure drop was assumed to be zero. Under the ‘Reactions’ tab, the ‘add reaction’ option was selected. Next, ‘dry pine wood’ was chosen as the reaction ID and 100% conversion of the compound ‘dry pine wood’ was used. This conversion was deemed as a typical conversion for producing fuels (Passamonti & Sedran, 2012). The flowsheet was then solved using the Solve icon.
- The flowrate, pressure and temperature from the outlet stream of the reactor were automatically calculated by the simulator.
- A compound splitter to split a stream into two streams was drawn and a cyclone unit inserted in the place of the compound splitter. Coolers were added and the composition of the two streams (pressure, temperature and mass flowrate) was calculated automatically by the simulator. The bottom stream of the cyclone is the Biochar stream and the top stream from the cyclone is the inlet stream to the flash separator unit.
- A flash separator unit was then inserted using the ‘Insert unit operation’ icon. Two outlet streams were drawn from the top and the bottom of the flash separator unit. Coolers were added and outlet streams added for the Flue Gas (Top stream) and Bio-oil stream (Bottom stream) respectively. Once again, the composition of the streams (pressure, temperature and mass flowrate) was calculated automatically by the simulator.
- All streams were renamed to be more representative of the process.
- The ‘Solve’ icon was used once again to solve the entire flowsheet and collate results.

3.3.1.3 Varying Parameters

A number of parameters were changed from the creation of the simulation until the final report was printed. The changes included the following adjustments which are not exhaustive:

- The Biomass Technology Group (BTG) Pyrolysis Sample Process Flow was initially modified and used as part of the study. However, it was then discarded and a new process flow was created from scratch.
- The pyrolysis reactions taking place in the reactor were amended
- The conversion in the reactor was increased from 60% to 100%
- The separator temperature was adjusted to operate at 40˚C instead of 50˚C

In essence; the process conditions, phases, mole fractions and components selection were all adjusted.

3.3.2 Value Analysis Method To Measure The Economic Margins Of Recovered Products

For differential economic marginal analysis from process streams to process networks, a value analysis tool was created. The Value Analysis Method was developed by (Sadhukhan et al., 2008; Sadhukhan, 2014) and Martinez-Hernandez, Campbell & Sadhukhan (2014). The Value Analysis Method assists in measuring the economic margins of recovered products from municipal solid waste is adopted from the above-mentioned citations. It allows a network margin to be measured and graphically displayed in terms of cost of production (COP), value of processing (VOP) and margins of individual streams (Martinez-hernandez, Campbell & Sadhukhan, 2014).

The assumption for the simulation and this project is that this is a new plant therefore the cost data is not readily available. The cost data is scarce, not easily available, or may be proprietary to organizations. Consequently, the cost of equipment will need to be estimated on the basis of current methodologies or related equipment provider quotes. Different sources collect the basic costs and scale variables (Sadhukhan, Ng & Martinez Hernandez, 2014).

The overall economic margin is given by aggregating the economic margins of the exit flows. The maximization of the positive economic margins of goods that do not make profit and the minimization or removal of the negative economic margins of goods that do not make profit and exit flows will thus offer the overall system the biggest economic margin (Sadhukhan & Martinez-Hernandez, 2017).

3.3.2.1 Capital expenses required

According to Sadhukhan, Ng & Martinez Hernandez (2014), the fixed capital expenses are the cost of a plant being constructed. It tends to be partitioned into direct capital and indirect capital expenses. Direct capital expenses apply to the buying and installing of unit equipment for the plant. The costs of equipment assembly, piping, instrumentation and control, electrical work, yard overhauls and supporting facilities such as administration offices are part of the direct capital expenses (Sadhukhan & Martinez-Hernandez, 2017). On the other hand, the engineering, management, construction cost, legal, and independent service provider costs form part of the indirect expenses (Patel et al., 2020). Pricing information and correlation for standard equipment have been collected from literature and assumptions made have been mentioned throughout the chapter.

Using price and size correlation, the delivered equipment expenditure can be determined first by utilizing Equation (1) which incorporates a scaling factor. The scaling factor is used to measure a system's cost dependent on the system's known cost for a dissimilar size (Sadhukhan, Ng & Martinez Hernandez, 2014). This is followed by updating the expense from a previous/baseline year to the present year. This is accomplished by using the Chemical Engineering Plant Cost Index (CEPCI) as demonstrated in Equation (2). The diverse CEPCI for different base years were obtained from Dutta et al., (2015). The CEPCI utilized for the present year is the 2019 CEPCI of 607.5 (“Chem Eng Online”, 2021).

$$\text{Latest price at the baseline year} = \text{Baseline Price x} \left(\frac{\text{New Size}}{\text{Baseline Size}}\right)^{\text{Scaling Factor}} \tag{1}$$

$$\text{Latest price at the present year} = \text{Latest price at the baseline year x} \left(\frac{\text{Latest year CEPCI}}{\text{Baseline year CEPCI}}\right) \tag{2}$$

The total capital expenditure is the sum of direct expenses, indirect expenses and working capital. This total capital expenditure is additionally alluded to as the capital expense (CAPEX). Typically, the FCI is determined as a factor of the delivered equipment cost, known as the Lang Factor (Peters, Timmerhaus & West, 2003). For example, the FCI for a fluid-processing plant is 5.03 times the delivered equipment expenditure (Sadhukhan, Ng & Martinez Hernandez, 2014). As indicated by Sadhukhan (2014), the delivered equipment cost is determined utilizing Equation 1 and Equation 2 above. A yearly investment fee of 13 % corresponding to a 10 % discount value, a 15-year life cycle and a 2-year cycle for establishment can be applied to the CAPEX to gauge the yearly investment expense. This would need to correspond with investment usage of 25 % for the first year, followed by 75 % for the second year (Sadhukhan, Ng & Martinez-Hernandez, 2016).

To calculate the overall annual operating expense of the process, the yearly unit capital expense should be included to the yearly operating expenses. Variable operating expenses, such as raw materials and utilities, are dependent on the production capacity of the plant. Sadhukhan, (2014) provides the estimates for determining the fixed operational costs like labour, management, maintenance, plant overheads and so forth.

The fixed operating cost elements are listed below (Sadhukhan & Martinez-Hernandez, 2017):

- Maintenance expenses, support charges, insurance, state expenses and sovereignties = 24% of the indirect capital expense.

- Overhead costs of supervision, laboratory and plant = 90 % of labour costs.

- Fixed Costs for Personnel = $\frac{\text{Percentage CAPEX of individual process unit}}{100}$

The direct production cost (DPC) is the sum of the variable and fixed operating expenses. This is composed as DPC = variable operating expenses (for instance this alludes to raw materials, utilities and so forth) + fixed operating expense. The DPC can be increased by 30% to consider sundry items. These sundry items include items such as sales and marketing costs, R&D and general overheads (Sadhukhan & Martinez-Hernandez, 2017) . The assumption made is that the yearly working hours are 8000 hours.

The following parameters in Table 3.5 need to be calculated as part of using the value analysis method for determining the economic margins of the recovered products. These are known as capital costs. The formulas used for these calculations are provided by Sadhukhan & Martinez-Hernandez (2017).

Table 3.5 Capital costs parameters and formulas

Parameter	Formula
Delivered Equipment Cost	Latest Price at the Baseline Year (Process Unit) = Baseline Price x (New Size/Baseline Size) $^{\text{Scaling Factor}}$ Latest Price at the Present Year (Process Unit) = Latest Price at the Baseline Year x (Latest Year CEPCI / Baseline Year CEPCI)
CAPEX	CAPEX (Process Unit) = 5.03 x Delivered Equipment Cost
% CAPEX	Percentage CAPEX (Process Unit) = $\frac{\text{CAPEX for Process Unit}}{Overall\ Total\ CAPEX}$
Annual Capital Cost	Annual Capital Cost (Process Unit) = Annual charge x Total CAPEX
Fixed Costs (Indirect Capital Cost)	Indirect Capital Cost (Process Unit) = 0.3024 x Delivered Equipment Cost x Annual capital charge
Fixed Costs (Personnel)	Fixed Costs (Personnel) = $\frac{\text{Percentage CAPEX of individual process unit}}{100}$
Total Operating Costs	Total Fixed Costs (Process Unit) = Fixed Costs (Indirect Capital Cost) + Fixed Costs (Personnel) Total Operating Cost (Process Unit) = 1.3 x Total Fixed Costs (Process Unit)
Total Annual Costs	Total Annual Cost = Annual Capital Cost + Annual Operating Cost

3.3.2.2 Cost of Production (COP), Value on Processing (VOP) and Economic Margins

To get the economic margin of a stream, the flowrate of the stream is multiplied with the difference between its processing value (VOP) and its production cost (COP). This equation is illustrated in Equation (3). As this is a South African-based research, the South African currency of Rands will be used. The units for the flowrate (F) is kg/h as an example. Ultimately the units of the COP is Rand/kg. The Economic Margin (M) unit is Rand/h respectively.

$$Em_i = F_i \, x \, (VOP_i - COP_i) \tag{3}$$

Once the COP and VOP values have been determined, it is simple to calculate the economic margin

where

Em_i = Economic Margin (Rand/h)

F_i =Stream Flowrate (kg/h)

VOP_i = Value on Processing Value of stream (Rand/kg)

COP_i = Cost of Production Value of stream (Rand/kg)

A stream's VOP is the final product prices minus the prices of additional feedstock, services, and the yearly capital expenditure of process units that lead to its continued conversion into the end product(s). Accordingly, the VOP of a feed to a unit of the method is determined from the known VOP values of the outlet sources and the overall process costs unit. An illustration of this is provided by Equation (4).

$$VOP_{f=}[\sum_{p=1}^{q} VOP_p P_p - O_k] / \sum_{f=1}^{g} F_f \tag{4}$$

where

q = product number

g = feedstock number

P_p =commodity mass flow rate (kg/h)

F_f = feedstock mass flow rate (kg/h)

O_k = total unit costs (million Rand/year)

In the above equation, q is the product number and g is the feedstock number (This excludes supplementary raw materials) known as primary material sources. P_p and F_f refer to commodity and feedstock mass flowrate, respectively. Remember that for a finished product, the stream VOP will correlate to the market price. All related cost elements such as the raw material prices, supplementary feedstocks, services and yearly investment expenditures that have contributed to the output of the stream, are summarized by the COP of a stream. This suggests that solitary certain partial costs engaged with the handling of the stream are remembered for its COP. The COP of an item from a measure unit is resolved based on the known expense of taking care of streams f and of the absolute expense of process unit k. This is indicated by Equation (5).

$$COP_{f=}[\sum_{f=1}^{q} COP_f P_f + O_k] / \sum_{f=1}^{g} F_f \qquad (5)$$

where

q = product number

g = feedstock number

P_f = commodity mass flow rate (kg/h)

F_f = feedstock mass flow rate (kg/h)

O_k = total unit costs (million Rand/year)

The COP is calculated first, followed by the VOP and ultimately the economic margin is calculated. A positive economic margin value indicates a profit. However, a negative economic margin indicates a loss (Sadhukhan, Ng & Martinez Hernandez, 2014). According to Martinez-Hernandez, Campbell & Sadhukhan (2014) if a stream has a negative economic margin, the buying of that stream from the marketplace will be better than manufacturing it within the process. Therefore, to commence with the calculations of the VOP, the feedstock cost has to be known. If the feedstock cost is unknown, it will be impossible to calculate the COP. To determine the COP of a product, the COP of its feed material must be added to the unit charge of the responsible process for generating it. The feedstock cost is determined by the disposal cost of the feedstock, in this case the garden waste, from the Ekurhuleni municipality.

The charge for disposing garden waste at local Ekurhuleni municipality = R155.43/Ton (City of Ekurhuleni, 2019). When converted to Rand/Ton to suit the units used throughout the study, this amounts to R 0.155/kg. The researcher used the category that has a cost for disposing clean compostable garden refuse by independent service providers or by the citizens. This disposal cost of garden waste is the cost of feedstock and is useful when determining the Cost of Production (COP).

A rebate is not applicable to business institutions such as this biorefinery plant therefore there is no gate fee applicable from the local Ekurhuleni municipality for treating the municipal solid waste. Therefore, the R 0.15/kg value is the final cost of feedstock that will be used throughout this chapter.

It is worth noting that COP only meets the market price if a stream is an externally supplied feedstock or input flow to the system.

To evaluate the COP, one begins from knowing the raw material market prices and continues in the forward way stream by stream until the finished products are attained. The market prices of feedstocks are obtained from various journals. The sum of all cost factors such as utilities, feedstock costs, annual capital costs etc. make up the COP of a stream.

On the other hand, the VOP is evaluated differently. It starts backwards from the market prices of the final product until the feedstock is found. The market prices of products are obtained from various journals. A stream's VOP is summed up from the product costs that will be generated from it. Then the auxiliary raw materials, cost of utilities, annual capital costs etc are deducted from the summation of the product prices.

3.4 SIMULATION OUTPUT

Once the simulation has been processed, certain outputs are expected from the simulation. These outputs are:

- Mass flowrates for each main process
- Energy balances of the system
- Mass flowrates of value-added products (Bio-oil, Flue Gas and Biochar)

The results and discussion that have been acquired from this methodology will be discussed and analysed in the next chapter.

REFERENCES

Antal, M.J. & Gronli, M. 2003. The Art , Science , and Technology of Charcoal Production. *Industrial & Engineering Chemistry Research*. 42(8):1619–1640.

Boateng, A. 2020. Pyrolysis of Biomass For Fuels and Chemicals. In *Pyrolysis of Biomass For Fuels and Chemicals*. Akwasi A. Boateng, Ed. Academic Press. 1–21.

Chem Eng Online. 2021. Available: https://www.chemengonline.com/2020-cepci-updates-december-prelim-and-november-final/ [2022, January 31].

City of Ekurhuleni. 2019. Tariffs: Waste Management Services and Incidental Charges. 1–9.

COCO Simulator. 2020. Available: https://www.cocosimulator.org/ [2020, July 03].

Disco, Y., Mahanta, P. & Bora, U. 2017. Comprehensive characterization of lignocellulosic biomass through proximate , ultimate and compositional analysis for bioenergy production. *Renewable Energy*. 103:490–500.

Dutta, A., Sahir, A., Tan, E., Humbird, D., Snowden-Swan, L.J., Meyer, P., Ross, J., Sexton, D., Yap, R., Lukas, J.L. 2015. *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Thermochemical Research Pathways with In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors*. Available: http://www.osti.gov/servlets/purl/1215007/.

Hu, Y., Bassi, A. & Xu, C.C. 2020. Energy from biomass. In *Future Energy: Improved, Sustainable and Clean Options for Our Planet*. Elsevier. 447–471.

Jahirul, M.I., Rasul, M.G., Chowdhury, A.A. & Ashwath, N. 2012. Biofuels production through biomass pyrolysis- A technological review. *Energies*. 5(12):4952–5001.

Martinez-hernandez, E., Campbell, G.M. & Sadhukhan, J. 2014. Economic and environmental impact marginal analysis of biore fi nery products for policy targets. *Journal of Cleaner Production*. 74(2014):74–85.

Passamonti, F.J. & Sedran, U. 2012. Recycling of waste plastics into fuels. LDPE conversion in FCC. *Applied Catalysis B: Environmental*. 125:499–506.

Patel, A.D., Zabeti, M., Seshan, K. & Patel, M.K. 2020. Economic and Environmental Assessment of Catalytic and Thermal Pyrolysis Routes for Fuel Production from Lignocellulosic Biomass. *Processes*. 8(12):1–18.

Peters, M.S., Timmerhaus, K.D. & West, R.E. 2003. *Plant Design and Economics for Chemical Engineers*. V. 369. Available: http://dx.doi.org/10.1016/j.jsames.2011.03.003%0Ahttps://doi.org/10.1016/j.gr.2017.08.001%0Ahttp://dx.doi.org/10.1016/j.precamres.2014.12.018%0Ahttp://dx.doi.org/10.1016/j.precamres.2011.08.005%0Ahttp://dx.doi.org/10.1080/00206814.2014.902757%0Ahttp://dx.

Sadhukhan, J. 2014. Distributed and micro-generation from biogas and agricultural application of sewage sludge : Comparative environmental performance analysis using life cycle approaches. *Applied Energy*. 122:196–206.

Sadhukhan, J. & Martinez-Hernandez, E. 2017. Material flow and sustainability analyses of biorefining of municipal solid waste. *Bioresource Technology*. 243:135–146.

Sadhukhan, J., Mustafa, M.A., Misailidis, N., Mateos-salvador, F., Du, C. & Campbell, G.M. 2008. Value analysis tool for feasibility studies of biorefineries integrated with value added production. 63:503–519.

Sadhukhan, J., Ng, K.S. & Martinez Hernandez, E. 2014. *Biorefineries and Chemical Processes: Design, Integration and Sustainability Analysis*. First ed. John Wiley & Sons, Ltd.

Sadhukhan, J., Ng, K.S. & Martinez-Hernandez, E. 2016. Novel integrated mechanical biological chemical treatment (MBCT) systems for the production of levulinic acid from fraction of municipal solid waste: A comprehensive techno-economic analysis. *Bioresource Technology*. 215:131–143.

Sheng, C. & Azevedo, J.L.T.Ã. 2005. Estimating the higher heating value of biomass fuels from basic analysis data. 28:499–507.

Towler, G. & Sinnott, R. 2008. *Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design*. Second edi ed. G. Towler & R. Sinnott, Eds. California: Elsevier Inc.

UNISA. 2005. *Solid Waste Treatment (Chemical) IV*. First ed. Pretoria.

Venderbosch, R.H. 2019. Fast Pyrolysis Thermochemical Processing of Biomass. 32:175–206.

Vigouroux, R.Z. 2001. Pyrolysis of Biomass. Royal Institute of Technology.

Wright, M.M., Satrio, J.A., Brown, R.C., Daugaard, D.E. & Hsu, D.D. 2010. Techno-economic analysis of biomass fast pyrolysis to transportation fuels. Technical Report NREL/TP-6A20-46586. *Nrel*. 89(November):463–469. Available: https://doi.org/10.1016/j.fuel.2010.07.029.

Yang, H., Yao, J. & Chen, G. 2014. Overview of upgrading of pyrolysis oil of biomass. *Energy Procedia*. 61:1306–1309.

Yang, Y., Wang, J., Chong, K. & Bridgwater, A. V. 2018. A techno-economic analysis of energy recovery from organic fraction of municipal solid waste (MSW) by an integrated intermediate pyrolysis and combined heat and power (CHP) plant. *Energy Conversion and Management*. 174:406–416.

Zaman, C.Z., Pal, K., Yehye, W.A., Sagadevan, S., Shah, S.T., Adebisi, G.A., Marliana, E., Rafique, R.F., et al. 2017. Pyrolysis: A Sustainable Way to Generate Energy from Waste. *Pyrolysis*. 3–36.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter presents the results obtained from the CAPE-OPEN to CAPE-OPEN (COCO) simulation software which aids in answering the objectives of this research. In addition to the simulation software results, the findings for the challenges faced by landfills in Johannesburg East are included in this chapter. The rest of the chapter focuses on the discussion of the results obtained from the research. The recovered products obtained from the fast pyrolysis process are bio-oil, biochar and flue gas. The mass and energy balances for the process units have been included in this chapter. The rest of the mass and energy balances for each individual stream are included in the simulation report in Appendix D. In addition to the above, a sensitivity analysis has been conducted to analyse the effect of certain variables on the output from the simulation.

4.2 CHALLENGES FACED BY LANDFILLS IN THE EAST OF JOHANNESBURG

4.2.1 Challenges identified through the Rietfontein Landfill Site tour

During the site tour and discussion with the Ekurhuleni Metropolitan Municipality Landfill Site Supervisor several challenges were identified (personal communication, 13 February 2020).

Reclaimers

One of the major challenges identified is the issue of reclaimers on site. Reclaimers are people from the community who are based on the landfill site to separate and sort the waste before it is landfilled (Letlape & Gumbo, 2016). However, they are not employed by the Ekurhuleni Metropolitan Municipality and this leads to the municipality not having proper control over them. Proper control refers to the fact that they do not make use of the main entrance gate when coming to the landfill site, instead they gain access illegally such as through using man-made holes in the fence or by jumping over the fence. As a result of this, the security at the entrance gate had no record of how many reclaimers are on site and this is important for safety protocols as required by the Occupational Health and Safety Act (Republic of South Africa, 1993) . The reclaimers do not adhere to site rules as no site induction has been carried out for them. This causes them to be quite unruly and ungovernable. They reclaimed items from the municipal waste into their white recycling bags, moved their white recycling bags to the outside of the landfill site and burnt some of the reclaimed items to get valuable minerals such as copper which they sold for money. Reclaimers do not understand the importance of wearing personal protective equipment (PPE). This poses potential safety and health risk as they are exposed to hazards daily. A report by South African Cities Network (SACN) (2014) states that the existence of reclaimers on landfill sites indeed creates a health problem and presents danger. With the reclaimers on the landfill sites, they are salvaging items on their own, posing a greater challenge for the municipality in handling the waste disposal operation.

A designated area has been allocated for them to place the bags containing the recycled items but at times they do not adhere to that and can leave their bags lying all over the site as indicated in Figure 4.1 and Figure 4.2. There was also an issue of odour emanating from the reclaimers' bags.

Figure 4.1: White recycling bags used by reclaimers at Rietfontein Landfill Site (13 February 2020)

Figure 4.2: Reclaimers with their white recycling bags scattered at Rietfontein Landfill Site (13 February 2020)

Reclaimers need to be accounted for legally and should be prohibited from entering the landfill site unlawfully without signing the register at the gate. One of the proposed actions from the South African Cities Network (SACN) (2014) is to encourage the formalization of the informal waste industry which is the industry that reclaimers fall under. Formalizing the informal waste industry will likely curb all the current issues experienced in landfill sites. This is still in progress because as of August 2022, the Council for Scientific and Industrial Research (CSIR) and the waste reclaimer organizations have stated that there is a planned training and awareness programme for waste reclaimers. Other proposed actions by the South African Cities Network (SACN) (2014) include providing reclaimers with resources to form cooperatives, access to funding for improving their equipment, agreeing on contracts for accessing waste sources, ensuring the protection of their livelihood through preparing strategies and improving the quality of life of the informal recycling sector. All of these proposed actions have not been implemented as the informal waste industry needs to be formally legalized first. The issue of reclaimers seems to be a common problem for all the landfill sites as per the discussion with the Ekurhuleni Metropolitan Municipality Landfill

Site Supervisor. Proper Personal Protective Equipment (PPE) needs to be sought for them to prevent them from being exposed to harmful odours on site. Issuing them the necessary PPE will fulfil the requirements of the Constitution of the Republic of South Africa. As per Section 24 of the Constitution of the Republic of South Africa (The Constitution of the Republic of South Africa, 1996), it is laid out that each citizen of the Republic is qualified for an environment that is not hurtful to their wellbeing and health. The Constitution further commands the local government with the obligation of giving refuse collection services to the citizen to guarantee that their Constitutional rights are not abused. The reclaimers need an induction to give them more insight into environmental impacts and safety legislation. They also need to understand the consequences of not adhering to the site rules such as not placing their white recycling bags in the designated area. To persuade reclaimers to comply is an exercise that will not happen overnight. This is due to the fact that the reclaimers' core focus is on benefitting economically from selling the recycled waste to the informal waste market (Letlape & Gumbo, 2016). However, proper control needs to be implemented as this affects the operation of landfill sites.

Table 4.1 provides a summary of the above challenges together with the actions that have taken place or need to take place and the responsible body.

Table 4.1 Summary of challenges posed by waste reclaimers

Challenge Identified	What has been done/What can be done?	Responsible department/person /government arm
No formalisation of waste reclaimers resulting in illegal access to landfill sites	As of August 2022, efforts have been made to formalise waste reclaimers and there is a planned training and awareness programme for the waste reclaimers (South African Government News Agency, 2022). However, it has not been indicated when this training and awareness programme will take place.	Council for Scientific and Industrial Research (CSIR) and waste reclaimer organisations
Waste reclaimers do not use Personal Protective Equipment (PPE) or seem to know of the dangers they are exposed to on landfill sites	Once the waste reclaimers' industry is formalised and the awareness training has taken place, they need to be provided with Personal Protective Equipment (PPE) once they have undergone SHE training.	Ekurhuleni Metropolitan Municipality personnel ie. Landfill Site Supervisor and Safety Officer
Waste reclaimers do not place their recycling bags at the designated area or adhere to landfill site rules	Landfill Site Induction Training needs to take place	Ekurhuleni Metropolitan Municipality personnel ie. Landfill Site Supervisor and Safety Officer

Leachate dams

The leachate dams are a concern as they were filled to capacity (Figure 4.3) and the site only relies on evaporation for their capacity to decrease. The Ekurhuleni Metropolitan Municipality Landfill Site Supervisor highlighted that this was a daily challenge and stems from many years ago (personal communication, 13 February 2020). Furthermore, he mentioned that during the rainy seasons the leachate dams tend to get full and there is no covering for the leachate dams to prevent rainwater from flowing into the leachate dams. There was also a slight odour coming from the leachate.

Figure 4.3: Leachate dam at Rietfontein Landfill Site (13 February 2020)

The issue of the leachate dams being filled to capacity with no mechanical mechanism in place to empty them, is a great concern. Firstly, the reliance on evaporation is not a reliable method as the weather changes drastically from time to time. During rainy days, the leachate dam capacity is challenged as the dams are close to overflowing. Putting covers over the dams may or may not work. It will be a labour-intensive exercise which is open to human error should the responsible person forget to put on the cover. The best option would be to install a mechanical mechanism that will pump the leachate to a holding tank to be treated offsite for the reduction of organic and inorganic impurities in the leachate. The type of leachate treatment required varies greatly on a number of factors. These factors can include: the class of leachate (Miao et al., 2016), leachate composition and volume (Jagaba et al., 2021), and so forth. The majority of these treatment techniques have been developed for treating wastewater and can be classified into two categories: biological and physical/chemical treatments (Raghab et al., 2013).

Secondly, slight odours coming from the leachate dams may affect the health of people on the landfill site in the future should they not be properly controlled. Once again, should the health of people on the landfill site get affected, this will be contravening Section 24 of the Constitution of the Republic of South Africa (The Constitution of the Republic of South Africa, 1996). The Ekurhuleni municipality needs to find urgent solutions to prevent possible environmental impacts from occurring in the long run. This is a challenge that can be solved over time through continuous environmental impact monitoring and enforcing strict adherence to environmental regulations.

4.2.2 Recovered Products From CAPE-OPEN TO CAPE-OPEN (COCO) Simulation Software

As mentioned in the previous chapter, the pyrolysis process produces: flue gas, bio-oil and biochar. The compositions of each of these value-added products are expressed in more detail in the below sections. Table 4.2 provides the overall compositions of recovered products from the pyrolysis process.

Table 4.2 Overall compositions of recovered products from pyrolysis process

COMPONENT	BIOCHAR (Mole Fraction)	FLUE GAS (Mole Fraction)	BIO-OIL (Mole Fraction)
Water	0	9.6×10^{-02}	0.57
Oxygen	0	4.6×10^{-02}	1.1×10^{-05}
High MW lig A	0	1.4×10^{-20}	1.1×10^{-02}
High MW lig B	0	1.9×10^{-21}	1.1×10^{-02}
Benzaldehyde, 3-hydroxy-4-methoxy-	0	4.7×10^{-08}	3.3×10^{-02}
2-Butenoic acid, (E)-	0	9.8×10^{-04}	0.08
Dehydroabietic acid	0	4.6×10^{-06}	1.1×10^{-02}
Isoeugenol	0	1.8×10^{-06}	2.1×10^{-02}
Levoglucosan	0	5×10^{-09}	8.1×10^{-02}
Maltose	0	3.3×10^{-22}	0.08
P-hydroquinone	0	4.9×10^{-06}	6.3×10^{-02}
Carbon Monoxide	0	0.43	2.6×10^{-05}
Carbon Dioxide	0	0.33	1.5×10^{-03}
Methane	0	9.7×10^{-02}	2.9×10^{-05}
Char	1	0	0
Hydroxyacetone	0	2.9×10^{-4}	3.8×10^{-2}

The biochar stream contains 100% char from the pyrolysis process. The flue gas contains 9.6% Water, 4.6% Oxygen, 0.09% 2-Butenoic acid (E) gas, 43% Carbon Monoxide, 33%

Carbon Dioxide, 9.7% Methane and 0.029% Hydroxyacetone. An article on the current status of the pyrolysis and gasification mechanism of biomass by Glushkov et al., (2021) has reviewed the data on flue gas product composition. The article indicates that flue gas compositions for a pyrolysis process operating at temperature of 700°C - 800°C should be 35-36% Carbon Monoxide, 16-22% Carbon Dioxide and 12-13% Methane. Flue gas composition data for a pyrolysis process operating at lower temperatures could not be obtained from literature. The results from Glushkov et al., (2021) are slightly lower than those obtained from this study as the current reactor temperature for this study is 500°C. These results are unexpected because at lower temperatures the gas composition becomes lower. The bio-oil contains 57% Water, 8% Maltose, 8% 2-Butenoic acid, 8.1% Levoglucosan and small fractions of other components. The composition of the pyrolysis bio-oil was researched by Paiva et al., (2019). According to that research, the water content entrained in bio-oil should fall within the 15-30% range. This does not match the findings from this study as the water content is almost double the stipulated amount. However, the research by Paiva et al., (2019) does not indicate whether the water content range of 15-30% for the bio-oil is the range after water separation has taken place or not. Furthermore, the research by Paiva et al., (2019) states that the amount of levoglucosan in pyrolysis must be more than 5 wt %. The results from this study are in line with what is stated by Paiva et al., (2019) regarding the levoglucosan level.

To obtain the recovered products above, a number of process units were utilised. Each process unit performed a specific function. The purpose of the Flash Separator shown in Figure 4.5 is to separate the input stream into vapor and remaining phases. Whilst the purpose of the compound splitter which is represented in Figure 4.5 of this chapter by a cyclone; is to separate solids out from the reactor product stream. The top stream extracted from the cyclone was in the vapor phase. This top stream from the cyclone was then cooled down and a phase change took place. The cooled stream from the cyclone then consisted of a combination of vapour and liquid phases after being cooled. Then this cooled top stream from the cyclone now entered the Flash Separator to separate it into the bio-oil and flue gas streams. Both the bio-oil and flue gas streams were cooled down. The biochar product stream did not enter the Flash Separator as it was the bottom stream of the cyclone. After extraction from the bottom stream of the cyclone, the char product stream was cooled down.

Figure 4.4 indicates the yield for these recovered products as: 13% flue gas, 18% biochar and 69% bio-oil. Figure 4.4 below highlights that from this pyrolysis process bio-oil was the highest recovered product because fast pyrolysis is associated with high yields of bio-oil (van Schalkwyk, 2019).

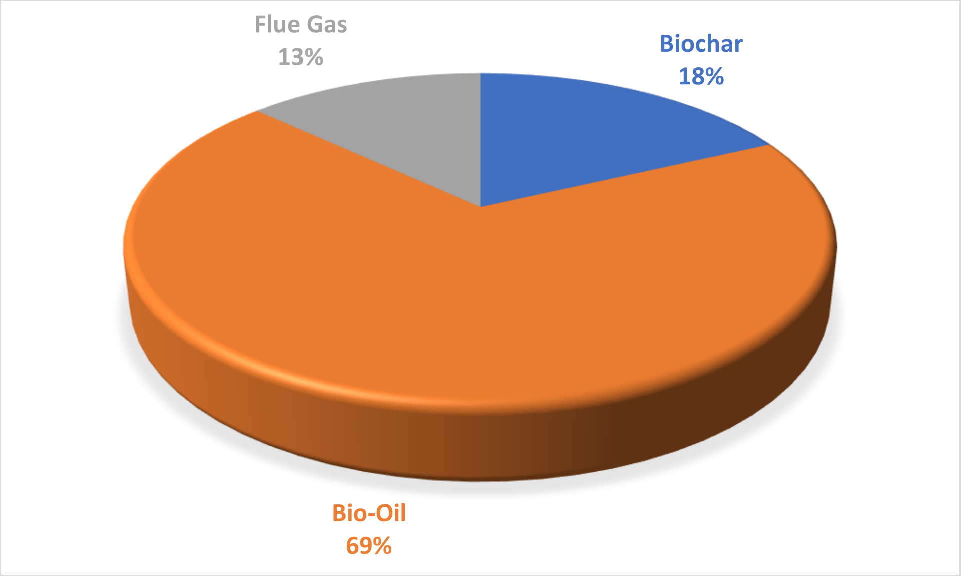


Figure 4.4: Yield (%) for the recovered products

4.2.2.1 Flue gas

After undergoing separation in the Flash Separator, the top stream from the Flash Separator became the Flue Gas product stream. This stream is vapor. The results for the composition are given in Table 4.2. The simulation has provided a mass flowrate result of **5.16 kg/h** Flue gas for this respective product stream. This stream has the smallest yield of 13% compared to the biochar and bio-oil streams.

4.2.2.2 Biochar

The amount of biochar produced from the process is at a rate of **7.24 kg/hr**. This biochar was produced from the pyrolysis reactor and then extracted from the cyclone after cooling. After being extracted from the cyclone, the biochar stream underwent cooling and turned into a liquid phase after cooling. The biochar stream consists of 100% char. No other components are entrained in this stream. The yield from this stream is the second highest at 18% compared to the Flue Gas stream.

4.2.2.3 Bio-oil

The bio-oil, which is the main product, gives a rate of **27.60 kg/hr** from the simulation. However, this pyrolysis oil still has 57% of water which is not useable. No further separation process was included to remove water in this research. This means that it will have to undergo further processing for the removal of water. This stream also produces the highest yield of 69% compared to the biochar and flue gas streams.

Literature from Jahirul et al., (2012) states that depending on the kind of feedstock used as well as the operating conditions of pyrolysis; fast pyrolysis generates certain ranges for the end products obtained from the fast pyrolysis process. The literature indicates wood feedstock as one of the feedstock type that can be used for the fast pyrolysis process (Jahirul et al., (2012). Wood feedstock was used for this study and therefore aligns with the author's literature. The bio-oil generated should be 60% to 75%, biochar must be about 15% to 25% and the flue gas range is 10% to 20% (Jahirul et al., (2012). This is all based on weight percentage. The results from the simulation indicate 12.9% of flue gas, 18.1% biochar and 69% of bio-oil with water entrained being produced. These results from the simulation are acceptable as they fall within the ranges highlighted by Jahirul et al., (2012) for fast pyrolysis products.

To validate that the simulation results are accurate and a good representation of the results, the experimental data from Winjobi (2017) was used. This process is for producing biofuel production from woody biomass through torrefaction fast pyrolysis and catalytic upgrading. The feedstock used by Winjobi (2017) was also pine wood which is similar to the feedstock used for this research . The inlet conditions of the experimental data were then entered into the COCO simulator (pressure = 100 kPa, biomass flowrate = 41 667 kg/hr of dry feed, temperature = 25°C). The reactor operated at a temperature of 530°C. A comparison of the experimental data results of the simulation and the literature results by Winjobi (2017) are given in Table 4.3.

Table 4.3 Validation results for comparison of simulation and literature results for pyrolysis process

	Validation Pyrolysis Process (Simulation)	**Literature Results (% Yield)**	**Validation Pyrolysis Process (Simulation) (% Yield)**	**Difference in Yield % between Literature & Simulation Results**
Feedstock Used	Pine wood	N/A	N/A	N/A
Process Conditions	Feed: 41 667kg/hr	N/A	N/A	N/A
	Pressure: 100 kPa	N/A	N/A	N/A
	Reactor Temperature: 530°C	N/A	N/A	N/A
Flue gas Produced		28	13	15
Bio-oil Produced		59	69	-10
Biochar Produced		10	18	-8

The results from Table 4.3 above indicate that the simulation provides more yield for the bio-oil and biochar and less yield for the flue gas. This is supported by the difference in yield between the literature and simulation results being between 8 – 15%. Therefore, this is an indication that the researcher's simulation is a good representation of the pyrolysis process.

4.2.3 Material and Energy Balances

The law of conversation states that whatever enters a system must be equal to what leaves the system at steady state. The principle that can be used to support this statement is the rule of conserving matter or energy (Zeller et al., 2018). However, Vinet & Zhedanov (2011) state that the overall enthalpy of the exit streams and feed streams will not be equal if the energy is generated or utilized in the processes. The authors support this statement by indicating the heat of reaction is an example of the generation or usage of energy.

4.2.3.1 Mass and Mole Flow Balances

The schematic diagram indicating the process stream numbers is provided by Figure 4.5.

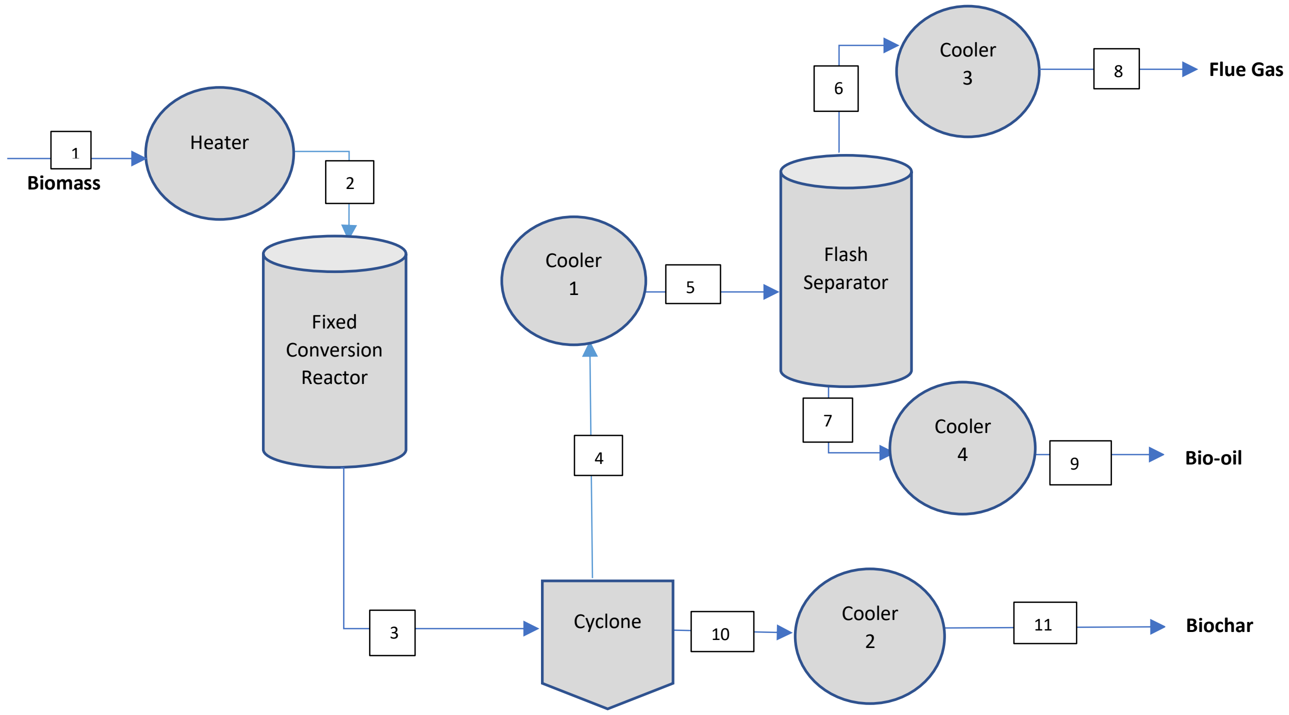


Figure 4.5: The pyrolysis process indicating the number allocation for each stream

The mass and mole flow balances of the process streams are provided in Table 4.4.

Table 4.4 Mass and mole flow balance around process units in kilograms per hour (kg/hr) and kilomoles per hour (kmol/hr)

Streams	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Mass Flow (kg/hr)	40	40	40	32.76	32.76	5.16	27.60	5.16	27.60	7.24	7.24
Mole Flow (kmol/hr)	1.67	1.67	0.55	0.48	0.48	0.16	0.31	0.16	0.31	0.07	0.07

From the results shown in Table 4.4, the mass is conserved for all the process streams. The mass and moles that entered the different process units and the mass leaving the different process units is equal. This is confirmation that the simulation abided with the Law of Conservation of Mass.

4.2.3.2 Energy Balances

There are different forms of energy such as kinetic energy, potential energy, internal energy, work, heat and electrical energy. However, the kinetic and potential energies are minor and considered negligible for chemical processes. The rest of the different energies are manipulated into creating a heat balance equation (Vinet & Zhedanov, 2011). Enthalpy change of reaction is the amount of heat that is absorbed or released during the course of a chemical reaction. The energy of the system is represented as enthalpy on the simulation report. The energy balance change results for the process units in the simulation will be reported on in this section. This entails looking at the difference between the energy coming into and leaving each process unit. Figure 4.6 is a schematic diagram indicating the change in enthalpy of the pyrolysis process.

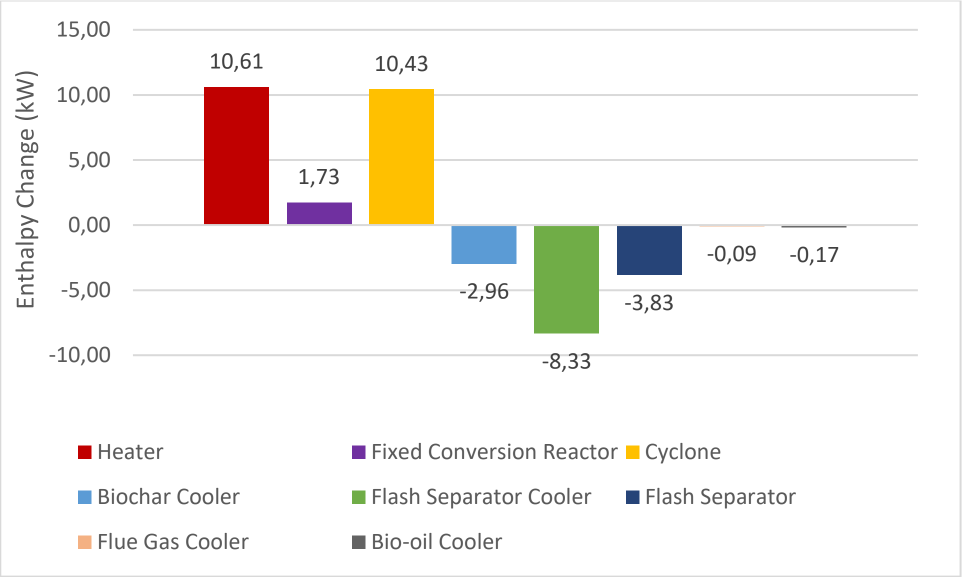


Figure 4.6: Results for the change in energy balance (Enthalpy Change) for the process units in the simulation

There are energy losses that occurred during the pyrolysis process. It can be observed from the change in energy balance in Figure 4.6 that endothermic and exothermic processes took place during the pyrolysis process. It is common knowledge that the heater and Fixed Conversion Reactor required an input of energy to proceed. This is indicated by the positive change in enthalpy. Although the cyclone is operating at high temperatures, it does not require high energy content to perform its task of separating biochar from flue gas/bio-oil as it operates by using the difference in densities and not heat energy. The biomass needed to be heated up before it could enter the reactor to commence with the pyrolysis conversion process. After the conversion took place in the reactor, the reactor product still had the energy entrained as the reactor product was not yet cooled off. Lastly, flue gas is a vapour that requires a high energy input as there has to be a temperature increase for the flue gas to be produced. All these justify the positive change in enthalpy. However, the Biochar Cooler, Flash Separator Cooler, Flash Separator, Flue Gas Cooler and Bio-oil Cooler have a negative change in enthalpy because the processes released energy once they were completed. The energy loss of streams with negative enthalpy change took place when these streams were cooled off. The negative change in enthalpy indicates that the heat was released to the surroundings. The explanation for the Flash Separator releasing energy even though its purpose is to separate a liquid phase from a liquid/vapor phase is because the temperature has already been reduced in the cooler before it and now it is separating the volatile liquid fraction from the permanent gases/vapour stream.

4.2.4 Combined Economic Value And Environmental Impact Method To Measure The Economic Margins And Environmental Impact Saving Margins Of Recovered Products

4.2.4.1 Capital Costs Required

The detailed capital costs are indicated in Appendix A. For the purpose of this section, only the delivered cost of equipment and total annual costs of units will be discussed. To calculate the total annual cost, the annual capital cost of a process unit is combined with the annual operating expense of the process unit. The delivered cost of equipment and total annual costs required for each process unit are shown in Table 4.5. The Total Annual Cost of a Process Unit follows the same order from the least expensive to the most expensive as the delivered cost of equipment. Annually, the plant is required to spend R1 856 256,28 on the Reactor. This figure includes the cost for operating the reactor. With the reactor being the core process of pyrolysis where conversion takes place, it is not surprising that it is the most expensive unit.

Table 4.5 Delivered cost of equipment and annual capital costs required for each process unit

Process Unit	**Delivered Cost of Equipment**	**Total Annual Cost of Process Unit**
Heater	R117 772.72	R197 011,58
Cooler	R26 564.24	R47 370,36
Fixed Conversion Reactor	R1 095 360.58	R1 856 256,28
Flash Separator	R36 869.82	R64 109,18
Cyclone	R20 128.54	R43 162,05
TOTAL	**R1 296 695,90**	**R2 207 909,45**

The Total Capital Cost (CAPEX) is 5.03 times the Delivered Cost of Equipment (Sadhukhan & Martinez-Hernandez, 2017). For this study, the Total Capital Cost (CAPEX) required is R6 522 380,38. Figure 4.7 indicates the cost portion required for each piece of equipment. The least expensive equipment is the Cyclone which takes up 1.53% of the CAPEX. The most expensive equipment is the Fixed Conversion Reactor which requires 83.92% of the CAPEX. A process of investigating an environmental analysis of bio-oil production from forest residues by Van Schalkwyk (2019) was looked at. A pyrolysis reactor with a flowrate of 1000 kg/hr was used. The reactor has a delivered cost of equipment of 1 016 000 million US Dollars (This is equivalent to R15 342 920). This cost was then updated to the 2020 cost using a cost index and ended up as R16 118 853. On the other hand, the Fixed Conversion Reactor from this study has a delivered cost of equipment of R1 076 069 for a 40 kg/hr plant. This cost was also updated to the 2020 cost using a cost index and became R1 095 360. A cost-capacity equation utilizes historical costs and capacity to determine the current costs for an equipment, plant facility or piece of machinery. The cost-capacity calculation has indicated that there is a 53.95% difference between the reactor cost for this study as well as the reactor cost from Van Schalkwyk (2019). According to Towler & Sinnott (2008), this level of accuracy is acceptable for order-of-magnitude estimates based on the cost data of a similar plant. Both these costs indicate how expensive reactors are. Comparing the delivered cost of equipment and the CAPEX required for the Fixed Conversion Reactor with the results from Van Schalkwyk (2019), it is evident that these results regarding the Fixed Conversion Reactor are valid.

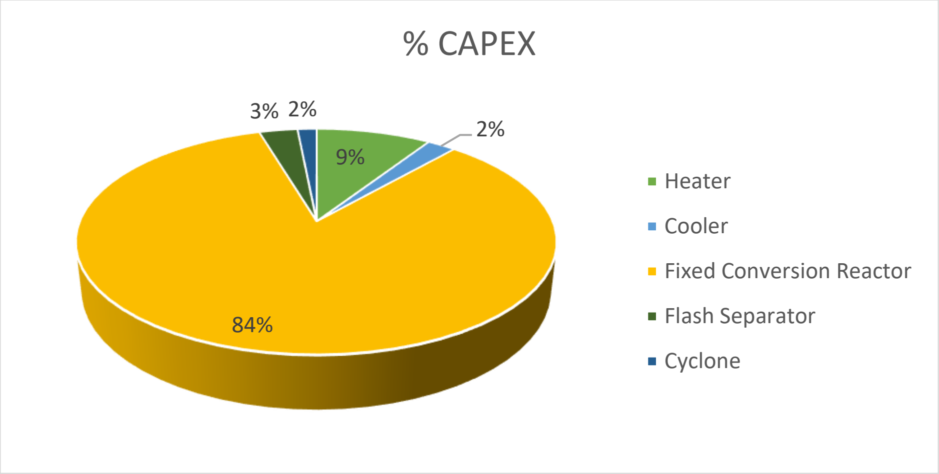


Figure 4.7: Percentage (%) CAPEX of each process unit

4.2.4.2 Cost of Production (COP), Value on Processing (VOP), Economic Margins, ICP (Impact Cost of Production), CVP (Credit Value on Processing) and EI (Environmental Impact) Savings

The streams for the pyrolysis process (Figure 4.8) were used to assess the economic and environmental impacts of each stream. This provides a holistic view of whether a stream is worth producing or not. The streams were allocated a number for easier identification during the analysis.

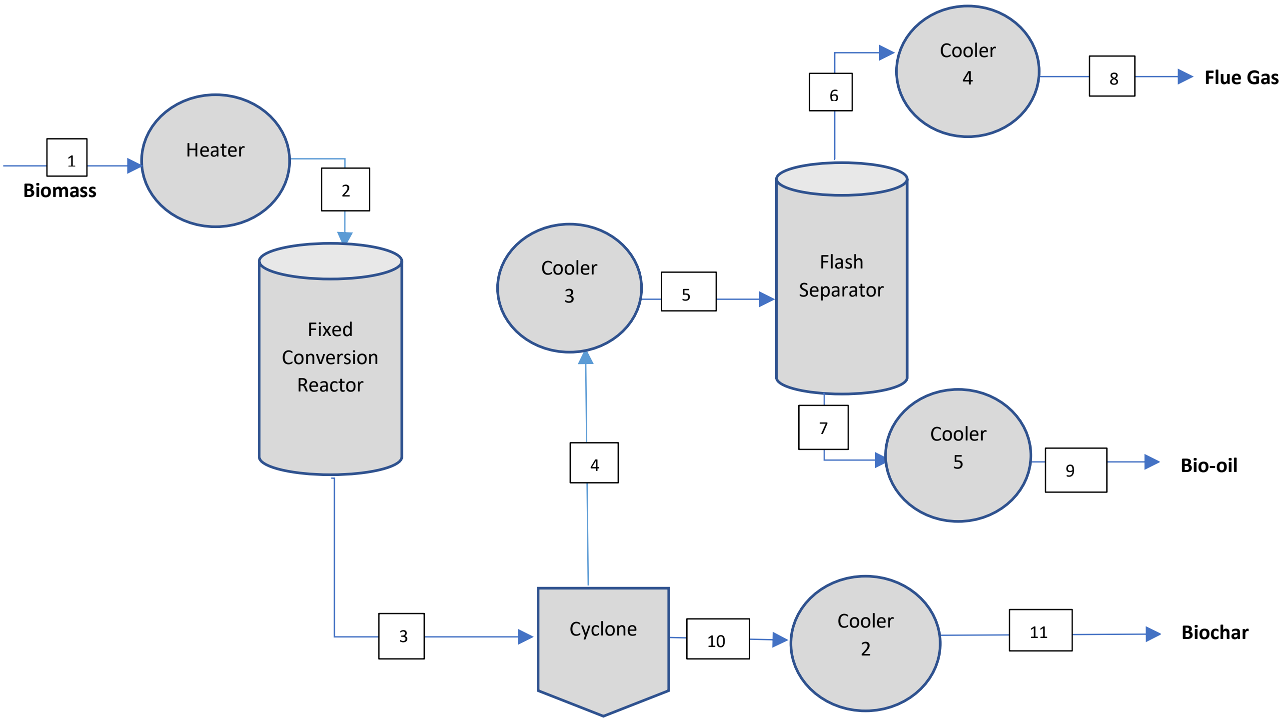


Figure 4.8: The pyrolysis process indicating the number allocation for each stream for EVEI analysis

Table 4.6 provides the results for the different streams. It provides the stream number (according to Figure 4.8), the flowrate of each stream, the COP, the VOP, economic margin, ICP, CVP and EI savings margin.

Table 4.6 Results for each stream (COP, VOP, EM, CVP, ICP and EI Saving Margin)

Stream No	Flowrate (Ton/Year)	COP (Rand/Ton)	VOP (Rand/Ton)	Δ E (Economic Margin) Rand/Ton	CVP (Mt /Mt)	ICP (Mt /Mt)	Δ I (EI Saving Margin)
1	322.56	155.43	-5.56 × 10^{3}	-5.71 × 10^{3}	3,45 x 10^{12}	17,366	3,45 x 10^{12}
2	322.56	766,20	-4.94 × 10^{3}	-5.71 × 10^{3}	3,45 x 10^{12}	892,37	3,45 x 10^{12}
3	322.56	289,24	956,79	667,55	-2.14 × 10^{07}	1.46 × 10^{03}	-2,16 x 10^{05}
4	264.17	334,75	679,46	344,71	1.87 × 10^{09}	586,17	1,87 x 10^{09}
5	264.17	398,11	858,78	460,67	-520,67	932,88	-1,45 x 10^{03}
6	41.61	1.69 × 10^{3}	-992,72	-2.69 × 10^{3}	-930,43	2.70 × 10^{03}	-3,64 x 10^{03}
7	222.56	443,48	2.44 × 10^{3}	2.00 × 10^{3}	-174	988,42	-1,16 x 10^{03}
8	41.61	1.29 × 10^{3}	548	-745,87	0,258	3.19 × 10^{03}	-3,19 x 10^{03}
9	222.56	368,27	2.73 × 10^{03}	2.36 × 10^{3}	3,20 x 10^{-08}	988,42	-9,88 x 10^{02}
10	58.38	894,76	1.09 × 10^{3}	195,84	-663,29	1.65 × 10^{03}	-2,32 x 10^{03}
11	58.38	966,84	1.82 × 10^{03}	863,09	0,0008	2.51 × 10^{03}	-2,52 x 10^{03}

The streams that have positive economic margins are streams 3, 4, 5, 7, 9, 10 and 11. This amounts to 58% of the pyrolysis process having positive economic margins. Furthermore, these results indicate that the final flue gas product stream will be uneconomical to produce. With bio-oil being the main product, it is economical to obtain an economic margin from streams 7 and 9. It is expected for all the other streams to have a negative economic margin because of the heat losses from these streams. This implies economic losses from the streams. According to Martinez-Hernandez, Campbell & Sadhukhan (2014) if a stream has a negative economic margin, the buying of that stream from the marketplace will be better than manufacturing it within the process. Therefore, it will not be economical to produce this pyrolysis process as most of these streams will have to be bought from the marketplace.

For the environmental aspects, positive EI savings can be obtained from only streams 1, 2 and 4. This suggests that producing 75% of the streams in the pyrolysis process will result in more environmental impacts compared to the EI credit received. Similar to the economic aspects, streams with negative EI savings margins will have to be bought from the marketplace. Alternatively, the production steps during the manufacturing process for a product with a positive economic value must be enhanced using the integration of a process (Martinez-hernandez, Campbell & Sadhukhan, 2014).

4.2.4.3 Sensitivity Analysis

The first sensitivity analysis was conducted on the conversion of reactants taking place in the pyrolysis reactor as the conversion affects the total amount of products that will be produced from the process. The aim of the analysis was to analyse the effect of conversion rates on the end products. The conversion rates were adjusted to 65%, 70% and 75% respectively. These conversion rates were chosen based on an article by Passamonti & Sedran (2012) where waste plastics were turned into fuels. These is not much literature available on the conversion rates of the fast pyrolysis process. The results are depicted in Figure 4.9.

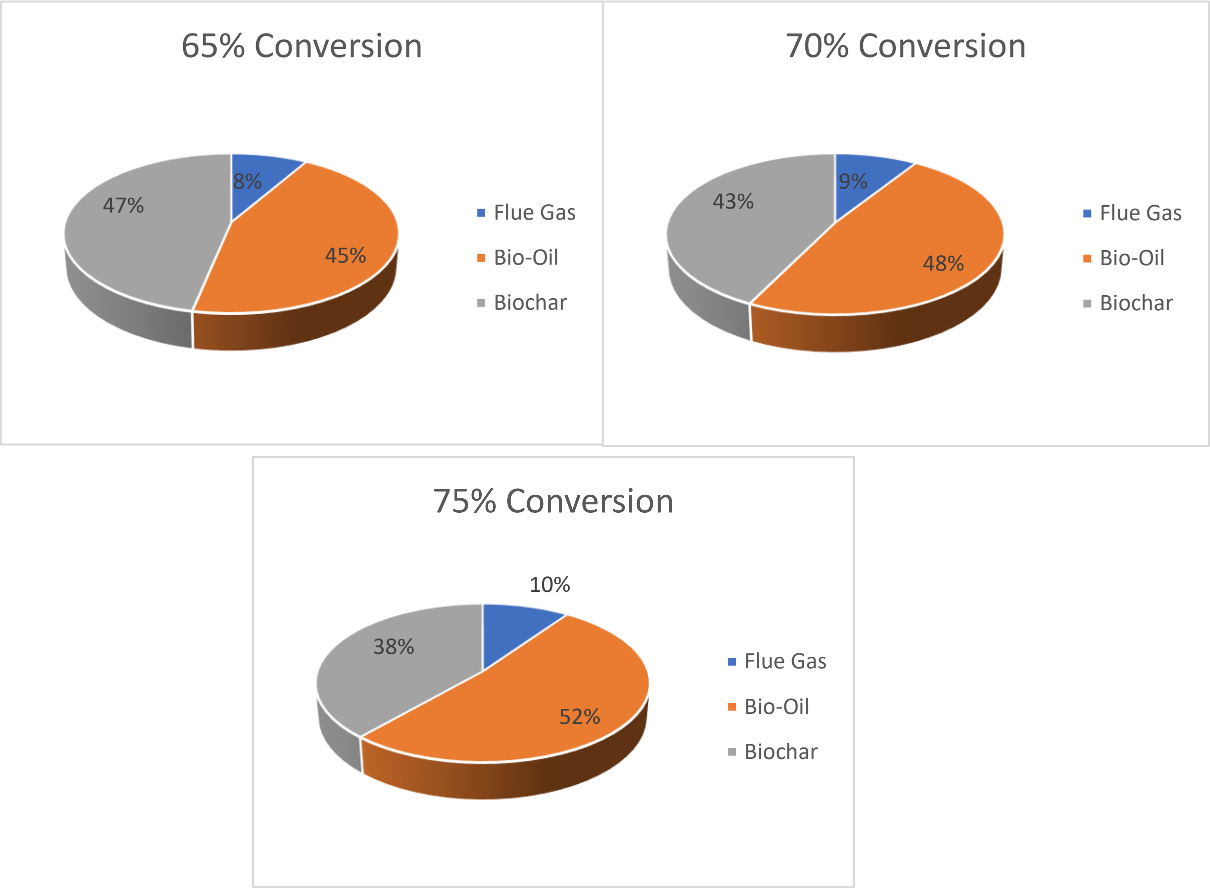


Figure 4.9: Sensitivity analysis for the effect of conversion rates on the yield of the end products

In the above figure, the flue gas has a 1% decrease change when the conversion is increased from 65% to 70% and 75%. However, there is a slight change in the bio-oil production. At 65% conversion, the bio-oil production is at a rate of 17.94 kg/h. Then at 70% and 75% conversion rates, the bio-oil increases to 19.32 kg/h and 20.70 kg/h respectively due to a decrease in the conversion rates. This indicates a 3% and 4% increase when the conversion rates are increased from 65% to 70% and from 70% to 75%. With regards to the biochar production, there was a 4% decline when the conversion rate was increased from 65% to 70%. Furthermore, when the conversion rate was increased from 70% to 75%, there was a further 5% decrease in the amount of biochar produced. These results indicate that the lower the conversion rate is, the more biochar is being produced. At low conversion rates, there is less bio-oil and flue gas generated. Subsequently high conversion rates favour the bio-oil but produce less biochar and flue gas. Therefore, to determine how efficient the conversion is and how much yield to expect from the products; relies on the pyrolysis temperature (Hanif et al., 2020).

Another variable adjusted for a sensitivity analysis was the feed flowrate. The objective was to look at the effect of feed flowrate and whether having a larger plant will affect the quantity of pyrolysis products produced. These feed flowrates were selected based on research by authors who investigated the fast pyrolysis processes. The feed flowrates were adjusted to 5 kg/hr (Van Schalkwyk, 2019), 3000 kg/hr (Shemfe, Gu & Ranganathan, 2015), 22 916 kg/hr (Wright et al., 2010) and 83 333 kg/hr (Jones et al., 2009; Wright et al., 2010). The results for the sensitivity analysis on the effect of feed flowrate on pyrolysis products are provided in Table 4.7.

Table 4.7 Sensitivity analysis results for the effect of feed flowrate on pyrolysis products

Product Produced	**Feed Flowrate: 5 kg/hr**	**Feed Flowrate: 3000 kg/hr**	**Feed Flowrate: 22 916 kg/hr**	**Feed Flowrate: 83 333 kg/hr**
Flue gas	0.65 kg/hr	387.17 kg/hr	2 957.42 kg/hr	10 754.50 kg/hr
Bio-oil	3.45 kg/hr	2 070.03 kg/hr	15 812.30 kg/hr	57 500.70 kg/hr
Biochar	0.90 kg/hr	542.80 kg/hr	4 146.30 kg/hr	15 077.80 kg/hr

The results above indicate that the feed flowrate has an effect on the pyrolysis products produced from the pyrolysis process. An increase in the feed flowrate results in a directly proportional increase of the quantity of flue gas, bio-oil and biochar being produced (Qureshi et al., 2021).

4.2.5 The Economic And Environmental Profiles

An EVEI (Economic Value and Environmental Impact) profile of a product is a graph that shows the product's EI (environmental impact) on the y axis against EV (economic value) on the x axis. An EVEI composite curve indicates the entire amount of economic expenses incurred in each EI period in such a profile. From a material to a product, the EI amount of a manufacturing route rises. The auxiliary raw material, exhaust streams, feed and utility all have EI and economic costs (Sadhukhan, Ng & Martinez Hernandez, 2014). The results for the economic and environmental profiles of the flue gas, bio-oil and biochar are represented below by Figure 4.10 to Figure 4.12. The purpose of the profiles is to assess whether a stream is profitable and sustainable or not through graphical representation (Martinez-Hernandez et al., 2013). The graphical representations indicate the Value Line, Limiting Line and Costs Composite Curve. The Value Line shows a reference limit for obtaining EI savings margins as well as economic savings margins that are positive. On the other hand, the Limiting Line demonstrates a benchmark for the EI cost target from the manufacturing of a biorefinery product that is formed from policy. The Costs Composite Curve however indicates the increasing EI costs which are plotted against the economic costs from utilities, feed, fixed costs, auxiliary raw materials and process emissions which are assigned to a specific product (Martinez-hernandez, Campbell & Sadhukhan, 2014). The economic value was plotted against the environmental impact of each product.

4.2.5.1 Flue Gas

The results for the economic and environmental profile for the flue gas is represented by Figure 4.10 below.

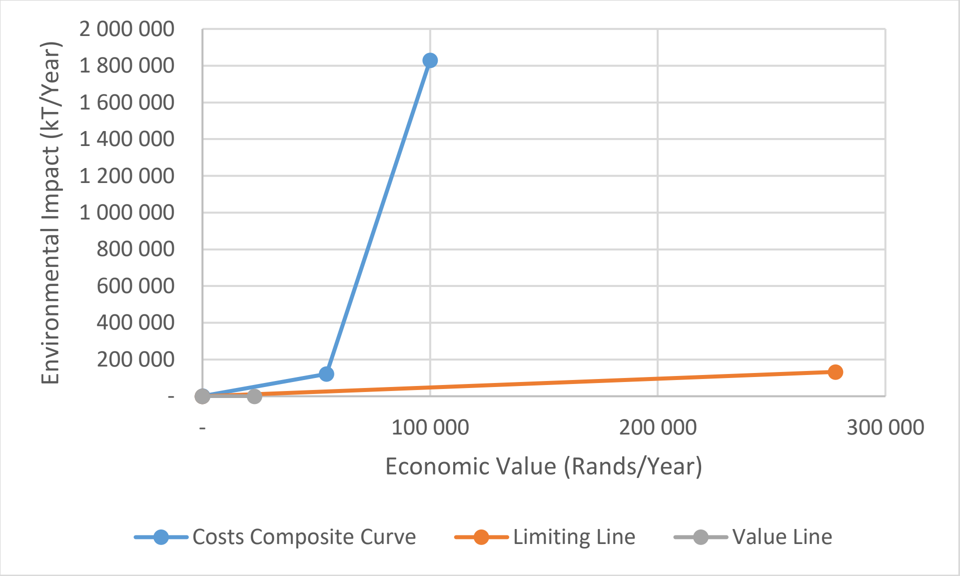


Figure 4.10: Economic Value and Environmental Impact (EVEI) Profile of flue gas

The Costs Composite Curve slope is steep and quite high. This indicates that there is a higher Environmental Impact contribution for every amount of money that is spent. The purpose of the value line is to show a reference limit for obtaining positive economic margins and positive EI margins. However, the value line for this flue gas stream is slightly lower than the limiting line. The value line highlights that there is little economic value and little environmental impact for the stream in the beginning. The EI cost limiting line shows a benchmark for the EI cost focus from the creation of a biorefinery item generated from the policy targets of biorefinery products when coming to equivalent products that are fossil-based. Equivalent products in this case are products that have the same function but are environmentally friendlier than fossil-based products. These equivalent products and policy targets are better explained by European Union (2009) together with US Congress (2012). The Acts stipulated specify the targets for the amount of renewable energy that must be consumed and focus on reducing the greenhouse gas emissions. This indicates that there is no environmental benefit on this product. In addition to this, the composite curve is not below the limiting line. This will result in no EI savings and GHG emissions policy targets cannot be met (Martinez-Hernandez, Campbell & Sadhukhan, 2014).

4.2.5.2 Bio-Oil

The economic and environmental profile for the bio-oil is represented by Figure 4.11 below.

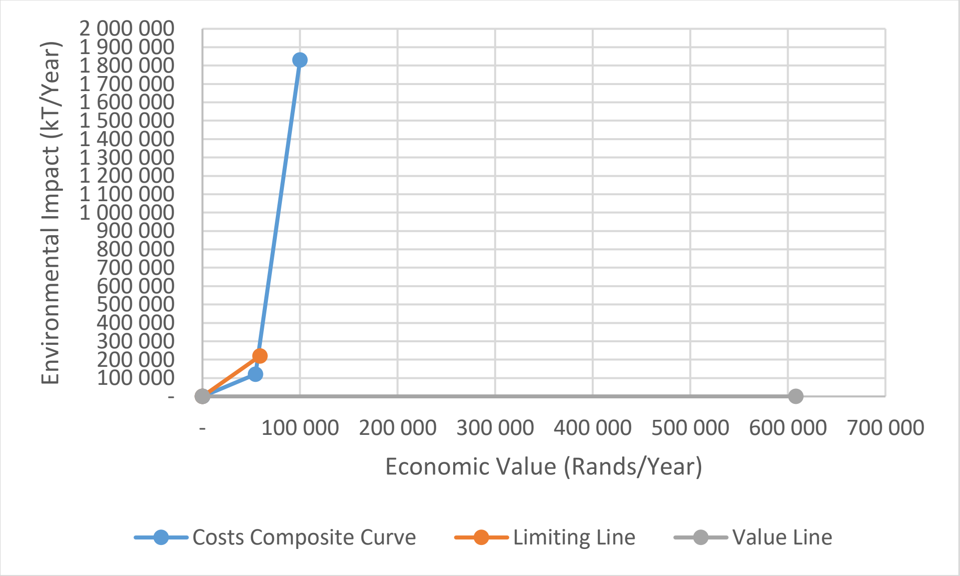


Figure 4.11: Economic Value and Environmental Impact (EVEI) Profile of bio-oil

The limiting line is above the value line and the Costs Composite Curve indicating a slightly positive economic value of the stream. However, the Costs Composite Curve indicates that there are higher environmental impact costs when producing this bio-oil stream. This is not sustainable as this will not result in any EI savings. The Costs Composite Curve and limiting line are above the value line. The purpose of the value line is to show a reference limit for obtaining positive economic margins and positive EI margins. In this instance, the value line is below the Costs Composite Curve and limiting line indicating negative economic and EI savings margins. The EI cost limiting line shows a benchmark for the EI cost focus from the creation of a biorefinery item generated from policies.

4.2.5.3 Biochar

Figure 4.12 below illustrates the economic and environmental profile for the biochar.

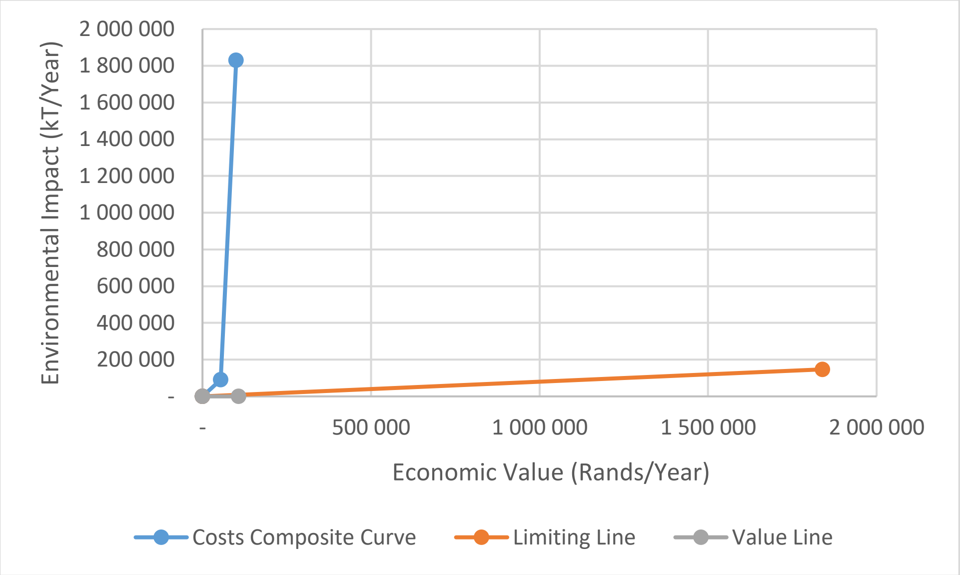


Figure 4.12: Economic Value and Environmental Impact (EVEI) Profile of biochar

This biochar stream has a Costs Composite Curve that indicates high environmental impacts. High environmental impacts will result in high environmental costs to produce this stream. The Costs Composite Curve and limiting line are above the value line although the value line and limiting line are almost linear. The economic value of the limiting line is almost steady. The purpose of the value line is to show a reference limit for obtaining positive economic margins and positive EI margins. In this instance, the value line is slightly below the limiting line indicating that there is not much value that can be obtained from this stream.

Overall, the EVEI calculations for this pyrolysis process have indicated certain streams which provide both positive economic and environmental (EI savings). However, when coming to the product streams, the flue gas and biochar streams have both negative economic and EI saving margins. The bio-oil stream on the other hand has a positive economic and negative EI saving margin. These results for this bio-oil stream interlink with the results from the EVEI profile for the bio-oil stream. The results obtained from this study slightly match other studies which propose that there are positive economic and environmental benefits on the pyrolysis products through an EVEI analysis of biorefinery products (Martinez-hernandez et al., 2013; Martinez-hernandez, Campbell & Sadhukhan, 2014; Sadhukhan, Ng & Martinez-Hernandez, 2016). This is because not only were there positive economic and environmental margins obtained from the streams, but there were also negative margins obtained from this study. This could be as a result of the small capacity of the plant which is a lot smaller compared to other fast pyrolysis studies.

REFERENCES

European Union. 2009. *Directive 2009 / 28 / EC of 23 April 2009 on the promotion of the use of energy from renewable sources*.

Glushkov, D., Nyashina, G., Shvets, A. & Pereira, A. 2021. Current Status of the Pyrolysis and Gasification Mechanism of Biomass. *Energies*. 14(22):7541.

Hanif, M.U., Zwawi, M., Capareda, S.C., Iqbal, H., Algarni, M., Felemban, B.F., Bahadar, A. & Waqas, A. 2020. Influence of Pyrolysis Temperature on Product Distribution and Characteristics of Anaerobic Sludge. *Energies*. 13(1):1–12.

Jagaba, A.H., Kutty, S.R.M., Lawal, I.M., Abubakar, S., Hassan, I., Zubairu, I., Umaru, I., Abdurrasheed, A.S., Adam, A.A., Ghaleb, A.A.S., Almahbashi, N.M.Y., Al-dhawi, S., Noor, A. 2021. Sequencing batch reactor technology for landfill leachate treatment : A state-of-the-art review. *Journal of Environmental Management*. 282(December 2020):111946.

Jahirul, M.I., Rasul, M.G., Chowdhury, A.A. & Ashwath, N. 2012. Biofuels production through biomass pyrolysis- A technological review. *Energies*. 5(12):4952–5001.

Jones, S., Valkenburg, C., Walton, C., Elliott, D., Holladay, J., Stevens, D., Kinchin, C. & Czernik, S. 2009. *Production of Gasoline and Diesel from Biomass via Fast Pyrolysis , Hydrotreating and Hydrocracking : A Design Case*. Washington.

Letlape, B. & Gumbo, T. 2016. The Role of Innovations In Municipal Solid Waste Management To Attaining Sustainable Cities : Case of City of Johannesburg. In *SAPI Conference 2016*. 1–14.

Martinez-hernandez, E., Campbell, G., Sadhukhan, J., Centre, S., Engineering, P. & Manchester, M. 2013. Economic value and environmental impact (EVEI) analysis of biorefinery systems. *Chemical Engineering Research and Design*. 91(8):1418–1426.

Martinez-hernandez, E., Campbell, G.M. & Sadhukhan, J. 2014. Economic and environmental impact marginal analysis of biore fi nery products for policy targets. *Journal of Cleaner Production*. 74(2014):74–85.

Miao, L., Wang, S., Cao, T., Peng, Y., Zhang, M. & Liu, Z. 2016. Advanced nitrogen removal from landfill leachate via Anammox system based on Sequencing Biofilm Batch Reactor (SBBR): Effective protection of biofilm. *Bioresource Technology*. 220:8–16.

Paiva, A., Pires, P., Arauzo, J., Fonts, I., Domine, M.E., Arroyo, F., Garcia-perez, M.E., Montoya, J., Jane, F.C., Garcia-Perez, M. 2019. Challenges and Opportunities for Bio-oil Refining : A Review. *Energy Fuels*. 33(6):4683–4720.

Passamonti, F.J. & Sedran, U. 2012. Recycling of waste plastics into fuels. LDPE conversion in FCC. *Applied Catalysis B: Environmental*. 125:499–506.

Qureshi, K.M., Ng, A., Lup, K., Khan, S., Abnisa, F., Mohd, W. & Wan, A. 2021. Effect of temperature and feed rate on pyrolysis oil produced via helical screw fluidized bed reactor. 38(9):1797–1809.

Raghab, S.M., Abd, A.M., Meguid, E. & Hegazi, H.A. 2013. Treatment of leachate from municipal solid waste landfill. *Housing and Building National Research Center*. 9:187–192.

Republic of South Africa. 1993. *Occupational Health and Safety Act, Act 85 of 1993*. South Africa: Government Gazette.

Sadhukhan, J. & Martinez-Hernandez, E. 2017. Material flow and sustainability analyses of biorefining of municipal solid waste. *Bioresource Technology*. 243:135–146.

Sadhukhan, J., Ng, K.S. & Martinez Hernandez, E. 2014. *Biorefineries and Chemical Processes: Design, Integration and Sustainability Analysis*. First ed. John Wiley & Sons, Ltd.

Sadhukhan, J., Ng, K.S. & Martinez-Hernandez, E. 2016. Novel integrated mechanical biological chemical treatment (MBCT) systems for the production of levulinic acid from fraction of municipal solid waste: A comprehensive techno-economic analysis. *Bioresource Technology*. 215:131–143.

Shemfe, M.B., Gu, S. & Ranganathan, P. 2015. Techno-economic performance analysis of biofuel production and miniature electric power generation from biomass fast pyrolysis and bio-oil upgrading. *Fuel*. 143:361–372.

South African Cities Network (SACN). 2014. *State of Waste Management in Cities – Phase 2: Modelling the Effects of Landfilling As A Disposal Method*. Braamfontein.

The Constitution of the Republic of South Africa. 1996. *Constitution of The Republic of South Africa (No. 108 of 1996)*. Pretoria: Government Printers, South Africa.

Towler, G. & Sinnott, R. 2008. *Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design*. Second edi ed. G. Towler & R. Sinnott, Eds. California: Elsevier Inc.

US Congress. 2012. *Energy Independence and Security Act OF 2007 as of 2012*.

Van Schalkwyk, D.L. 2019. Techno-economic and Environmental Analysis of Bio-oil Production from Forest Residues via Non-catalytic and Catalytic Pyrolysis Processes. Stellenbosch University.

Vinet, L. & Zhedanov, A. 2011. A “missing” family of classical orthogonal polynomials. *Journal of Physics A: Mathematical and Theoretical*. 44(8):1–8.

Winjobi, O. 2017. Techno-Economic and Life Cycle Assessments of Biofuel Production From Woody Biomass Through Torrefaction-Fast Pyrolysis and Catalytic Upgrading. Michigan Technological University.

Wright, M.M., Satrio, J.A., Brown, R.C., Daugaard, D.E. & Hsu, D.D. 2010. Techno-economic analysis of biomass fast pyrolysis to transportation fuels. Technical Report NREL/TP-6A20-46586. *Nrel*. 89(November):463–469. Available: https://doi.org/10.1016/j.fuel.2010.07.029.

Zeller, V., Towa, E., Degrez, M. & Achten, W.M.J. 2018. Urban waste flows and their potential for a circular economy model at city-region level. *Waste Management*. 83:83–94.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 INTRODUCTION

This chapter summarises the findings obtained from this research and also provides an overall conclusion in relation to the aims and objectives that were set for this study. In addition to this, it further provides any recommendations for future work.

The aim of this study was to identify challenges that were faced by landfill sites in the Eastern part of Johannesburg as well as to seek a method of recovering products or materials from the waste in the landfill. The manner of achieving this was through using biorefinery methods. A simulation software was used to design a pyrolysis biorefinery system to model the process using the waste quantities from the Rietfontein Landfill Site as the feedstock quantities. A pyrolysis biorefinery system uses biomass to convert the biomass into useful valuable products. The findings from the simulation results were discussed in the previous chapter.

5.2 SUMMARY OF FINDINGS

5.2.1 OBJECTIVE: To assess the different challenges faced by the landfills in the East Rand of Johannesburg

- Through the site tour and discussion with the Ekurhuleni Metropolitan Municipality Landfill Site Supervisor, it was discovered that the main issues experienced by the Rietfontein Landfill Site were around the reclaimers and leachate dams.
- However, the issue of reclaimers seems to be a common problem amongst all the landfill sites in the Ekurhuleni region. Not only are the reclaimers ungovernable but they also compromise their health and safety as well as the health and safety of all who are on the landfill site.
- There are no systems or controls in place to manage the reclaimers on landfill sites. The action of reclaimers burning the recycled material is considered an environmental impact. The emissions from these burnt reclaimed items are released into the air and

not measured or controlled through proper air quality monitoring methods. The air quality is thus compromised and affected. The surrounding communities can suffer from long-term health effects due to the air pollutants they are exposed to.

- In addition to this, air pollution will contribute towards ozone depletion and global warming. The released air pollutants consist mainly of methane, carbon dioxide and ammonia.
- Although reclaimers are assisting the municipality with further separation and sorting of municipal solid waste, they greatly contribute to negative environmental impacts at this stage.
- Secondly, the issue of the leachate dams stems around the leachate dams being filled to capacity and relying on evaporation for their levels to decrease. The environmental impact of the leachate dams can be quite severe if the solution is not found soon. Should it happen that the leachate dams overflow, there is a huge possibility of severe groundwater contamination.
- Once again, should the odours being emitted from the leachate dams not be thoroughly controlled, this can impact the health of the surrounding community. These are issues that are critical and that need to be dealt with by the Ekurhuleni Metropolitan Municipality. Therefore, this objective has been achieved as the challenges have been revealed.

5.2.2 OBJECTIVE: To identify the useful products which can be recovered from municipal solid waste

- Literature review indicated that the products that can be generated through the pyrolysis process are flue gas, bio-oil and biochar. Furthermore, the literature review revealed that the fast pyrolysis process would yield bio-oil as the main product. These were indeed the products that were generated in this research; indicating that the objective has been met.

5.2.3 OBJECTIVE: To model a process to derive value from the municipal solid waste based on a chosen biorefinery technology

- This objective revolved around using a simulation software to determine the useful products that can be recovered from MSW by using biorefinery concepts. A CAPE-OPEN to CAPE-OPEN (COCO) simulator was used to imitate a fast pyrolysis biorefinery plant.
- The simulation yielded 27.60 kg/hr of bio-oil, 7.24 kg/hr of biochar and 5.16 kg/hr of flue gas. It can also be drawn from the simulation that the main product from the pyrolysis process is the bio-oil as the stream contains the highest flowrate and yield from all other product streams. This was an expected result as the literature review had indicated that the fast pyrolysis process favours the bio-oil production more than the other pyrolysis products.
- The limitation with the simulation software includes the inability for the Fixed Conversion Reactor to provide updated pyrolysis products results when the temperature profiles are adjusted. However, this limitation was overcome by conducting a feed flowrate sensitivity analysis rather than a reactor temperature sensitivity analysis.
- Another factor that can affect the results from the simulation is the assumption that the biomass has already been dried. The moisture content for this study was assumed to be 10% after drying. Therefore, the simulation excluded the drying section as the 10% moisture content after drying had already been assumed for this pyrolysis process. Had a higher moisture content been used, a dryer would have been added at the beginning of the pyrolysis process. Adding the dryer would have affected the operating costs of the pyrolysis plant as well. By analysing the number of products obtained from the pyrolysis process as well as their mass flowrates, this is a clear indication that the objective has been met.

5.2.4 OBJECTIVE: To apply the combined economic value and environmental impact method to measure the economic margins and environmental impact saving margins of each product produced.

- The economic and environmental impacts of each recovered product were assessed using a combined Economic Value and Environmental Impact (EVEI) analysis method. The results from the EVEI analysis revealed that the pyrolysis process is partially feasible economically and environmentally. Eight out of the twelve streams in the study had positive economic margins.
- Furthermore, the EVEI results indicated that from the recovered products, the flue gas and biochar product streams will be uneconomical to produce. The bio-oil product stream was the only stream that was going to be economical to produce.
- On the other hand, analysing the environmental aspects, only three streams out of twelve streams indicated positive environmental impact margins. This is an indication that producing 75% of the streams in the pyrolysis process will result in more negative environmental impacts.
- These results from the EVEI analysis were quite useful as they have shown that this pyrolysis process can actually be recommended to the Ekurhuleni Municipality as a result of the positive economic margins that were obtained from study. The economic value is a useful measure for allocating impacts to the recovered products seeing as it portrays a product's value in the actual economy. This means that for the 264 tonnes (264 000 kilograms) of garden waste that the Ekurhuleni Metropolitan Municipality landfilled for January to October 2019, valuable products could be recovered.
- Provisions will have to be made for the streams that have environmental unfavourable environmental impacts. These streams that contain high environmental impacts will have to be bought from the market. To offset the low economic and environmental effects, the biochar is being used as fertilizer and this improves the overall process environmental impact. The biggest win is that waste is being re-utilized to produce fuel and this will reduce the waste being landfilled and ultimately its impact on the environment. However, some negative impacts can be offset by combined waste from different locations and then making a plant with bigger capacity and this will also work. However, the objective has been achieved seeing that the EVEI method was used to analyse both the economic and environmental impacts of the recovered products.

5.3 RECOMMENDATIONS

The first recommendation is for the Ekurhuleni Metropolitan Municipality to formalise the informal waste industry as the reclaimers offer their services of further separation and sorting out of the waste before it gets landfilled. Proper control mechanisms have to be put in place to ensure that all environmental, health and safety regulations are adhered to. Secondly, a mechanical mechanism must be put in place to assist with draining or reducing the levels of the leachate dams. The mechanical mechanism can be installed to pump the leachate to a holding tank to be treated offsite.

The plant capacity was quite small as compared to other similar processes which had bigger plant capacities of more than 3 000 kg/hr. The sensitivity analysis has revealed that plant capacities with feed flowrates from 3000 kg/hr would be more economically viable. Using a bigger plant capacity is a recommendation for obtaining more bio-oil from the fast pyrolysis process.

It is also recommended that South Africa to start exploring the pyrolysis option as opposed to the common method of incineration. The pyrolysis process generated a large quantity of bio-oil. This environmentally friendly bio-oil replaces the fossil fuel crude oil or diesel oil that was previously used. The generated bio-oil will be used for biobased chemicals, transportation fuels and heat generation.

Although the final bio-oil still contains traces of water, a further process must be explored for removing all the water during the process. If the bio-oil is used without the further removal of water, it can damage the internal components of the transportation mode being used. Removing the water during the pyrolysis process will eliminate the need for bio-oil upgrading. The water removal process was not included in this study as the objective was to analyse the products that could be recovered from the pyrolysis process. Literature has indicated that the drawback with the pyrolysis bio-oil is the large water content entrained in the bio-oil.

Further research is to be conducted to investigate how the other biorefinery options such as gasification and incineration perform economically and environmentally as compared to the pyrolysis process.

The biggest recommendation from the entire research is to perform either lab or pilot scale experiments to check these findings from this study as these will help to answer the question on bio-oil quality which was never discussed in the study. In addition to this, it will answer a lot of questions around how big the capacity should be and also how much waste can actually be processed economically.

APPENDICES

APPENDIX A: CAPITAL COSTS

Equipment	Delivered Cost of Equipment	Total CAPEX	% CAPEX	Annual Capital Cost	Fixed Costs: Indirect Capital	Fixed Costs: Personnel	Total Operating Costs	Total Annual Cost
Heater	R117 772,72	R592 396,78	9,08	R77 011,58	R4 629,88	R90 000,00	R120 000,00	R197 011,58
Cooler	R26 564,24	R133 618,13	2,05	R17 370,36	R1 044,29	R20 000,00	R30 000,00	R47 370,36
Reactor	R1 095 360,58	R5 509 663,72	84,47	R716 256,28	R43 060,82	R84 000,00	R1 140 000,00	R1 856 256,28
Flash Separator	R36 869,82	R185 455,19	2,84	R24 109,18	R1 449,43	R30 000,00	R40 000,00	R64 109,18
Cyclone	R20 128,54	R101 246,56	1,55	R13 162,05	R791,29	R20 000,00	R30 000,00	R43 162,05
TOTAL	**R1 296 695,90**	**R6 522 380,38**	**9,08**	**R847 909,45**	**R50 975,71**	**R244 000,00**	**R1 360 000,00**	**R2 207 909,45**

APPENDIX B: COST CAPACITY EQUATIONS

$C_2 = C_1 \left(\frac{S2}{S1}\right)^n$

where C_1 = capital cost of a plant with capacity S_1

C_2 = capital cost of a plant with capacity S_2

n =cost exponent or scaling factor

The general equation used to update costs by making use of a cost index is as follows:

$C_t = C_o \left(\frac{It}{Io}\right)$

where C_t = estimated cost at present time t

C_o = cost at previous time time t_o

I_t = Index value at time t

I_o = Index value at time t_o

Heater

$C_2 = C_1 \left(\frac{S2}{S1}\right)^n$

C_2 = R113 339 194 $\left(\frac{40}{83\ 333}\right)^{0.6}$

C_2 = R115 698 .56

$C_t = C_o \left(\frac{It}{Io}\right)$

C_t = R115 698.56 $\left(\frac{596.2}{585.7}\right)$

C_t = R117 772.72

Cooler

$C_2 = C_1 \left(\frac{S2}{S1}\right)^n$

C_2 = R2 557 613 $\left(\frac{40}{83\ 333}\right)^{0.6}$

C_2 = R26 096.40

$C_t = C_o \left(\frac{It}{Io}\right)$

C_t = R26 096.40 $\left(\frac{596.2}{585.7}\right)$

C_t = R26 564.24

Fixed Conversion Reactor

C_2 = C_1 $\left(\frac{S2}{S1}\right)^n$

C_2 = R105 461 653 $\left(\frac{40}{83\ 333}\right)^{0.6}$

C_2 = R1 076 069.59

C_t = C_o $\left(\frac{It}{Io}\right)$

C_t = R1 076 069.59 $\left(\frac{596.2}{585.7}\right)$

C_t = R1 095 360.58

Flash Separator

C_2 = C_1 $\left(\frac{S2}{S1}\right)^n$

C_2 = R3 438 318.11 $\left(\frac{40}{83\ 333}\right)^{0.6}$

C_2 = R35 082.61

C_t = C_o $\left(\frac{It}{Io}\right)$

C_t = R35 082.61 $\left(\frac{596.2}{567.3}\right)$

C_t = R36 869.82

Cyclone

C_2 = C_1 $\left(\frac{S2}{S1}\right)^n$

C_2 = R1 937 982 $\left(\frac{40}{83\ 333}\right)^{0.6}$

C_2 = R19 774.05

$C_t = C_o \left(\frac{It}{Io}\right)$

$C_t = \text{R}19\ 774.05 \left(\frac{596.2}{585.7}\right)$

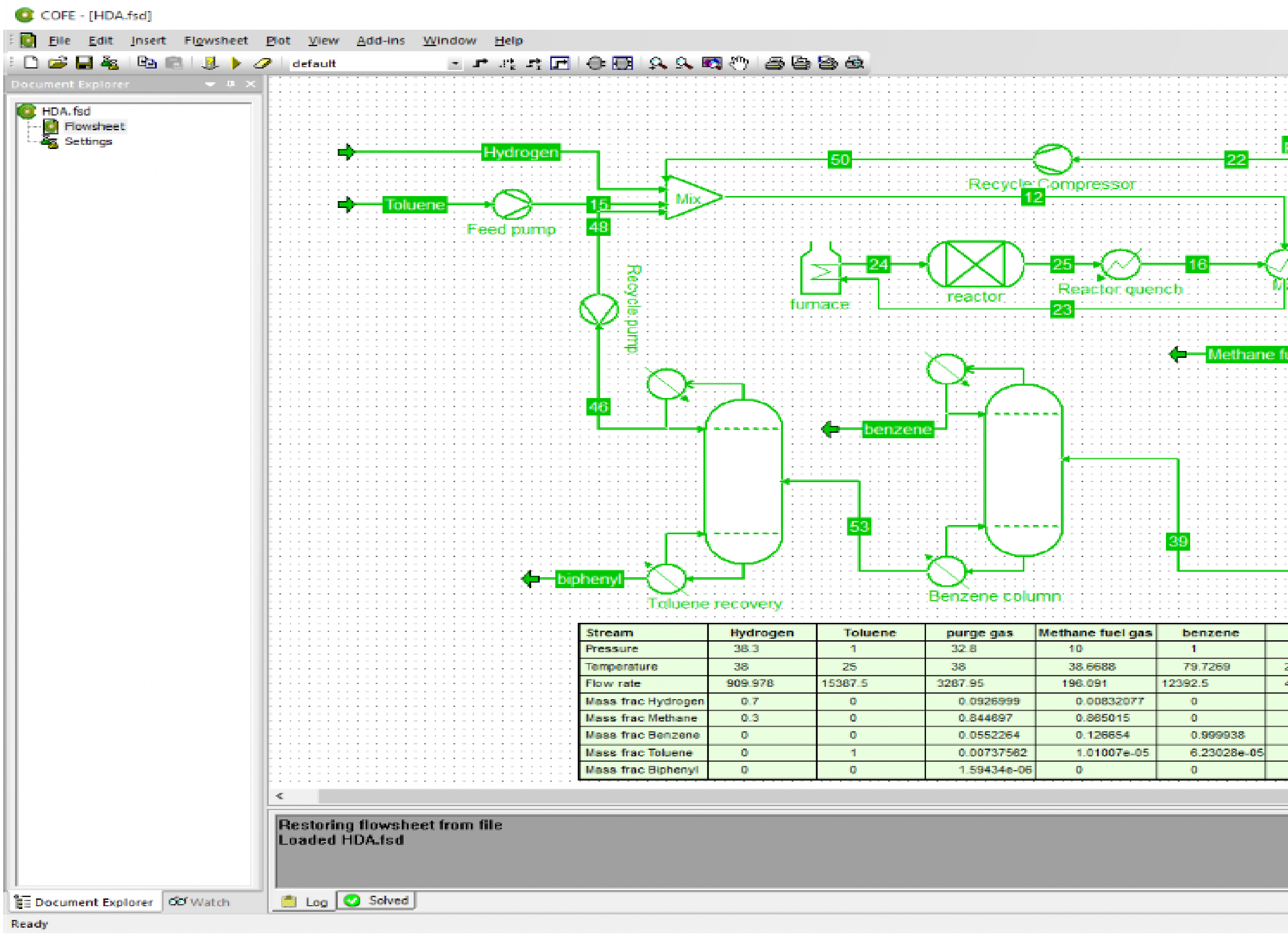
$C_t = \text{R}20\ 128.54$

APPENDIX C: COCO (CAPE-OPEN to CAPE-OPEN) SIMULATION PROGRAM

ELEMENTS IN COCO

COFE

It is an efficient graphical user interface for chemical flow sheeting. COFE uses automated tear streams with a sequential solution algorithm. COFE shows stream properties, manages the conversion of units and offers facilities for plotting. COFE flowsheets can be utilized as CAPE-OPEN unit operations, so that COFE flowsheets can be used within COFE (flowsheets in flowsheets) or within other simulators as unit operations. All elements are imported from CAPE-OPEN models (unit processes, thermodynamics and reactions). Under each document window, alerts and errors as well as additional information are logged to the output. Figure D.1 provides a representation of a COFE flowsheet.

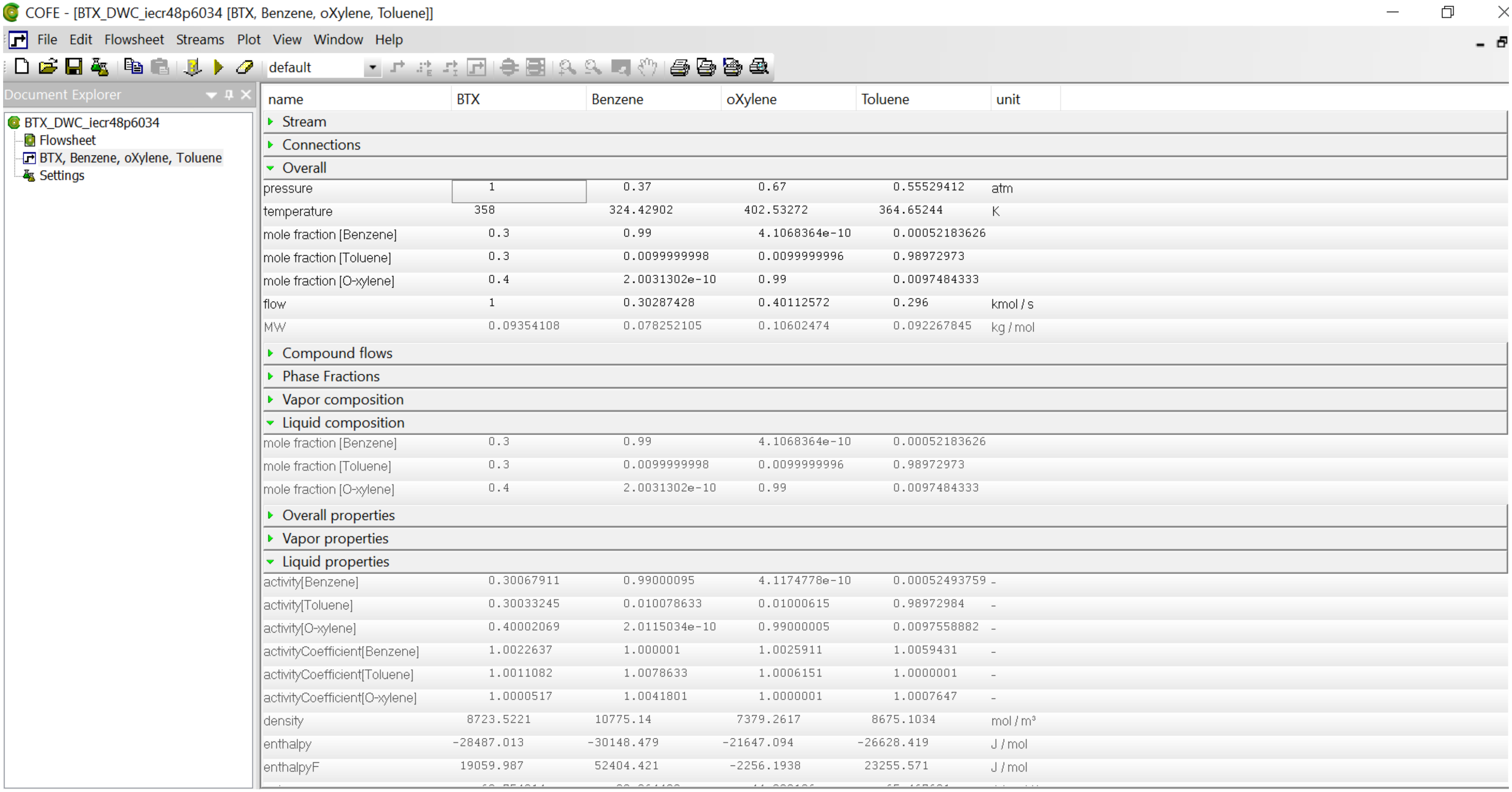


Stream	Hydrogen	Toluene	purge gas	Methane fuel gas	benzene
Pressure	38.3	1	32.8	10	1
Temperature	38	25	38	38.6688	79.7269
Flow rate	909.978	15387.5	3287.95	196.091	12392.5
Mass frac Hydrogen	0.7	0	0.0926999	0.00832077	0
Mass frac Methane	0.3	0	0.844697	0.865015	0
Mass frac Benzene	0	0	0.0552264	0.126654	0.999938
Mass frac Toluene	0	1	0.00737562	1.01007e-05	6.23028e-05
Mass frac Biphenyl	0	0	1.59434e-06	0	0

```
Restoring flowsheet from file
Loaded HDA.fsd
```

Figure D.1: Graphical representation of a COFE flowsheet (“COCO Simulator”, 2020)

Streams in COFE: An infinite number of streams is shown in the stream dialog. For each stream, composition, temperature, pressure or phase fraction may be specified. Any input will trigger a flash calculation and an update of the properties automatically. COCO also provides unit conversion facilities. An example of this is displayed in Figure D.2.

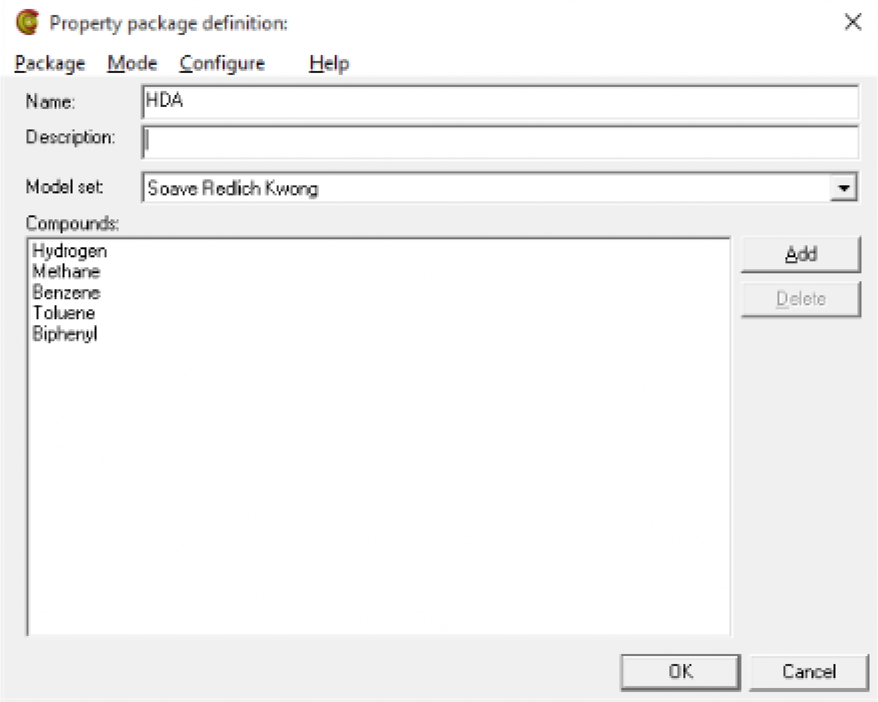


name	BTX	Benzene	oXylene	Toluene	unit
Stream					
Connections					
Overall					
pressure	1	0.37	0.67	0.55529412	atm
temperature	358	324.42902	402.53272	364.65244	K
mole fraction [Benzene]	0.3	0.99	4.1068364e-10	0.00052183626	
mole fraction [Toluene]	0.3	0.0099999998	0.0099999996	0.98972973	
mole fraction [O-xylene]	0.4	2.0031302e-10	0.99	0.0097484333	
flow	1	0.30287428	0.40112572	0.296	kmol / s
MW	0.09354108	0.078252105	0.10602474	0.092267845	kg / mol
Compound flows					
Phase Fractions					
Vapor composition					
Liquid composition					
mole fraction [Benzene]	0.3	0.99	4.1068364e-10	0.00052183626	
mole fraction [Toluene]	0.3	0.0099999998	0.0099999996	0.98972973	
mole fraction [O-xylene]	0.4	2.0031302e-10	0.99	0.0097484333	
Overall properties					
Vapor properties					
Liquid properties					
activity[Benzene]	0.30067911	0.99000095	4.1174778e-10	0.00052493759	-
activity[Toluene]	0.30033245	0.010078633	0.01000615	0.98972984	-
activity[O-xylene]	0.40002069	2.0115034e-10	0.99000005	0.0097558882	-
activityCoefficient[Benzene]	1.0022637	1.000001	1.0025911	1.0059431	-
activityCoefficient[Toluene]	1.0011082	1.0078633	1.0006151	1.0000001	-
activityCoefficient[O-xylene]	1.0000517	1.0041801	1.0000001	1.0007647	-
density	8723.5221	10775.14	7379.2617	8675.1034	mol / m³
enthalpy	-28487.013	-30148.479	-21647.094	-26628.419	J / mol
enthalpyF	19059.987	52404.421	-2256.1938	23255.571	J / mol

Figure D.2: Streams in COFE (“COCO Simulator”, 2020)

TEA

The Thermodynamics for Engineering Applications (TEA) of COCO is based on the coding of the ChemSep thermodynamic library and provides a database of over 430 chemicals widely used. With their analytical or numerical derivatives, the kit demonstrates over 100 property measurement methods (Figure D.3).



Name: HDA

Description:

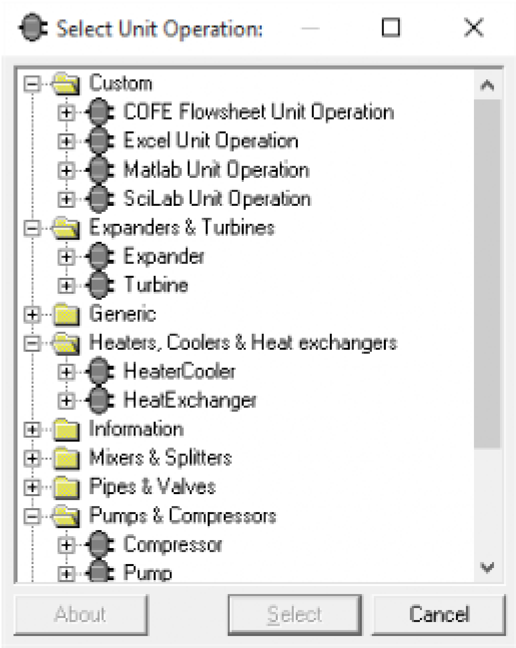
Model set: Soave Redlich Kwong

Compounds:
Hydrogen
Methane
Benzene
Toluene
Biphenyl

Figure D.3: The TEA property package display ("COCO Simulator", 2020)

COUSCOUS

The CAPE-OPEN Unit-operations Basic Kit is provided by COCO. It includes, among other unit operations, heat exchangers, a divider, pumps, a mixer and reactors. In COCO, ChemSep-LITE, a restricted version of ChemSep with a limit of 40 compounds and 300 phases, can serve as an operational equilibrium distillation unit (Figure D.5).



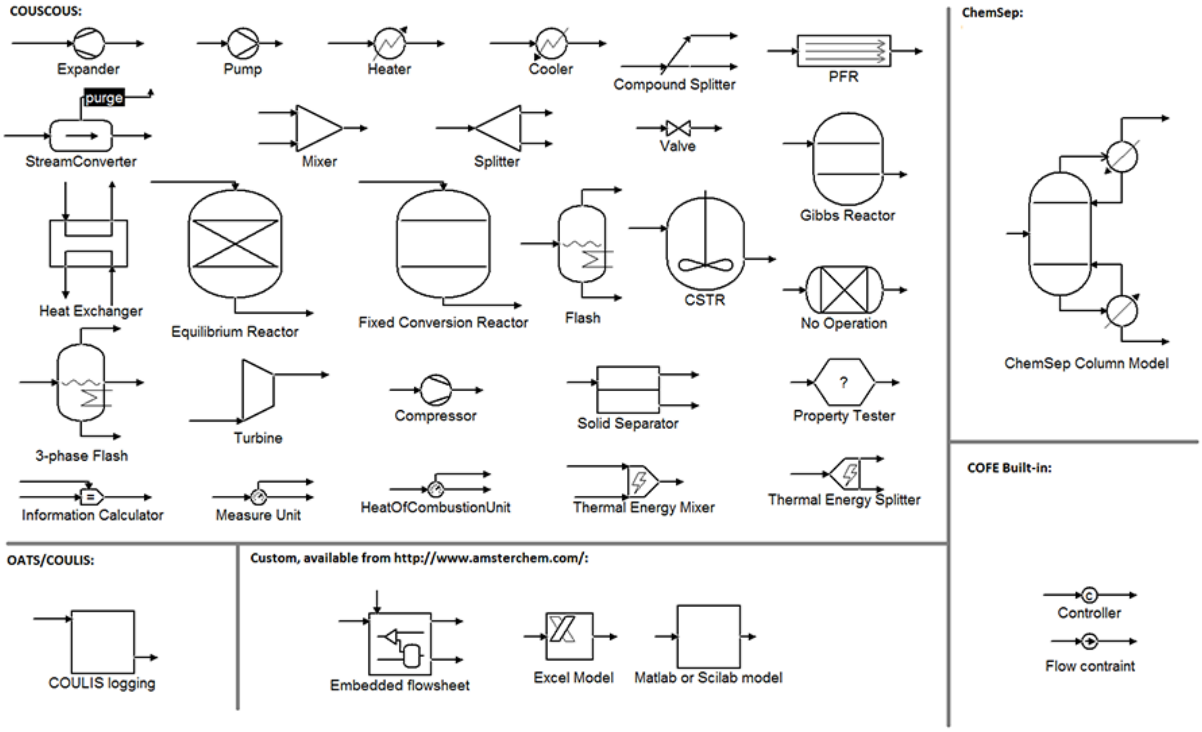
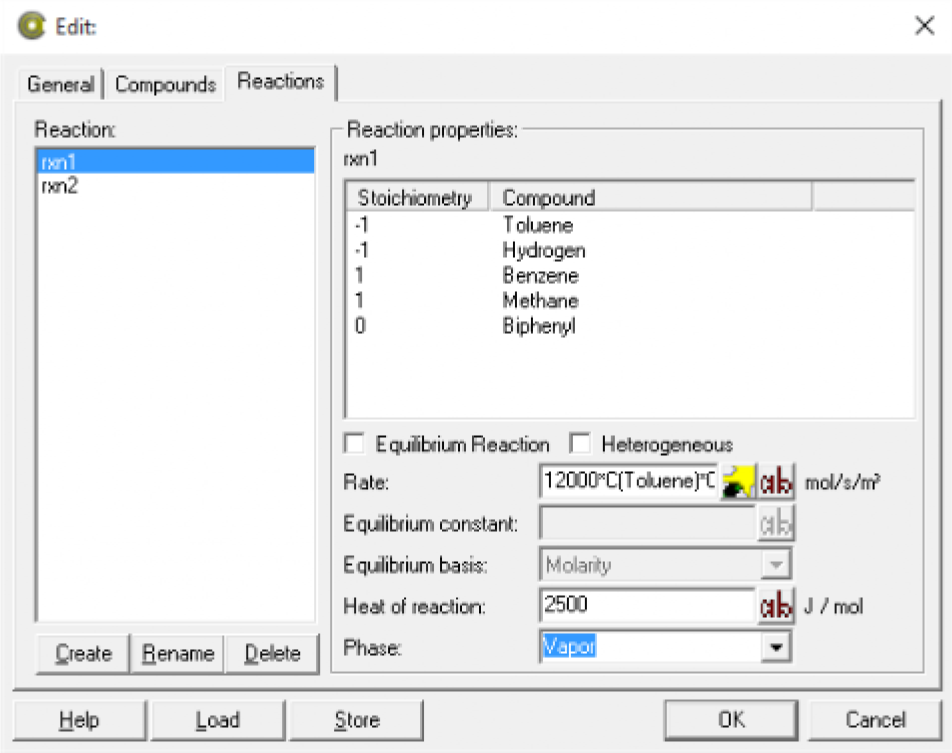


Figure D.5: Unit Operations in Couscous ("COCO Simulator", 2020)

CORN

The CAPE-OPEN Reaction Numerics kit within COCO allows any form of kinetic or equilibrium reaction to be defined. The COUSCOUS kit comes with basic reactor units such as Continuous Stirred Tank Reactors, conversion reactors and plug flow reactors that can use the CORN kit. A computer language is used to analyse the string of data. This enables the entry of reaction rate, equilibrium constants and the heat of reaction as indicated by Figure D.6. The reaction rate is built on the power law kinetic expression as well as Langmuir- kinetics.



Reaction:

rxn1
rxn2

Reaction properties:

rxn1

Stoichiometry	Compound
-1	Toluene
-1	Hydrogen
1	Benzene
1	Methane
0	Biphenyl

☐ Equilibrium Reaction ☐ Heterogeneous

Rate: 12000*C(Toluene)*C mol/s/m³

Equilibrium constant:

Equilibrium basis: Molarity

Heat of reaction: 2500 J / mol

Phase: Vapor

Figure D.6: CORN reaction package (“COCO Simulator”, 2020)

APPENDIX B: MASS AND ENERGY BALANCES (SIMULATION REPORT)

```
Flowsheet report for "Fast Pyrolysis Simulation - Matlala TM":

----------------------------------------------- flowsheet document ------------------

Title                                           Biomass Pyrolysis
Author                                          TM Matlala 45857547
Company                                         M.Tech Chemical Engineering
Created                                         Mar 18, 2020
Report                                          Mar 13, 2023
Status                                          Solved

----------------------------------------------- stream type default -----------------

Property package                                16092019 Pyrolysis SRK
Phases                                          Vapor, Liquid, Solid
Compounds                                       Sand / quartz, Water, Oxygen, High MW
                                                3-hydroxy-4-methoxy- (=benzaldehyde -
                                                4,4-dimethoxystilbene, 2-Butenoic aci
                                                levoglucosan, maltose, p-hydroquinone
                                                monoxide, Carbon dioxide, Methane, Et
                                                Propylene, Methyl acetate, Nitrogen, 
                                                (=dibenzofuran), char, hydroxyacetone

Stream table:

                                                ------------ ------------ -----------
Stream                                             Biomass   Reactor Feed      998
                                                ------------ ------------ -----------
From                                               <FEED>       Heater    Fixed Con..
To                                                 Heater    Fixed Con...    Cyclone
                                                ------------ ------------ -----------
Mole frac Sand / quartz                             0            0            0
Mole frac Water                                     0            0            0.35
Mole frac Oxygen                                    0            0            0.014
Mole frac High MW lig A                             0            0            0.0063
Mole frac High MW lig B                             0            0            0.0063
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-        0            0            0.019
Mole frac 4,4-dimethoxystilbene                     0            0            0
Mole frac 2-Butenoic acid, (E)-                     0            0            0.046
Mole frac dehydroabietic acid                       0            0            0.006
Mole frac Isoeugenol                                0            0            0.012
Mole frac levoglucosan                              0            0            0.046
Mole frac maltose                                   0            0            0.045
Mole frac p-hydroquinone                            0            0            0.036
Mole frac sorbitol                                  0            0            0
Mole frac Carbon monoxide                           0            0            0.13
Mole frac Carbon dioxide                            0            0            0.099
Mole frac Methane                                   0            0            0.029
Mole frac Ethane                                    0            0            0
Mole frac Propane                                   0            0            0
Mole frac N-butane                                  0            0            0
Mole frac Ethylene                                  0            0            0
Mole frac Propylene                                 0            0            0
Mole frac Methyl acetate                            0            0            0
Mole frac Nitrogen                                  0            0            0
Mole frac Dry pine wood                             1            1            0
Mole frac dibenzofurane                             0            0            0
Mole frac char                                      0            0            0.13
Mole frac hydroxyacetone                            0            0            0.022
Enthalpy                                            0           23           27
Flow rate                                          40           40           40
Temperature                                        25            5e+02        5e+02
Pressure                                            1e+02        1e+02        1e+02
Volume                                              4.8e-05      4.8e-05      0.064
                                                ------------ ------------ -----------
                                                                              Vapor
                                                ------------ ------------ -----------
Mole frac Sand / quartz                                                       0
Mole frac Water                                                               0.35
Mole frac Oxygen                                                              0.014
Mole frac High MW lig A                                                       0.0063
Mole frac High MW lig B                                                       0.0063
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-                                  0.019
Mole frac 4,4-dimethoxystilbene                                               0
Mole frac 2-Butenoic acid, (E)-                                               0.046
Mole frac dehydroabietic acid                                                 0.006
Mole frac Isoeugenol                                                          0.012
Mole frac levoglucosan                                                        0.046
Mole frac maltose                                                             0.045
Mole frac p-hydroquinone                                                      0.036
Mole frac sorbitol                                                            0
Mole frac Carbon monoxide                                                     0.13
Mole frac Carbon dioxide                                                      0.099
Mole frac Methane                                                             0.029
Mole frac Ethane                                                              0
Mole frac Propane                                                             0
Mole frac N-butane                                                            0
Mole frac Ethylene                                                            0
Mole frac Propylene                                                           0
Mole frac Methyl acetate                                                      0
```

```
Mole frac Nitrogen                                            0
Mole frac Dry pine wood                                       0
Mole frac dibenzofurane                                       0
Mole frac char                                                0.13
Mole frac hydroxyacetone                                      0.022
Density                                                      16
Viscosity                                                     1.5e-05
Mole phase fraction                                           1
MolecularWeight                                              73
                                                ------------ ------------ -----------
                                                                              Solid
                                                ------------ ------------ -----------
Mole frac Sand / quartz                             0            0
Mole frac Water                                     0            0
Mole frac Oxygen                                    0            0
Mole frac High MW lig A                             0            0
Mole frac High MW lig B                             0            0
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-        0            0
Mole frac 4,4-dimethoxystilbene                     0            0
Mole frac 2-Butenoic acid, (E)-                     0            0
Mole frac dehydroabietic acid                       0            0
Mole frac Isoeugenol                                0            0
Mole frac levoglucosan                              0            0
Mole frac maltose                                   0            0
Mole frac p-hydroquinone                            0            0
Mole frac sorbitol                                  0            0
Mole frac Carbon monoxide                           0            0
Mole frac Carbon dioxide                            0            0
Mole frac Methane                                   0            0
Mole frac Ethane                                    0            0
Mole frac Propane                                   0            0
Mole frac N-butane                                  0            0
Mole frac Ethylene                                  0            0
Mole frac Propylene                                 0            0
Mole frac Methyl acetate                            0            0
Mole frac Nitrogen                                  0            0
Mole frac Dry pine wood                             1            1
Mole frac dibenzofurane                             0            0
Mole frac char                                      0            0
Mole frac hydroxyacetone                            0            0
Density                                             2.1e+04      2.1e+04
Viscosity
Mole phase fraction                                 1            1
MolecularWeight                                    24           24
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
Stream                                               991          986          985
                                                ------------ ------------ -----------
From                                            Flash Sep... Flash Sep... Flash Sep..
To                                              Flash Sep... Bio-Oil C... Flue Gas ..
                                                ------------ ------------ -----------
Mole frac Sand / quartz                             0            0            0
Mole frac Water                                     0.41         0.57         0.096
Mole frac Oxygen                                    0.016        1.1e-05      0.046
Mole frac High MW lig A                             0.0072       0.011        1.4e-20
Mole frac High MW lig B                             0.0072       0.011        1.9e-21
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-        0.022        0.033        4.7e-08
Mole frac 4,4-dimethoxystilbene                     0            0            0
Mole frac 2-Butenoic acid, (E)-                     0.053        0.08         0.00098
Mole frac dehydroabietic acid                       0.0069       0.011        4.6e-06
Mole frac Isoeugenol                                0.014        0.021        1.8e-06
Mole frac levoglucosan                              0.053        0.081        5.3e-09
Mole frac maltose                                   0.052        0.08         3.3e-22
Mole frac p-hydroquinone                            0.042        0.063        4.9e-06
Mole frac sorbitol                                  0            0            0
Mole frac Carbon monoxide                           0.15         2.6e-05      0.43
Mole frac Carbon dioxide                            0.11         0.0015       0.33
Mole frac Methane                                   0.033        2.9e-05      0.097
Mole frac Ethane                                    0            0            0
Mole frac Propane                                   0            0            0
Mole frac N-butane                                  0            0            0
Mole frac Ethylene                                  0            0            0
Mole frac Propylene                                 0            0            0
Mole frac Methyl acetate                            0            0            0
Mole frac Nitrogen                                  0            0            0
Mole frac Dry pine wood                             0            0            0
Mole frac dibenzofurane                             0            0            0
Mole frac char                                      0            0            0
Mole frac hydroxyacetone                            0.025        0.038        0.00029
Enthalpy                                          -46          -74           -1.3
Flow rate                                          33           28            5.2
Temperature                                        50           40           40
Pressure                                            1e+02        1e+02        1e+02
Volume                                              0.0099       7e-05        0.025
                                                ------------ ------------ -----------
                                                                              Vapor
                                                ------------ ------------ -----------
Mole frac Sand / quartz                             0            0            0
Mole frac Water                                     0.15         0.096        0.059
```

```
Mole frac Oxygen                                    0.043        0.046        0.048
Mole frac High MW lig A                             1.5e-19      1.4e-20      0
Mole frac High MW lig B                             2.4e-20      1.9e-21      0
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-        1.3e-07      4.7e-08      3.3e-08
Mole frac 4,4-dimethoxystilbene                     0            0            0
Mole frac 2-Butenoic acid, (E)-                     0.0018       0.00098      0.001
Mole frac dehydroabietic acid                       5.9e-06      4.6e-06      4.7e-06
Mole frac Isoeugenol                                3.7e-06      1.8e-06      1.9e-06
Mole frac levoglucosan                              2.2e-08      5.3e-09      4.3e-12
Mole frac maltose                                   8e-21        3.3e-22      0
Mole frac p-hydroquinone                            1.2e-05      4.9e-06      2.1e-07
Mole frac sorbitol                                  0            0            0
Mole frac Carbon monoxide                           0.4          0.43         0.45
Mole frac Carbon dioxide                            0.31         0.33         0.34
Mole frac Methane                                   0.091        0.097        0.1
Mole frac Ethane                                    0            0            0
Mole frac Propane                                   0            0            0
Mole frac N-butane                                  0            0            0
Mole frac Ethylene                                  0            0            0
Mole frac Propylene                                 0            0            0
Mole frac Methyl acetate                            0            0            0
Mole frac Nitrogen                                  0            0            0
Mole frac Dry pine wood                             0            0            0
Mole frac dibenzofurane                             0            0            0
Mole frac char                                      0            0            0
Mole frac hydroxyacetone                            0.00058      0.00029      0.00029
Density                                            37           38           38
Viscosity                                           1.7e-05      1.7e-05      1.7e-05
Mole phase fraction                                 0.37         0            0.96
MolecularWeight                                    31           31           32
                                                ------------ ------------ -----------
                                                                              Liquid
                                                ------------ ------------ -----------
Mole frac Sand / quartz                             0            0            0
Mole frac Water                                     0.56         0.57         1
Mole frac Oxygen                                    1.1e-05      1.1e-05      1.2e-07
Mole frac High MW lig A                             0.011        0.011        0
Mole frac High MW lig B                             0.011        0.011        0
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-        0.034        0.033        4e-07
Mole frac 4,4-dimethoxystilbene                     0            0            0
Mole frac 2-Butenoic acid, (E)-                     0.082        0.08         5.7e-05
Mole frac dehydroabietic acid                       0.011        0.011        2e-25
Mole frac Isoeugenol                                0.021        0.021        3.9e-09
Mole frac levoglucosan                              0.084        0.081        1.3e-07
Mole frac maltose                                   0.083        0.08         0
Mole frac p-hydroquinone                            0.066        0.063        0.00012
Mole frac sorbitol                                  0            0            0
Mole frac Carbon monoxide                           2.8e-05      2.6e-05      5.9e-08
Mole frac Carbon dioxide                            0.0013       0.0015       2.4e-05
Mole frac Methane                                   2.9e-05      2.9e-05      1e-07
Mole frac Ethane                                    0            0            0
Mole frac Propane                                   0            0            0
Mole frac N-butane                                  0            0            0
Mole frac Ethylene                                  0            0            0
Mole frac Propylene                                 0            0            0
Mole frac Methyl acetate                            0            0            0
Mole frac Nitrogen                                  0            0            0
Mole frac Dry pine wood                             0            0            0
Mole frac dibenzofurane                             0            0            0
Mole frac char                                      0            0            0
Mole frac hydroxyacetone                            0.039        0.038        5.8e-05
Density                                             1.4e+04      1.4e+04      7e+04
Viscosity                                           0.00055      0.00051      0.00065
Mole phase fraction                                 0.63         1            0.039
MolecularWeight                                    90           88           18
                                                ------------ ------------ -----------


                                                ------------
Stream                                            Flue Gas
                                                ------------
From                                            Flue Gas ...
To                                                <PRODUCT>
                                                ------------
Mole frac Sand / quartz                             0
Mole frac Water                                     0.096
Mole frac Oxygen                                    0.046
Mole frac High MW lig A                             1.4e-20
Mole frac High MW lig B                             1.9e-21
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-        4.7e-08
Mole frac 4,4-dimethoxystilbene                     0
Mole frac 2-Butenoic acid, (E)-                     0.00098
Mole frac dehydroabietic acid                       4.6e-06
Mole frac Isoeugenol                                1.8e-06
Mole frac levoglucosan                              5.3e-09
Mole frac maltose                                   3.3e-22
Mole frac p-hydroquinone                            4.9e-06
Mole frac sorbitol                                  0
Mole frac Carbon monoxide                           0.43
Mole frac Carbon dioxide                            0.33
Mole frac Methane                                   0.097
```

```
Mole frac Ethane                                    0
Mole frac Propane                                   0
Mole frac N-butane                                  0
Mole frac Ethylene                                  0
Mole frac Propylene                                 0
Mole frac Methyl acetate                            0
Mole frac Nitrogen                                  0
Mole frac Dry pine wood                             0
Mole frac dibenzofurane                             0
Mole frac char                                      0
Mole frac hydroxyacetone                            0.00029
Enthalpy                                           -3.5      kJ / mol
Flow rate                                           5.2      kg / h
Temperature                                        25        °C
Pressure                                            1e+02    kPa
Volume                                              0.023    m³ / mol
                                                ------------
                                                    Vapor
                                                ------------
Mole frac Sand / quartz                             0
Mole frac Water                                     0.024
Mole frac Oxygen                                    0.049
Mole frac High MW lig A                             0
Mole frac High MW lig B                             0
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-        1.9e-08
Mole frac 4,4-dimethoxystilbene                     0
Mole frac 2-Butenoic acid, (E)-                     0.0011
Mole frac dehydroabietic acid                       4.9e-06
Mole frac Isoeugenol                                2e-06
Mole frac levoglucosan                              4.1e-13
Mole frac maltose                                   0
Mole frac p-hydroquinone                            4.1e-08
Mole frac sorbitol                                  0
Mole frac Carbon monoxide                           0.47
Mole frac Carbon dioxide                            0.35
Mole frac Methane                                   0.11
Mole frac Ethane                                    0
Mole frac Propane                                   0
Mole frac N-butane                                  0
Mole frac Ethylene                                  0
Mole frac Propylene                                 0
Mole frac Methyl acetate                            0
Mole frac Nitrogen                                  0
Mole frac Dry pine wood                             0
Mole frac dibenzofurane                             0
Mole frac char                                      0
Mole frac hydroxyacetone                            0.0003
Density                                            40        mol / m³
Viscosity                                           1.6e-05  Pa s
Mole phase fraction                                 0.93
MolecularWeight                                    32        -
                                                ------------
                                                    Liquid
                                                ------------
Mole frac Sand / quartz                             0
Mole frac Water                                     1
Mole frac Oxygen                                    8.3e-08
Mole frac High MW lig A                             0
Mole frac High MW lig B                             0
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-        4.1e-07
Mole frac 4,4-dimethoxystilbene                     0
Mole frac 2-Butenoic acid, (E)-                     7.6e-05
Mole frac dehydroabietic acid                       2.7e-27
Mole frac Isoeugenol                                2.7e-09
Mole frac levoglucosan                              7.1e-08
Mole frac maltose                                   0
Mole frac p-hydroquinone                            6.6e-05
Mole frac sorbitol                                  0
Mole frac Carbon monoxide                           3.3e-08
Mole frac Carbon dioxide                            2.2e-05
Mole frac Methane                                   6.3e-08
Mole frac Ethane                                    0
Mole frac Propane                                   0
Mole frac N-butane                                  0
Mole frac Ethylene                                  0
Mole frac Propylene                                 0
Mole frac Methyl acetate                            0
Mole frac Nitrogen                                  0
Mole frac Dry pine wood                             0
Mole frac dibenzofurane                             0
Mole frac char                                      0
Mole frac hydroxyacetone                            0.00011
Density                                             7.1e+04  mol / m³
Viscosity                                           0.0009   Pa s
Mole phase fraction                                 0.074
MolecularWeight                                    18        -
                                                ------------

--------------------------------------------- stream type TEA_SOLIDS -----------------
```

```
Property package                                <none>

Stream table:

                                                ------------ ------------ -----------
Stream                                             Biomass   Reactor Feed      998
                                                ------------ ------------ -----------
From                                               <FEED>       Heater    Fixed Con..
To                                                 Heater    Fixed Con...    Cyclone
                                                ------------ ------------ -----------
Mole frac Sand / quartz                             0            0            0
Mole frac Water                                     0            0            0.35
Mole frac Oxygen                                    0            0            0.014
Mole frac High MW lig A                             0            0            0.0063
Mole frac High MW lig B                             0            0            0.0063
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-        0            0            0.019
Mole frac 4,4-dimethoxystilbene                     0            0            0
Mole frac 2-Butenoic acid, (E)-                     0            0            0.046
Mole frac dehydroabietic acid                       0            0            0.006
Mole frac Isoeugenol                                0            0            0.012
Mole frac levoglucosan                              0            0            0.046
Mole frac maltose                                   0            0            0.045
Mole frac p-hydroquinone                            0            0            0.036
Mole frac sorbitol                                  0            0            0
Mole frac Carbon monoxide                           0            0            0.13
Mole frac Carbon dioxide                            0            0            0.099
Mole frac Methane                                   0            0            0.029
Mole frac Ethane                                    0            0            0
Mole frac Propane                                   0            0            0
Mole frac N-butane                                  0            0            0
Mole frac Ethylene                                  0            0            0
Mole frac Propylene                                 0            0            0
Mole frac Methyl acetate                            0            0            0
Mole frac Nitrogen                                  0            0            0
Mole frac Dry pine wood                             1            1            0
Mole frac dibenzofurane                             0            0            0
Mole frac char                                      0            0            0.13
Mole frac hydroxyacetone                            0            0            0.022
Enthalpy                                            0           23           27
Flow rate                                          40           40           40
Temperature                                        25            5e+02        5e+02
Pressure                                            1e+02        1e+02        1e+02
Volume                                              4.8e-05      4.8e-05      0.064
                                                ------------ ------------ -----------
                                                                              Vapor
                                                ------------ ------------ -----------
Mole frac Sand / quartz                                                       0
Mole frac Water                                                               0.35
Mole frac Oxygen                                                              0.014
Mole frac High MW lig A                                                       0.0063
Mole frac High MW lig B                                                       0.0063
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-                                  0.019
Mole frac 4,4-dimethoxystilbene                                               0
Mole frac 2-Butenoic acid, (E)-                                               0.046
Mole frac dehydroabietic acid                                                 0.006
Mole frac Isoeugenol                                                          0.012
Mole frac levoglucosan                                                        0.046
Mole frac maltose                                                             0.045
Mole frac p-hydroquinone                                                      0.036
Mole frac sorbitol                                                            0
Mole frac Carbon monoxide                                                     0.13
Mole frac Carbon dioxide                                                      0.099
Mole frac Methane                                                             0.029
Mole frac Ethane                                                              0
Mole frac Propane                                                             0
Mole frac N-butane                                                            0
Mole frac Ethylene                                                            0
Mole frac Propylene                                                           0
Mole frac Methyl acetate                                                      0
Mole frac Nitrogen                                                            0
Mole frac Dry pine wood                                                       0
Mole frac dibenzofurane                                                       0
Mole frac char                                                                0.13
Mole frac hydroxyacetone                                                      0.022
Density                                                                      16
Viscosity                                                                     1.5e-05
Mole phase fraction                                                           1
MolecularWeight                                                              73
                                                ------------ ------------ -----------
                                                                              Solid
                                                ------------ ------------ -----------
Mole frac Sand / quartz                             0            0
Mole frac Water                                     0            0
Mole frac Oxygen                                    0            0
Mole frac High MW lig A                             0            0
Mole frac High MW lig B                             0            0
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-        0            0
Mole frac 4,4-dimethoxystilbene                     0            0
Mole frac 2-Butenoic acid, (E)-                     0            0
Mole frac dehydroabietic acid                       0            0
```

```
Mole frac Isoeugenol                                0            0
Mole frac levoglucosan                              0            0
Mole frac maltose                                   0            0
Mole frac p-hydroquinone                            0            0
Mole frac sorbitol                                  0            0
Mole frac Carbon monoxide                           0            0
Mole frac Carbon dioxide                            0            0
Mole frac Methane                                   0            0
Mole frac Ethane                                    0            0
Mole frac Propane                                   0            0
Mole frac N-butane                                  0            0
Mole frac Ethylene                                  0            0
Mole frac Propylene                                 0            0
Mole frac Methyl acetate                            0            0
Mole frac Nitrogen                                  0            0
Mole frac Dry pine wood                             1            1
Mole frac dibenzofurane                             0            0
Mole frac char                                      0            0
Mole frac hydroxyacetone                            0            0
Density                                             2.1e+04      2.1e+04
Viscosity
Mole phase fraction                                 1            1
MolecularWeight                                    24           24
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
Stream                                               991          986          985
                                                ------------ ------------ -----------
From                                            Flash Sep... Flash Sep... Flash Sep..
To                                              Flash Sep... Bio-Oil C... Flue Gas ..
                                                ------------ ------------ -----------
Mole frac Sand / quartz                             0            0            0
Mole frac Water                                     0.41         0.57         0.096
Mole frac Oxygen                                    0.016        1.1e-05      0.046
Mole frac High MW lig A                             0.0072       0.011        1.4e-20
Mole frac High MW lig B                             0.0072       0.011        1.9e-21
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-        0.022        0.033        4.7e-08
Mole frac 4,4-dimethoxystilbene                     0            0            0
Mole frac 2-Butenoic acid, (E)-                     0.053        0.08         0.00098
Mole frac dehydroabietic acid                       0.0069       0.011        4.6e-06
Mole frac Isoeugenol                                0.014        0.021        1.8e-06
Mole frac levoglucosan                              0.053        0.081        5.3e-09
Mole frac maltose                                   0.052        0.08         3.3e-22
Mole frac p-hydroquinone                            0.042        0.063        4.9e-06
Mole frac sorbitol                                  0            0            0
Mole frac Carbon monoxide                           0.15         2.6e-05      0.43
Mole frac Carbon dioxide                            0.11         0.0015       0.33
Mole frac Methane                                   0.033        2.9e-05      0.097
Mole frac Ethane                                    0            0            0
Mole frac Propane                                   0            0            0
Mole frac N-butane                                  0            0            0
Mole frac Ethylene                                  0            0            0
Mole frac Propylene                                 0            0            0
Mole frac Methyl acetate                            0            0            0
Mole frac Nitrogen                                  0            0            0
Mole frac Dry pine wood                             0            0            0
Mole frac dibenzofurane                             0            0            0
Mole frac char                                      0            0            0
Mole frac hydroxyacetone                            0.025        0.038        0.00029
Enthalpy                                          -46          -74          -1.3
Flow rate                                          33           28           5.2
Temperature                                        50           40          40
Pressure                                            1e+02        1e+02        1e+02
Volume                                              0.0099       7e-05        0.025
                                                ------------ ------------ -----------
                                                                              Vapor
                                                ------------ ------------ -----------
Mole frac Sand / quartz                             0            0            0
Mole frac Water                                     0.15         0.096        0.059
Mole frac Oxygen                                    0.043        0.046        0.048
Mole frac High MW lig A                             1.5e-19      1.4e-20      0
Mole frac High MW lig B                             2.4e-20      1.9e-21      0
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-        1.3e-07      4.7e-08      3.3e-08
Mole frac 4,4-dimethoxystilbene                     0            0            0
Mole frac 2-Butenoic acid, (E)-                     0.0018       0.00098      0.001
Mole frac dehydroabietic acid                       5.9e-06      4.6e-06      4.7e-06
Mole frac Isoeugenol                                3.7e-06      1.8e-06      1.9e-06
Mole frac levoglucosan                              2.2e-08      5.3e-09      4.3e-12
Mole frac maltose                                   8e-21        3.3e-22      0
Mole frac p-hydroquinone                            1.2e-05      4.9e-06      2.1e-07
Mole frac sorbitol                                  0            0            0
Mole frac Carbon monoxide                           0.4          0.43         0.45
Mole frac Carbon dioxide                            0.31         0.33         0.34
Mole frac Methane                                   0.091        0.097        0.1
Mole frac Ethane                                    0            0            0
Mole frac Propane                                   0            0            0
Mole frac N-butane                                  0            0            0
Mole frac Ethylene                                  0            0            0
Mole frac Propylene                                 0            0            0
Mole frac Methyl acetate                            0            0            0
```

```
Mole frac Nitrogen                                  0            0            0
Mole frac Dry pine wood                             0            0            0
Mole frac dibenzofurane                             0            0            0
Mole frac char                                      0            0            0
Mole frac hydroxyacetone                            0.00058      0.00029      0.00029
Density                                            37           38           38
Viscosity                                           1.7e-05      1.7e-05      1.7e-05
Mole phase fraction                                 0.37         0            0.96
MolecularWeight                                    31           31           32
                                                ------------ ------------ -----------
                                                                              Liquid
                                                ------------ ------------ -----------
Mole frac Sand / quartz                             0            0            0
Mole frac Water                                     0.56         0.57         1
Mole frac Oxygen                                    1.1e-05      1.1e-05      1.2e-07
Mole frac High MW lig A                             0.011        0.011        0
Mole frac High MW lig B                             0.011        0.011        0
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-        0.034        0.033        4e-07
Mole frac 4,4-dimethoxystilbene                     0            0            0
Mole frac 2-Butenoic acid, (E)-                     0.082        0.08         5.7e-05
Mole frac dehydroabietic acid                       0.011        0.011        2e-25
Mole frac Isoeugenol                                0.021        0.021        3.9e-09
Mole frac levoglucosan                              0.084        0.081        1.3e-07
Mole frac maltose                                   0.083        0.08         0
Mole frac p-hydroquinone                            0.066        0.063        0.00012
Mole frac sorbitol                                  0            0            0
Mole frac Carbon monoxide                           2.8e-05      2.6e-05      5.9e-08
Mole frac Carbon dioxide                            0.0013       0.0015       2.4e-05
Mole frac Methane                                   2.9e-05      2.9e-05      1e-07
Mole frac Ethane                                    0            0            0
Mole frac Propane                                   0            0            0
Mole frac N-butane                                  0            0            0
Mole frac Ethylene                                  0            0            0
Mole frac Propylene                                 0            0            0
Mole frac Methyl acetate                            0            0            0
Mole frac Nitrogen                                  0            0            0
Mole frac Dry pine wood                             0            0            0
Mole frac dibenzofurane                             0            0            0
Mole frac char                                      0            0            0
Mole frac hydroxyacetone                            0.039        0.038        5.8e-05
Density                                             1.4e+04      1.4e+04      7e+04
Viscosity                                           0.00055      0.00051      0.00065
Mole phase fraction                                 0.63         1            0.039
MolecularWeight                                    90           88           18
                                                ------------ ------------ -----------

                                                ------------
Stream                                            Flue Gas
                                                ------------
From                                            Flue Gas ...
To                                                <PRODUCT>
                                                ------------
Mole frac Sand / quartz                             0
Mole frac Water                                     0.096
Mole frac Oxygen                                    0.046
Mole frac High MW lig A                             1.4e-20
Mole frac High MW lig B                             1.9e-21
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-        4.7e-08
Mole frac 4,4-dimethoxystilbene                     0
Mole frac 2-Butenoic acid, (E)-                     0.00098
Mole frac dehydroabietic acid                       4.6e-06
Mole frac Isoeugenol                                1.8e-06
Mole frac levoglucosan                              5.3e-09
Mole frac maltose                                   3.3e-22
Mole frac p-hydroquinone                            4.9e-06
Mole frac sorbitol                                  0
Mole frac Carbon monoxide                           0.43
Mole frac Carbon dioxide                            0.33
Mole frac Methane                                   0.097
Mole frac Ethane                                    0
Mole frac Propane                                   0
Mole frac N-butane                                  0
Mole frac Ethylene                                  0
Mole frac Propylene                                 0
Mole frac Methyl acetate                            0
Mole frac Nitrogen                                  0
Mole frac Dry pine wood                             0
Mole frac dibenzofurane                             0
Mole frac char                                      0
Mole frac hydroxyacetone                            0.00029
Enthalpy                                           -3.5      kJ / mol
Flow rate                                           5.2      kg / h
Temperature                                        25        °C
Pressure                                            1e+02    kPa
Volume                                              0.023    m³ / mol
                                                ------------
                                                    Vapor
                                                ------------
Mole frac Sand / quartz                             0
Mole frac Water                                     0.024
```

```
Mole frac Oxygen                                    0.049
Mole frac High MW lig A                             0
Mole frac High MW lig B                             0
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-        1.9e-08
Mole frac 4,4-dimethoxystilbene                     0
Mole frac 2-Butenoic acid, (E)-                     0.0011
Mole frac dehydroabietic acid                       4.9e-06
Mole frac Isoeugenol                                2e-06
Mole frac levoglucosan                              4.1e-13
Mole frac maltose                                   0
Mole frac p-hydroquinone                            4.1e-08
Mole frac sorbitol                                  0
Mole frac Carbon monoxide                           0.47
Mole frac Carbon dioxide                            0.35
Mole frac Methane                                   0.11
Mole frac Ethane                                    0
Mole frac Propane                                   0
Mole frac N-butane                                  0
Mole frac Ethylene                                  0
Mole frac Propylene                                 0
Mole frac Methyl acetate                            0
Mole frac Nitrogen                                  0
Mole frac Dry pine wood                             0
Mole frac dibenzofurane                             0
Mole frac char                                      0
Mole frac hydroxyacetone                            0.0003
Density                                            40        mol / m³
Viscosity                                           1.6e-05  Pa s
Mole phase fraction                                 0.93
MolecularWeight                                    32        -
                                                ------------
                                                    Liquid
                                                ------------
Mole frac Sand / quartz                             0
Mole frac Water                                     1
Mole frac Oxygen                                    8.3e-08
Mole frac High MW lig A                             0
Mole frac High MW lig B                             0
Mole frac Benzaldehyde, 3-hydroxy-4-methoxy-        4.1e-07
Mole frac 4,4-dimethoxystilbene                     0
Mole frac 2-Butenoic acid, (E)-                     7.6e-05
Mole frac dehydroabietic acid                       2.7e-27
Mole frac Isoeugenol                                2.7e-09
Mole frac levoglucosan                              7.1e-08
Mole frac maltose                                   0
Mole frac p-hydroquinone                            6.6e-05
Mole frac sorbitol                                  0
Mole frac Carbon monoxide                           3.3e-08
Mole frac Carbon dioxide                            2.2e-05
Mole frac Methane                                   6.3e-08
Mole frac Ethane                                    0
Mole frac Propane                                   0
Mole frac N-butane                                  0
Mole frac Ethylene                                  0
Mole frac Propylene                                 0
Mole frac Methyl acetate                            0
Mole frac Nitrogen                                  0
Mole frac Dry pine wood                             0
Mole frac dibenzofurane                             0
Mole frac char                                      0
Mole frac hydroxyacetone                            0.00011
Density                                             7.1e+04  mol / m³
Viscosity                                           0.0009   Pa s
Mole phase fraction                                 0.074
MolecularWeight                                    18        -
                                                -----------

--------------------------------------------- unit operation: Heater ----------------

Type                                            HeaterCooler
Description                                     HeaterCooler - heat or cool stream sp
Status                                          Solved

Ports:

Port                                            Inlet
Description                                     Feed
Direction                                       INLET
Type                                            material
Connected to                                    Biomass

Port                                            Outlet
Description                                     Product
Direction                                       OUTLET
Type                                            material
Connected to                                    Reactor Feed

Port                                            Heat
Description                                     Heat that is consumed or produced
Direction                                       OUTLET
```

```
Type                                            energy
Connected to                                    <not connected>

                                                ------------
Parameter                                           Value
                                                ------------
Type                                            Temperature
Outlet temperature                                  5e+02    °C
Heat duty                                           0.011    MW
Pressure drop                                       0        Pa
Thermo Version                                  1.0
                                                ------------

Balances:

                                                ------------ ------------ -----------
                                                    Mass       Enthalpy     EnthalpyF
                                                    kg/s           W            W
                                                ------------ ------------ -----------
Biomass                                             0.011        0           -5.4e+04
Reactor Feed                                       -0.011       -1.1e+04      4.4e+04
Total In                                            0.011        0           -5.4e+04
Total Out                                           0.011        1.1e+04     -4.4e+04
Net Gain                                            0            1.1e+04      1.1e+04
Rel.Gain                                            0            N/A         -0.19
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Sand / qu...     Water       Oxygen
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
Biomass                                             0            0            0
Reactor Feed                                       -0           -0           -0
Total In                                            0            0            0
Total Out                                           0            0            0
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Benzaldeh... 4,4-dimet... 2-Butenoi..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
Biomass                                             0            0            0
Reactor Feed                                       -0           -0           -0
Total In                                            0            0            0
Total Out                                           0            0            0
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                levoglucosan    maltose   p-hydroqu..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
Biomass                                             0            0            0
Reactor Feed                                       -0           -0           -0
Total In                                            0            0            0
Total Out                                           0            0            0
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Carbon di...    Methane      Ethane
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
Biomass                                             0            0            0
Reactor Feed                                       -0           -0           -0
Total In                                            0            0            0
Total Out                                           0            0            0
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                  Ethylene     Propylene  Methyl ac..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
Biomass                                             0            0            0
Reactor Feed                                       -0           -0           -0
Total In                                            0            0            0
Total Out                                           0            0            0
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                dibenzofu...     char     hydroxyac..
                                                    mol/s        mol/s        mol/s
```

```
                                                ------------ ------------ -----------
Biomass                                             0            0            0
Reactor Feed                                       -0           -0           -0
Total In                                            0            0            0
Total Out                                           0            0            0
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------


----------------------------------- unit operation: Fixed Conversion Reactor -------

Type                                            FixedConversionReactor
Description                                     FixedConversionReactor - perform reac
Status                                          Solved

Ports:

Port                                            Inlet
Description                                     Reactor feed
Direction                                       INLET
Type                                            material
Connected to                                    Reactor Feed

Port                                            Outlet
Description                                     Reactor product
Direction                                       OUTLET
Type                                            material
Connected to                                    998

Port                                            Heat duty
Description                                     Heat duty
Direction                                       OUTLET
Type                                            energy
Connected to                                    <not connected>

                                                ------------
Parameter                                           Value
                                                ------------
Pressure drop                                       0        Pa
Heat duty type                                  Isothermal
Temperature                                         5e+02    °C
Heat duty                                          -0.0052   MW
Enthalpy Type                                   Use Entha...
Thermo Version                                  1.0
Conversion Dry pine wood reaction dry pine wood     1
Conversion Dry pine wood reaction Straw             0
Conversion Dry pine wood reaction straw 2           0
                                                ------------

Balances:

                                                ------------ ------------ -----------
                                                    Mass       Enthalpy     EnthalpyF
                                                    kg/s           W            W
                                                ------------ ------------ -----------
Reactor Feed                                        0.011        1.1e+04     -4.4e+04
998                                                -0.011       -4.1e+03      4.9e+04
Total In                                            0.011        1.1e+04     -4.4e+04
Total Out                                           0.011        4.1e+03     -4.9e+04
Net Gain                                            9.5e-09     -6.5e+03     -5.2e+03
Rel.Gain                                            8.5e-07     -0.61         0.12
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Sand / qu...     Water       Oxygen
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
Reactor Feed                                        0            0            0
998                                                -0           -0.054       -0.0021
Total In                                            0            0            0
Total Out                                           0            0.054        0.0021
Net Gain                                            0            0.054        0.0021
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Benzaldeh... 4,4-dimet... 2-Butenoi..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
Reactor Feed                                        0            0            0
998                                                -0.0029      -0           -0.007
Total In                                            0            0            0
Total Out                                           0.0029       0            0.007
Net Gain                                            0.0029       0            0.007
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                levoglucosan    maltose   p-hydroqu..
```

```
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
Reactor Feed                                        0            0            0
998                                                -0.0071      -0.007       -0.0055
Total In                                            0            0            0
Total Out                                           0.0071       0.007        0.0055
Net Gain                                            0.0071       0.007        0.0055
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Carbon di...    Methane      Ethane
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
Reactor Feed                                        0            0            0
998                                                -0.015       -0.0044      -0
Total In                                            0            0            0
Total Out                                           0.015        0.0044       0
Net Gain                                            0.015        0.0044       0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                  Ethylene     Propylene  Methyl ac..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
Reactor Feed                                        0            0            0
998                                                -0           -0           -0
Total In                                            0            0            0
Total Out                                           0            0            0
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                dibenzofu...     char     hydroxyac..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
Reactor Feed                                        0            0            0
998                                                -0           -0.02        -0.0033
Total In                                            0            0            0
Total Out                                           0            0.02         0.0033
Net Gain                                            0            0.02         0.0033
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------


--------------------------------------------- unit operation: Cyclone ---------------

Type                                            CompoundSplitter
Description                                     CompoundSplitter - split compounds in
Status                                          Solved

Ports:

Port                                            Inlet
Description                                     Splitter feed port
Direction                                       INLET
Type                                            material
Connected to                                    998

Port                                            Main outlet
Description                                     CompoundSplitter main product
Direction                                       OUTLET
Type                                            material
Connected to                                    983

Port                                            Split outlet
Description                                     CompoundSplitter separated compounds
Direction                                       OUTLET
Type                                            material
Connected to                                    984

                                                ------------
Parameter                                           Value
                                                ------------
Pressure drop                                       0
Thermo Version                                  1.0
Split factor char                                   1
Split factor Dry pine wood                          1
                                                ------------

Balances:

                                                ------------ ------------ -----------
                                                    Mass        Enthalpy     EnthalpyF
                                                    kg/s            W            W
                                                ------------ ------------ -----------
998                                                 0.011        4.1e+03     -4.9e+04
983                                                -0.0091      -2.2e+03      4.8e+04
```

```
984                                                -0.002       -1.9e+03     6.8e+02
Total In                                            0.011        4.1e+03     -4.9e+04
Total Out                                           0.011        4.1e+03     -4.9e+04
Net Gain                                            0           -0.26        -0.26
Rel.Gain                                            0           -6.5e-05      5.4e-06
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Sand / qu...     Water       Oxygen
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
998                                                 0            0.054        0.0021
983                                                -0           -0.054       -0.0021
984                                                -0           -0           -0
Total In                                            0            0.054        0.0021
Total Out                                           0            0.054        0.0021
Net Gain                                            0            0            0
Rel.Gain                                            N/A          0            0
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Benzaldeh... 4,4-dimet... 2-Butenoi..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
998                                                 0.0029       0            0.007
983                                                -0.0029      -0           -0.007
984                                                -0           -0           -0
Total In                                            0.0029       0            0.007
Total Out                                           0.0029       0            0.007
Net Gain                                            0            0            0
Rel.Gain                                            0            N/A          0
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                levoglucosan    maltose   p-hydroqu..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
998                                                 0.0071       0.007        0.0055
983                                                -0.0071      -0.007       -0.0055
984                                                -0           -0           -0
Total In                                            0.0071       0.007        0.0055
Total Out                                           0.0071       0.007        0.0055
Net Gain                                            0            0            0
Rel.Gain                                            0            0            0
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Carbon di...    Methane      Ethane
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
998                                                 0.015        0.0044       0
983                                                -0.015       -0.0044      -0
984                                                -0           -0           -0
Total In                                            0.015        0.0044       0
Total Out                                           0.015        0.0044       0
Net Gain                                            0            0            0
Rel.Gain                                            0            0            N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                  Ethylene     Propylene  Methyl ac..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
998                                                 0            0            0
983                                                -0           -0           -0
984                                                -0           -0           -0
Total In                                            0            0            0
Total Out                                           0            0            0
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                dibenzofu...     char     hydroxyac..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
998                                                 0            0.02         0.0033
983                                                -0           -0           -0.0033
984                                                -0           -0.02        -0
Total In                                            0            0.02         0.0033
Total Out                                           0            0.02         0.0033
Net Gain                                            0            0            4.3e-19
Rel.Gain                                            N/A          0            1.3e-16
                                                ------------ ------------ -----------


----------------------------------------- unit operation: Biochar Cooler ------------

Type                                            HeaterCooler
Description                                     HeaterCooler - heat or cool stream sp
```

```
Status                                          Solved

Ports:

Port                                            Inlet
Description                                     Feed
Direction                                       INLET
Type                                            material
Connected to                                    984

Port                                            Outlet
Description                                     Product
Direction                                       OUTLET
Type                                            material
Connected to                                    Biochar

Port                                            Heat
Description                                     Heat that is consumed or produced
Direction                                       OUTLET
Type                                            energy
Connected to                                    <not connected>

                                                ------------
Parameter                                           Value
                                                ------------
Type                                            Temperature
Outlet temperature                                 25        °C
Heat duty                                          -0.0031   MW
Pressure drop                                       0        Pa
Thermo Version                                  1.0
                                                ------------

Balances:

                                                ------------ ------------ -----------
                                                    Mass       Enthalpy     EnthalpyF
                                                    kg/s          W            W
                                                ------------ ------------ -----------
984                                                 0.002        1.9e+03     -6.8e+02
Biochar                                            -0.002        1.1e+03      3.7e+03
Total In                                            0.002        1.9e+03     -6.8e+02
Total Out                                           0.002       -1.1e+03     -3.7e+03
Net Gain                                            0           -3.1e+03     -3.1e+03
Rel.Gain                                            0           -1.6          4.5
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Sand / qu...     Water       Oxygen
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
984                                                 0            0            0
Biochar                                            -0           -0           -0
Total In                                            0            0            0
Total Out                                           0            0            0
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Benzaldeh... 4,4-dimet... 2-Butenoi..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
984                                                 0            0            0
Biochar                                            -0           -0           -0
Total In                                            0            0            0
Total Out                                           0            0            0
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                levoglucosan    maltose   p-hydroqu..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
984                                                 0            0            0
Biochar                                            -0           -0           -0
Total In                                            0            0            0
Total Out                                           0            0            0
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Carbon di...    Methane      Ethane
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
984                                                 0            0            0
Biochar                                            -0           -0           -0
Total In                                            0            0            0
Total Out                                           0            0            0
```

```
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                  Ethylene     Propylene  Methyl ac..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
984                                                 0            0            0
Biochar                                            -0           -0           -0
Total In                                            0            0            0
Total Out                                           0            0            0
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                dibenzofu...     char     hydroxyac..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
984                                                 0            0.02         0
Biochar                                            -0           -0.02        -0
Total In                                            0            0.02         0
Total Out                                           0            0.02         0
Net Gain                                            0            0            0
Rel.Gain                                            N/A          0            N/A
                                                ------------ ------------ -----------


------------------------------------- unit operation: Flash Separator Cooler --------

Type                                            HeaterCooler
Description                                     HeaterCooler - heat or cool stream sp
Status                                          Solved

Ports:

Port                                            Inlet
Description                                     Feed
Direction                                       INLET
Type                                            material
Connected to                                    983

Port                                            Outlet
Description                                     Product
Direction                                       OUTLET
Type                                            material
Connected to                                    991

Port                                            Heat
Description                                     Heat that is consumed or produced
Direction                                       OUTLET
Type                                            energy
Connected to                                    <not connected>

                                                ------------
Parameter                                           Value
                                                ------------
Type                                            Temperature
Outlet temperature                                 50        °C
Heat duty                                          -0.0083   MW
Pressure drop                                       0        Pa
                                                ------------

Balances:

                                                ------------ ------------ -----------
                                                    Mass       Enthalpy     EnthalpyF
                                                    kg/s           W            W
                                                ------------ ------------ -----------
983                                                 0.0091       2.2e+03     -4.8e+04
991                                                -0.0091       6.1e+03      5.6e+04
Total In                                            0.0091       2.2e+03     -4.8e+04
Total Out                                           0.0091      -6.1e+03     -5.6e+04
Net Gain                                            0           -8.3e+03     -8.3e+03
Rel.Gain                                            0           -3.8          0.17
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Sand / qu...     Water       Oxygen
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
983                                                 0            0.054        0.0021
991                                                -0           -0.054       -0.0021
Total In                                            0            0.054        0.0021
Total Out                                           0            0.054        0.0021
Net Gain                                            0            0            0
Rel.Gain                                            N/A          0            0
                                                ------------ ------------ -----------
```

```
                                                ------------ ------------ -----------
                                                Benzaldeh... 4,4-dimet... 2-Butenoi..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
983                                                 0.0029       0            0.007
991                                                -0.0029      -0           -0.007
Total In                                            0.0029       0            0.007
Total Out                                           0.0029       0            0.007
Net Gain                                            0            0            0
Rel.Gain                                            0            N/A          0
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                levoglucosan    maltose   p-hydroqu..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
983                                                 0.0071       0.007        0.0055
991                                                -0.0071      -0.007       -0.0055
Total In                                            0.0071       0.007        0.0055
Total Out                                           0.0071       0.007        0.0055
Net Gain                                            0            0            0
Rel.Gain                                            0            0            0
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Carbon di...    Methane      Ethane
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
983                                                 0.015        0.0044       0
991                                                -0.015       -0.0044      -0
Total In                                            0.015        0.0044       0
Total Out                                           0.015        0.0044       0
Net Gain                                            0            0            0
Rel.Gain                                            0            0            N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                  Ethylene     Propylene  Methyl ac..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
983                                                 0            0            0
991                                                -0           -0           -0
Total In                                            0            0            0
Total Out                                           0            0            0
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                dibenzofu...     char     hydroxyac..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
983                                                 0            0            0.0033
991                                                -0           -0           -0.0033
Total In                                            0            0            0.0033
Total Out                                           0            0            0.0033
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          0
                                                ------------ ------------ -----------


----------------------------------------- unit operation: Flash Separator -----------

Type                                            Flash
Description                                     Flash - separate input stream into va
Status                                          Solved

Ports:

Port                                            Inlet
Description                                     Flash feed
Direction                                       INLET
Type                                            material
Connected to                                    991

Port                                            Vapor
Description                                     Flash vapor product
Direction                                       OUTLET
Type                                            material
Connected to                                    985

Port                                            Liquid
Description                                     Flash liquid (and solid) product
Direction                                       OUTLET
Type                                            material
Connected to                                    986

Port                                            Heat
Description                                     Heat that is consumed or produced by
Direction                                       OUTLET
```

```
Type                                            energy
Connected to                                    <not connected>

                                                ------------
Parameter                                           Value
                                                ------------
Pressure spec.                                  Pressure ...
Pressure drop                                       0        Pa
Pressure                                            1e+02    kPa
Flash specification                             Temperature
Heat duty                                         -0.00026  MW
Temperature                                        40        °C
TP Outlet Flash                                 No
Thermo Version                                  1.0
Vapor fraction                                      0.34
3-phase flash                                   No
Number of inlets                                1
                                                ------------

Balances:

                                                ------------ ------------ -----------
                                                    Mass       Enthalpy     EnthalpyF
                                                    kg/s           W            W
                                                ------------ ------------ -----------
991                                                 0.0091      -6.1e+03     -5.6e+04
985                                                -0.0014      61            9.5e+03
986                                                -0.0077       6.4e+03      4.7e+04
Total In                                            0.0091      -6.1e+03     -5.6e+04
Total Out                                           0.0091      -6.5e+03     -5.7e+04
Net Gain                                           -1.7e-18     -3.4e+02     -3.4e+02
Rel.Gain                                           -1.9e-16      0.055        0.006
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Sand / qu...     Water        Oxygen
                                                    mol/s        mol/s         mol/s
                                                ------------ ------------ -----------
991                                                 0            0.054         0.0021
985                                                -0           -0.0044       -0.0021
986                                                -0           -0.05         -9.4e-07
Total In                                            0            0.054         0.0021
Total Out                                           0            0.054         0.0021
Net Gain                                            0            0             0
Rel.Gain                                            N/A          0             0
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Benzaldeh... 4,4-dimet... 2-Butenoi..
                                                    mol/s        mol/s         mol/s
                                                ------------ ------------ -----------
991                                                 0.0029       0             0.007
985                                                -2.2e-09     -0            -4.5e-05
986                                                -0.0029      -0            -0.0069
Total In                                            0.0029       0             0.007
Total Out                                           0.0029       0             0.007
Net Gain                                            4.3e-19      0             0
Rel.Gain                                            1.5e-16      N/A           0
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                levoglucosan    maltose   p-hydroqu..
                                                    mol/s        mol/s         mol/s
                                                ------------ ------------ -----------
991                                                 0.0071       0.007         0.0055
985                                                -2.4e-10     -1.5e-23      -2.2e-07
986                                                -0.0071      -0.007        -0.0055
Total In                                            0.0071       0.007         0.0055
Total Out                                           0.0071       0.007         0.0055
Net Gain                                            0            0             0
Rel.Gain                                            0            0             0
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Carbon di...    Methane       Ethane
                                                    mol/s        mol/s         mol/s
                                                ------------ ------------ -----------
991                                                 0.015        0.0044        0
985                                                -0.015       -0.0044       -0
986                                                -0.00013     -2.5e-06      -0
Total In                                            0.015        0.0044        0
Total Out                                           0.015        0.0044        0
Net Gain                                            0            0             0
Rel.Gain                                            0            0             N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                  Ethylene     Propylene  Methyl ac..
                                                    mol/s        mol/s         mol/s
                                                ------------ ------------ -----------
```

```
991                                                 0            0            0
985                                                -0           -0           -0
986                                                -0           -0           -0
Total In                                            0            0            0
Total Out                                           0            0            0
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                dibenzofu...     char     hydroxyac..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
991                                                 0            0            0.0033
985                                                -0           -0           -1.3e-05
986                                                -0           -0           -0.0033
Total In                                            0            0            0.0033
Total Out                                           0            0            0.0033
Net Gain                                            0            0            4.3e-19
Rel.Gain                                            N/A          N/A          1.3e-16
                                                ------------ ------------ -----------


----------------------------------------- unit operation: Bio-Oil Cooler ------------

Type                                            HeaterCooler
Description                                     HeaterCooler - heat or cool stream sp
Status                                          Solved

Ports:

Port                                            Inlet
Description                                     Feed
Direction                                       INLET
Type                                            material
Connected to                                    986

Port                                            Outlet
Description                                     Product
Direction                                       OUTLET
Type                                            material
Connected to                                    Bio-Oil

Port                                            Heat
Description                                     Heat that is consumed or produced
Direction                                       OUTLET
Type                                            energy
Connected to                                    <not connected>

                                                ------------
Parameter                                           Value
                                                ------------

Type                                            Temperature
Outlet temperature                                 25        °C
Heat duty                                          -0.00017  MW
Pressure drop                                       0        Pa
Thermo Version                                  1.0
                                                ------------

Balances:

                                                ------------ ------------ -----------
                                                    Mass       Enthalpy     EnthalpyF
                                                    kg/s           W            W
                                                ------------ ------------ -----------
986                                                 0.0077      -6.4e+03     -4.7e+04
Bio-Oil                                            -0.0077       6.6e+03      4.7e+04
Total In                                            0.0077      -6.4e+03     -4.7e+04
Total Out                                           0.0077      -6.6e+03     -4.7e+04
Net Gain                                            0           -1.7e+02     -1.7e+02
Rel.Gain                                            0            0.027        0.0036
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Sand / qu...     Water       Oxygen
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
986                                                 0            0.05         9.4e-07
Bio-Oil                                            -0           -0.05        -9.4e-07
Total In                                            0            0.05         9.4e-07
Total Out                                           0            0.05         9.4e-07
Net Gain                                            0            0            0
Rel.Gain                                            N/A          0            0
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Benzaldeh... 4,4-dimet... 2-Butenoi..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
986                                                 0.0029       0            0.0069
```

```
Bio-Oil                                            -0.0029      -0           -0.0069
Total In                                            0.0029       0            0.0069
Total Out                                           0.0029       0            0.0069
Net Gain                                            0            0            0
Rel.Gain                                            0            N/A          0
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                levoglucosan    maltose   p-hydroqu..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
986                                                 0.0071       0.007        0.0055
Bio-Oil                                            -0.0071      -0.007       -0.0055
Total In                                            0.0071       0.007        0.0055
Total Out                                           0.0071       0.007        0.0055
Net Gain                                            0            0            0
Rel.Gain                                            0            0            0
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Carbon di...    Methane      Ethane
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
986                                                 0.00013      2.5e-06      0
Bio-Oil                                            -0.00013     -2.5e-06     -0
Total In                                            0.00013      2.5e-06      0
Total Out                                           0.00013      2.5e-06      0
Net Gain                                            0            0            0
Rel.Gain                                            0            0            N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                  Ethylene     Propylene  Methyl ac..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
986                                                 0            0            0
Bio-Oil                                            -0           -0           -0
Total In                                            0            0            0
Total Out                                           0            0            0
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                dibenzofu...     char     hydroxyac..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
986                                                 0            0            0.0033
Bio-Oil                                            -0           -0           -0.0033
Total In                                            0            0            0.0033
Total Out                                           0            0            0.0033
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          0
                                                ------------ ------------ -----------


----------------------------------------- unit operation: Flue Gas Cooler -----------

Type                                            HeaterCooler
Description                                     HeaterCooler - heat or cool stream sp
Status                                          Solved

Ports:

Port                                            Inlet
Description                                     Feed
Direction                                       INLET
Type                                            material
Connected to                                    985

Port                                            Outlet
Description                                     Product
Direction                                       OUTLET
Type                                            material
Connected to                                    Flue Gas

Port                                            Heat
Description                                     Heat that is consumed or produced
Direction                                       OUTLET
Type                                            energy
Connected to                                    <not connected>

                                                ------------
Parameter                                           Value
                                                ------------
Type                                            Temperature
Outlet temperature                                 25        °C
Heat duty                                          -9.8e-05  MW
Pressure drop                                       0        Pa
Thermo Version                                  1.0
```

```
                                                ------------

Balances:

                                                ------------ ------------ -----------
                                                    Mass       Enthalpy     EnthalpyF
                                                    kg/s         W            W
                                                ------------ ------------ -----------
985                                                 0.0014     -61           -9.5e+03
Flue Gas                                           -0.0014       1.6e+02      9.6e+03
Total In                                            0.0014     -61           -9.5e+03
Total Out                                           0.0014      -1.6e+02     -9.6e+03
Net Gain                                            0          -98          -98
Rel.Gain                                            0            1.6          0.01
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Sand / qu...     Water       Oxygen
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
985                                                 0            0.0044       0.0021
Flue Gas                                           -0           -0.0044      -0.0021
Total In                                            0            0.0044       0.0021
Total Out                                           0            0.0044       0.0021
Net Gain                                            0            0            0
Rel.Gain                                            N/A          0            0
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Benzaldeh... 4,4-dimet... 2-Butenoi..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
985                                                 2.2e-09      0            4.5e-05
Flue Gas                                           -2.2e-09     -0           -4.5e-05
Total In                                            2.2e-09      0            4.5e-05
Total Out                                           2.2e-09      0            4.5e-05
Net Gain                                            0            0            0
Rel.Gain                                            0            N/A          0
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                levoglucosan    maltose   p-hydroqu..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
985                                                 2.4e-10      1.5e-23      2.2e-07
Flue Gas                                           -2.4e-10     -1.5e-23     -2.2e-07
Total In                                            2.4e-10      1.5e-23      2.2e-07
Total Out                                           2.4e-10      1.5e-23      2.2e-07
Net Gain                                            0            0            0
Rel.Gain                                            0            0            0
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                Carbon di...    Methane      Ethane
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
985                                                 0.015        0.0044       0
Flue Gas                                           -0.015       -0.0044      -0
Total In                                            0.015        0.0044       0
Total Out                                           0.015        0.0044       0
Net Gain                                            0            0            0
Rel.Gain                                            0            0            N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                  Ethylene     Propylene  Methyl ac..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
985                                                 0            0            0
Flue Gas                                           -0           -0           -0
Total In                                            0            0            0
Total Out                                           0            0            0
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------

                                                ------------ ------------ -----------
                                                dibenzofu...     char     hydroxyac..
                                                    mol/s        mol/s        mol/s
                                                ------------ ------------ -----------
985                                                 0            0            1.3e-05
Flue Gas                                           -0           -0           -1.3e-05
Total In                                            0            0            1.3e-05
Total Out                                           0            0            1.3e-05
Net Gain                                            0            0            0
Rel.Gain                                            N/A          N/A          0
                                                ------------ ------------ -----------

------------------------------------------------ overall balances -------------------
```

```
                                                 ------------ ------------ -----------
                                                     Mass       Enthalpy     EnthalpyF
                                                     kg/s           W            W
                                                 ------------ ------------ -----------
Biomass                                              0.011        0            -5.4e+04
Flue Gas                                            -0.0014       1.6e+02       9.6e+03
Bio-Oil                                             -0.0077       6.6e+03       4.7e+04
Biochar                                             -0.002        1.1e+03       3.7e+03
Total In                                             0.011        0            -5.4e+04
Total Out                                            0.011       -7.9e+03      -6.1e+04
Net Gain                                             9.5e-09     -7.9e+03      -6.6e+03
Rel.Gain                                             8.5e-07      N/A           0.12
                                                 ------------ ------------ -----------

                                                 ------------ ------------ -----------
                                                 Sand / qu...     Water       Oxygen
                                                     mol/s        mol/s         mol/s
                                                 ------------ ------------ -----------
Biomass                                              0            0             0
Flue Gas                                            -0           -0.0044       -0.0021
Bio-Oil                                             -0           -0.05         -9.4e-07
Biochar                                             -0           -0            -0
Total In                                             0            0             0
Total Out                                            0            0.054         0.0021
Net Gain                                             0            0.054         0.0021
Rel.Gain                                             N/A          N/A           N/A
                                                 ------------ ------------ -----------

                                                 ------------ ------------ -----------
                                                 Benzaldeh... 4,4-dimet... 2-Butenoi..
                                                     mol/s        mol/s         mol/s
                                                 ------------ ------------ -----------
Biomass                                              0            0             0
Flue Gas                                            -2.2e-09     -0            -4.5e-05
Bio-Oil                                             -0.0029      -0            -0.0069
Biochar                                             -0           -0            -0
Total In                                             0            0             0
Total Out                                            0.0029       0             0.007
Net Gain                                             0.0029       0             0.007
Rel.Gain                                             N/A          N/A           N/A
                                                 ------------ ------------ -----------

                                                 ------------ ------------ -----------
                                                 levoglucosan    maltose   p-hydroqu..
                                                     mol/s        mol/s         mol/s
                                                 ------------ ------------ -----------
Biomass                                              0            0             0
Flue Gas                                            -2.4e-10     -1.5e-23      -2.2e-07
Bio-Oil                                             -0.0071      -0.007        -0.0055
Biochar                                             -0           -0            -0
Total In                                             0            0             0
Total Out                                            0.0071       0.007         0.0055
Net Gain                                             0.0071       0.007         0.0055
Rel.Gain                                             N/A          N/A           N/A
                                                 ------------ ------------ -----------

                                                 ------------ ------------ -----------
                                                 Carbon di...    Methane      Ethane
                                                     mol/s        mol/s         mol/s
                                                 ------------ ------------ -----------
Biomass                                              0            0             0
Flue Gas                                            -0.015       -0.0044       -0
Bio-Oil                                             -0.00013     -2.5e-06      -0
Biochar                                             -0           -0            -0
Total In                                             0            0             0
Total Out                                            0.015        0.0044        0
Net Gain                                             0.015        0.0044        0
Rel.Gain                                             N/A          N/A           N/A
                                                 ------------ ------------ -----------

                                                 ------------ ------------ -----------
                                                   Ethylene     Propylene  Methyl ac..
                                                     mol/s        mol/s         mol/s
                                                 ------------ ------------ -----------
Biomass                                              0            0             0
Flue Gas                                            -0           -0            -0
Bio-Oil                                             -0           -0            -0
Biochar                                             -0           -0            -0
Total In                                             0            0             0
Total Out                                            0            0             0
Net Gain                                             0            0             0
Rel.Gain                                             N/A          N/A           N/A
                                                 ------------ ------------ -----------

                                                 ------------ ------------ -----------
                                                 dibenzofu...     char     hydroxyac..
                                                     mol/s        mol/s         mol/s
                                                 ------------ ------------ -----------
Biomass                                              0            0             0
```

```
Flue Gas                                           -0           -0           -1.3e-05
Bio-Oil                                            -0           -0           -0.0033
Biochar                                            -0           -0.02        -0
Total In                                            0            0            0
Total Out                                           0            0.02         0.0033
Net Gain                                            0            0.02         0.0033
Rel.Gain                                            N/A          N/A          N/A
                                                ------------ ------------ -----------
```

```
------------------------------




------------------------------


 lig A, High MW lig B, Benzaldehyde,
 3 hydroxy - 4 methoxy),
d, (E)-, dehydroabietic acid, Isoeugenol,
 (=Hydroquinone), sorbitol, Carbon
hane, Propane, N-butane, Ethylene,
Dry pine wood, dibenzofurane



- ------------ ------------
       984          983
- ------------ ------------
.    Cyclone      Cyclone
  Biochar C... Flash Sep...
- ------------ ------------
      0            0
      0            0.41
      0            0.016
      0            0.0072
      0            0.0072
      0            0.022
      0            0
      0            0.053
      0            0.0069
      0            0.014
      0            0.053
      0            0.052
      0            0.042
      0            0
      0            0.15
      0            0.11
      0            0.033
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      1            0
      0            0.025
     95           16         kJ / mol
      7.2         33         kg / h
      5e+02        5e+02    °C
      1e+02        1e+02    kPa
      0.064        0.064    m³ / mol
- ------------ ------------

- ------------ ------------
      0            0
      0            0.41
      0            0.016
      0            0.0072
      0            0.0072
      0            0.022
      0            0
      0            0.053
      0            0.0069
      0            0.014
      0            0.053
      0            0.052
      0            0.042
      0            0
      0            0.15
      0            0.11
      0            0.033
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
```

```
      0            0
      0            0
      0            0
      1            0
      0            0.025
     16           16        mol / m³
      1.7e-05      1.5e-05  Pa s
      1            1
      1e+02       68        -
- ------------ ------------

- ------------ ------------
```

```
                            mol / m³
                            Pa s

                            -
- ------------ ------------

- ------------ ------------
     Biochar      Bio-Oil
- ------------ ------------
. Biochar C... Bio-Oil C...
.   <PRODUCT>    <PRODUCT>
- ------------ ------------
      0            0
      0            0.57
      0            1.1e-05
      0            0.011
      0            0.011
      0            0.033
      0            0
      0            0.08
      0            0.011
      0            0.021
      0            0.081
      0            0.08
      0            0.063
      0            0
      0            2.6e-05
      0            0.0015
      0            2.9e-05
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      1            0
      0            0.038
    -57          -75        kJ / mol
      7.2         28        kg / h
     25           25        °C
      1e+02        1e+02    kPa
      0.00011      6.9e-05  m³ / mol
- ------------ ------------

- ------------ ------------
```

```
                            mol / m³
                            Pa s

                            -
- ------------ ------------

- ------------ ------------
      0            0
      0            0.57
      0            1.1e-05
      0            0.011
      0            0.011
      0            0.033
      0            0
      0            0.08
      0            0.011
      0            0.021
      0            0.081
      0            0.08
      0            0.063
      0            0
      0            2.6e-05
      0            0.0015
      0            2.9e-05
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      1            0
      0            0.038
      9.5e+03      1.4e+04  mol / m³
      0.0077       0.00047  Pa s
      1            1
      1e+02       88        -
- ------------ ------------
```

```
- ------------ ------------
       984          983
- ------------ ------------
.    Cyclone      Cyclone
  Biochar C... Flash Sep...
- ------------ ------------
      0            0
      0            0.41
      0            0.016
      0            0.0072
      0            0.0072
      0            0.022
      0            0
      0            0.053
      0            0.0069
      0            0.014
      0            0.053
      0            0.052
      0            0.042
      0            0
      0            0.15
      0            0.11
      0            0.033
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      1            0
      0            0.025
     95           16         kJ / mol
      7.2         33         kg / h
      5e+02        5e+02     °C
      1e+02        1e+02     kPa
      0.064        0.064     m³ / mol
- ------------ ------------

- ------------ ------------
      0            0
      0            0.41
      0            0.016
      0            0.0072
      0            0.0072
      0            0.022
      0            0
      0            0.053
      0            0.0069
      0            0.014
      0            0.053
      0            0.052
      0            0.042
      0            0
      0            0.15
      0            0.11
      0            0.033
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      1            0
      0            0.025
     16           16         mol / m³
      1.7e-05      1.5e-05   Pa s
      1            1
      1e+02       68         -
- ------------ ------------

- ------------ ------------
```

```
                            mol / m³
                            Pa s

                            -
- ------------ ------------

- ------------ ------------
     Biochar      Bio-Oil
- ------------ ------------
. Biochar C... Bio-Oil C...
.   <PRODUCT>    <PRODUCT>
- ------------ ------------
      0            0
      0            0.57
      0            1.1e-05
      0            0.011
      0            0.011
      0            0.033
      0            0
      0            0.08
      0            0.011
      0            0.021
      0            0.081
      0            0.08
      0            0.063
      0            0
      0            2.6e-05
      0            0.0015
      0            2.9e-05
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      0            0
      1            0
      0            0.038
    -57          -75        kJ / mol
      7.2         28        kg / h
     25           25        °C
      1e+02        1e+02    kPa
      0.00011      6.9e-05  m³ / mol
- ------------ ------------

- ------------ ------------
```

```
                            mol / m³
                            Pa s

                            -
- ------------ ------------

- ------------ ------------
      0             0
      0             0.57
      0             1.1e-05
      0             0.011
      0             0.011
      0             0.033
      0             0
      0             0.08
      0             0.011
      0             0.021
      0             0.081
      0             0.08
      0             0.063
      0             0
      0             2.6e-05
      0             0.0015
      0             2.9e-05
      0             0
      0             0
      0             0
      0             0
      0             0
      0             0
      0             0
      0             0
      0             0
      1             0
      0             0.038
      9.5e+03       1.4e+04  mol / m³
      0.0077        0.00047  Pa s
      1             1
      1e+02        88        -
- ------------ ------------
```

```
------------------------------

ecifying heat duty or outlet temperature
```

```
- ------------ ------------
     Entropy     EntropyF
       W/K          W/K
- ------------ ------------
      0            1.1e-41
    -21          -21
      0            1.1e-41
     21           21
     21           21
      N/A          1.9e+42
- ------------ ------------

- ------------ ------------
  High MW l... High MW l...
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

- ------------ ------------
. dehydroab...  Isoeugenol
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

- ------------ ------------
.   sorbitol   Carbon mo...
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

- ------------ ------------
     Propane     N-butane
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

- ------------ ------------
.   Nitrogen   Dry pine ...
      mol/s        mol/s
- ------------ ------------
      0            0.46
     -0           -0.46
      0            0.46
      0            0.46
      0            0
      N/A          0
- ------------ ------------

-
.
```

```
-



-

------------------------------

tions using a specified conversion
```

```
- ------------ ------------
     Entropy     EntropyF
       W/K          W/K
- ------------ ------------
     21           21
    -11          -63
     21           21
     11           63
    -10           42
     -0.5          2
- ------------ ------------

- ------------ ------------
  High MW l... High MW l...
      mol/s        mol/s
- ------------ ------------
      0            0
     -0.00096     -0.00096
      0            0
      0.00096      0.00096
      0.00096      0.00096
      N/A          N/A
- ------------ ------------

- ------------ ------------
. dehydroab...  Isoeugenol
      mol/s        mol/s
- ------------ ------------
      0            0
     -0.00092     -0.0018
      0            0
      0.00092      0.0018
      0.00092      0.0018
      N/A          N/A
- ------------ ------------

- ------------ ------------
.   sorbitol   Carbon mo...
```

```
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0.02
      0            0
      0            0.02
      0            0.02
      N/A          N/A
- ------------ ------------

- ------------ ------------
     Propane     N-butane
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

- ------------ ------------
.   Nitrogen   Dry pine ...
      mol/s        mol/s
- ------------ ------------
      0            0.46
     -0           -0
      0            0.46
      0            0
      0           -0.46
      N/A         -1
- ------------ ------------

-
.

-






-


------------------------------


to pre-defined fractions

















product

















- ------------ ------------
     Entropy     EntropyF
       W/K          W/K
- ------------ ------------
     11           63
     -6.5        -52
```

```
     -3.6        -11
     11           63
     10           62
     -0.49        -0.49
     -0.046       -0.0079
- ------------ ------------

- ------------ ------------
  High MW l... High MW l...
      mol/s        mol/s
- ------------ ------------
      0.00096      0.00096
     -0.00096     -0.00096
     -0           -0
      0.00096      0.00096
      0.00096      0.00096
      0            0
      0            0
- ------------ ------------

- ------------ ------------
. dehydroab...  Isoeugenol
      mol/s        mol/s
- ------------ ------------
      0.00092      0.0018
     -0.00092     -0.0018
     -0           -0
      0.00092      0.0018
      0.00092      0.0018
      0            0
      0            0
- ------------ ------------

- ------------ ------------
.   sorbitol   Carbon mo...
      mol/s        mol/s
- ------------ ------------
      0            0.02
     -0           -0.02
     -0           -0
      0            0.02
      0            0.02
      0            0
      N/A          0
- ------------ ------------

- ------------ ------------
     Propane     N-butane
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

- ------------ ------------
.   Nitrogen   Dry pine ...
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

-
.

-







-


-----------------------------


ecifying heat duty or outlet temperature
```

```
- ------------ ------------
     Entropy     EntropyF
       W/K          W/K
- ------------ ------------
      3.6         11
      2.6         -4.5
      3.6         11
     -2.6          4.5
     -6.2         -6.2
     -1.7         -0.58
- ------------ ------------

- ------------ ------------
  High MW l... High MW l...
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

- ------------ ------------
. dehydroab...  Isoeugenol
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

- ------------ ------------
.   sorbitol   Carbon mo...
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

- ------------ ------------
     Propane     N-butane
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
      0            0
      0            0
```

```
      0            0
      N/A          N/A
- ------------ ------------

- ------------ ------------
.   Nitrogen   Dry pine ...
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

-
.

-




-

------------------------------

ecifying heat duty or outlet temperature
```

```
- ------------ ------------
     Entropy     EntropyF
       W/K          W/K
- ------------ ------------
      6.5         52
     11          -34
      6.5         52
    -11           34
    -18          -18
     -2.8         -0.35
- ------------ ------------

- ------------ ------------
  High MW l... High MW l...
      mol/s        mol/s
- ------------ ------------
      0.00096      0.00096
     -0.00096     -0.00096
      0.00096      0.00096
      0.00096      0.00096
      0            0
      0            0
- ------------ ------------
```

```
- ------------ ------------
. dehydroab...  Isoeugenol
      mol/s        mol/s
- ------------ ------------
      0.00092      0.0018
     -0.00092     -0.0018
      0.00092      0.0018
      0.00092      0.0018
      0            0
      0            0
- ------------ ------------

- ------------ ------------
.   sorbitol   Carbon mo...
      mol/s        mol/s
- ------------ ------------
      0            0.02
     -0           -0.02
      0            0.02
      0            0.02
      0            0
      N/A          0
- ------------ ------------

- ------------ ------------
     Propane     N-butane
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

- ------------ ------------
.   Nitrogen   Dry pine ...
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

-
.

-






-

------------------------------


por and remaining phases
```

this unit

```
- ------------ ------------
     Entropy     EntropyF
       W/K          W/K
- ------------ ------------
    -11           34
     -0.32        -9.5
     13          -23
    -11           34
    -13           32
     -1.1         -1.1
      0.093       -0.032
- ------------ ------------

- ------------ ------------
  High MW l... High MW l...
      mol/s        mol/s
- ------------ ------------
      0.00096      0.00096
     -6.6e-22     -8.7e-23
     -0.00096     -0.00096
      0.00096      0.00096
      0.00096      0.00096
      0            0
      0            0
- ------------ ------------

- ------------ ------------
. dehydroab...  Isoeugenol
      mol/s        mol/s
- ------------ ------------
      0.00092      0.0018
     -2.1e-07     -8.3e-08
     -0.00092     -0.0018
      0.00092      0.0018
      0.00092      0.0018
      0            0
      0            0
- ------------ ------------

- ------------ ------------
.   sorbitol   Carbon mo...
      mol/s        mol/s
- ------------ ------------
      0            0.02
     -0           -0.02
     -0           -2.3e-06
      0            0.02
      0            0.02
      0            0
      N/A          0
- ------------ ------------

- ------------ ------------
     Propane     N-butane
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

- ------------ ------------
.   Nitrogen   Dry pine ...
      mol/s        mol/s
- ------------ ------------
```

```
      0            0
     -0           -0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

-
.

-







-


------------------------------


ecifying heat duty or outlet temperature
```

```
- ------------ ------------
     Entropy     EntropyF
       W/K          W/K
- ------------ ------------
    -13          23
     13         -22
    -13          23
    -13          22
      -0.56       -0.56
      0.044       -0.025
- ------------ ------------

- ------------ ------------
  High MW l... High MW l...
      mol/s        mol/s
- ------------ ------------
      0.00096      0.00096
     -0.00096     -0.00096
      0.00096      0.00096
      0.00096      0.00096
      0            0
      0            0
- ------------ ------------

- ------------ ------------
. dehydroab...  Isoeugenol
      mol/s        mol/s
- ------------ ------------
      0.00092      0.0018
```

```
     -0.00092     -0.0018
      0.00092      0.0018
      0.00092      0.0018
      0            0
      0            0
- ------------ ------------

- ------------ ------------
.   sorbitol   Carbon mo...
      mol/s        mol/s
- ------------ ------------
      0            2.3e-06
     -0           -2.3e-06
      0            2.3e-06
      0            2.3e-06
      0            0
      N/A          0
- ------------ ------------

- ------------ ------------
     Propane     N-butane
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

- ------------ ------------
.   Nitrogen   Dry pine ...
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

-
.

-




-

------------------------------

ecifying heat duty or outlet temperature
```

```
- ------------ ------------
     Entropy     EntropyF
       W/K         W/K
- ------------ ------------
      0.32        9.5
     -0.0019     -9.2
      0.32        9.5
      0.0019      9.2
     -0.32       -0.32
     -0.99       -0.033
- ------------ ------------

- ------------ ------------
  High MW l... High MW l...
      mol/s       mol/s
- ------------ ------------
      6.6e-22     8.7e-23
     -6.6e-22    -8.7e-23
      6.6e-22     8.7e-23
      6.6e-22     8.7e-23
      0           0
      0           0
- ------------ ------------

- ------------ ------------
. dehydroab...  Isoeugenol
      mol/s       mol/s
- ------------ ------------
      2.1e-07     8.3e-08
     -2.1e-07    -8.3e-08
      2.1e-07     8.3e-08
      2.1e-07     8.3e-08
      0           0
      0           0
- ------------ ------------

- ------------ ------------
.   sorbitol   Carbon mo...
      mol/s       mol/s
- ------------ ------------
      0           0.02
     -0          -0.02
      0           0.02
      0           0.02
      0           0
      N/A         0
- ------------ ------------

- ------------ ------------
     Propane     N-butane
      mol/s       mol/s
- ------------ ------------
      0           0
     -0          -0
      0           0
      0           0
      0           0
      N/A         N/A
- ------------ ------------

- ------------ ------------
.   Nitrogen   Dry pine ...
      mol/s       mol/s
- ------------ ------------
      0           0
     -0          -0
      0           0
      0           0
      0           0
      N/A         N/A
- ------------ ------------

-
.

-




-

------------------------------
```

```
- ------------ ------------
     Entropy     EntropyF
       W/K         W/K
- ------------ ------------
      0           1.1e-41
     -0.0019      -9.2
     13          -22
      2.6         -4.5
      0           1.1e-41
    -16           36
    -16           36
      N/A         3.3e+42
- ------------ ------------

- ------------ ------------
  High MW l... High MW l...
      mol/s        mol/s
- ------------ ------------
      0            0
     -6.6e-22     -8.7e-23
     -0.00096     -0.00096
     -0           -0
      0            0
      0.00096      0.00096
      0.00096      0.00096
      N/A          N/A
- ------------ ------------

- ------------ ------------
. dehydroab...  Isoeugenol
      mol/s        mol/s
- ------------ ------------
      0            0
     -2.1e-07     -8.3e-08
     -0.00092     -0.0018
     -0           -0
      0            0
      0.00092      0.0018
      0.00092      0.0018
      N/A          N/A
- ------------ ------------

- ------------ ------------
.   sorbitol   Carbon mo...
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0.02
     -0           -2.3e-06
     -0           -0
      0            0
      0            0.02
      0            0.02
      N/A          N/A
- ------------ ------------

- ------------ ------------
     Propane     N-butane
      mol/s        mol/s
- ------------ ------------
      0            0
     -0           -0
     -0           -0
     -0           -0
      0            0
      0            0
      0            0
      N/A          N/A
- ------------ ------------

- ------------ ------------
.   Nitrogen   Dry pine ...
      mol/s        mol/s
- ------------ ------------
      0            0.46
     -0           -0
     -0           -0
     -0           -0
      0            0.46
      0            0
      0           -0.46
      N/A         -1
- ------------ ------------

-
.

-
```