

A Decision Support System for Decentralised Waste Utilisation in South Africa

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Abstract

Waste valorisation, turning waste into a resource, remains a relatively unexplored and undefined concept in South Africa's historically linear waste economy. This research recognizes the opportunity for sustainable business development within this space, specifically through decentralised waste utilisation driven by small, medium and micro enterprises (SMMEs). In response, this study introduces a novel Waste Utilisation Decision Support System (WUDSS), a five-tier process aiming to optimise various influencing parameters such as financial, social, technical, legal, environmental, and risk-based considerations. A mathematical modelling framework was created to describe the WUDSS, consisting of two parts, namely the Process Calculations as well as the Integrated Optimisation Model. To evaluate the framework, a problem domain was identified. Seven feedstocks were selected based on the highest waste production quantities in South Africa, and a final shortlist of 40 waste conversion and end-product production processes were included in the WUDSS. Financial modelling was employed to analyse potential project viability. A prototype of the WUDSS was created, verified, and validated against historical projects, literature, and case studies. The verification of the system demonstrated a high level of accuracy, with 94% of technical outputs and 82% of financial data falling within required ranges. Further verification was achieved through three case studies, all closely matching actual results. Finally, verification of the Integrated Optimisation Model was achieved by exact match with the first principle calculation outputs. Thus, the WUDSS proved to be a valuable tool for decision-making in decentralised waste management in South Africa, contributing to the discourse on industrial ecology and circular economy.

Keywords: Waste management; decision support; industrial ecology; circular economy; decentralisation; business development

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List of abbreviation

Abbreviation	Meaning
AD	Anaerobic Digestion
AHP	Analytic Hierarchy Process
BFD	Block Flow Diagram
C&I	Criteria and Indicators
CAC	Command and Control
CAPEX	Capital Expenditure
CFBC	Circulating Fluidised Bed Combustion
CHP	Combined Heat and Power
COP	UN Climate Change Conference
CSTR	Continuous Stirred Tank Reactor
DEA	Department of Environmental Affairs
DEFF	Department of Environment, Forestry and Fisheries
EI	Economic instrument
EIA	Environmental Impact Assessment
EPR	Extended Producer Responsibility
EU	European Union
FEL	Front-End Loading
GDP	Gross Domestic Product

Abbreviation	Meaning
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GN	General Notice
GSM/GPRS	Mobile/General Radio Packet Service
GW	General Waste
HW	Hazardous Waste
IndWMP	Industry Waste Management Plan
IPP	Independent Power Producer
LCA	Life Cycle Assessment
MBT	Mechanical Biological Treatment
MEA	Multilateral Environmental Agreement
MHT	Mechanical Heat Treatment
MILP	Mixed Integer Linear Programming
MRF	Materials Recovery Facility
MSW	Municipal Solid Waste
MSW	Municipal Solid Waste
NEM: WA	National Environmental Management: Waste Act
NIST	National Institute of Standards and Technology
NWMS	National Waste Management Strategy
OEM	Original Equipment Manufacturer
OPEX	Operating Expenditure
PHB	Polyhydroxybutyrate
POP	Persistent Organic Pollutants
PPP	Polluter Pays Principle
RFID	Radiofrequency Identification
SAWIS	South African Waste Information System
SMME	Small, Medium and Micro Enterprises
STP	Standard Temperature and Pressure
SWM	Solid Waste Management
USD	United States Dollar
WCMS	Waste Classification and Management System

Abbreviation	Meaning
WEEE	Waste from Electrical and Electronic Equipment
WML	Waste Management Licence
WMT	Waste Management Theory
WTE	Waste to Energy
WUDSS	Waste Utilisation Decision Support System

Nomenclature

Symbol	Unit	Definition
C_p	$(kJ.kg^{-1}.K^{-1})$	Specific Heat Capacity
C_1	(ZAR)	Cost of referenced system
C_2	(ZAR)	Cost of current system
cf	%	Cost Factor
H^{vap}	$(kJ.kg^{-1}.K)$	Enthalpy of Vaporisation
H_{water}^{vap}	$(kJ.kg^{-1})$	Enthalpy of Vaporisation of Water
S_1	$(ton.day^{-1})$	Size of referenced system
S_2	$(ton.day^{-1})$	Size of current system
$c_{p,g,i}$	-	Fraction of input relating to all the inputs over a node
$f_{i,p,j,g}$	(ton)	Output material flow per group
$k_{p,g,i}$	-	Fraction of output relating to all the inputs over a node
$\dot{m}$	$(kg.s^{-1})$	Mass flow rate
o_i	-	Constraint for group
s_i	(ton)	Supply inputs
$x_{i,p,j,g}$	(ton)	Input material flow per group

Symbol	Unit	Definition
$z_{i, L -1}$	(ton)	Output
$z_{i,0}$	(ton)	Input
$\delta_{p,g,o}$	-	Relationship between inputs from different groups
$\zeta_{i,l,k}, l \neq k,$ $l, k \in L \setminus \{0, L - 1\}$	(ton)	Intermediate flow between layers
κ_p	(ZAR)	Cost associated per process
ρ_a	(ZAR)	Demand price
$\sigma_{p,l}$	-	Process selection
ΔH	(kJ.kg ⁻¹)	Change in enthalpy
N	-	Time period indices
r	%	Discount rate
E	(kW)	Energy
LHV	(MJ.kg ⁻¹)	Lower Heating Value
M	-	Constant
T	(K)	Temperature
X	-	Conversion
β	-	Costing Integration Factor
η	(%)	Efficiency

Chapter 1: Background and Problem Statement

1.1 Introduction

In South Africa, a developing nation with a rapidly growing middle-class population, waste management is a significant challenge [1]. The country operates on a linear economy model where resources are extracted for use, with minimal emphasis on recycling or reuse. This approach not only risks resource depletion and over-exploitation, but it also offers a compelling business and economic development opportunity [2].

While waste management is exclusively a municipal responsibility in South Africa [3], there is an unexplored potential for a decentralised model. Decentralised waste management seeks to treat or process waste at or near its generation source, which could significantly alter business models, regulatory requirements, and technology choices due to reduced waste transportation requirements and smaller waste treatment volumes [4].

This reduced processing scale introduces an ideal opportunity for sustainable business development within the small, medium, and micro-enterprise (SMME) sector. For such business development to be successful, the selection of appropriate waste types, output end-products, and processing technologies is crucial. Furthermore, the chosen setup must comply with financial, environmental, social, and legal sustainability guidelines.

This study introduces the Waste Utilisation Decision Support System (WUDSS), a novel tool designed for South Africa's decentralised general waste management. Central to the WUDSS is a mixed integer linear programming model which provides optimised solutions for sustainable SMME development. By considering a wide array of factors, the WUDSS aims to transform waste management into a sustainable, profitable, and socially responsible venture. The following sections of this study will provide a detailed exploration of the WUDSS, its operational mechanisms, and its verification and validation process.

1.2 Understanding the Needs of SMMEs

The development and successful operation of SMMEs are key drivers to most countries' social and economic development. These enterprises are commonly associated with reductions in poverty, improved food security, creation of economic and social wealth, job creation, economic efficiency improvement and are catalysts for economic growth [5].

However, though the advantages associated with SMME development and operation is well-understood in South Africa, the country's rate of creating new SMMEs is one of the lowest internationally [6]. The failure rate for new SMMEs is also excessive [7]. As stated by Van Scheers [8], 40% of small businesses typically fail in their first year, 60% in their second year and 90% within their first 10 years. For this reason, it is vital to understand the barriers to SMME development, factors influencing success and factors causing SMME failure.

According to multiple studies ([5], [6], [7], [8], [9]), a lack of access to finance is the biggest contributor to SMME failure internationally followed by a lack of experience, knowledge of the industry and training in SMME owners. Similarly, Yang *et al.* [10] states that the ability to acquire business/project financing is the single most common restriction to SMME development. Other studies note the business concept itself as well as planning during early project phases to be critical success factors [7].

According to Zhang *et al.* [10], the base measurement for SMME performance is their economic success, followed closely by their environmental and social performance. Typically, the requirement for environmental and social performance is driven by external forces, such as consumer and partner requirements, whereas the need for economic performance is driven by internal factors such as executives, managers and owners.

Based on this assessment, economic, social and environmental aspects are considered key output requirements when providing decision support to SMMEs. Furthermore, outputs defining the general business case or project concept must be provided, which will include technical aspects. To address the potential lack of experience, knowledge of the industry and training, general guidance with regards to project selection and early project planning must be provided.

Given the highlighted challenges and success factors for SMMEs, this study seeks to provide a significant contribution to SMME development in the field of waste management. It does so by introducing the Waste Utilisation Decision Support System (WUDSS), which employs both Process Engineering Calculations and a novel mixed integer linear programming optimisation model. This model aids in the selection of viable projects, while also providing guidance on project selection and early project planning. By incorporating economic, social, environmental, risk, legal and technical aspects into the optimisation process, the WUDSS systematically addresses the key barriers to SMME success, primarily financial access and industry knowledge. Furthermore, the focus on decentralised waste management offers a new avenue for sustainable business development in the SMME space, which is currently underexplored. Therefore, this study is positioned uniquely at the intersection of waste management, SMME development, optimisation modelling, and decision support systems, offering a novel approach to drive sustainable growth in South Africa's economy.

1.3 Focus of the Study

The aim of this research is to conceptualise, construct, and assess an innovative decision support system for decentralised waste management in South Africa, specifically designed for Small, Medium, and Micro Enterprises (SMMEs). The study focuses on the utilisation of general, solid waste due to its predominant role in the mixture of waste generated in South Africa and its significant potential for recovery and value creation.

The focus will be to define and understand the unique requirements of SMMEs within the waste utilisation domain. This understanding will shape the formulation of key factors for investment decision-making in this field. These factors will span technical, environmental, legal, social, financial, and risk-based considerations. We will introduce these factors as essential output components of our decision support system.

To operationalise these factors, we will employ Process Engineering Calculations to quantify them. These calculations will be integral in generating meaningful and applicable outputs for the decision support system. This quantification process will allow for the translation of raw data into useful information for investment decisions.

Subsequently, we will develop an Integrated Optimisation Model based on a mixed-integer linear programming framework. This model aims to aid users in determining the most beneficial configuration for their waste management practices. The results from the Process Calculations will be used as inputs for the Optimisation Model, linking the two components into a comprehensive Waste Utilisation Decision Support System.

A structured approach is employed for the research methodology that takes into account a variety of factors. This approach considers potential waste types, processing methods, and final products for inclusion in the decision support system. Market inputs, in terms of high-level value chain assessments, is evaluated to provide an external perspective on potential configurations. Additionally, feasibility analyses or 'fatal flaw assessments' are conducted to ensure the selected processes are viable and relevant.

In conclusion, this study seeks to make a significant contribution to the field of decentralised waste management by providing a tool that meets the needs of SMMEs in South Africa. Through this research, the aim is to promote sustainable and efficient waste management practices while simultaneously fostering the development of local businesses.

1.4 Problem Statement

South Africa's waste management industry holds considerable potential for growth. Current statistics reveal that only about 10% of waste in South Africa is recycled, with the remaining 90% disposed of via landfill [11]. The South African government, guided by the National Waste Management Strategy (NWMS), aims to divert waste from landfills and expand the waste sector's contribution to the green economy [12]. However, despite various studies advocating for the involvement of the private sector in waste management ([12]; [13]; [14]; [15]), it remains under municipal governance [3]. The majority of research in this domain focuses on broad, centralized strategies.

This study pivots the focus towards invigorating waste management through private sector participation and the establishment of decentralised facilities by Small, Medium, and Micro-sized Enterprises (SMMEs). For these entities to successfully contribute to waste management, the initiatives must primarily be economically viable [16]. Additionally, several factors must be evaluated for new business developments, including process complexity, technical considerations, overall project risk, environmental and legal implications, and social implications such as job creation.

To achieve this, it is essential to create a tool that aids SMMEs in making informed decisions. The solution proposed in this study is a novel Waste Utilisation Decision Support System (WUDSS), incorporating a mixed-integer linear programming model. This system will guide SMMEs towards ([4], [17], [18], [19], [20], [21]):

- Understanding and optimising economics of scale
- Eliminating unnecessary cost items
- Minimising capital investment requirements
- Optimising the business case by shortening payback periods and optimising capital budgeting metrics (IRR, NPV, etc.)
- Reducing risks related to various aspects of the project, such as commercial risks, technical risks, environmental risks, etc.
- Selecting the best process for the specific waste stream
- Selecting the best process for the specific end product to be generated
- Understanding social implications of waste management
- Understanding basic legal requirements for specific processes and actions (permits, authorisations or assessments)

Thus, the WUDSS aims to provide the following decision support within the waste utilisation environment:

1. Assist SMME's to comparatively select the most fitting waste utilisation configuration.
2. Guide SMMEs in ascertaining whether the selected configuration is eligible for project funding and provide fundamental information for the funding application.
3. Guide SMMEs regarding general project requirements at a conceptual level, thereby addressing potential barriers related to lack of experience, knowledge of the industry, and training.

1.5 Research Objectives

The research objectives for this study include:

- Defining the concepts surrounding decentralisation of waste utilisation in South Africa.
- Defining the conceptual requirements for a decentralised waste utilisation decision support system for SMME business/project development.
- Developing the mathematical modelling framework for a decision support system aimed at SMME business development in South Africa within a decentralised waste utilisation field.
- Creating a prototype model of the decision support system for concept demonstration
- Evaluating the working of the prototype decision support system by comparison of its outputs to benchmark data, literature data and first principle calculations (verification).
- Evaluating whether the study addressed the objectives set as well as the gaps identified in literature (validation).

1.6 Purpose of the Study

This project entails the development of a system to assist in the concept-level decision making for decentralised waste management projects in South Africa. The focus is on the handling of general, solid waste.

The purpose of the decision support system is to assist small and medium enterprises to undertake or incorporate waste management projects in an economically viable, lawful, and technically optimised manner, as well as to assist in the development of small projects in the waste sector. The system will aid the end-user to select the most relevant process and identify the most profitable operating configuration. The model will calculate various criteria that might help convince investors or other potential stakeholders of a project's potential.

This system developed as part of this study aims to assist in the development of decentralised SMMEs. In line with the definition of decentralisation, the target end-users form part of the private sector and the envisioned waste management facilities should be located close to or at the source

of waste generation [4]. The considered processes include the raw feedstock (waste directly from the waste generator), and all waste management or utilisation processes up to the production of the end-product. Additionally, the logistic complexity and cost of waste transportation from source to waste management location are expected to be negligible due to the decentralised focus. The focus of the study is summarised in Table 1-1.

Table 1-1: Focus of the study (design specification)

Process Description	Study Focus
Decision Support System End-User	The target end-user of the decision support system includes small to medium scale private sector investors or developers planning to reduce, treat or manage their waste onsite (close to the source of waste generation). Sources of waste generation to be considered for this study include, for example, hotels, shopping malls, restaurants, food courts, camping areas or vacation facilities, office parks, mine sites or communities, closed gate communities or small towns, etc.
Capacity	Small-scale, decentralized facilities are defined in this study to avoid triggering a Waste Management License [22]: • Recycling Processes < 500 kg/day • Treatment and Disposal Processes < 10 tonnes/day Lastly, the National Small Business Act (102 of 1996) definitions of SMME businesses, including total full-time paid employees (equivalent), turnover and gross asset value (excl. fixed property), are applicable.
Generation	Generation of waste to be categorized by waste type due to the small-scale, focused nature of the proposed implementations.
Waste Collection	Waste collection will be simplified by the decentralized nature of the end-users (intended facility owners). Waste management facilities are to be set up onsite or close to the waste generation source. This study will feed into existing waste collection systems, e.g., waste collection to a central location at a camping site, office park, shopping mall, etc., for further disposal. For this reason, waste transport and logistics are not considered in the model.
Transport or Logistics	See Waste Collection.
Treatment or Disposal	The decision support system will provide a list of viable treatment options that may be used for the specific waste type and volume.

Process Description	Study Focus
	Additional information or outputs will be generated to assist the end-user in selecting the appropriate option.

During the development of the system, the requirement to minimise a project's development and engineering cost by reducing the amount of additional expert input required at concept-level before allowing the project to continue to pre-feasibility or feasibility level will be considered.

Selection of the output requirements of the WUDSS is based primarily on the SMME's needs, as summarised in Section 1.2. Based on SMME success factors, these requirements include guidance in terms of project potential for financial, social and environmental impact, as well as general guidance with regards to a project's concept, selection and early project planning. However, since the goal is also to assist SMMEs to evaluate a project's eligibility for funding, a typical project funding screening requirement is used as secondary basis for selecting the model's required outputs. Due to their long history of funding projects in South Africa, as well as their specific focus on SMME development, the Industrial Development Corporation (IDC) of South Africa's funding minimum requirements are used [23]. The minimum requirements can be summarised as follows:

1. The business/project must be capable of creating jobs
2. The business/project must be sustainable from an economic and profitability point of view
3. The project/business must comply with international environmental standards
4. Other business-specific requirements, which includes that financial contributions and security must be provided from the business/owners; the business itself must be registered and comply with South Africa's business statutory requirements and a business plan must be submitted.

Based on these minimum requirements, it can be seen that the end-user will have to understand very specific factors of the project before applying for funding. This includes selecting the correct technical solution and understanding the basics of the project. Therefore, the system should assist and guide the end-user in:

1. Defining the overall project by:
 - a. Selecting the optimum waste conversion technology for the specific waste being considered
 - b. Selecting the optimum technology to produce the selected end-product
 - c. Providing a basic process design

- d. Providing a typical facility footprint
2. Understanding the project economic considerations and proving its profitability, using outputs such as:
 - a. Capital Expenditure (CAPEX)
 - b. Annual Operating Expenditure (OPEX)
 - c. Total Capital Investment and Total Production Cost per Annum
 - d. Expected annual income
 - e. Capital budgeting metrics, such as internal rate of return (IRR), net present value (NPV) and payback period (PBP)
 - f. Economy of scale for the given project to assist the user in selecting the appropriate process throughput size
3. Considering project risks for the selected process under specific project conditions
4. Understanding environmental concerns and benefits, such as gaseous emissions produced (given as carbon dioxide mass equivalent) as well as emission reduction achieved by this project (comparing the selected process to waste landfilling)
5. Noting the basic legal considerations, such as licenses required
6. Quantifying other investment considerations, such as employment generated.

For the development of the decision support system, all waste conversion processes are to be modelled, costed and assessed. An optimised configuration will be selected by the decision support system taking into account the various aspects mentioned above (Integrated Optimisation Model).

A summary of the concept for the WUDSS is shown in Figure 1-1.

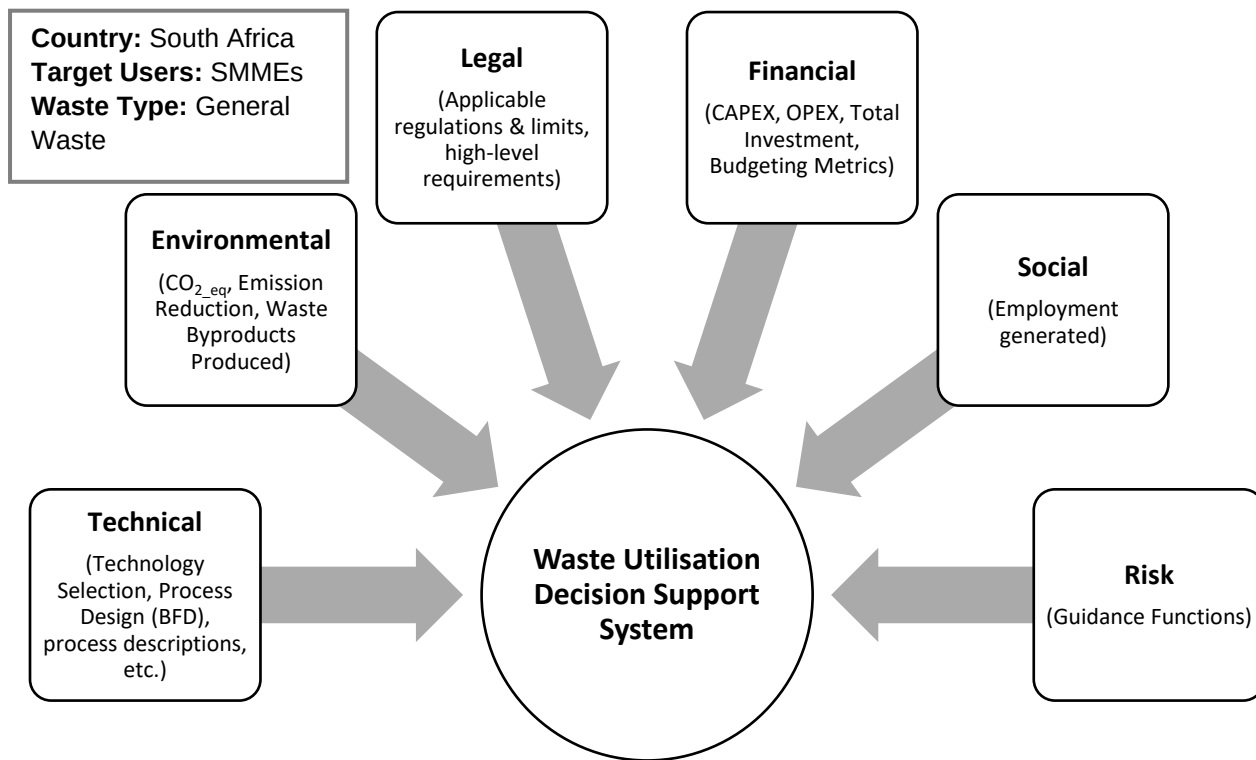


Figure 1-1: WUDSS concept

1.7 Methodological Approach

The approach applied to this thesis is grounded in Design Science Research, as defined by Van Aken and Romme [24] and follows a quantitative research design. Within this research paradigm, the thesis is structured so as to develop a mathematical modelling framework for a decision support system to support business development in decentralised waste management in South Africa. This framework consists of the Process Calculations and the Integrated Optimisation Model.

The decision support system's Process Calculations section is based on chemical engineering process design principles [25]. Within this field, the calculations can be described as a theoretical mathematical model created from first principles (process synthesis), containing some components of empirical modelling that are well-referenced where used. As for all concept-level process designs, a lumped parameter model is developed based on a steady state approach [26].

Finally, to better describe the integrated nature of the model as well as the optimisation applications, a mixed integer linear programming (MILP) model (Integrated Optimisation Modelling section of the WUDSS) is created. This modelling methodology was selected due to its ability to solve large and complex problems within a system analysis, interdependence, or process integration environment [27]. The use of a MILP model to test and optimise complex process synthesis models is a well-understood method, since it allows for the simultaneous consideration of various sources of

uncertainty as well as complex or conflicting criteria in decision-making [28]. The model is based on a multi-commodity flow formulation.

In terms of business/project development context, the Front End Loading (FEL) methodology is applied. The FEL approach is a well-understood project development framework that allows for a project lifecycle to be broken into distinct phases from project initiation to project completion. The FEL approach is selected due to its ability to break a project into phases, limiting cost exposure during early project phases when the project definition is ill-defined and the risk is high. As the project progresses, engineering and commercial definition is improved and at the end of each FEL phase, the project passes through a gate, where go/no-go decisions are made based on the project's feasibility, risk profile, cost and other aspects [29].

When considering SMMEs as final user of the WUDSS, as explained in Section 1.2, one of the common failure factors for SMMEs is a lack of proper project planning and project/business concept development during early project phases. With the use of the structured FEL methodology, this risk is reduced. According to Maples [30], properly planning and defining a project is one of the most essential aspects of project management input, since 90% of the project outcome is defined in the first 10% of the project. For this reason, the FEL approach emphasizes the planning process associated with project development.

The WUDSS operates in the FEL 1 or Concept Study regime, which looks mainly at opportunity assessment (evaluating and selecting a most preferred option) and business opportunity identification. Thus, at the end of FEL 1, a business case is typically developed around a conceptual business/project definition [31]. For FEL 1, a class 5 estimate is required based on AACE International Recommended Practices 18R-97. This implies an estimate accuracy of between 30% and 50% for option comparison purposes [32]. Furthermore, it is vital to include risk analysis in the early FEL phases, especially for projects that consider the use of new or challenging technologies [30]. This is included in the WUDSS by adding risk-based considerations.

1.8 Summary of Study Contribution

This study contributes to the existing literature by introducing a novel decision support system for decentralised waste management in South Africa. The main contribution of the study is as follows:

- Development of a mathematical framework which comprises of detailed abstractions of processes and a Mixed Integer Linear Programming optimisation model (theoretical contribution). The Integrated Optimisation Model developed as part of this study can be applied to any waste to value configuration within the context of the WUDSS. Use of an optimisation model approach to decentralised waste management is unique and has not been addressed in existing research.

- Modelling of various advanced waste utilisation processes as well as end-product production processes to process specific South African waste compositions to provide information to the user for selection of a viable business case/project configuration. Though some studies exist that consider various technologies, the number of processes modelled as well as the concept of using a primary and secondary process for waste valorisation is unique for decision support modelling within a South African context (theoretical contribution). Furthermore, where most studies include a specific waste type or feed category (e.g. biowaste), this study considers various waste types, including both organic or inorganic wastes.
- Development of a decision support system for business/project development in waste utilisation with a decentralised focus (theoretical contribution). The intended end-users of the decision support system are potential SMMEs and the main goal of the study output is to aid business development, as stated in Section 1.4. Internationally, the typical focus of decision support systems is to provide strategic advice to specific role players, such as municipalities, national governments or planning decision-makers (e.g., city planners or policymakers). Very little work has been done towards addressing the private sector, specifically SMMEs. No studies were found on business development decision support for decentralised waste utilisation or valorisation of both organic and inorganic wastes. No decision support systems exist within the decentralised waste utilisation space in South Africa. No decision support systems were found that consider the project approach in this domain.

Further contributions include:

- Application of a market-related value chain assessment for final end-product selection for waste utilisation processes, taking into account the South African market (practical contribution). Based on current literature, the value chain approach has not been utilised for decision support aimed at SMME development around waste management in South Africa.
- Investigation of the risk-based approach and further providing the option to integrate the outputs into the financial analysis that forms part of the overall decision support system. Risk and project-based approaches to decision support have not been incorporated into waste management decision support systems based on existing literature (theoretical contribution). This approach will assist to guide the user with basic project requirements on a conceptual level, as per the project objectives.
- Incorporation of the legal requirements into waste decision support. This is an aspect of decision support that has not been explored previously within this field (theoretical contribution).

1.9 Layout of the Thesis

The basic layout of the thesis is shown in Figure 1-2. In Chapter 1, the background of the study is presented, and the focus of the study, problem statement, objectives, methodological approach and study contributions are introduced. In Chapter 2, relevant literature is presented with the main aim of introducing specific concepts, setting the scene for the study and identify the limits of the existing research. In Chapter 3, the mathematical modelling framework of the decision support system, including both the Process Calculations and Integrated Optimisation Model, is described. In Chapter 4, the problem domain is introduced and the technical inputs into the Process Calculations are explained for the prototype WUDSS. The technical design basis for each process included in the decision support system is given as well as all relevant assumptions and design inputs used to create the WUDSS. In Chapter 5, all additional parameters included in the WUDSS are described and defined, including social, environmental, legal, financial, and risk-based factors. In Chapter 6, the prototype WUDSS is validated and verified. The outputs of the Process Calculations are tested against specific literature and benchmark data, as well as South African case studies for small scale systems. The outputs of the Integrated Optimisation Model are furthermore verified against first principle calculation results. Lastly, Chapter 7 describes the summary and conclusions of the study.

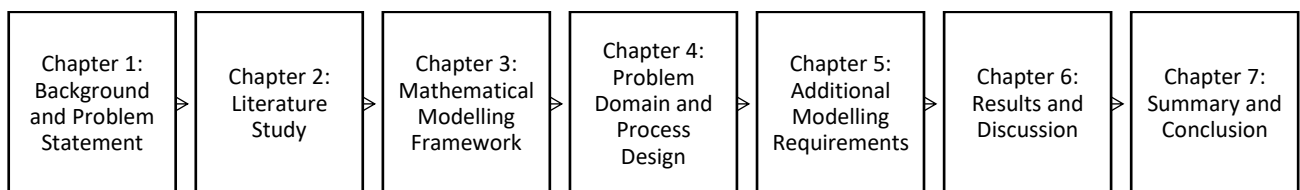


Figure 1-2: Layout of the thesis

Chapter 2: Literature Survey

2.1 Introduction

This chapter reviews existing literature regarding waste management, key concepts related to waste management and industrial ecology, as well as waste decision support tools or systems. The status quo of the field is explained, with a focus on research frontiers and current topics of interest. Lastly, gaps are identified in the current literature. The identified gaps, which are directly related to this study, will be addressed with detailed descriptions.

To provide a solid background, this chapter begins by focusing on key concepts in waste management and industrial ecology. Thereafter, a review is done on waste management internationally, followed by a more in-depth look at waste management in South Africa. Next, the decentralised approach is introduced with a focus on the identification of gaps and opportunities.

Lastly, a review is done on waste-based decision support tools, both on an international and national level, and a structured literature review is undertaken using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method. This method structures the reporting of systematic literature reviews and meta-analysis [33]. For this study, the PRISMA method was used to prove the existence of the literature gap.

2.2 Waste Management Concepts

According to Pongrácz *et al.* [34], waste management is defined as the prevention of waste to avoid harming human health and the environment, as well as promoting optimisation of resource use. Waste Management Theory (WMT), a relatively young science, was introduced to bridge the gap between science and technology. In so doing, Waste Management Theory translates the foundational concepts of environmental science with regard to waste into engineering design.

The basis of WMT is the need for a sound theoretical background to select and design the most suitable waste management system for a given scenario. The aim is to systematise the existing field of waste-related environmental science to explain and predict problems in the waste management field [34].

2.2.1 Industrial Ecology and Waste Management

The most important concept of modern waste management is seeing waste as an unused resource. A waste stream has no purpose in relation to its current setting, process, use or form. However, changing one or more of these factors may add value back to the resource [35].

WMT overlaps certain existing fields of study, most notably Industrial Ecology and Design Theory. Industrial Ecology is a subfield of sustainable development that focuses on the flow of energy and material in a closed-loop system between the natural ecosystem and the human industrial system. Industrial Ecology also promotes the concept of Industrial Symbiosis, where the relationship between various and diverse industries can be used to efficiently utilise resources. This is done by using the unused resources or waste products from one industry as an input stream for a second industry [35].

For waste recovery, an international paradigm shift is taking place where waste is no longer seen as a problem but as a resource. Where in the past urban areas were seen as systems with material streams moving in (raw materials) and out (waste streams), various concepts have been defined to either extend the time spent by the material inside the system or to increase the circularity of the material flows [36].

Concepts such as regenerative urbanism include basic changes to infrastructure, as well as cultural and social thinking, where the urban environment is seen as a source of materials in contrast to a pure user of materials. Regenerative urbanism includes a focus on the reuse of waste materials on an urban level. Examples include textile remanufacturing, food waste co-ops, community energy trusts and local composting initiatives [36].

Urban mining is a second concept that changes the way of thinking about urban environments and waste. Urban mining focuses on recovering materials from waste streams, such as the recovery of metals from electricity networks or concrete for reuse in the building industry [36].

2.2.2 Waste Definition and Waste Hierarchy

As usual in the development of a new theoretical field, the first step is to define certain key concepts, after which core issues, including relevant fields of study, epistemologies, and ontologies, are mapped out, and the overlap with existing bodies of knowledge is defined. Currently, in the development of the WMT field, key concepts have been scientifically defined, while the advance of WMT using Industrial Ecology concepts is currently in progress [34].

One of the key concepts that act as a baseline in waste treatment is the definition of waste. In 2004, a two-day workshop was held in Leipzig by the European Commission and Members of State to discuss the classification of waste treatment methods and to set the definition of waste [37]. According to Pongrácz *et al.* [34], it was remarked that potential for ambiguity exists regarding at which point a specific resource starts or stops being seen as a waste stream.

However, setting an explicit definition of waste is vital to creating a strong foundation for WMT. For this reason, four waste classes are defined, as shown in Table 2-1.

Table 2-1: The waste definition according to the four waste classes [37]

Waste Class	Description
Class 1	Things that are created to be unwanted and without purpose.
Class 2	Things designed for a specific purpose that therefore become worthless after the purpose is fulfilled.
Class 3	Things with an explicit purpose, but their performance is no longer acceptable due to a flaw in structure or state.
Class 4	Things with a well-defined purpose, and acceptable performance, but their users failed to use them for their intended purpose.

Under the concept of WMT, the overall strategy is dictated by the waste hierarchy. The key elements of this hierarchy are used internationally to inform sectors on waste management and influence regulations and policies [38].

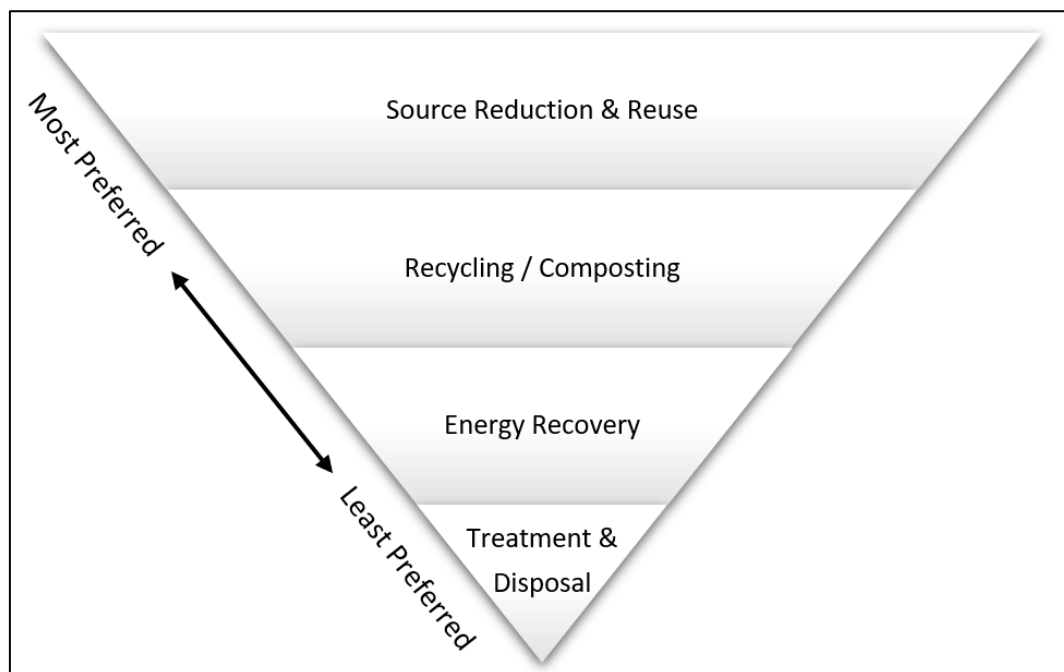


Figure 2-1: The waste hierarchy [39]

The waste hierarchy ranks methodologies to prevent waste, from most to least preferred. According to Figure 2-1, the methods are ranked as follows [39]:

- Source Reduction & Reuse:
 - Source reduction is the most preferred method of waste management since it prevents the amount of waste generated while reducing the number of resources used. This also minimises waste-related lifecycle emissions and costs [38]. An

example of source reduction is to stop the production of plastic grocery bags in favour of using reusable cloth bags. Another example of source reduction is to reduce the amount of packaging needed per item, e.g., to use reusable containers to transport goods instead of plastic wrapping.

- Reuse is the second most preferred method of managing waste. Reuse implies using a single item multiple times, for example refilling glass milk bottles.
- Recycling or Composting:
 - Recycling is the best option for the sustainable management of inorganic waste after reuse. Recycling is the conversion of waste into a new object or material. Recycling differs from reuse since it requires physical or chemical changes to the waste stream during the conversion step [40].
 - Composting is a method of treating organic waste. During composting, waste is broken down under aerobic or anaerobic conditions. This decomposition can be achieved using various types of microorganisms, such as bacteria, actinomycetes or fungi [41]. Compost is used to improve the nutrient density in soil or to act as a natural pesticide both on small scale and for industrial applications. However, compost to be used for growing food must cohere to certain regulations for food safety [38].
- Energy Recovery
 - Energy recovery refers to the use of waste as an input stream for heat, cooling, fuel or electricity production. This includes, amongst others, gasification, anaerobic digestion, incineration with energy recovery, and pyrolysis [38]. Though energy recovery is ideal for waste volume reduction and waste utilisation, it is less preferred than recycling or composting due to the production of unwanted by-products, such as air emissions, solid waste, leachate, etc.
- Treatment or Disposal
 - Waste treatment is the second least preferred option since no secondary value is gained from handling the waste stream [40]. The resource is therefore wasted. An example of waste treatment is incineration without heat or energy recovery. Waste treatment may sometimes still be the best choice simply due to system costs (e.g. extremely small-scale systems) or the specific characteristics of the waste stream (e.g. some forms of hazardous waste are simply treated to neutralise negative environmental effects. No additional energy, heat or resource recovery is attempted).
 - Disposal is the least preferred option for waste management. Disposal includes dumping or landfilling. During landfilling or dumping, all resources are lost and there

is potential for negative downstream effects since the waste is not treated or neutralised [40].

The worst type of disposal is open dumping where the waste is abandoned at an unmanaged site (not an engineered landfill). During dumping, leachate from the waste can easily make its way into the groundwater, causing pollution and affecting human health. Heavy metals in these leachates can accumulate in the food chain, damaging both fauna, flora and humans. Emissions from landfills and dumps – especially methane emissions due to natural organic waste decomposition – are a huge contributor to global warming (methane has a high carbon dioxide equivalent). Lastly, even engineered landfills are a huge fire risk, causing an average of around 8,300 fires per year in the USA and 300 per year in the UK [42].

Sadly, waste disposal currently remains the most popular waste management option, with around 37% of all waste globally ending up in landfills or dumps. In lower-income countries, 93% of waste is still openly dumped according to the World Bank Group's global solid waste report of 2018 [43].

Though the waste hierarchy is used internationally to rank waste management options, it has been found that some exceptions exist. For example, for food waste, evidence suggests that anaerobic digestion is a more sustainable solution than recovery options such as composting. Another example is the case of garden waste and mixed food waste samples, where it was found that dry anaerobic digestion is environmentally preferable. Composting is ranked second in terms of environmental benefits for these two waste streams. Lastly, it was found that energy recovery options are better solutions for utilising lower-grade wood waste compared to recycling [44].

A full summary of the top waste management options according to both scientific evidence and the waste hierarchy is shown in Figure 2-2 [44]. This figure shows the waste hierarchy applied to each waste type and shows the most preferred (dark green) to least preferred (red) solutions. It should be noted that the summary only considers the environmental sustainability for ranking the waste management options. Techno-economic and other drivers are not considered [44], which makes this a one-dimensional analysis which cannot be directly applied to select a waste management practice.

Paper and Card	Food	Garden Waste	Textiles	Wood	Glass	Metals	Plastics	WEEE	Tyres	Residual "black bag"
Prevention	Prevention	Prevention	Prevention	Prevention	Prevention	Prevention	Prevention	Prevention	Prevention	Prevention
Preparation for re-use			Preparation for re-use	Preparation for re-use	Preparation for re-use	Preparation for re-use	Preparation for re-use	Preparation for re-use	Re-treading	
									Recovery: use in road surfaces	
Recycling	Anaerobic Digestion Composting; other energy recovery technologies	Anaerobic Digestion Composting; other energy recovery technologies	Recycling	Recycling; energy recovery (preferable to recycling for lower grade materials)	Recycling in a remelt process Other recycling	Recycling	Closed loop recycling Other recycling	Recycling (esp. suitable for metals and high quality plastic)	Energy recovery in cement kilns Energy recovery through pyrolysis	Solid Recovered fuel derived from MHT or MBT (replace coal) Energy Recovery, all technologies (Heat Only) Energy Recovery, all technologies (CHP)
Energy recovery (esp. suitable for short fibres or contaminated materials)			Energy Recovery				Energy Recovery	Energy recovery (esp. suitable for non-hazardous mixed plastic)	Other recovery (e.g. drainage fill & sea defences)	Energy Recovery, all technologies (Electrical Only)
					Energy recovery	Recycling after energy recovery			Gasification / Incineration with EfW	MBT or MHT outputs used as fuel (not replace coal) or disposed
Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Microwave Treatment	Disposal

Figure 2-2: Summary of waste hierarchy for various waste streams [44]

In general, moving up in the waste hierarchy holds numerous benefits for a country. Firstly, more resources are re-introduced into the economy. Secondly, environmental implications and social costs are minimised, and thirdly, economic growth and job creation are maximised by growing the country's waste management sector [11].

For the waste management industry in developing countries such as South Africa, strategic solid waste management planning in terms of technology mapping – taking into account sustainability and techno-economic parameters – has not been addressed by current literature ([20], [21]). This is a gap that will be addressed by this study.

2.2.3 The Waste Management Process

Internationally, the waste management sector is segmented based on service, region and waste type. Based on service, the sector is once more segmented into collection services and disposable services, where [45]:

- Collection services are subdivided into collection & transportation, storage & handling, and sorting

- Disposal services are subdivided into recycling or composting, energy recovery or disposal

Both collection and disposal services form part of the overall waste management process. Though the waste management process might differ depending on the type of waste, the general process steps remain the same. In short, the traditional waste management process consists of the basic steps shown in Figure 2-3, with modern, more sustainable processes replacing the Disposal to Dumping Site step with waste reduction, treatment or recovery steps [46].

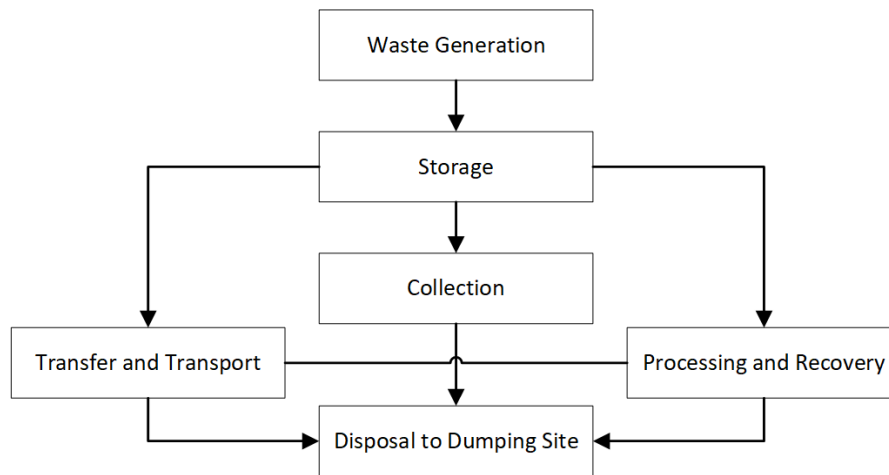


Figure 2-3: Solid waste management system [46]

To manage the generation of waste, production monitoring is a basic step in all international waste management strategies. By monitoring the production of waste, waste types and quantities can be matched to treatment methodologies and logistic plans to optimise the overall strategy of a country or municipality. Various methods are available to monitor waste production. High-end methods used to monitor the collection from bins and trucks include geographic information systems (GISs), ultrasonic sensors, radiofrequency identification (RFID), and the international system for mobile or general radio packet service (GSM/GPRS). These methods are not used commonly in developing countries, where untrained rag-picking is still the predominant method of waste collection and separation. Today, rag picking is still the only collection method used in about 63% of countries [47].

Other potential steps included in modern waste management include waste sorting (which could be undertaken either at the source or at the processing facility), cleaning or washing (rare), shredding, compacting or other pre-processing techniques. Figure 2-4 shows an example of generic waste management routes in everyday industry [48].

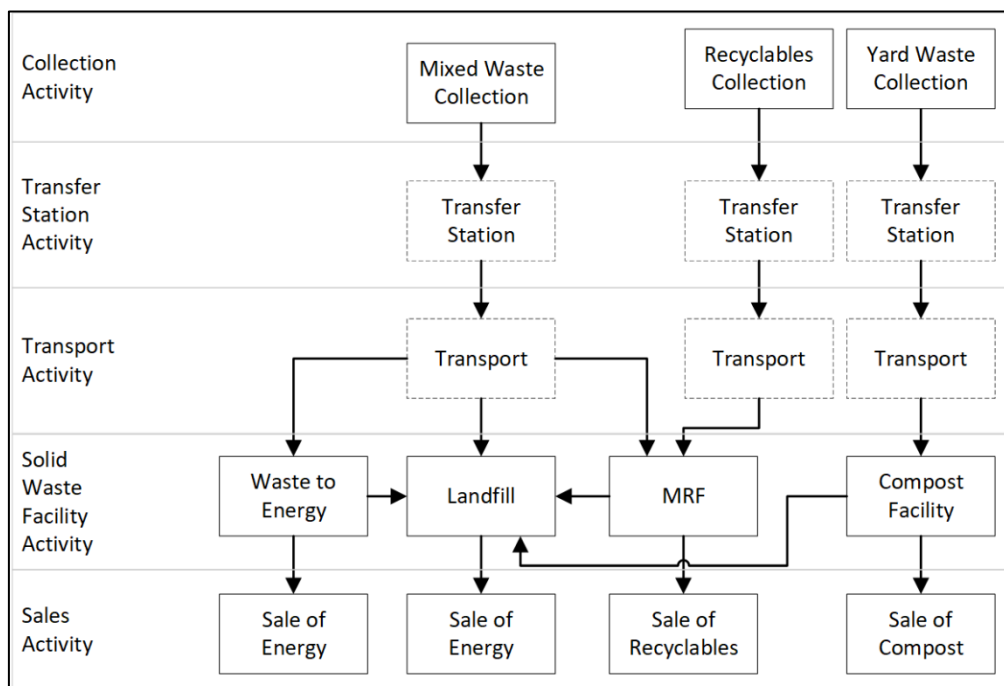


Figure 2-4: Generic solid waste management flow chart [48]

Though various paths can be followed for the management of a waste stream, Figure 2-5 indicates the potential routes and activities linked to the generic process shown in Figure 2-4 [48].

MSW Activities	Recycling Path	Composting Path	WTE Path	Land Disposal Path
Collection	?	?	?	?
Transfer Station(s)	?	?	?	?
Transport	?	?	?	?
Facility(ies)	✓	✓	✓	✓
Residuals Disposal	✓	✓	✓	
By-Product Sales	✓	✓	✓	?
Education / Outreach	?	?	?	?

Figure 2-5: Activities and paths for waste management, using MSW as example [48]

As seen, recent changes in the waste management field are causing a shift away from the disposal of waste, based on the waste-as-resource philosophy [36]. This opens the door to numerous new technologies centred around waste value addition.

2.2.4 Circular Economy and the Waste Treatment Value Chain

The concept of value addition in waste management focuses on the middle levels of the waste management hierarchy. Though source reduction of waste is always the most preferred option, the basic dependency of humans on resources necessitates that there will always be waste streams to be managed, whether via reusing, recycling, recovery, or disposal [40].

The concept of circular economy addresses this reality by introducing a feedback system to minimise raw material inputs as well as waste disposal to landfills. Circular economy focuses on keeping the resources being used inside the circular economic system for as long as possible to optimise resource usage [40].

Circular economy is a modern ideal that is being accepted internationally as a basis for managing resources, resource and waste policy development and as well as for strategic economic planning. Though moving towards a circular economy is ideal, true circularity is impossible, due to material and energy balance constraints, as well as the comparable costs of sourcing new versus recycled or treated materials [49].

For a waste utilisation, reuse or recycling process to be viable, the cost of treatment must be low enough for the final product to be sold at the same price or cheaper than similar products produced from raw materials. This introduces several problems (barriers of entry) for green applications, such as:

- Lack of technology:
 - Since waste utilisation is a relatively young field, numerous promising technologies are still at low levels of technology readiness. For projects with large capital costs, developers will often not consider new or unproven technologies due to risk [25].
- The cost of commercialisation of new technologies.
 - Commercialisation is costly due to troubleshooting and optimisation requirements. Several solutions to this barrier are currently utilised internationally [50], such as green project funding, incentives, tipping fees, etc.
- End-user convenience or expectations:
 - Consumers are used to certain products looking, feeling and operating in a certain way. Changes to the status quo are not easily accepted. This is a major barrier to the concept of waste reduction. For waste utilisation, consumer convenience or expectations should also be considered in the fact that products produced from waste must be comparable to or better than products produced from raw materials (open market model) [36]. Consideration should also be given to current designs of end-use systems.

An example of this is the addition of ethanol to diesel, which was received extremely negatively by the public upon announcement. This changed slightly upon adaptation of government regulation for mandatory blending of 5% ethanol (v/v) in diesel. The permitted range of bioethanol blending in petrol is 2% to 10% (v/v). Due to negative publicity, and since the volume for petrol blending is not mandatory, blended petrol is a much rarer occurrence in South Africa [51].

- Economy of scale concept
 - In general, a certain scale of operation is required to balance the CAPEX and OPEX requirements for any given process and achieve realistic economic metrics for the project [50]. For waste utilisation, this concept applies and adds complexity in terms of waste production requirements (supply). For any system, a certain feedstock buffer is required (e.g., stockpile or storage) to avoid process interruptions.

To bypass these barriers to entry, various initiatives and schools of thought exist. Examples of drivers for improving the viability of the circular economy concept include:

- Policies pushing research and development in the waste management field.
 - Waste management technologies are currently experiencing a growth curve due to focused research and development efforts being applied internationally. Research grants are made available based on selected strategic topics that align with the country's strategic development plan and roadmap. An example of this is South Africa's recent surge in biofuel industry development efforts due to the prioritisation of this topic as part of the Biofuels Industrial Strategy (approved by the Cabinet in 2007) and subsequent funding being made available. The biofuel subsidy made available addresses the difference between the transfer price and the production cost of the biofuel for 1st generation biofuel (fuel from agricultural sources) only, due to a higher job creation expectation for biofuel type. For this reason, the country has seen a surge in biofuel from agricultural sources, while very little development has been made in terms of 2nd and 3rd generation biofuels (biofuels from other agricultural waste types, industrial wastes and emissions) [51].
- Economic trade-off between process complexity and the monetary value of the product being produced (value chain assessment).
 - According to Pennotec [52], a rough correlation exists between the market value of the end-product produced and the technological complexity and cost of the process required to transform the waste feedstock into the specific end-product. Though the focus of this statement is on biomass utilisation, the same can be said for all waste types. In general, the process required to produce lower-value end-products is simpler (e.g. gasification to produce syngas or composting to produce biomass compost) than the processes required to produce high-value end-product (e.g.

gasification followed by Fischer Tropsch synthesis for liquid fuel production, or pyrolysis to produce crude oil followed by distillation to increase the market value of the distilled oil end-product). An example of this concept is shown in Figure 2-6, where the economic value of commodity nutrients is much lower than that of Speciality chemicals, nutrients and actives.

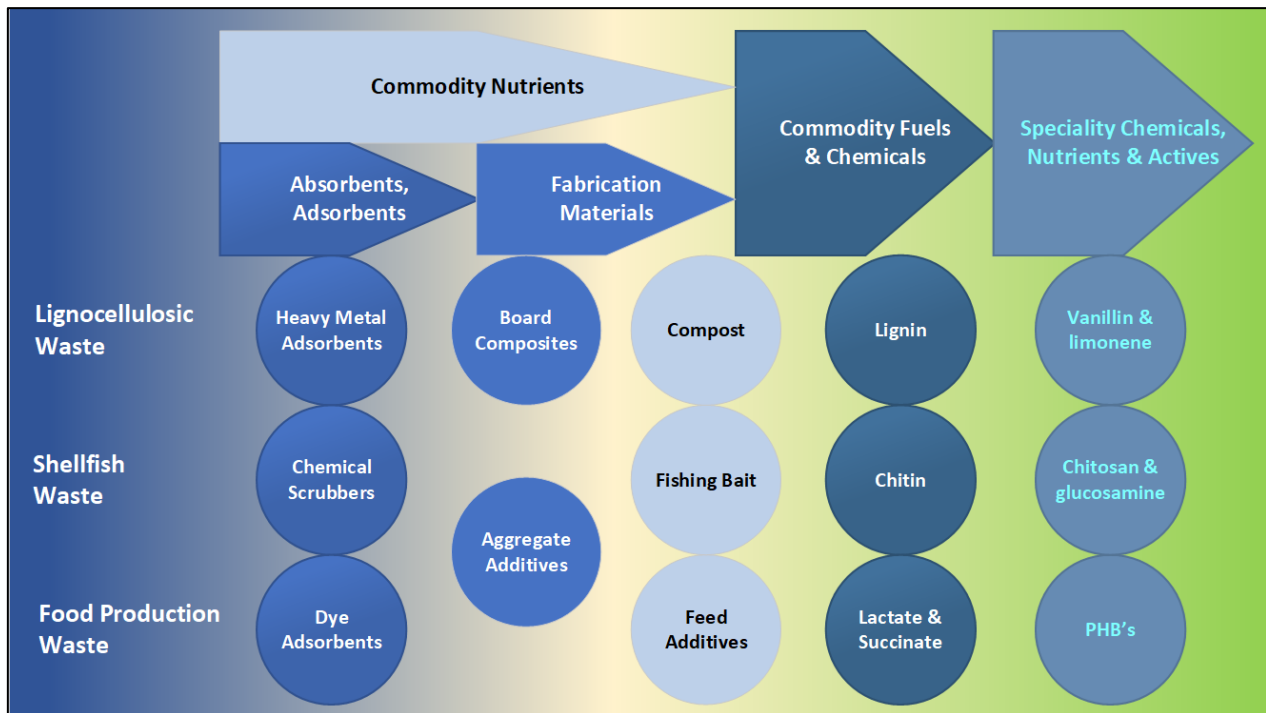


Figure 2-6: Waste value chain for biomass [52]

- Considering the value chain correlation between process complexity and end-product value, a value-chain approach can be followed for waste utilisation where waste is considered as a feedstock to the process. Using a value chain approach, opportunities for financially viable waste utilisation may be identified.

Work has been done internationally on value chain considerations for waste, though most studies focus on a specific waste type. Integrated studies have been undertaken, such as the work done by Mahajan and Vakharia [53] (Figure 2-7), though this study focuses only on general issues and opportunities with regard to the larger waste industry and does not include a monetary assessment of the waste value chain.

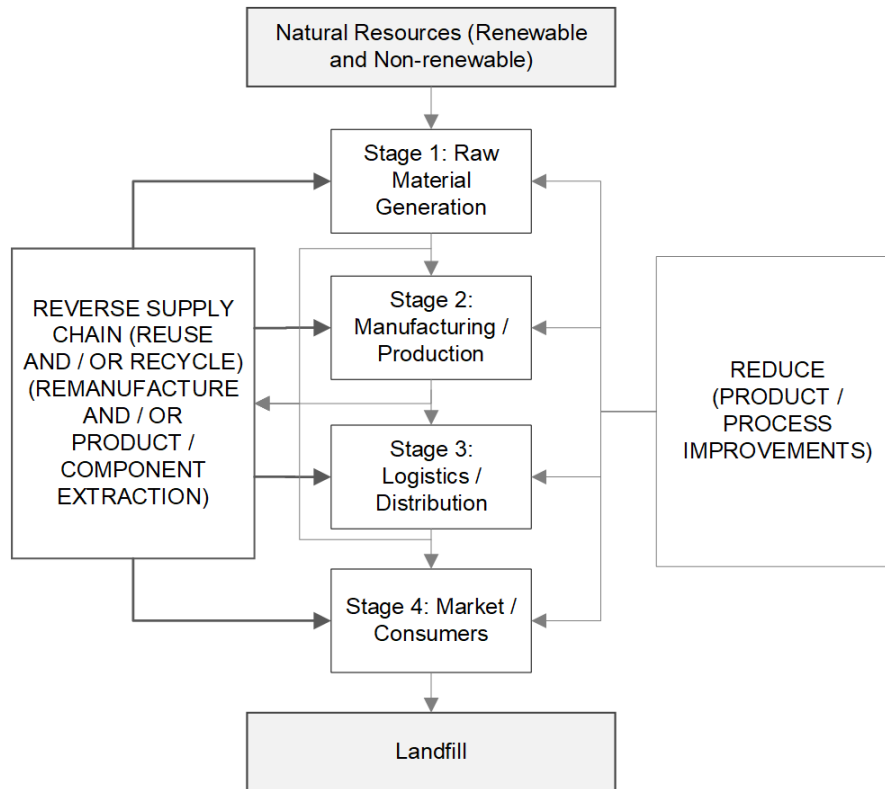


Figure 2-7: The reverse supply chain model proposed by Mahajan and Vakharia [53]

An assessment considering the waste end-product value chain (including technology considerations, environmental impacts, risks and legislative influences via an integrated approach) has not been undertaken for South Africa. Using the value chain approach, opportunities for private sector business development in the waste utilisation field may be identified. This is a gap in current research that will be addressed by this study.

2.3 International Waste Management Perspectives

To provide context for waste management in South Africa, the international perspective must be understood as baseline. Typical trends around the economic effect of waste management, waste compositions and market effects are discussed in more detail in this section.

2.3.1 Global Waste and Waste Management Trends

Waste management forms a significant part of any economy. In low-income countries, solid waste management commonly ranks as the highest cost item for local administrations, requiring up to 20% of municipal budgets. In middle-income countries, solid waste management on average accounts for up to 10% of municipal budgets, while in high-income countries about 4% of municipal budgets are spent on solid waste management [43].

Currently, most of the world's waste is being generated by the Pacific region as well as East Africa (~ 23% of global waste), as seen in Figure 2-8. North Africa and the Middle East are producing the smallest amount of waste (~ 6% of global waste). The highest growth in waste generation is seen in South Asia, the Middle East and Sub-Saharan Africa. By 2050, the waste generated per annum in South Asia and the Middle East is expected to double, while annual waste generation in Sub-Saharan Africa is expected to triple [43].

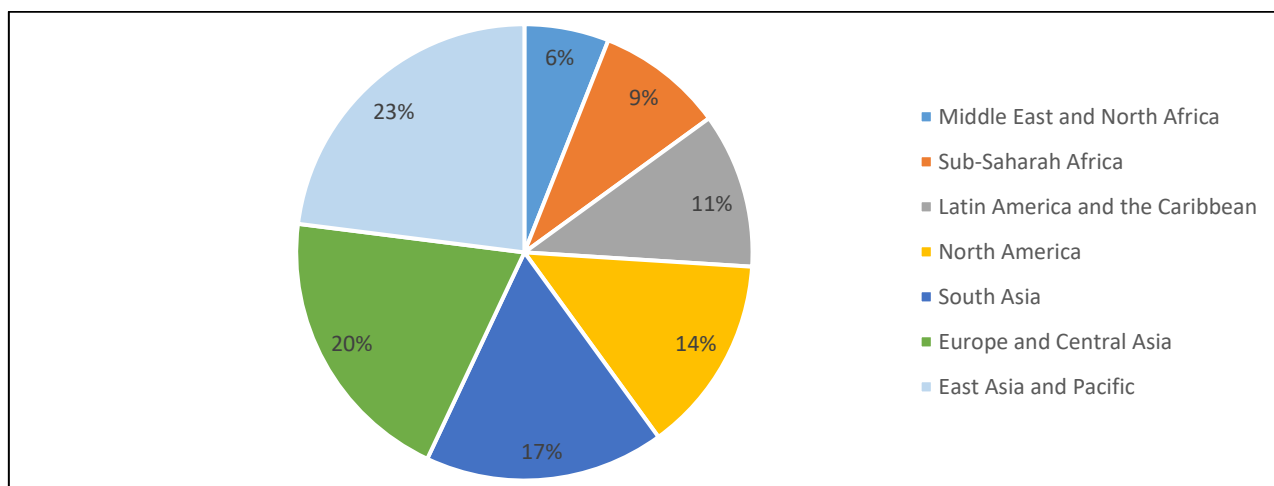


Figure 2-8: Global share of waste generated by region [43]

The average amount of waste generated per region is shown in Figure 2-9 (data used for this study was adjusted for 2016 using information from more than 215 countries and economies). The projected level of waste generation growth in these regions is seen as a significant issue – especially since, at present, around 50% of the waste generated is openly dumped [43].

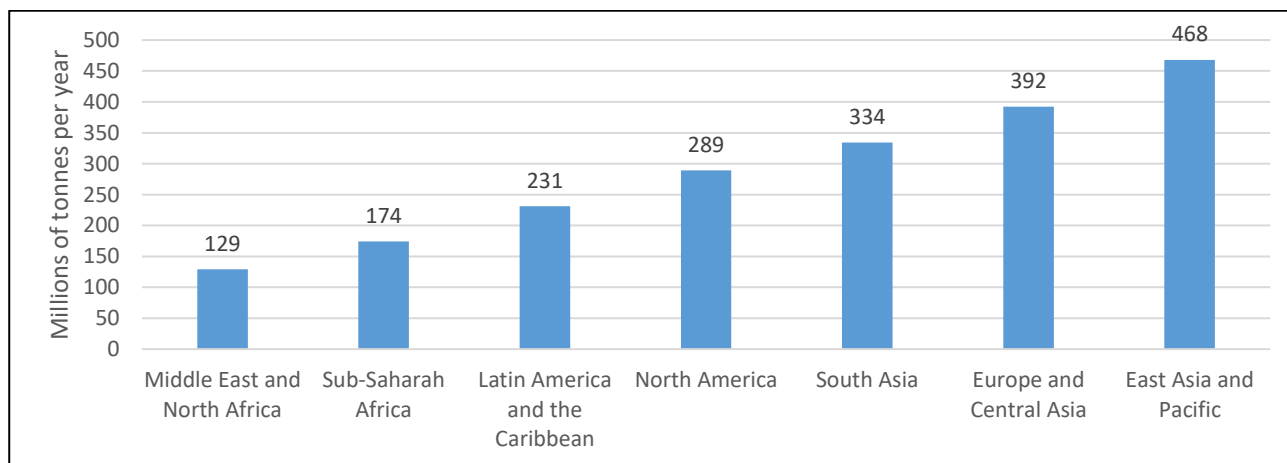


Figure 2-9: Global amount of waste generated by region [43]

Waste composition, generation and collection rates vary not only by region but also based on the specific country's income level. In low-income countries, food and green waste commonly make up 50% or more of the total waste composition. This value decreases to around 32% for high-income countries. The reason for this is the presence of more inorganics and recyclables (including packaging, metal, paper, glass, etc.) in the solid waste streams of high-income countries. The current averaged composition of waste per income group is shown in Figure 2-10. As seen, waste from the high-income group contains the least amount of food and green waste and the highest amount of inorganic or recyclable waste compared to other groups. The low-income group, on the other hand, contains the highest fraction of food and green waste (organic waste) [43].

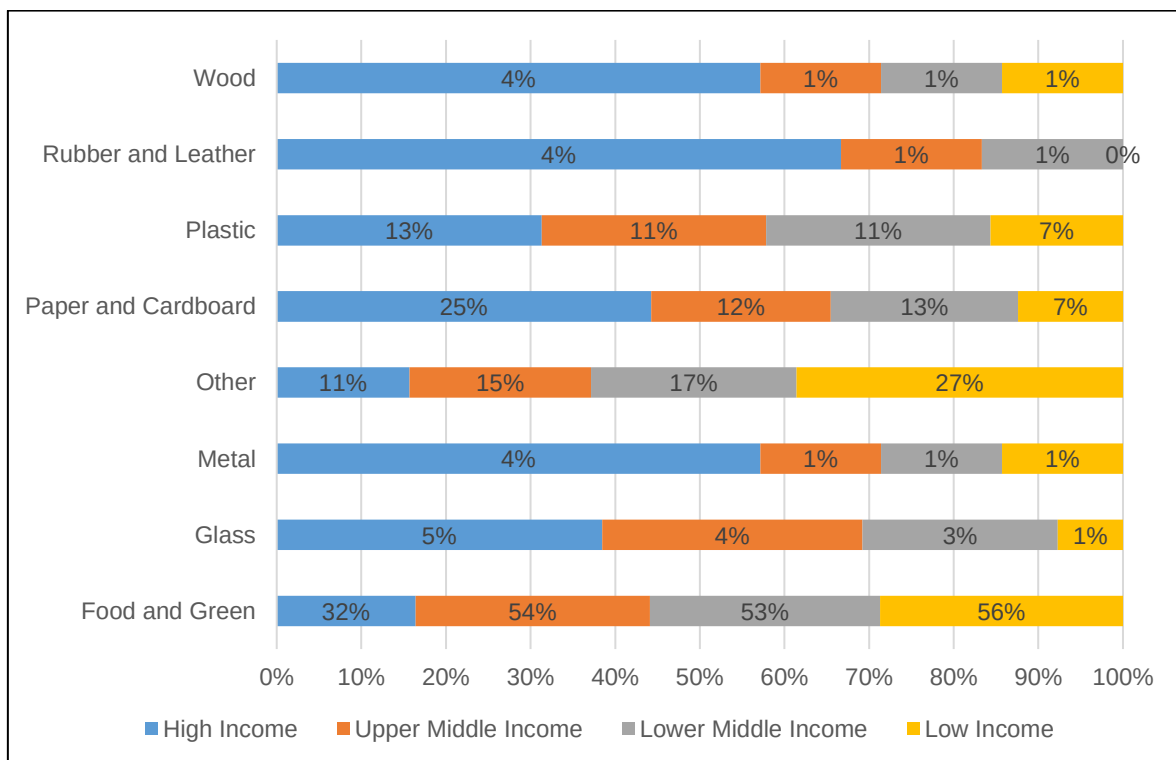


Figure 2-10: Global waste composition per income group [43]

Waste collection is another critical aspect of the waste management process that differs greatly with income level. In high-income countries, more waste is collected for processing than in low-income countries. In high-income countries such as Europe, Central Asia and North America, up to 90% of waste is collected, where in low-income countries around 48% of waste is collected in urban regions, with less than 26% collected in rural areas [43].

Furthermore, the significant difference in waste generation per income group, also including the projected annual waste generation rates for the years 2030 and 2050 by income group, are shown in Figure 2-11 [43].

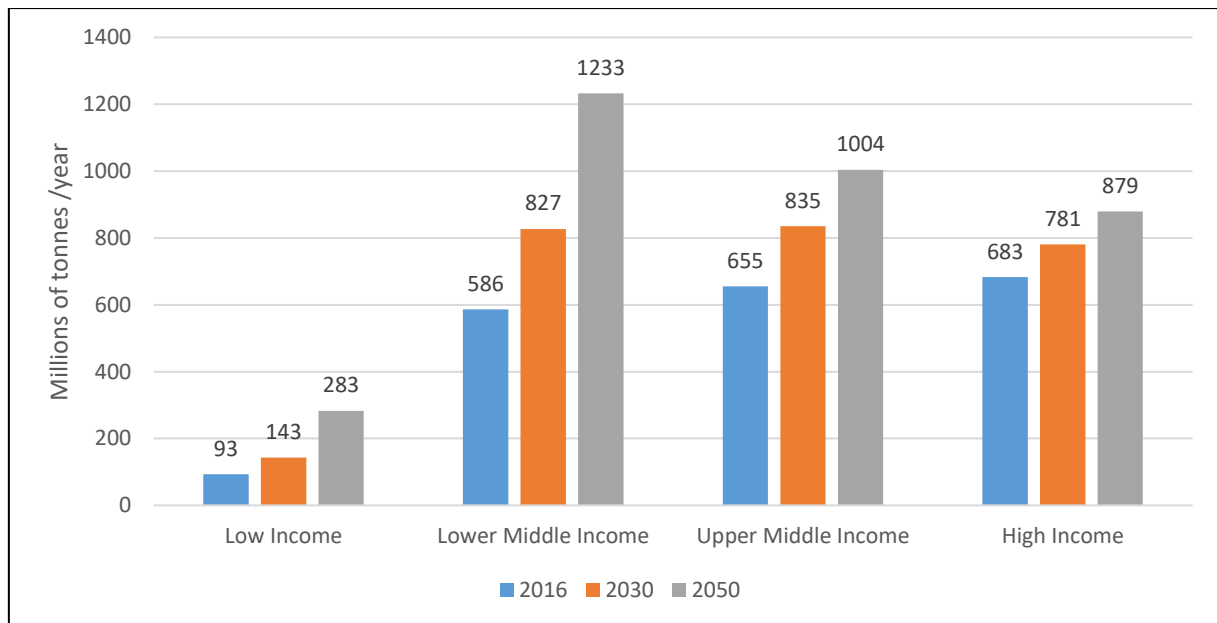


Figure 2-11: Projected annual waste generation per income group [43]

2.3.2 Global Waste Management Market

According to a market study conducted by Global Market Insights, Inc. in 2020 [54], it is estimated that the global market for municipal solid waste (MSW) management will exceed USD 90 billion by the year 2026. The total global waste market (including Municipal Waste, Industrial Waste, and Hazardous Waste) is expected to reach USD 530 billion in 2025 [45].

Apart from the growth in population causing an increase in waste that needs to be managed, the projected sectoral growth is partially driven by increased environmental awareness. Globally, this change in thinking is leading to stricter government regulations and policies. This in turn increases investment in waste management technologies and solutions [54].

Internationally, waste dumping as a method of disposal is decreasing in popularity and use. Instead, sustainable and efficient methods of solid waste management are being funded and applied more often. This change is experienced to a lesser extent in developing or low-income countries where sophisticated waste management strategies are used less commonly due to a lack of necessary infrastructure [54].

Industrialisation in developing countries has a notable effect on waste management growth. Naturally, municipal solid waste generation increases due to industrialisation. However, industrialisation also causes industry growth in various other industries, specifically including the chemical, automobile, oil & gas, and medical industries [45].

These trends were recently observed in emerging economies such as China, Taiwan and India, where the large cost of waste management solutions often hampered industry growth in the aforementioned sectors. However, the same issue also led to a ramp in waste management solution development (specifically considering waste-to-energy solutions) to reduce the cost for future implementation [45].

The major findings in the industry sector market report for 2020 are summarised as follows [54]:

- A paradigm shift towards sustainability in waste management is stimulating the industry outlook. This is caused to a great extent by rapid urbanization in developing countries.
- Business growth is taking place due to a rapid shift from open dumping to more sustainable options. These options include recycling, anaerobic digestion and combustion.
- Key players in the MSW management market globally include (amongst others) Waste Connections, Veolia, Recology, Hitachi, SUEZ, Waste Management Inc, and Biffa Group.
- Key players in the overall waste management market globally include Clean Harbors, Biffa Group, Inc., Veolia, Covanta Holding Corporation, Hitachi Zosen Corporation, Daiseiki Co. Ltd., Environment S.A., Waste Management Inc., Advanced Disposal Services Remondis AG & Co. Kg, and Suez Environment S.A.
- MSW used as a cyclic and clean energy source is expected to drastically drive sectorial growth in the waste management industry.
- Investment in waste treatment plants is expected to increase significantly due to the inevitable increase in waste generation. This will supplement technology improvement and innovation in the waste management field.

Awareness of the health effects of inadequate waste management is already leading to growth in the waste management sector internationally. New policies and regulations are striving to favourably influence the adaptation of sustainable waste management solutions. In general, all legislation toward waste generation implemented internationally can be classified as either Coasean or Pigouvian. Coasean legislation assigns ownership of waste by taxing or charging firms for the waste they generate. Pigouvian legislation levies taxes to assist in covering the marginal cost between waste disposal and waste utilisation or management [53].

In the EU, some recent policies or directives on this topic include the 7th Environment Action Programme and the Waste Framework Directive. The governmental push towards sustainability is increasing awareness, while the EU's ambitious waste reduction targets are already improving business growth in this sector [54].

2.4 Waste Management in South Africa

Optimising waste management in South Africa is vital for various reasons. Firstly, South Africa sends about 90% of its total generated waste to landfills [11]. Secondly, only about 44% of South Africa's 1280 recognized landfills are authorised, which means that regulatory compliance is unmonitored throughout most of the country. Thirdly, South Africa has a high rate of waste generation compared to other developing countries [55], as seen in Figure 2-12, which means a large volume of waste is generated in the country.

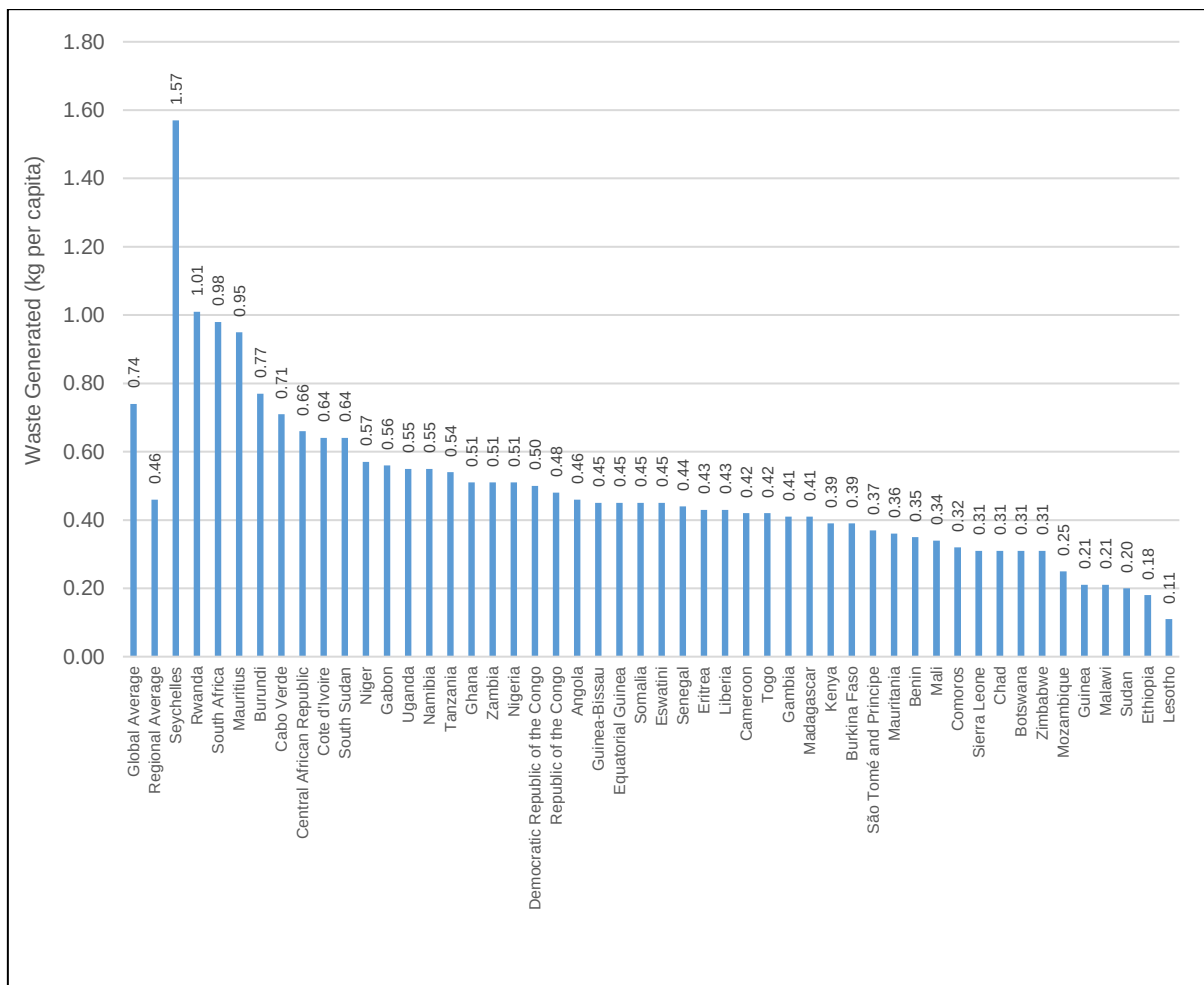


Figure 2-12: Waste generation per capita for Sub-Saharan Africa [43]

The waste generation per province in South Africa is shown in Figure 2-13.

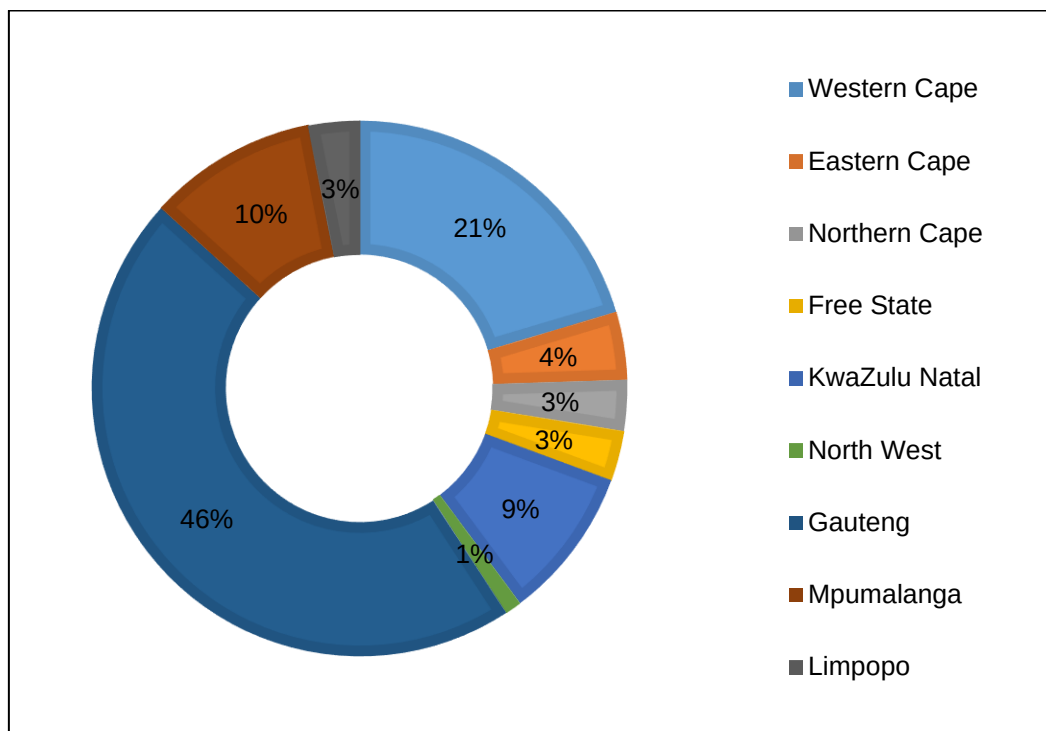


Figure 2-13: Percentage of waste generated per South African province [56]

Fortunately, the South African government is actively generating policies and regulations to steer South Africa towards improving its waste management practices. This was first proven by the implementation of the National Environmental Management: Waste Act (NEM: WA) (Act 59 of 2008). Thereafter, various policies and strategies were brought into play to improve various facets influencing the country's waste management strategy. These include, amongst others, waste information systems, hazardous waste management regulations, research and development, determination of the economic value of waste, waste trends, opportunities and implementation frameworks, including a waste management roadmap ([57], [12], [56] and [13]).

South Africa is taking part in the internationally driven climate change minimisation goals set out at UN Climate Change Conference (COP21) and highlighted in Agenda 21 (of which waste management is a key area of focus). South Africa is also committed to the four Multilateral Environmental Agreements (MEAs), namely the Basel, Montreal, Stockholm and Rotterdam MEAs, which are key to the global sustainability push. As part of these MEAs, South Africa is submitting annual reports on waste (Basel Convention), with specific a focus on hazardous waste statistics and management [55].

The legal framework for waste management in South Africa is set by the NEM:WA also referred to as the Waste Act. To achieve the goals as set out in the Waste Act, the National Waste Management Strategy (NWMS) of 2012 [12] was set in motion. According to the NWMS, the main waste management challenges faced by South Africa include:

1. Waste generation increases due to population growth
2. Increase in waste stream complexity caused by industrialisation and urbanisation
3. Waste management services backlog, especially in rural or informal areas
4. Lack of understanding and data on waste streams, flows and compositions
5. Limited economic growth in the waste management industry due to a regulatory environment that does not endorse the application of the waste hierarchy
6. Lack of waste separation technology (especially for recycling or material recovery applications)
7. Aging waste management infrastructure
8. Under-pricing of waste management services which promotes disposal
9. Low availability of waste management options
10. Lack of adequate hazardous waste management facilities and compliant landfills

The NWMS requires both state structures and private influenced parties to actively take part in furthering the strategy's goals and targets. The eight goals laid out in NWMS are shown in Figure 2-14.

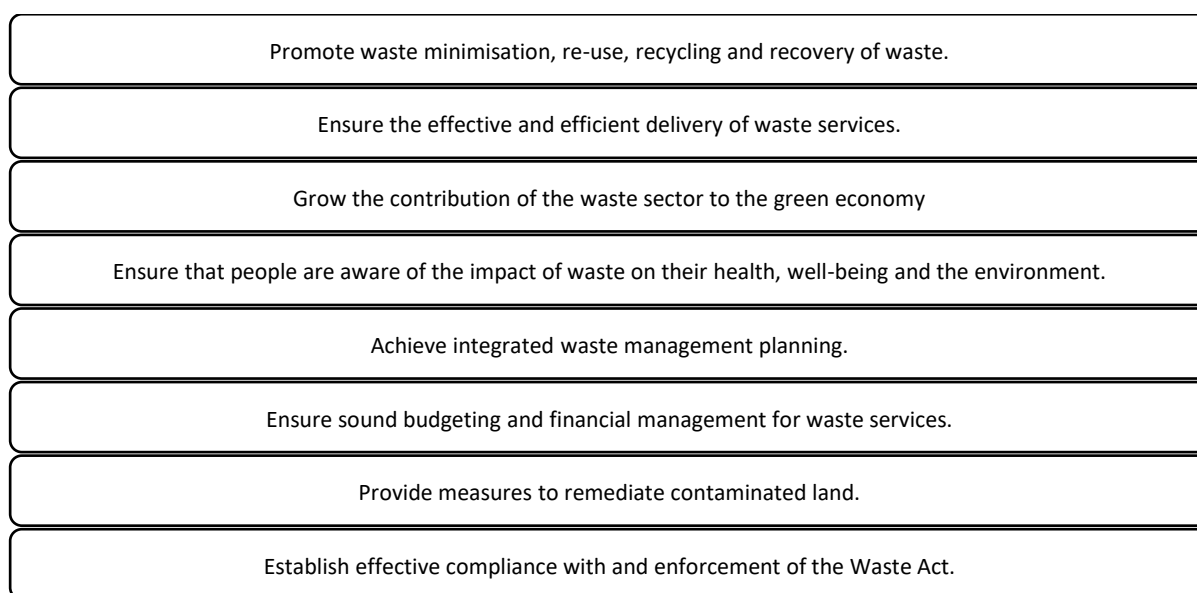


Figure 2-14: Eight goals of the National Waste Management Strategy [12]

Though the importance of information and data systems has been emphasized in recent years, very little data is currently available on waste production and management in South Africa. To fill this gap, the South African government created the South African Waste Information System (SAWIS) [56]. All companies generating waste will be obliged to register and record their waste generation data on

this system. All waste streams will be categorised under the South African Waste Classification and Management System (WCMS) framework for reporting to SAWIS. A summary of the WCMS framework can be seen in Figure 2-15, including its three subcategories: waste classification (A), waste management (B) and waste categorisation and reporting (C).

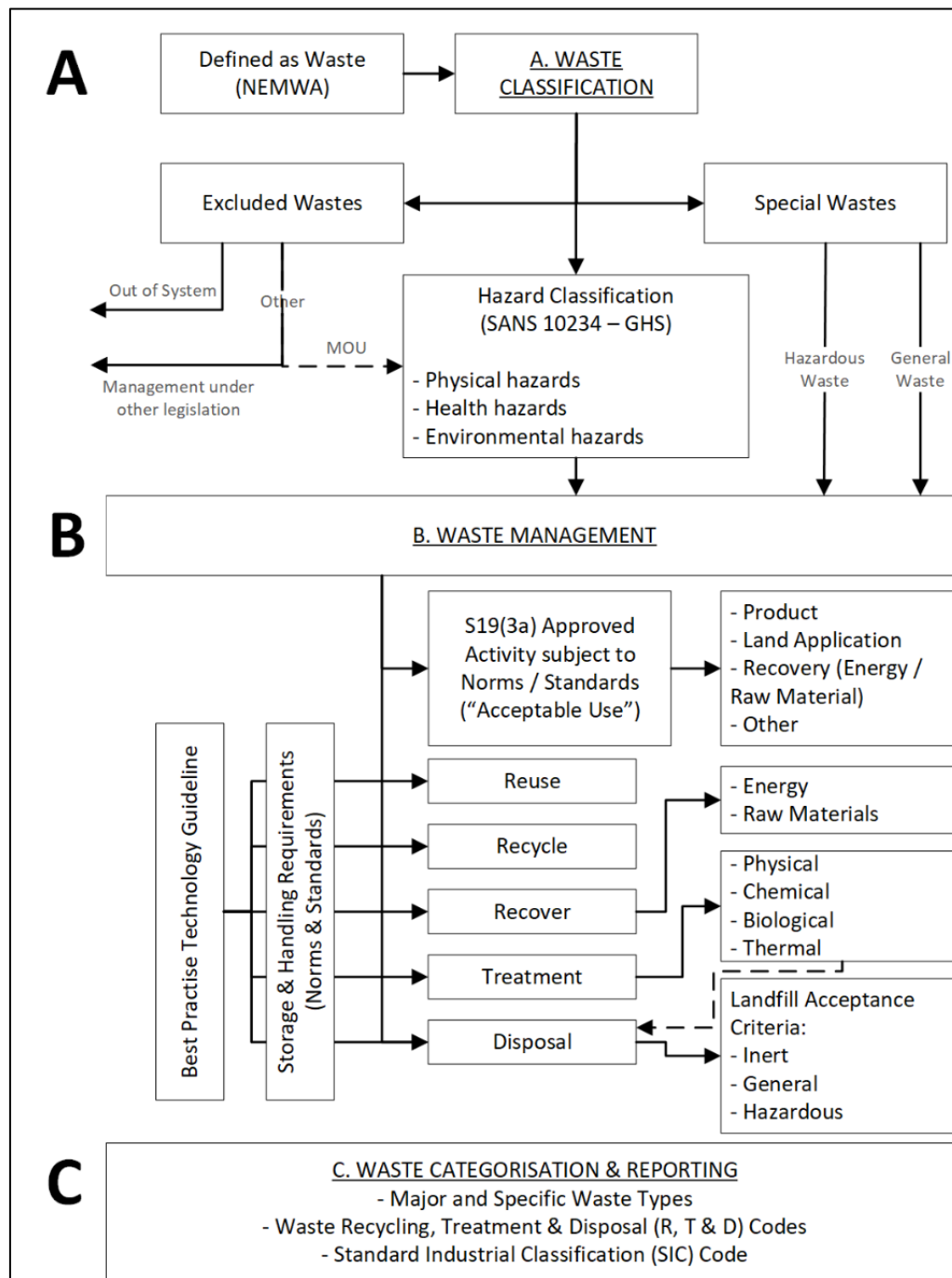


Figure 2-15: The South African WCMS [58]

However, so far, the SAWIS has not been declared fully operational (submitting waste data to SAWIS is currently optional) and lack of data remains one of the biggest challenges to countrywide waste management [56].

Apart from the issue of data collection on waste generation, there is also a lack of trust in the accuracy of data being collected. According to the Department of Environmental Affairs' (DEA's) National Waste Information Baseline Report, 62% of the total 69% of municipalities that are collecting waste-related data in some form or another believe that the data they are collecting is unreliable. This creates an issue for waste management projects since additional costs must be incurred to establish an accurate design baseline [56].

An example of the variance in data collected on waste can be seen in the historical waste generation growth rate calculations. According to the DEA's National Waste Information Baseline Report [56], waste generation growth rates in South Africa were calculated as part of several studies. Using only data from South African municipalities, calculated waste generation growth rate values from eight studies are presented in this report and range between 1.66% to 3.98%. The actual waste generation data from these studies, however, vary more drastically, with waste generation per annum measured for 2011 ranging from 12 tonnes/annum to 24 tonnes/annum.

At present, records of waste streams and waste management are available solely for the Western Cape province. For this reason, the majority of data used to represent the country as a whole is based on conditions in the Western Cape.

According to studies done on waste management in the Western Cape, positive growth has taken place in the South African waste economy. Since 2014, a shift in focus has taken place from waste disposal to waste beneficiation. Investments in waste management by the private sector have increased, which also led to an increase in both the scale and overall scope of waste management projects [59].

The most important advances in the South African waste management domain were listed in a market intelligence report on waste management in the Western Cape and include [59]:

- Attention to extended producer responsibility
- Governmental push for waste diversion from landfills
- Initiatives to gather data on waste
- Government-driven chemical and waste economy fast-tracking strategies
- Municipal investment in waste infrastructure

2.4.1 Waste Classifications

Various waste classification systems exist, not only in South Africa but also globally. Legal classification allows countries to categorise, track and manage waste streams. However, other classifications such as compositional classification, risk-based classifications or source-based classifications also exist to assist in selecting the appropriate waste treatment and handling methodologies.

In South Africa, waste is legally classified as either Hazardous or General Waste (Level 1 Classifications), as explained in Figure 2-15, Section A (Waste Classification). Under these two categories, the waste is divided into various subcategories (Level 2 Classifications). The full list of waste categories is shown in Table 2-2. For this project, the focus is on General Wastes.

Table 2-2: Legal waste classification in South Africa [19]

Level 1 Classifi cation	General Waste		Hazardous Waste	
	Level 2 Classification			
	GW01	Municipal waste	HW01	Gaseous waste
	GW10	Commercial and industrial waste	HW02	Mercury-containing waste
	GW13	Brine	HW03	Batteries
	GW14	Fly ash and dust from miscellaneous filter sources	HW04	POP (Persistent Organic Pollutants) Waste
	GW15	Bottom ash	HW05	Inorganic waste
	GW16	Slag	HW06	Asbestos-containing waste
	GW17	Mineral waste	HW07	Waste Oils
	GW18	Waste of Electric and Electronic Equipment (WEEE)	HW08	Organic halogenated and /or sulphur containing solvents
	GW20	Organic waste	HW09	Organic halogenated and/or sulphur containing waste
	GW21	Sewage sludge	HW10	Organic solvents without halogens and sulphur
	GW30	Construction and demolition waste	HW11	Other organic waste without halogen or sulphur
	GW50	Paper	HW12	Tarry and Bituminous waste
	GW51	Plastic	HW13	Brine
	GW52	Glass	HW14	Fly ash and dust from miscellaneous filter sources
	GW53	Metals	HW15	Bottom ash
	GW54	Tyres	HW16	Slag
	GW99	Other	HW17	Mineral waste
			HW18	Waste of Electric and Electronic Equipment (WEEE)
			HW19	Health Care Risk Waste
			HW20	Sewage sludge
			HW99	Miscellaneous

According to 2011 data reported by DEA [56], general waste makes up around 55% of the total generated waste in South Africa, followed by unclassified wastes at 44% and hazardous waste at 1% of the national total. Compositions of each waste stream according to this study are shown in Figure 2-16.

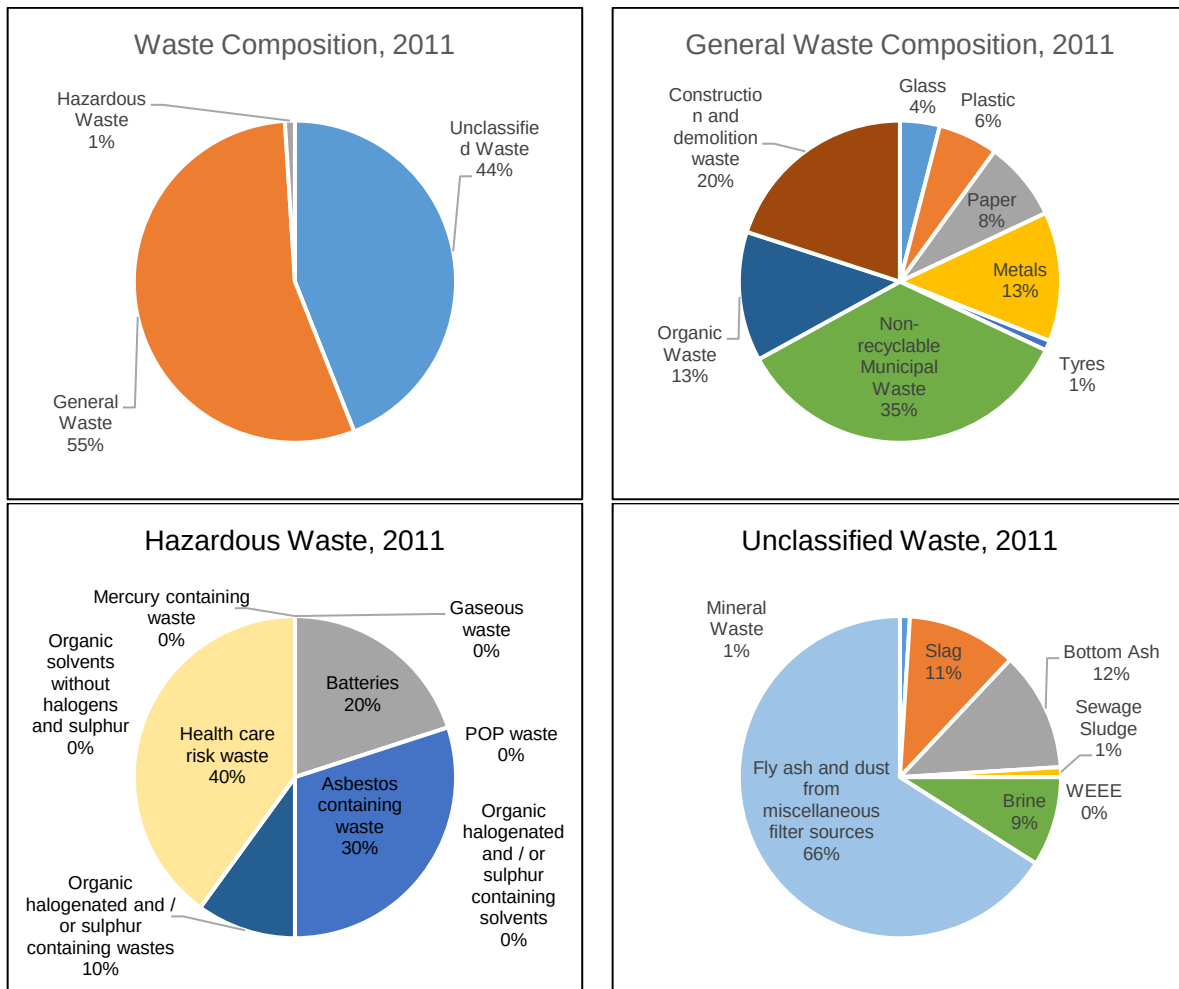


Figure 2-16: Waste types and compositions according to the National Waste Information Baseline Report of South Africa [56]

More up to date data is available solely for the Western Cape (City of Cape Town), adapted from a study done by JG Afrika and reported by GreenCape in their 2019 market intelligence report [59], as shown in Figure 2-17.

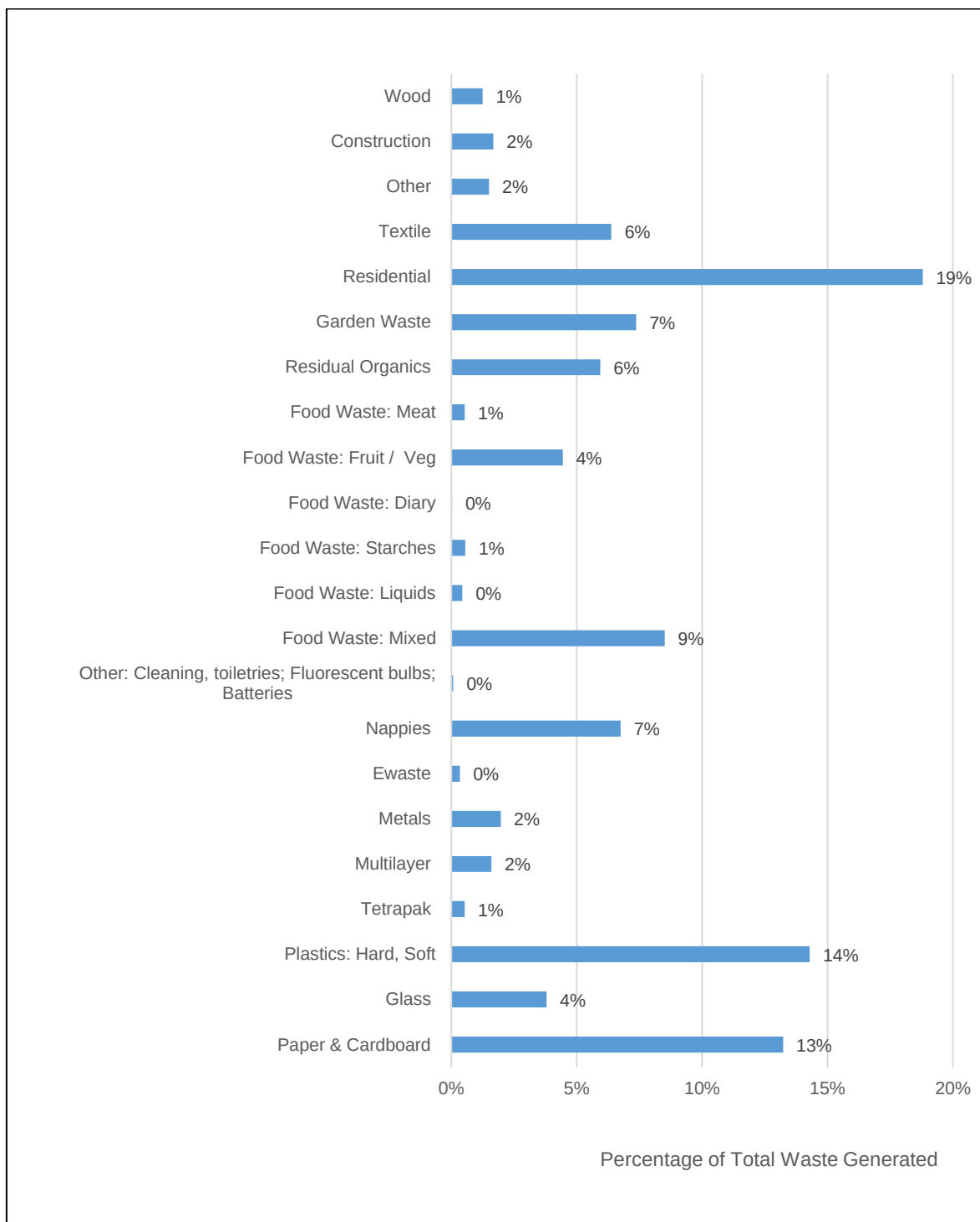


Figure 2-17: Western Cape waste characterisation data [59]

2.4.2 The Socio-Economic Impact of Waste in South Africa

Solid waste management is identified by the National Treasury as an area of great potential for job creation for municipalities. This is especially true regarding semi-skilled or unskilled labour in the labour-intensive recycling industry. As seen in Figure 2-18, the recycling industry is by far the largest employment generator, followed by the public and lastly the private sectors.

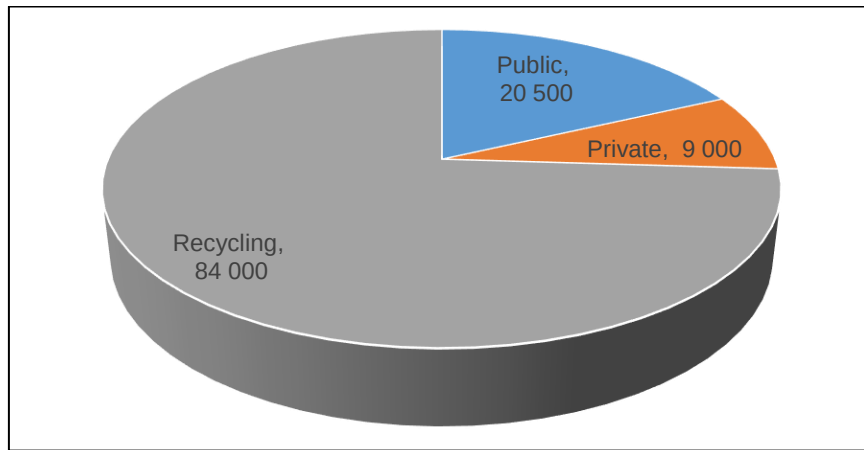


Figure 2-18: Employment estimate for the South African waste sector (2009) [60]

Waste management is also a significant contributor to the national economy. In 2016, the South African waste economy contributed around ZAR 24.3 billion to the country's gross domestic product (GDP). According to the DEA, an additional ZAR 11.5 billion per annum could be added to this amount by 2023 by diverting around 20 million tonnes of waste from landfills. In addition, a further 45,000 formal jobs and 82,000 indirect jobs could be created, and 4,300 SMMEs could be established [59].

These findings were made during the 2017 workshop entitled Operation Phakisa: Chemicals and Waste Economy hosted by the DEA. Twenty initiatives were found that could potentially achieve the mentioned waste diversion target and identified the need to reform regulations, support SMMEs and invest in waste management infrastructure [15].

Based on GreenCape's market intelligence report, potential economic values, as shown in Table 2-3, were identified for organics, e-waste, plastics and builders' rubble in the Western Cape province.

Table 2-3: Economic opportunity values of waste streams in the Western Cape [59]

Waste Type	ZAR/Tonne Waste	ZAR Million/Annum
Organics	100 - 188	83 - 158
E-Waste	1309 - 1636	54.5 - 108.4
Plastics	1950 - 2600	462.2 - 616.2
Builder's Rubble	Wide Range	132 - 309

Apart from the planned industry growth from Operation Phakisa, existing facility limitations are forcing further investment in the short term. An example of this is landfill airspace limits which are forcing certain municipalities to invest heavily in waste management. In 2020, Stellenbosch municipality (one of the largest municipalities in the Western Cape by both population and GDP

contribution) ran out of airspace and had to start transporting its waste to landfills in Cape Town. As a result, Stellenbosch municipality is investing heavily in landfill diversion initiatives [15].

2.4.3 Waste Management Legislation, Regulation and Policies

The National Environmental Management: Waste Act, 2008 (Act No 59 of 2008), also referred to as the NEM:WA is the dominating law for waste management in South Africa. This law refers to various other supportive documents, strategies and notices that further explain and support the aims mentioned in NEM:WA. It also connects to other South African regulations within the same domain, such as the National Environmental Management Act, 1998 (Act No 107 of 1998), commonly referred to as the NEMA.

The regulatory framework governing waste management activities and entities on a national level includes at least the following:

- National Environmental Management Act, 1998 (Act No 107 of 1998)
- National Environmental Management: Waste Act, 2008 (Act No 59 of 2008)
- National Environmental Management: Air Quality Act (Act No 39 of 2004)
- Various Municipal Waste Management By-Laws

Since the responsibility for waste management in South Africa is assigned to local municipalities (South African Constitution, Section 156(1)(a) and Schedule 5) [61], a lack of uniformity exists regarding the legal requirements for waste management activities between provinces. This pushes the responsibility for understanding the requirements as well as observing them back onto the waste generators and handlers. According to GreenCape's 2020 Market Report [15], the DEA is developing a by-law template for use by municipalities for guidance with regard to bylaws. Though this template will hopefully improve the uniformity of regulations between municipalities, its goal is simply to act as a blueprint and will not require municipalities to make any actual changes to by-laws. It should thus be noted that the need exists for guidance with regards to legal requirements for new waste management companies trying to establish themselves in the market. This need will be addressed on a high level by the Decision Support System developed as part of this study.

According to the National Waste Management Strategy (NWMS), one of the key strategies used by the government to implement the NEM:WA is the regulation of waste management activities through licencing. The waste management activities and specific conditions that require Waste Management Licences (WMLs) are given in GN No. 921 of 29 November 2013. These activities are divided into three categories, where Category A and B activities require both a WML and completion of an Environmental Impact Assessment (EIA), while Category C activities only require adherence to the norms and standards. The listed activities and accompanying conditions for each category are shown in Table 2-4 [22].

Table 2-4: Listed activities and categories as per GN No. 921 [22]

Activity	Category A		Category B		Category C	
	Waste Processed	Facility Size	Waste Processed	Facility Size	Waste Processed	Facility Size
Storage	Only storage in lagoons	-	Only storage in lagoons	-	> 100 m ³ general waste for > 90 days	All
					Storage of waste tyres	> 500 m ²
Recycling	> 500 kg/day	500 m ²	-	-	-	-
Recovery, Refining, Utilization or Co-Processing	> 10 tonnes/day	-	> 100 tonnes / day	-	Landfill gas extraction, flaring or recovery	All
					Vehicle scrapping or recovery	> 500 m ²
Treatment	> 10 tonnes/day	-	> 100 tonnes / day	-	-	-
Disposal	> 25 tonnes/day	50 m ²	> 25,000 tonnes	> 200 m ²	-	-

It should further be noted that the Department of Environment, Forestry and Fisheries (DEFF) is busy updating the draft national norms and standards to exempt composting facilities processing in excess of 10 tonnes/day of organic waste from requiring a WML [15].

Apart from licencing waste management activities, a call for Industry Waste Management Plans (IndWMPs) was published in December of 2017 (GN1353 of 2017). The goal of the IndWMPs was to push waste producers within specific industries to generate plans for the long-term management of their waste. After an initial delay in the implementation of the regulation, the notice was later withdrawn (GN1659 of 2019) [15].

Further developments with regard to national waste regulations include changes to the norms and standards for landfill disposal of waste (R. 636 of 2013). The existing norms and standards include a list of waste types that are banned from landfill disposal. Recent changes to these norms and standards include banning hazardous waste with an energy content higher than 20 MJ/kg as well as banning liquid wastes [15].

Various potential changes are being planned with regard to South African waste policies, legislation and regulations. These changes may influence future investments in the South African waste management sector. Known planned changes include:

- **Landfill Disposal:** Further planned changes to the landfill disposal norms and standards (R. 636 of 2013) are shown in Figure 2-19, with additional waste types to be banned from landfills. In addition, specific targets set by municipalities should result in a reduction of waste to landfills. An example includes the Organics Landfill Diversion Targets set by the DEA of the Western Cape, which plans for the diversion of 50% organic waste from landfills by 2022 and 100% by 2027. Implementation procedures for these targets are required at the local municipal level [15].

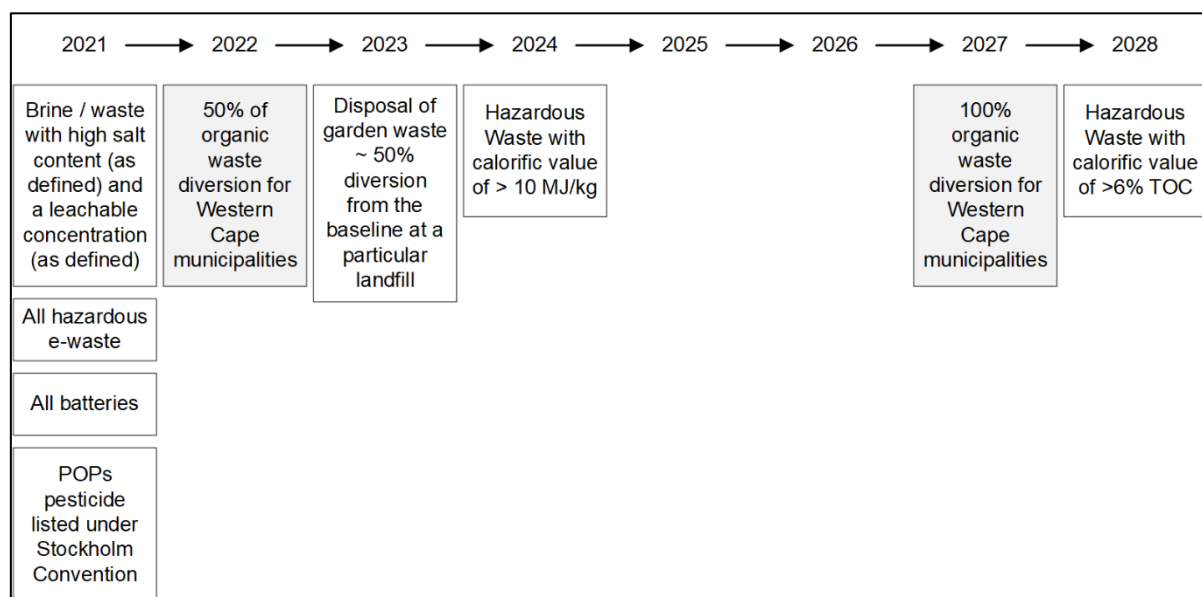


Figure 2-19: Planned additions to the regulated list of waste streams banned from landfills [15]

- **Separation at Source:** National norms and standards will be developed by the Chemical and Waste Operation Phakisa for the separation of waste at source. The norms and standards will be implemented as part of the municipal integrated waste management plans and are currently planned for the end of 2021 as part of the DEFF's target of 50% separation at source by households by 2023 [15].
- **Extended Producer Responsibility (EPR):** ERP implies that responsibility is placed on the Original Equipment Manufacturers (OEMs) for the end-of-life of their products. This may either include direct responsibility, where the OEM reuses, recycles or manages the waste product; or secondary responsibility, where a recycling fee or tax is charged to the OEM as an investment into downstream waste management [53]. Due to the withdrawal of the IndWMP requirements, a decision was made to directly engage various industries to investigate EPR implementation (Section 18 of the NEM:WA). This decision will delay the implementation of EPR in South Africa but is expected to improve access to EPR levies in the longer term [15].

- **Composting of Organic Waste:** The organic waste composting national norms and standards (GN 1135 of 2019) are being updated by the DEFF. Except for exempting composting facilities processing in excess of 10 tonnes/day from requiring a WML, the updated norms and standards will also include accepted best practices for composting activities [15].
- **Changes to the Definition of Waste:** A notice has been published (GN 1077 of 2019) for public participation in a list of potential materials to be removed from the definition of waste, according to the regulations of excluding waste streams (GN 715 of 2018). If removed, companies may apply for exclusion and take direct responsibility for handling these streams. Waste types being considered for exclusion include gypsum, slag, ash and biomass [15].

Historically, waste management in South Africa is trademarked by a lack of legislation as well as a lack of legislative enforcement [62]. Improvement in this field is expected due to the goals and targets set by the National Waste Management Strategy [12]. However, the strategy places heavy emphasis on integrated waste management on a national or municipal level, with little attention being given to the private sector. Though potential is created for private sector and SMME growth due to recent regulatory changes, municipal targets and governmental waste-sector investment, decision support and strategic guidance for upcoming firms remain limited.

2.4.4 Waste Economics

As noted in Section 2.2.4, an assessment considering the waste end-product value chain, technology considerations, environmental impacts, risks and legislative influences (integrated approach) for the private sector, has not been undertaken for South Africa. However, on an international level, work has been done towards qualifying the economic impact and drivers or barriers for the waste utilisation field. These aspects must be understood to understand the environment in which waste management companies and start-up companies operate as well as the risks and challenges to be considered before starting a new business in this field. Since very little work has been done on waste economics in South Africa, most of the concepts stated are generalised based on international findings.

Historically, preconceptions around waste are negative. In the linear economic model (make, use, dispose), the focus is placed on the management of waste. This means moving waste away from the economic hubs. This is a basic concept for city planning, where zoning is used to move waste management or disposal facilities away from residential areas for hygienic reasons [36].

A more modern approach to waste management is the circular economy model as explained in Section 2.2.4, where the value of waste is emphasized in its use as a raw material input to other processes (waste valorisation or waste-as-resource approach). The circular economy model is

currently being adopted worldwide. In Europe, the concept of circularity is a driving force for local and national governments and is implemented in development policies, including energy, utilities and urban development.

This feeds into the centralised concept of economic efficiency, which describes the optimality of managing the waste at each level of the waste hierarchy so that the cost of waste reduction matches the benefits (environmental, economic, etc.) of waste reduction. In all cases, the benefit must outweigh the cost [57]. According to Heidari *et al.* [16], a waste management system required three characteristics to be sustainable, namely, it should be environmentally effective, economically affordable and socially acceptable.

Local awareness and perception remain important considerations for waste economic activities. Commonly, the value of the end-product is influenced by the fact that remanufactured or recycled or reutilised materials are seen as secondary in worth to raw materials or new products [36]. Management of the perception of waste management activities is a social responsibility and is heavily dependent on the country, demographics, culture, environmental attitude, and general awareness [63].

Waste management has traditionally been directed using command and control regulations (CAC), which enforce obedience to certain rules using fines or penalties. A more modern approach to environmental issues such as waste management includes economic instruments (EIs), which indirectly influence general behaviour by association with either rewards or penalties. Economic instruments include subsidies, taxes or incentives associated with specific actions or outputs, such as deposit refunds or weight-based collection charges for waste [62].

EIs have been used successfully in developed countries since 1980 to encourage the implementation of the waste hierarchy on a national level. Recently, interest has been shown in the implementation of EIs in developing countries as well. Concepts such as cost-effectiveness, innovation incentives, economic efficiency, and revenue generation to finance environmental expenses or implement environmental policies, have exhibited significant advantages over CACs [62].

Certain prerequisites are required to successfully implement EIs, such as operational markets, functioning information-gathering systems, functioning systems to monitor illegal activity as well as the ability to effectively enforce policies and taxes. EIs have a high administrative impact and require a strong political will, especially considering that many of the EIs may be unpopular.

According to Nahman and Godfrey [62], waste management in South Africa is historically underfunded and badly managed. Recent regulations, including the NWMS and the Waste Act, acknowledge the need for South Africa to move up the waste management hierarchy. To achieve this goal, the use of EIs becomes necessary.

To manage the issue of lack of funding, the Polluter Pays Principle (PPP) is applied. This principle is raised by the NWMS and forms a basis for waste management in South Africa. According to Nahman and Godfrey [62], every generator of waste is responsible for the cost of managing that waste. This is true for both private stakeholders and businesses and includes all costs, whether it be direct waste management costs (collection, treatment and disposal), as well externalities, such as costs associated with damage to health and the environment.

Though the PPP can be implemented either via CAC or EI mechanisms according to the NWMS, it should be noted that environmental legislation in South Africa is heavily based on CAC. Some EIs do exist in South Africa, such as product tax, which is limited to plastic bag and tyre levies, with future levies proposed for electronics, batteries and packaging. Buy-back (or deposit-refund) schemes are mostly implemented by the private sector for specific waste streams, such as glass, steel or plastic containers [62].

General drivers for growth in the South African waste economy include the following:

- Extended Producer Responsibility (EPR)
 - EPR is applied to the plastic and e-waste industries in South Africa, with potential for future application to paper and packaging, electrical, lighting and electronic industries based on recent changes regarding the submission of Industry Waste Management Plans (GN1659 of 2019) [15].
- Carbon Tax
 - Carbon tax is charged to industries with direct GHG emissions above a certain threshold. With the implementation of Act 15 of 2019 (new South African Carbon Tax Act), private and public companies that produce more greenhouse gas emissions than the set threshold will be taxed accordingly [15]. In South Africa, carbon tax is set at R120/tonne CO₂. The tax-free threshold is set at 60% of the direct GHG emissions, which implies that the effective tax rate for emissions is R48/tonne of CO₂.
 - Three mechanisms exist to reduce carbon tax impact, the first of which includes relief for emitters such as exposed companies or companies whose emissions are not mitigatable. The second mechanism is to increase the company's tax-free threshold by improving the operational process efficiency. Lastly, offsets such as carbon crediting can be applied [64].
- Carbon Credits
 - Carbon credits form part of the carbon offset scheme that encourages investment in green technologies and GHG reduction. Carbon credits are traded and must be registered and carefully monitored. The concept is based on a monetary value associated with reducing, avoiding or sequestration of the GHGs produced normally

during a specific activity compared to a specific benchmark. By investing in carbon-offset projects, it is possible to reduce carbon tax liability. In some cases, this investment mechanism offers a cheaper solution to high-pollution entities than possible by altering their operations [65].

It should be noted that all Carbon Offset Developers in South Africa have to be registered for selling carbon credits. An application to the administrator of the programme can be made in the early phases of the project (project concept). A pre-screening will be conducted for the specific project based on specific eligibility criteria. After project verification, the project's verification reports will be evaluated. If successful, carbon credits are issued to the project developer (credits are recorded in the registry) and can be traded [65].

The value of carbon credits is linked to the carbon tax rate and is sold at just below R120/tonne CO₂. It should be noted that carbon tax rates in South Africa are expected to increase in the future [66]

- Perception of Green Initiatives
 - The positive perception of green initiatives remains one of the major drivers for environmental initiatives in the private sector. An example of this is the Net Zero Waste Certification launched by the Green Building Council of South Africa (GBCSA). This certification covers buildings that reduce, reuse and recovers 100% of their waste. Two levels of certification exist, namely Level One for the construction phase and Level Two for the operational phase. One of two rankings can be obtained. The first ranking is Net Zero, where zero waste is sent to landfill and all waste is managed or valorised on site. The second ranking is Net Positive, which means that the building can process waste from other sites as well as its waste, thus diverting even more waste from landfills [15].
- Tipping Fees
 - Tipping fees are traditionally charged by a waste management site to store or process waste (disposal tariff). Tipping fees can be charged by new waste management facilities as long as the charged fees do not outweigh the fees charged by existing facilities (open market principles apply). Though South Africa's tipping fees remain low compared to international rates, increases are being experienced due to reduced landfill airspace availability [15]. Disposal fees for 2021 are shown in Figure 2-20.

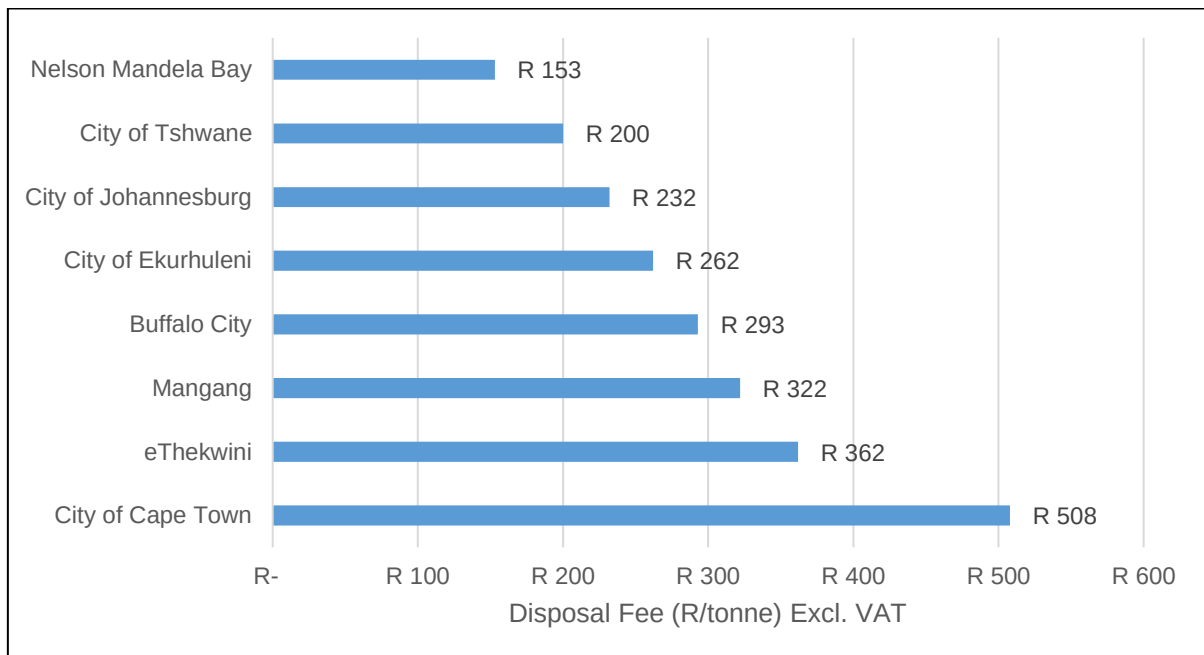


Figure 2-20: Landfill disposal (tipping) fees by metro [15]

For waste financing, charges and waste funding, numerous gaps have been identified in the current level of knowledge in South Africa. As part of the Municipal Waste Sector Plan (270 of 2012), various funding or financing gaps were identified to be addressed by municipalities, such as:

- Undertake a waste management services cost accounting exercise
- Create a CAPEX Funding Guideline
- Develop a strategy for reducing waste, including landfill reduction targets

Since waste management in South Africa is primarily the responsibility of local municipalities, the monitoring and guidance steps to be completed as part of the plan is aimed toward the municipalities. However, it should be noted that all the same issues and gaps are experienced by private sector waste management companies.

2.5 The Decentralised Approach

According to Kuznetsova *et al.* [4], dependence on a centralised waste management system is proven ineffective by various studies and is supported by experience from numerous countries. For centralised systems, increases in waste generation rates require expanding existing waste collection fleets, which not only damages road infrastructure but also significantly increases waste management costs. Another global issue is the inability of existing centralised waste management facilities to process the increasing waste volumes. This processing capacity gap leaves ample opportunity to improve the current status quo of waste management [4].

As explained in Section 2.2, the modern approach to the waste management issue is adopting the waste hierarchy as well as considering all waste streams as potentially valuable resources. In this way, waste can be used to address resource scarcity.

Thus, decentralisation becomes critical [4]. The concept of decentralisation considers numerous smaller waste management facilities that are located closer to or at the various sources of waste generation. Waste treatment, recycling or generation of end-products also take place closer to the end-users. In this way, the waste management infrastructure is directly integrated into the community that generates or uses the wastes [4].

2.5.1 SMMEs and the South African Economy

The focus of the decentralised approach is to move away from a single, largescale facility, and instead encourage the development of numerous small waste management facilities that are directly integrated with both the waste generators as well as the final product end-users. The concept of SMME (Small, Medium and Micro Enterprises) development, therefore, becomes vital.

According to South Africa's 2020 to 2025 Strategic Plan, South Africa's National Development Plan focuses on creating an enabling environment for SMME development and urges the private, civil and public sectors to assist. The reason for this lies in the current role played by SMMEs in the South African economy. In 2019, 66% of all jobs in South Africa (10.8 million jobs) were provided by the SMME sector. Of the jobs provided, only 2.55 million jobs were for SMME owners, while the rest (76% of the jobs provided) were for employees of the SMME sector. Furthermore, the number of jobs provided by the SMME sector is expected to increase to 90% of all jobs available in South Africa by 2030 [13].

The number of SMMEs as a percentage per economic sector is shown in Figure 2-21.

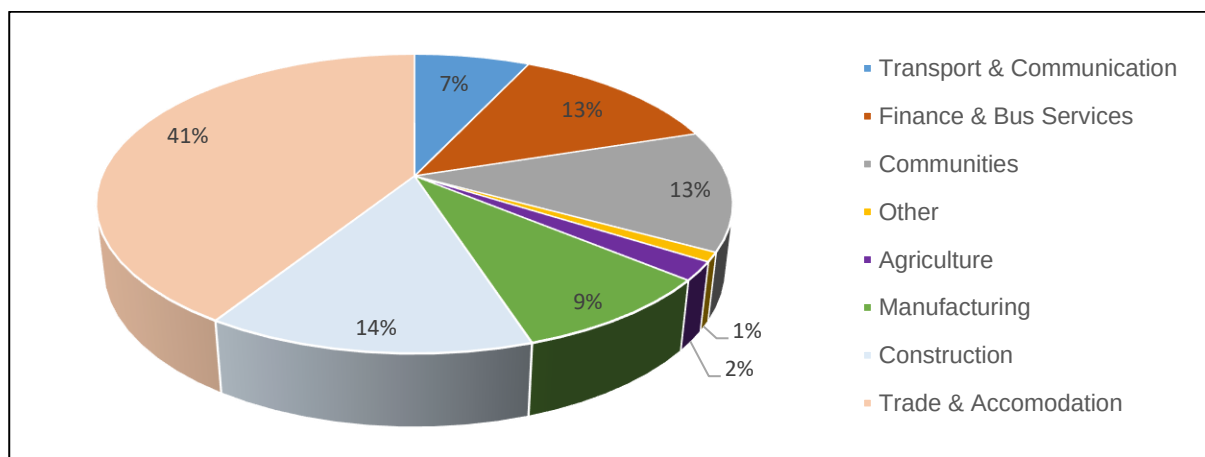


Figure 2-21: SMMEs per economic sector [13]

2.5.2 Definition of Small or Medium Enterprises in South Africa

For South Africa, the definition of SMMEs is dependent on the industrial sector under consideration. The National Small Business Act (102 of 1996) defines SMMEs based on five parameters of measurement, including the industrial sector and subsector, class size, paid employees equivalent, turnover and value of assets (not including fixed property) [67]. A summary of this classification system is shown in Table 2-5.

Table 2-5: National Small Business Act (102 of 1996) classification of SMMEs [67]

Standard Industrial Classification: Sector or Subsector	Size of class	Total full-time equivalent of paid employees	Total turnover	Total gross asset value (fixed property excluded)
Agriculture	Medium	100	R5m	R5m
	Small	50	R3m	R3m
	Very Small	10	R0.50m	R0.50m
	Micro	5	R0.20m	R0.10m
Mining and Quarrying	Medium	200	R39m	R23m
	Small	50	R10m	R6m
	Very Small	20	R4m	R2m
	Micro	5	R0.20m	R0.10m
Manufacturing	Medium	200	R51m	R19m
	Small	50	R13m	R5m
	Very Small	20	R5m	R2m
	Micro	5	R0.20m	R0.10m
Electricity, Gas and Water	Medium	200	R51m	R19m
	Small	50	R13m	R5m
	Very Small	20	R5.10m	R1.90m
	Micro	5	R0.20m	R0.10m
Construction	Medium	200	R26m	R5m
	Small	50	R6m	R1m
	Very Small	20	R3m	R0.50m
	Micro	5	R0.20m	R0.10m
Retail and Motor Trade and Repair Services	Medium	200	R39m	R6m
	Small	50	R19m	R3m
	Very Small	20	R4m	R0.60m
	Micro	5	R0.20m	R0.10m
Wholesale Trade, Commercial Agents and Allied Services	Medium	200	R64m	R10m
	Small	50	R32m	R5m
	Very Small	20	R6m	R0.60m
	Micro	5	R0.20m	R0.10m
Catering, Accommodation and other Trade	Medium	200	R13m	R3m
	Small	50	R6m	R1m
	Very Small	20	R5.10m	R1.90m
	Micro	5	R0.20m	R0.10m

Standard Industrial Classification: Sector or Subsector	Size of class	Total full-time equivalent of paid employees	Total turnover	Total gross asset value (fixed property excluded)
Transport, Storage and communications	Medium	200	R26m	R6m
	Small	50	R13m	R3m
	Very Small	20	R3m	R0.60m
	Micro	5	R0.20m	R0.10m
Finance and Business Services	Medium	200	R26m	R5m
	Small	50	R13m	R3m
	Very Small	20	R3m	R0.50m
	Micro	5	R0.20m	R0.10m
Community, Social and Personal Services	Medium	200	R13m	R6m
	Small	50	R6m	R3m
	Very Small	20	R1m	R0.60m
	Micro	5	R0.20m	R0.10m

Other definitions for SMMEs in South Africa may be based on their outputs, as per the official definition set out in the IPP Procurement Programme [68] for projects by Small Independent Power Producers (IPPs), which include onshore wind, biomass, landfill gas, biogas, and solar PV projects. In this study, the definition of Small Projects includes projects with a capacity between 1 to 5 MW.

It should be noted that the definition of SMMEs for the waste management industry itself is not clearly defined and will be set as part of this study.

2.5.3 Decentralisation of Waste Management in South Africa

As discussed, encouraging private sector development and SMME formation in South Africa is a government priority and forms part of the national development strategy. However, the concept of decentralisation concerning the private sector in the waste management field has largely been left untouched.

Decentralisation is discussed shortly as part of the National Municipal Waste Sector Plan [69], though the focus remains on the role of the government. Waste management decentralisation is seen as pushing the responsibility of waste services from the national government level to provincial and local government levels. Part of this is the requirement for Integrated Waste Management Plans (IWMPs) from each municipality as part of the NEM:WA of 2008. According to the National Treasury's Local Government Budgets and Expenditure Review [3], solid waste management in South Africa is primarily a function of the local governments.

Decentralisation, in terms of shifting the focus to the South African private sector, is currently not addressed by literature and will form part of this study.

According to a study conducted by Fakir in 2009 [14], recommendations for South Africa to improve recycling rates based on international trends are centred around the concepts of entrepreneurship and decentralisation to the municipal level. Amongst others, the study recommends that material recovery facilities be strategically placed to reduce the cost of transport, for market supply and demand to drive recycling rates, and for mapping of existing technologies to drive implementation in South Africa from a strategic point of view. The conclusion is that an integrated approach must be followed to improve waste management (in this case, recycling), taking into account technology types, regulations and policies, market drivers, as well as feedstocks and products to be produced.

It should be noted that, though encouragement of entrepreneurship is mentioned, decentralisation is recommended only with respect to disposal and separation. Development of the sector is still recommended to be led by the municipalities, which does not facilitate true decentralisation.

The recommendation of strategic planning of facilities (though in relation to Fakir [14], the concept is limited to recycling only) and mapping of international technologies with a specific focus on the South African environment is in line with the goal of this study. The focus of Fakir's [14] recommendations is on the creation of an economically driven national strategy for waste recycling.

Though these outcomes are recommended by Fakir [14], it should be noted that they have not been addressed and the gap in the current research still exists. According to Fakir [14], no work has been done to date to determine the cost/benefit trade-off, appropriateness, or likeliness of industry uptake for the various recycling technologies.

A study by the University of Cape Town [70] is currently in progress to undertake a national material flow analysis to establish the level of materials circularity. When completed, this study may add to the foundation of strategic waste management in South Africa. However, it still targets waste management on a national level and does not address the techno-economic ranking of waste management processes. Strategic analysis of South African waste management on a decentralised level remains a gap that will be addressed by the present work.

It is clear that the topic addressed by this study, though in line with recommendations on a national (governmental) and international level, has not previously been addressed and speaks to a gap in the current research. This study aims to close the gap by focussing on the SMME itself and assisting the individual or private sector player in strategically selecting the correct technology, end-product, process capacity, and further offering guidance regarding legal, risk, and environmental considerations.

2.6 Waste Decision Support Tools

Decision support systems or tools have been developed for decades for a wide range of application areas. Though the application areas may differ, typical goals or properties have been identified that

make specific tools effective. Specific areas of focus for decision support within the waste management space have also been identified over time as needs for decision guidance have evolved within this space. This section summarises these aspects of decision support systems, while also identifying the current status of decision support within the waste environment in South Africa.

2.6.1 Decision Support Goals

According to Jąderko-Skubis and Białecka [71], the core goals of decision support systems are to support the decision-making process and to be able to adapt to changing user requirements. As per Ciolofan [72], recognised challenges for decision tools are providing an intuitive interface for the user, being simple to use, responding rapidly, providing concise outputs and appropriate recommendations, and allowing the user to visualise results for ease of interpretation.

2.6.2 Review of Waste Decision Support or Management Systems

While the goals of decision support systems are clear, the application of these systems in the waste management sector presents a distinct landscape. The following section provides a review of such applications.

Internationally, extensive research has been done for waste management support tools on a strategic level. From recent reviews, it appears that most decision support tools are aimed at decision-making on a national level for centralised waste management planning or management. An example of this is given by Achillas *et al.* [73] in their review on the use of multicriteria analysis (MCA) for waste management decision-making. The studies included in the review summary were focused either on the location (33 studies) or strategy (37 studies) of waste management. The decision support studies were grouped by waste type, implying that an optimal location or waste management method was investigated for a specific waste type.

This methodology is seen in most decision support studies in the waste management field: Specific technologies, locations, risks, or costs are compared for the management of a single waste type. Most of the studies consider a selection of parameters for decision making, the most common of which include economic aspects (CAPEX & OPEX) and environmental impact [73].

Similar tendencies are noticed by Heidari *et al.* [74] in their work on MSW management systems, which included a review of 21 studies. The most common approaches seen in the literature were noted as the Life Cycle Assessment (LCA) approach, which focuses on the lifecycle environmental impact of materials from cradle to grave [75], and the industrial ecology approach. Most studies focused on environmental and economic considerations, with five of the 21 studies considering social impacts (notably job creation and gaseous emissions). All the studies focused on centralised waste

management. Some recent studies were found to centre around developing countries including India, Bangladesh and Nigeria.

Interestingly, MSW management systems were defined in this study to include three aspects, namely waste generation, waste separation and compacting, as well as waste processing, where waste processing includes five types of technology only (incineration, anaerobic digestion, recycling, composting, and landfilling) [74].

Vea *et al.* [19] also completed a review and assessment of waste management decision support tools, focused on LCA-based tools. The review considered 25 tools, which were assessed for their flexibility, inclusions, transparency, and accessibility. The authors noted that LCA-based tools usually include two main modules, namely impact assessment modules and lifecycle inventories. The focus of these tools is to map the environmental effects of various waste streams (MSW or fractions of MSW) over the life of the waste material, including aspects such as the effect on climate change, ozone depletion, human toxicity potential, eco-toxicity potential, etc. The main goal of these tools is therefore to assist government or decision-making stakeholders to select the least harmful approach to manage a specific waste stream.

As mentioned, decision support systems centred around location are ample. Some of the more modern systems utilise GIS (Geographic Information System) software to assist with location selection for a waste management facility or the logistics of waste management [71].

Various tools exist that utilise methods based on Industry 4.0, such as internet of things, big data, artificial intelligence, machine learning, and blockchain. Where internet of things drives data mining, inputs from big data allows for large and robust databases that can be used as inputs for decision support. Artificial intelligence-based decision support systems are typically customisable and allows for flexible optimisation [76].

From the above, it is clear that various methods exist for waste management decision support. The most popular methods utilised in literature include GIS, MCA (most commonly using the Analytic Hierarchy Process (AHP), which strives to simplify complex decision making by considering various parameters and weightings [77]) and LCA.

2.6.3 South African Waste Decision Support

For general waste management in South Africa, four decision support systems have been developed or are presently in development, as seen in Table 2-6. These decision support tools are all focused on municipal-level decision-makers and aim to provide decision support on a strategic level.

Table 2-6: South African waste decision support tools

System Name	Approach	Application	Source
SASCOST Model	Spreadsheet-based model	Aim: To assess the cost and benefits of source separation of municipal household waste. The model considers socio-economic and environmental considerations, including the impact of informal collectors on the S@S programme's viability, impact on employment and livelihoods, avoided emissions (MSW collection and transport), and avoided social and environmental effects (landfilling), savings and increased lifespan of landfills. Intended users: Municipalities	[78]
Municipal Integrated Waste Management Decision Support Tool (IWM DST)	System-based approach (not specified – this tool is in development stages)	Aim: To assist municipal decision making in waste management by establishing a vision and goals, developing a baseline for the existing waste management system, identifying key decision criteria, generating potential waste management scenarios that are in line with the vision and goals, evaluating the scenarios against the key decision criteria and highlight the benefits and drawbacks of each scenario. Intended users: Western Cape Municipalities	[79]
Resource Recovery & Logistics Decision Support Tool (the DST).	Spreadsheet-based model with GIS integration	Aim: To assist municipal decision makers in assessing infrastructure, logistics and waste management requirements in the city of Johannesburg. The tool considers waste quantities, logistics and fleet requirements, and financial aspects. Intended users: Municipality (City of Johannesburg)	[80]
Waste Resource Optimisation Scenario Evaluation (WROSE)	Spreadsheet-based model	Aim: To assist municipalities to evaluate and optimise their waste management strategies. This tool considers landfill gas to electricity, recycling, anaerobic digestion and composting scenarios and provides qualitative results. Intended users: Municipalities (KwaZulu-Natal)	[81]

2.7 Structured Literature Review for Gap Identification

A structured review of available literature was undertaken to confirm the gap in the research. The main gap addressed by this study concerns the decision support addressing the decentralised approach to waste utilisation. It is theorised that no integrated decision support system exists that looks at business/project development for decentralised waste utilisation.

It is noted by Kuznetsova *et al.* [4] that the maximum treatment capacity for decentralised facilities are notably different and that different company sizes, business models, investments and operation costs can be expected for these type of solutions compared to standard, centralised solutions. For this reason, the decentralised focus intrinsically changes the working and outputs of the decision support system. For decentralised municipal solid waste management systems, environmental impacts, economic feasibility, and energy and material recovery potential of waste still need to be

explored [20]. In a study on the selection of sustainability criteria and indicators (C&I) for bioenergy developments, it is noted that though stakeholder participation and empowerment have been included in decision C&Is in the past, C&Is focusing on decentralisation, such as local ownership and regional equity, have not been investigated [82]. Furthermore, a review of assessment methods supporting solid waste management in developing countries by Zurbrügg *et al.* [21] noted that, for developing countries, an integrated approach to solid waste management that considers economic, social, institutional, legal, environmental and technical aspects is required and has not yet been addressed in literature. It is further noted that the assessment phase of projects is critical – not just considering the technological aspect, which is found to a larger extent in literature, but rather to get a clear and holistic understanding of the overall system [21].

In order to prove the existence of the gap in the research, a structured approach was followed. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method allows for a structured way to report systematic reviews of literature as well as meta-analysis [33]. For this reason, the PRISMA method was applied to prove the gap in the literature. A systematic review was conducted, which requires specific steps to execute the process. These steps include setting specific exclusion and inclusion criteria, selection of databases, implementation of the keyword string and review process, data abstraction and presentation of results [83].

Specific keywords were selected to identify relevant publications that aligns to the identified gap, namely decision support for business/project development in waste utilisation with a decentralised focus. The keywords string used for the structured analysis was "decision support" & "waste management" & "decentralised". Databases included in the review were ScienceDirect, Scopus, Web of Science and Google Scholar.

The inclusion and exclusion criteria used for the analysis is summarised in Table 2-7. Inclusion criteria were selected to refine the search. Since very few studies with a decentralised focus were found, any studies focusing on decentralisation, including hybrid systems and general review articles, were included. The exclusion items were selected and refined based on repeated themes in the analysed literature. For example, decision support systems found in literature were most often found to have a strategic focus. Numerous studies were also found that focus on decision support or optimisation for systems that fall outside the definition of general solid waste. Examples of this include medical waste, construction and demolition waste, air pollution, energy systems and wastewater systems. Furthermore, supply chain as well as location (most often GIS) focused studies were found in abundance. Lastly, several studies were found that focus on existing systems, such as a review of a specific incinerator plant or optimisation of an existing anaerobic digester.

Table 2-7: Inclusion and exclusion criteria for the PRISMA method

Inclusion Criteria	Exclusion Criteria
Studies focused on decentralisation in the waste management/utilisation environment.	DSSs with a strategic focus.
Studies focused on the hybrid decentralised/centralised approach in the waste management/utilisation environment.	Studies focused on a specific waste stream or a waste type that is not general solid waste.
Reviews of waste management decision support systems.	Waste or product supply chain decision support systems
Peer reviewed journal and conference articles. Doctoral thesis and master's degree reports.	Spatial assessment or city planning decision support systems
Studies published in the English language	Reviews of existing systems or specific designs

The PRISMA flow diagram showing the literature review and selection process can be seen in Figure 2-22. Considering the records removed before screening, “records removed for other reasons” include records that were not in the English language or records that contained no literature information, e.g., conference programmes, introductory pieces, etc. It should also be noted that some contradicting definitions for decentralisation were found, e.g., decentralisation from the perspective of Industry 4.0 systems, which refers to interconnected information systems (shared authority) [76], or decentralised government systems, which refer to delegation of power to regional or local authorities [84].

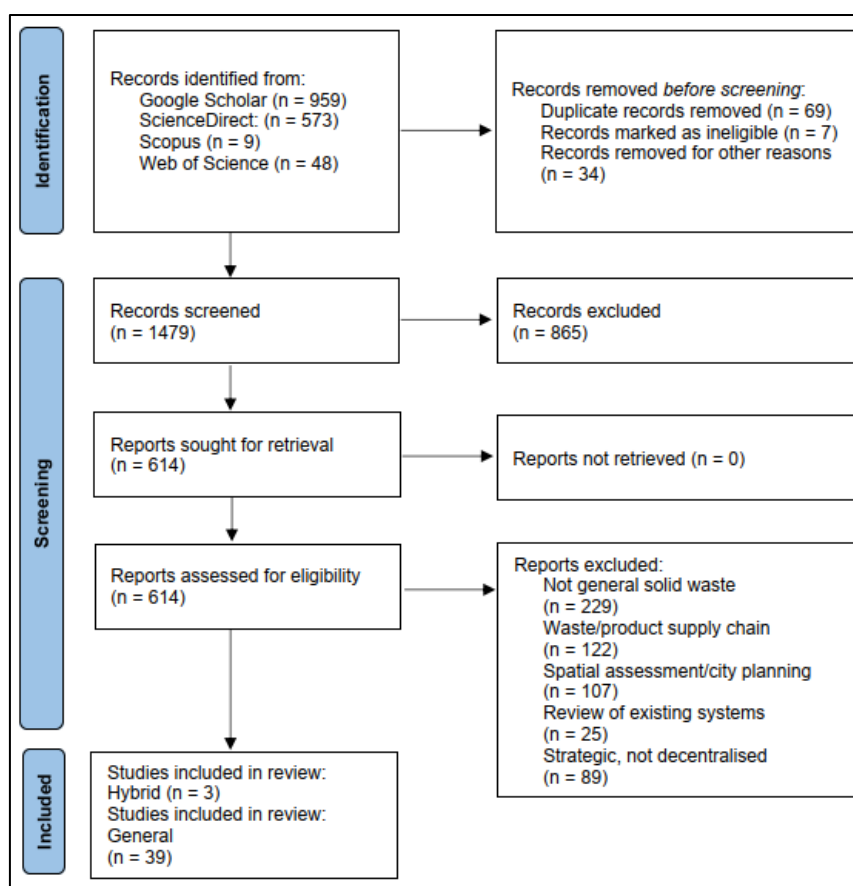


Figure 2-22: PRISMA literature selection process

Firstly, it is important to note that no studies were found that addresses the identified gap. No studies were found that consider decision support from the business/project development point of view with a focus on decentralised general waste utilisation. No studies were found that considered integrated decision support systems focusing on decentralised waste utilisation.

Two items were found that looked at decision support within the decentralised space. The first is a study by Pai *et al.* [85] that focused on the numerical analysis to quantify the impact of decentralised composting in the United States. Though this study looks at decentralised composting and considered various community projects as part of the analysis, the goal of the study is to provide planning information to strategic planners in order to understand, display and evaluate the impact of decentralised food waste composting within a region or for city planning purposes. It thus considers decentralised projects from a strategic perspective, for planning purposes, and does not incorporate a project-based approach. Furthermore, it is noted as part of this study that no framework exists to evaluate the environmental, social and financial impact of decentralised systems for the integrated solid waste management planning approach [85].

The second item considering decentralisation in the decision support space is a group of studies falling under the DECISIVE programme. This programme was co-funded by the European Commission and looked at creating a decision support system for decentralised urban biowaste valorisation. This project looked at the valorisation of biowaste using two specific technologies, namely micro-scale anaerobic digestion and solid-state fermentation [86]. The decision support system focused on the project location selection, project feasibility for these two technologies, optimising the capture and sorting of biowaste, and includes the waste hierarchy by promoting waste avoidance above waste utilisation [87]. The project also included developing these technologies on a decentralised scale and developing the system designs and constructing the prototypes. This system does therefore not focus on general waste utilisation or business/project development including numerous available waste valorisation processes (integrated waste utilisation). The system focuses specifically on biowaste management using two selected technologies as well as the engineering design and commercialisation of these technologies [86].

According to the DECISIVE solution statement, decentralised solutions are not widely implemented in Europe outside of wastewater treatment since the commonly found systems typically work at above 200 tonnes/annum throughput [87].

Various studies were conducted under the DECISIVE umbrella. Examples include a study by Angouria-Tsorochidou *et al.* [88] that looked at economic and environmental assessment of decentralised biorefinery and bioenergy networks for integrated planning; a study by Thiriet *et al.* [89] that looked at the optimisation of a decentralised network of micro-anaerobic digestors in urban or peri-urban areas; and a review by Vea *et al.* [19] that assessed 25 waste management decision

support systems for their ability to deliver sustainability assessments of biowaste management systems.

A study by Xiong *et al.* [90] created an economic optimisation model for decentralised waste to energy systems. However, apart from only considering energy as end-product, this study also defined decentralisation based only on ownership and not on location or facility size, thus setting it apart from other studies (including this work) that focus on decentralised processes.

Tellnes [91] tested the feasibility of biowaste management for energy recovery on a ward level in Mumbai and considered decentralised biomethanation and vermicomposting as potential solutions for implementation on a strategic level. Similarly, Karunathilake *et al.* [92] looked at decision support towards implementing renewable energy for net-zero communities from an energy and urban planning perspective. This study included some waste-based options, such as gasification, combustion and anaerobic digestion, along with other renewable energy sources such as solar, wind and hydro and geothermal processes for electricity production. A study by Mukoro *et al.* [93] also considered some waste-based processes (specifically solid and liquid biofuels) as part of their review of renewable energy life cycle assessment studies in Africa. Interestingly, it is noted that, though integrated life cycle assessments that include social, environmental and economic aspects are vital for renewable energy development in Africa, only environmental impacts have been addresses extensively in literature. Few studies exist that consider economic aspects along with environmental aspects, and only one study was found that exclusively considered social aspects.

Furthermore, a couple of studies were found focusing on specific processes or technologies within the decentralised waste environment, such as Tian *et al.* [94] who focused on centralised and decentralised anaerobic digestion, Bruyn *et al.* [95] who focused on decentralised plastic pyrolysis through biomass heating, and De Zilva [96] who focused on plastic waste management using pyrolysis on Utrecht University campus.

A couple of studies were found focusing on SMMEs in the waste, circular economy, bio-economy and green economy spaces, as summarised by Gregorio *et al.* [97]. The main focus of these studies was the inclusion of sustainable practises as part of the SMMEs' operations. Examples include the work by Ormazabal *et al.* [98] who looked at 17 case studies to evaluate the maturity of the SMME's environmental management practises, or the work by Franco [99] who looked at the struggles faced by SMME firms in the textile industry when trying to adapt their products to the requirements of the circular economy.

Lastly, a couple of studies considered the hybrid centralised-decentralised waste management approach. Dolla and Laishram [100] conducted a literature review on risk factors affecting public-private partnerships in municipal waste management in India. Horváth and Harazin [101] created a decision support system aimed at fostering partnerships between governments and businesses in the sustainable development field. Kuznetsova *et al.* [4] developed a decision support methodology

for the design of combined centralised-decentralised waste to energy systems. The goal of this decision support methodology is to design optimised long-term waste management strategies for large urban territories.

As seen from the summary given in this section, the theorised gap can be proved using a structured literature review method, namely the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method. No studies were found addressing integrated decision support around business/project development for decentralised waste utilisation. No studies were found on this topic focusing on SMME development. Lastly, no studies were found on this topic for developing countries.

Furthermore, it is stated by various authors ([20], [21]) that integrated decision support considering, amongst others, economic, social, environmental, legal and technical (material and energy flow) aspects still need to be addressed by literature. Furthermore, decision support focusing on local ownership for decentralised waste management (business/project approach) have not been addressed [82].

2.8 Summary

This section summarises the findings and gaps from the literature study completed in this chapter. The findings contextualise the current study and provides background for the chapters to come. The gap in the research confirms the importance of the current study in the context of the existing literature.

2.8.1 Main Findings

Improvement in waste management is vital for the development of the South African economy as well as to minimise the effect of solid waste on the environment. Internationally, the perception of waste as an unwanted by-product to be managed has changed over the last couple of years. Nowadays, the value of waste as a potential resource is more often recognised, and concepts such as circular economy, urban mining, industrial ecology, etc. have been developed around the concept of utilisation of waste streams. Though dumping remains the most common way of handling general waste, a shift towards more sustainable practices is taking place internationally.

In South Africa, about 90% of waste is currently being landfilled. Waste management has been identified as an area of focus in South Africa, with governmental pressure being applied to improve this sector. Important aspects of waste management in South Africa include the following:

- Currently, waste management is managed on a municipal level [61]. Because of this, the state of waste management systems and processes differ largely between municipalities [15].

- Information on waste generation and management is lacking. Though the synthesis of the South African Waste Information System (SAWIS) was expected to address this issue, SAWIS is not yet fully operational [56].
- To improve waste management in South Africa, various concepts are being considered and implemented, including but not limited to extended producer responsibility, landfill diversion targets, Industry Waste Management Plans, carbon tax and credits, etc [59].
- Since waste management is traditionally underfunded in South Africa on a national level, the Polluter Pays Principle (PPP) forms the basis of waste management in South Africa. The costs of waste management are thus pushed onto the polluter or waste generator, though waste is managed on a municipal level [62].
- South African waste management is largely managed using command and control regulations (CAC), though the NWMS makes provision for the use of both economic instruments (EIs) and CACs [62].
- There are presently four waste management decision support tools developed or in development for South Africa. All these tools address the municipalities as end-users ([78], [79], [80], [81]).

2.8.2 Gaps in the research

In completion of this literature review, gaps in the current research applicable to this study include the following:

1. Internationally, most of the decision support tools are focused on providing strategic advice to specific role players, such as municipalities, national governments or planning decision makers (e.g., city planners or policymakers). Very little work has been done towards addressing the private sector. No studies were found on business development integrated decision support for decentralised waste utilisation (see PRISMA analysis).
2. Waste management decision support for developing countries is another field that requires addressing [21], though some location-specific studies are currently being undertaken to fill this gap.
3. With regards to waste utilisation decision support in South Africa, all decision support tools are aimed to provide strategic advice to municipal stakeholders ([78], [79], [80], [81]). Decision support aimed toward decentralisation, business development and SMME development has not been addressed, even though the costs for waste management in South Africa are carried by the waste generator (Polluter Pays Principle) [62].

4. The use of a market-based or a value chain approach to waste valorisation [52] in South Africa has not been considered.
5. For the South African waste management industry, solid waste management planning in terms of technology mapping – considering sustainability and techno-economic parameters – has not been addressed by current literature ([20], [21]). This is a gap that will be addressed by this study.
6. Decentralisation, in terms of shifting the focus to the South African private sector, is currently not addressed by literature and will form part of this study ([69], [14]).
7. Risk-based approaches [101] to waste management have not been included in any waste decision support frameworks for South Africa. Integration of risk management into the cost model for the waste management decision support tool has not been addressed on a national or international level.
8. As noted in Section 2.2.4, an integrated approach to waste management or utilisation (considering waste end-product value chain, technology considerations, environmental impacts, risks and legislative influences) for the private sector has not been undertaken in the South African context [21].
9. A need exists for guidance with regards to legal requirements for new waste management companies trying to establish themselves in the market ([61], [15]). This need will be addressed on a high level by the Decision Support System developed as part of this study.

All the above-mentioned gaps in the current research will be addressed by this study.

Chapter 3: Mathematical Modelling Framework

3.1 Introduction

Chapter 3 focuses on the theoretical basis and mathematical modelling framework of the Waste Utilisation Decision Support System (WUDSS). The overall mathematical modelling framework is introduced with a focus on the logic followed as well as the methodology used to create the system. This includes explaining the relation between the Process Engineering Calculations and the Integrated Optimisation Model. Integration between the core system and the various support functions are also explained. Finally, the Integrated Optimisation Model is described.

3.2 Decision Support System

The overall WUDSS is made up of two main components, namely the Process Engineering Calculations and the Integrated Optimisation Model. The Process Engineering Calculations computes the technical, social, environmental, and financial metrics required as inputs to the Integrated Optimisation Model. Incorporated within this segment are various guidance functions. These functions exist to assist the user with additional information that might guide a final decision, especially with regard to the risk and legal aspects.

Results generated from the Process Engineering Calculations serve as the foundational inputs to the Integrated Optimisation Model. This model presents an optimised configuration (where the configuration is defined as a combination of feedstock, Waste Conversion Process, End-Product Production Process and end-product) from among all the possible configurations that form a part of the overall WUDSS. The description of the overall WUDSS model is given in Figure 3-1.

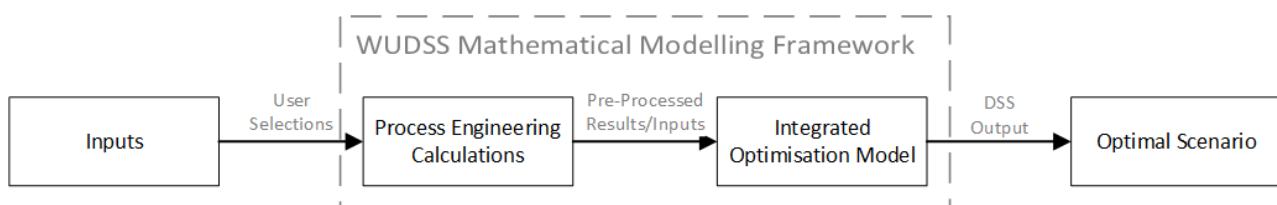


Figure 3-1: Description of the WUDSS model

The overall methodology employed by the Decision Support System is given in Figure 3-2. The flowchart shows the various steps required to generate the project-specific output information. As seen in Figure 3-2, certain aspects are made available to be selected by the end-user as inputs into

the WUDSS. The guidance functions assist the end-user in selecting the most appropriate inputs and provide more information regarding the selections. These selections act as inputs to the Process Engineering Calculations, which are described in Section 3.3. The outputs of the Process Engineering Calculations can be seen as pre-processed results that feed directly into the Integrated Optimisation Model, discussed in more detail in Section 3.4. The Integrated Optimisation Model selects the optimal configuration from among all the possible configurations, where the optimal configuration is defined as the most profitable configuration within the set constraints, which typically include land availability as well as social and environmental constraints.

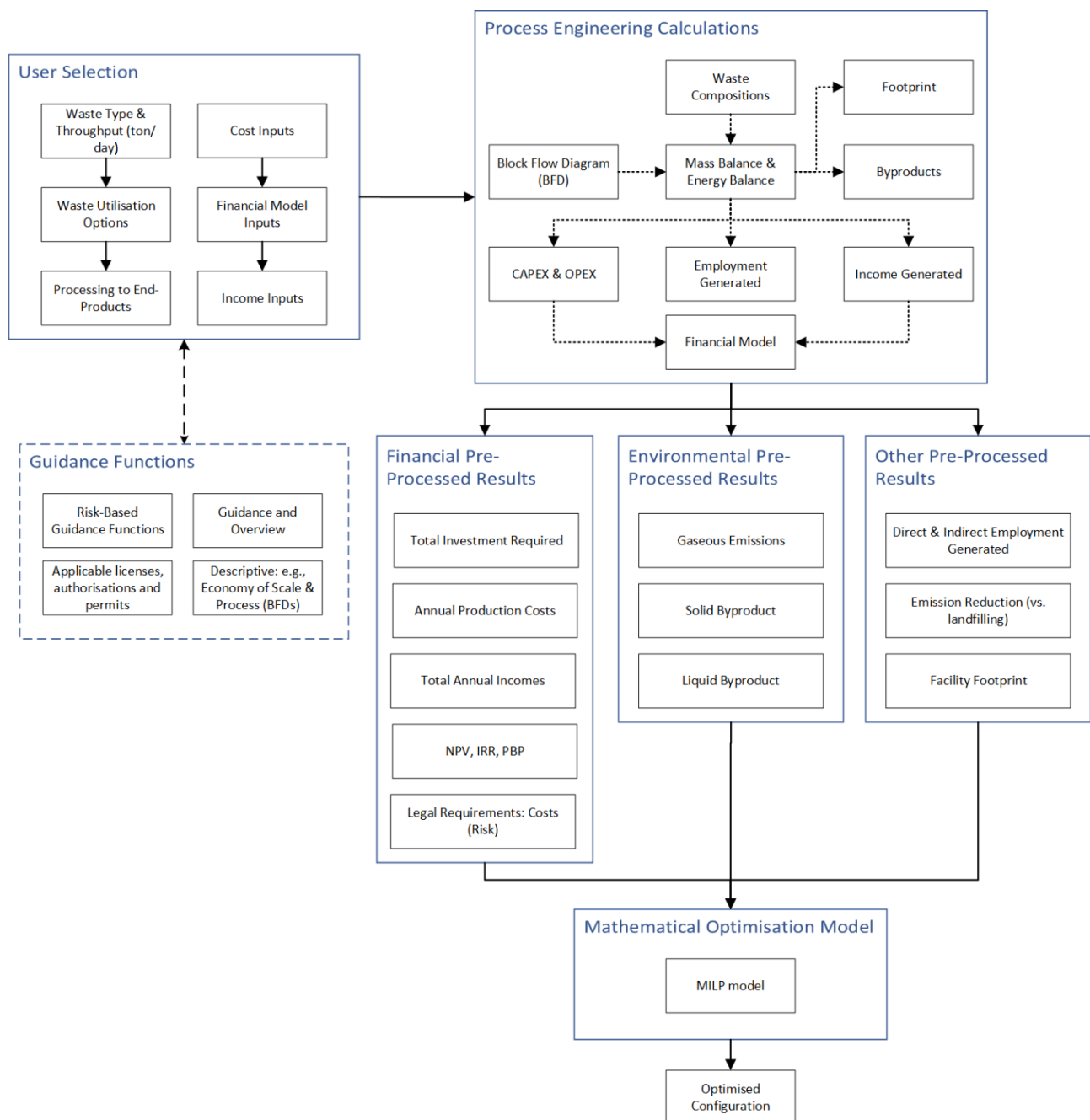


Figure 3-2: Decision Support System theoretical methodology

3.3 Process Engineering Calculations

The Process Engineering Calculations generate the inputs to the Integrated Optimisation Model and provides guidance to the user around other aspects influencing business development, such as risk and legal requirements. This section explains the Process Engineering Calculations development.

3.3.1 Process Engineering Calculations Basis

The theoretical model to be used for the Process Engineering Calculations of the WUDSS is a five-tier process as shown in Figure 3-3.

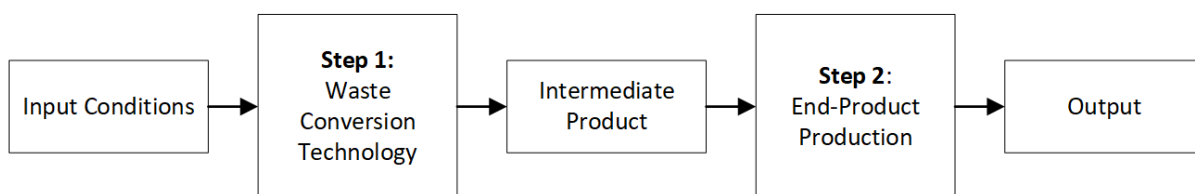


Figure 3-3: Summarised theoretical Process Engineering Calculations

First, specific input conditions are required, which are provided as inputs to the calculations by the end-user. Examples of inputs required for the system include the waste type, system throughput (tonne/day), Primary Waste Conversion Process and Secondary End-Product Production Process. To simplify the process, all options for the Waste Conversion Process (Step 1) and End-Product Production Process (Processing to End-Products, Step 2) values can be selected from a list of modelled processes. Other selection criteria required include land required (area) and additional income or expenses (e.g., tipping fees, carbon credits, land costs and waste costs). Recommended unit values for most of the incomes and costs are provided as base values.

To calculate the required outputs, process engineering mathematical models are created for all Step 1 and Step 2 processes. This includes selecting and defining the composition of each waste stream, setting a base case process design for each process, and calculating the process conversion factors (mass and energy balances). The balances include information on generated by-products and emissions (carbon dioxide equivalent). Hereafter, employment generated by the facility is calculated and the facility footprint is estimated. Finally, all financial outputs, environmental outputs, legal considerations, and other investment considerations for each configuration are given as Process Engineering Calculation outputs.

The outputs are of a concept-level accuracy for comparison purposes, as per the FEL methodology [30] for which the theoretical foundations are explained in Section 1.7. This eases the selection of

which technology, process, and process capacity best suits a specific requirement. The information attained as outputs from the decision support system could also be used directly to approach investors and other possible stakeholders. Further development of the engineering and financial definition is required for project execution, as per the FEL guidelines.

The method used to develop the Process Engineering Calculations is based on chemical engineering process design (process synthesis) and project organisation principles [28]. An example of a similar project organisation is given by Sinnott [25] in their typical representation of a chemical engineering project structure (Figure 3-4). As seen, all steps included in this study are selected with the aim of achieving authorisation of project funding (as per screening requirements).

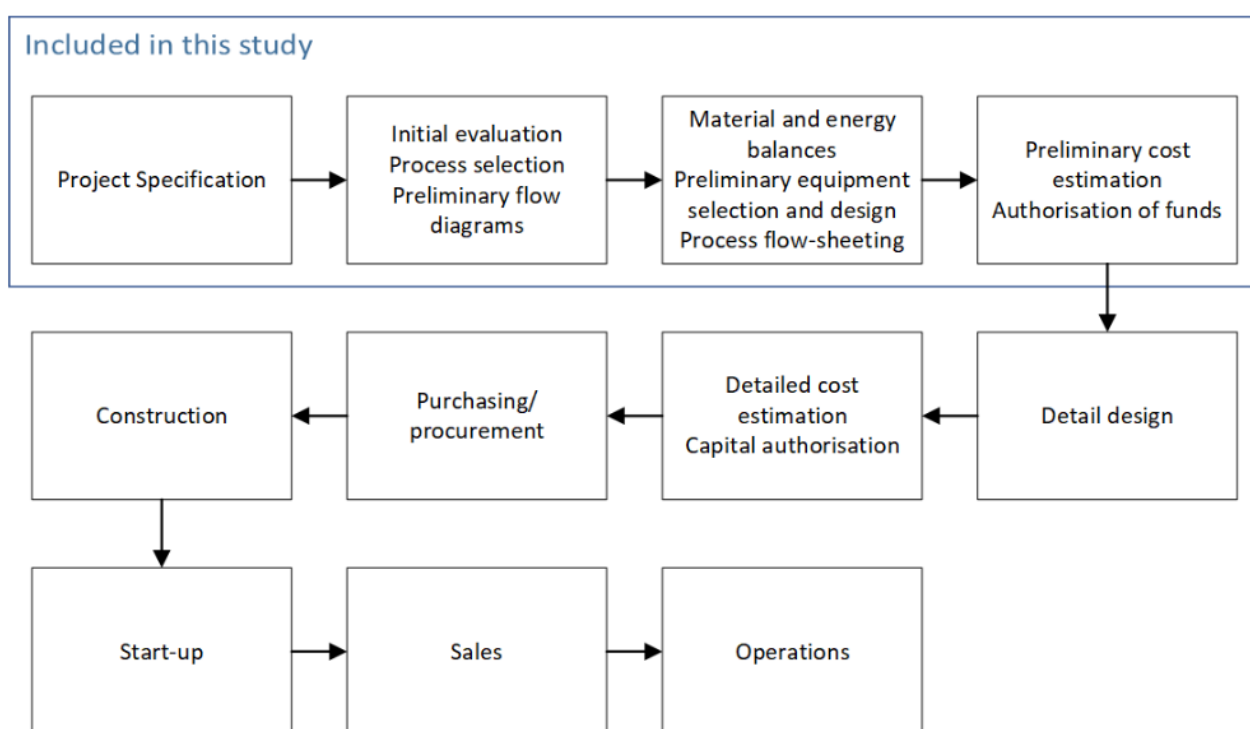


Figure 3-4: Structure of a chemical engineering project (adapted from Sinnott [25])

3.3.2 Guidance Functions input to the Process Engineering Calculations

Various guidance outputs are provided as part of the decision support system to assist in selecting the most appropriate solution as well as guide the end-user towards successful business development. The simplest guidance functions were selected to assist users to better understand the technical or commercial foundations of the project concept, as per the SMME need analysis completed in Section 1.2, by giving decision support information to aid with interpretation, such as the Process Description section. In this section, various primary or secondary processes can be

selected from a dropdown list. The decision support system gives a simple block flow diagram (BFD) and a written process description to explain the specific process. Another simple guidance function is the economy of scale graph, which shows the Total Capital Investment (TCI) required per waste throughput (tonne/day) for the selected process. This relationship is usually nonlinear, meaning that the increase in investment required per throughput becomes lower at higher throughputs. The graph also gives an indication of the maximum potential capital investment for the considered range of waste throughputs.

More detailed guidance functions are also included in the decision support system to guide the input data selection. The goal of all the guidance functions is to assist with the basic inputs for the decision support system. Selection of the specific guidance functions are based on the following:

- Guidance with regards to process selection, configuration comparison, high-level risks and regulatory considerations are included in the DSS based on the conclusions of the SMME need analysis, as given in Section 1.2. This analysis found that the most common reason for SMME failure, after lack of financing, is a lack of knowledge, experience and training in SMME owners ([7], [5]).
- Visual outputs and visual comparative guidance functions were selected based on the concept that large quantities of information are easier to process via visual recognition, which includes shapes, colours or patterns [102].

Examples of the guidance functions' outputs include providing decision support outputs:

- To gain an overall impression of the various feed and process combination outputs (visually comparative).
- To select the end-product to be produced considering the economic value of the final product, high-level risks and considerations
- To define the throughput requirements for a specific process and specific waste feedstock, considering aspects such as economy of scale, waste availability, etc.
- To provide a scenario-specific comparison considering specific priorities that are selected as inputs to the system, which would differ depending on the goals of the end-user.

As shown in Figure 3-5, the detailed guidance functions are divided into two sections, namely general Guidance and Overview and High-level Risk Management. Each of these sections has a unique function based on the potential WUDSS output requirements.

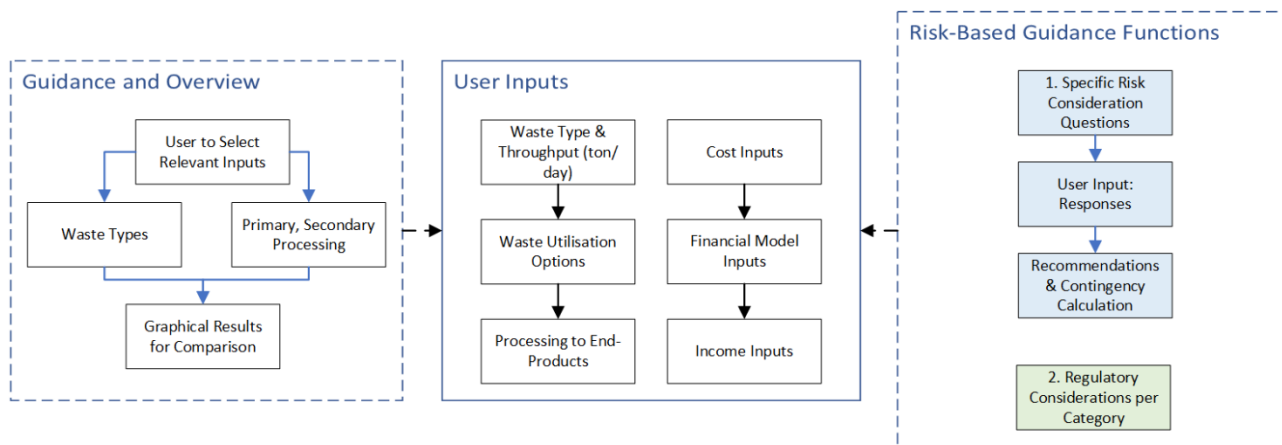


Figure 3-5: An overview of the guidance functions included in the theoretical model

3.3.2.1 Guidance and Overview of the WUDSS Outputs

The general Guidance and Overview section gives an overview of the complete results of the decision support system. It shows the outputs of every possible combination of feedstocks and processes (primary and secondary), as discussed in more detail in Section 5.5.1. The specific feedstock as well as processing combinations to be included in the overview can be selected as inputs to the model. The following outputs are represented graphically for ease of reference and easy comparison:

- Products produced (tonne/day or MW)
- Mean Total Capital Investment (TCI) required (ZAR)
- Mean Total Production Cost per Annum (TPC/a) required (ZAR/a)
- Carbon Dioxide emission reduction (tonne/day)
- Employment generated (direct and indirect)
- Waste generated (liquid waste, solid waste and carbon dioxide equivalent in kg/s)

3.3.2.2 Risk-based Guidance: Risk Management

The Risk Management section assists with considering risks in the option evaluation prior to selecting the final process. The risk management approach consists of two subsections, namely:

1. Specific Risk-based Considerations:

This section provides decision support by asking project-specific questions. The questions allow various responses to be selected from a dropdown list. Based on the selected responses, specific Risks and Recommendations are given to generate awareness of the risks or to propose potential mitigations. The project planning approach is followed to

calculate the potential cost of the risks based on the responses selected. First, the risk cost is calculated into a percentage value. Next, a recommendation is made to increase the project contingency, which helps to capitalise the uncertainty which cannot yet be mitigated.

2. Regulatory Considerations

In this section, a list of various regulatory categories and possible permits, licenses or authorisations which might be triggered for the potential project is given. These regulatory considerations are simply to be noted and to be considered during the subsequent project steps. Though the list is not exhaustive, it considers the most commonly encountered regulatory aspects for new projects within the waste utilisation field.

More information on the abovementioned guidance functions is provided in Section 5.5.2.

3.4 Integrated Optimisation Model

Using inputs from all previous chapters, an Integrated Optimisation Model was created to describe the WUDSS function. A mixed integer linear programming (MILP) model is produced based on graph theory employing branch and cut algorithms together with the standard simplex algorithms [103]. Using this method, the model can be represented visually as a graph containing nodes (or vertices) and arcs, as seen in Figure 3-6. The purpose of the model is to simplify the formulation of an optimisation scenario over the complex system.

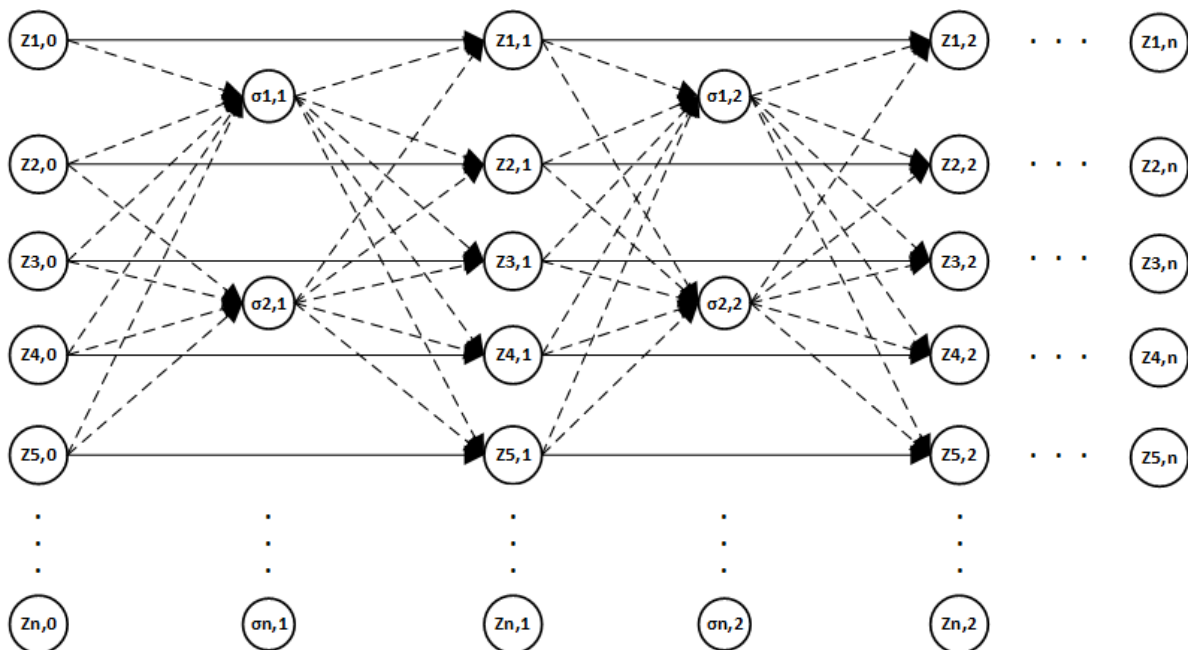


Figure 3-6: Graphical representation of the MILP Integrated Optimisation Model

The MILP model is formulated to show the optimisation of any of the considered inputs, such as the end-product quantity, economic considerations, employment generated, or land area required, while considering the various possible configurations or routes. This model allows for various input and output parameters to be defined over a number of layers consisting of various definable processes. In order to account for the balance of flows over the nodes, groups are defined to allow for variables of varying units, such as energy, mass, land or other output variables. The example shown in Figure 3-7 gives the material, energy and land relations for a specific case. For this case, energy is generated for one of the Integrated Optimisation Model material stream outputs only, while the second material stream output is a mass flow only. An example of this would be when steam is used to produce electricity and a dummy node is used to balance the inputs in order to account for efficiency losses over the system (e.g. a system operating at 90% efficiency will balance the remaining 10% using a dummy node). Similarly, for the land and employment generated groups, dummy nodes are used to balance the output, since both land area and employment generated are a function of the process only.

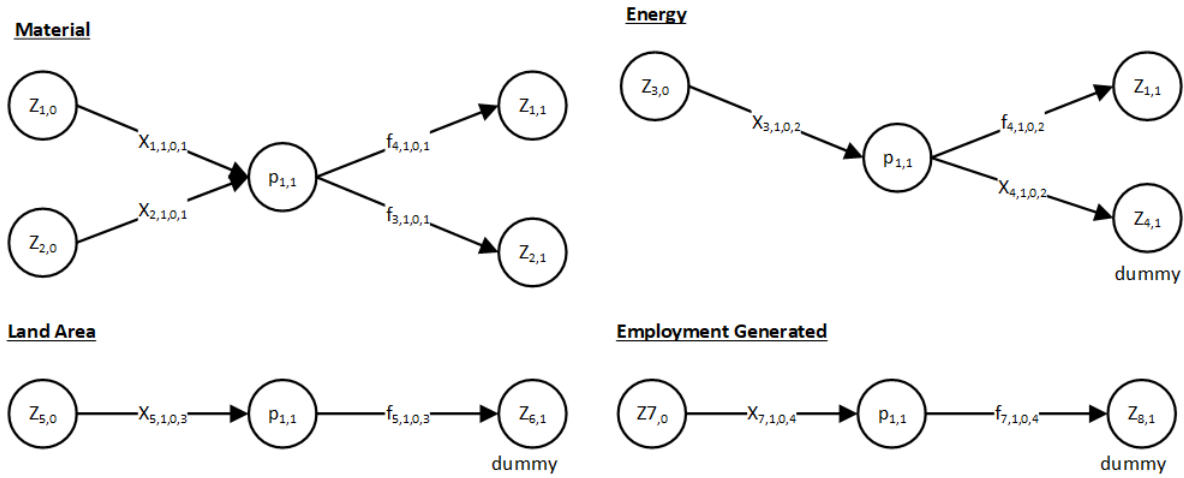


Figure 3-7: Example of the Integrated Optimisation Model groups

The primary decision variable in this model is the process selection, namely $\sigma_{p,l}$. The output material flow for a specific group is represented by $f_{i,p,j,g}$ and the input material flow for a specific group is represented by $x_{i,p,j,g}$. These parameters are calculated using the mass and energy balances which form part of the technical portion of the Process Calculations, which will be explained in detail in Chapter 4. The optimisation function in (3.1) determines a dependency graph using the highest calculated profit, where ρ_i is the demand price (or selling price), $z_{i,|L|-1}$ is the output, r_i is the supply

price, $z_{i,0}$ is the input and κ_p is the cost associated with the given process. The calculations of the financial parameters will be explained in more detail in Chapter 5.

$$\text{maximise } \sum_{i \in I} \rho_i z_{i,|L|-1} - \sum_{i \in I} r_i z_{i,0} - \sum_{i \in I} \sum_{p \in P} \sigma_{p,i} \kappa_p \quad (3.1)$$

Equations (3.2) and (3.3) defines the input and output flows of over the nodes, where $k_{p,g,i}$ is the fraction of output relating to all the inputs over a node for a specific process, group and input, and $c_{p,g,i}$ is the fraction of input relating to all the outputs over a node for a specific process, group and input. Equation (3.4) defines the balance of flows over a specific node, where the sum of all flows entering the node must equal the sum of all flows leaving the node.

$$f_{i,p,j,g} = \left[\sum_{k \in I} x_{k,p,j,g} \right] k_{p,g,i}, \forall i \in I, j \in L \setminus \{0\}, p \in P, g \in G \quad (3.2)$$

$$x_{i,p,j,g} = \left[\sum_{k \in I} x_{k,p,j,g} \right] c_{p,g,i}, \forall i \in I, j \in L \setminus \{0\}, p \in P, g \in G \quad (3.3)$$

$$\sum_{i \in I} x_{i,p,j,g} = \sum_{i \in I} f_{i,p,j,g}, \forall p \in P, j \in L \setminus \{0\}, g \in G \quad (3.4)$$

Equation (3.5) shows the relationship between inputs and outputs for different groups, where $\delta_{p,g,o}$ is a constant that describes the relationship between inputs $x_{k,p,j,g}$ and $x_{k,p,j,o}$ of groups g and o .

$$\sum_{k \in I} x_{k,p,j,g} = \left[\sum_{k \in I} x_{k,p,j,o} \right] \delta_{p,g,o}, \forall i \in I, j \in L \setminus \{0\}, p \in P, g \in G, o \in D(p, g) \quad (3.5)$$

As per Equation (3.6), the material flow values for the first layer must be smaller than the supply inputs (s_i). Additionally, the remaining flows must carry over to the next layer, as per Equations (3.7) and (3.8), where the intermediate flow between layers is represented by $\zeta_{i,l,l+1}$. If a process is in use, Equation (3.9) states that the setup cost must be included if there is a flow present. To activate this formula, M (a number larger than the left side of the equation) and $\sigma_{p,l}$ (which is assigned the values 0 or 1 depending on whether there is flow present) are used in the case where flow is present.

$$z_{i,l} \leq s_i, \forall i \in I, l \in L \cap \{0\} \quad (3.6)$$

$$z_{i,l} = \sum_{g \in G} \sum_{p \in P} x_{i,p,l+1,g} + \zeta_{i,l,l+1}, \forall i \in I, l \in L \setminus \{|L| - 1\} \quad (3.7)$$

$$z_{i,l} = \sum_{g \in G} \sum_{p \in P} f_{i,p,l,g} + \zeta_{i,l-1,l}, \forall i \in I, l \in L \setminus \{0\} \quad (3.8)$$

$$\sum_{g \in G} \sum_{i \in I} x_{i,p,l,g} \leq \sigma_{p,l} M, \forall p \in P, l \in L \quad (3.9)$$

Furthermore, a constraint can be added for a specific group, e.g. job creation. The constraint is applied to the final dummy node for the group and therefore applies to all the input values. For the job creation example, (3.10) will force the job creation of the selected solution to be larger than the defined constraint (o_i).

$$z_{i,|L|-1} \geq o_i, \forall i \in I \quad (3.10)$$

An alternative approach would be to apply a constraint for the group on the balance over a node, as shown in (3.11).

$$\sum_{l \in L \setminus \{0, |L|-1\}} \sum_{p \in P} \sum_{i \in I} x_{i,p,l,g} \geq n_g, \forall g \in G \quad (3.11)$$

However, this approach is limiting, since all inputs within a specific group will be balanced indiscriminately. Thus, when the group is mass, a constraint will be placed on the total mass flow, not on the mass flow per input. This means that the total mass flow can be constrained, but the mass flow per waste feedstock cannot. For this reason, the logic explained in (3.10) is preferred for adding constraints to a group.

Finally, the objective function shown in (3.1) can be updated to allow for direct optimisation of the capital budgeting metrics. An example of this is shown in (3.12), which determines a dependency graph using the highest Net Present Value (NPV), where r is the discount rate and N is the time period indices.

$$\text{maximise} \left(\sum_{n \in N} \left(\frac{1}{1+r} \right)^n \right) \cdot \left(\sum_{i \in I} \rho_i z_{i,|L|-1} - \sum_{i \in I} r_i z_{i,0} \right) - \sum_{i \in I} \sum_{p \in P} \sigma_{p,l} K_p \quad (3.12)$$

$$\text{where } N = \{1, 2, 3, \dots, |N|\} \quad (3.13)$$

The following domains are applicable to the variables used in this model:

$$f_{i,p,j,g} \in \mathbb{R}_+, \forall i \in I, p \in P, j \in L, g \in G \quad (3.14)$$

$$x_{i,p,j,g} \in \mathbb{R}_+, \forall i \in I, p \in P, j \in L, g \in G \quad (3.15)$$

$$z_{i,j} \in \mathbb{R}_+, \forall i \in I, j \in L \quad (3.16)$$

$$\zeta_{i,j,j} \in \mathbb{R}_+, \forall i \in I, j \in L, j \in L \quad (3.17)$$

$$\sigma_{p,l} \in \{0,1\}, \forall p \in P, l \in L \quad (3.18)$$

3.5 Generalisability and Transferability of the Research

Though the problem domain of the system is based on a South African context, the framework developed in this chapter is transferable to an international context. Figure 3-6 is a graphical representation of the generalised optimisation model.

The Process Calculations contain aspects can be directly applied in an international context, such as the technical and environmental calculations. For some of the other Process Calculation aspects, the content will need to be adapted to be applied within an international context. This includes the legal, financial, social and risk-based considerations. Legal, social and risk-based aspects are country-specific in nature, whereas the financial aspects can be adapted for international application by updating the specific country factors used in the financial analysis.

Finally, the Integrated Optimisation Model can be transferred to any context due to the generality of its design. Any number of layers can be added to the model to adapt its application to cases where more process steps need to be added to a configuration.

3.6 Mathematical Modelling Framework Summary

The purpose of this chapter was to establish a foundation for the mathematical underpinnings of the WUDSS. This chapter introduced the mathematical modelling framework for the WUDSS and explained the relationship between the Process Engineering Calculations and the Integrated Optimisation Model. The concept of the Process Engineering Calculations is explained together with the supporting guidance functions. Finally, the Integrated Optimisation Model is introduced.

Chapters 4 and 5 will introduce the problem domain in order to demonstrate the working of the WUDSS. Furthermore, all aspects of the Process Engineering Calculations shown in Figure 3-2 will be detailed.

Chapter 4: Problem Domain and Process Design

4.1 Introduction

This chapter introduces the problem domain for the Waste Utilisation Decision Support System (WUDSS). For the purpose of this study, the application of the problem domain, which includes specific feedstocks, processes and end-product, is called a prototype. The prototype will be used to demonstrate the working of the mathematical modelling framework introduced in Chapter 3.

The methodology used to define the WUDSS problem domain is further explained in this chapter. For this, the focus is placed on the reasoning behind the selections relating to the feedstocks, Step 1 and Step 2 processes, and the final end-products included in the study. Finally, the problem domain application is summarised in the form of the prototype WUDSS flow diagram. This diagram summarises all processes, feedstocks and products that are included in the prototype and also sets the limits of the study.

Lastly, this chapter focuses on defining the technical characteristics of the decision support system with regard to the abstraction of the overall prototype WUDSS. The technical design basis and calculations of the included processes form part of the Process Engineering Calculations and the results of these calculations are directly used as inputs into the Integrated Optimisation Model, as explained in Chapter 3.

4.2 Approach and Methodology

The procedure followed to create the prototype Decision Support System is shown in Figure 4-1. This explains all basic steps taken, from defining the problem domain to finding the optimisation model output.

The first four tiers of the approach shown in Figure 4-1 are conducted to set the prototype system problem domain and are described in detail in Section 4.3. This includes defining which waste streams, end-products, and processes (Steps 1 and 2) will be included in the decision support system.

Next, the prototype Process Engineering Calculations are synthesized, as shown in Figure 4-1 and described in detail in Sections 4.6 and 4.7, and Chapter 5. All the results from the Process Engineering Calculations are used as inputs into the Integrated Optimisation Model, which forms the overall Decision Support System.

After the prototype Decision Support System is created, various steps will be followed to verify and evaluate the system's outputs, compare them to existing data and assess the assumptions and other

input parameters used in the models (Chapter 6). Updates to the system will be made as required to assure optimised operations and comparability to real-world data.

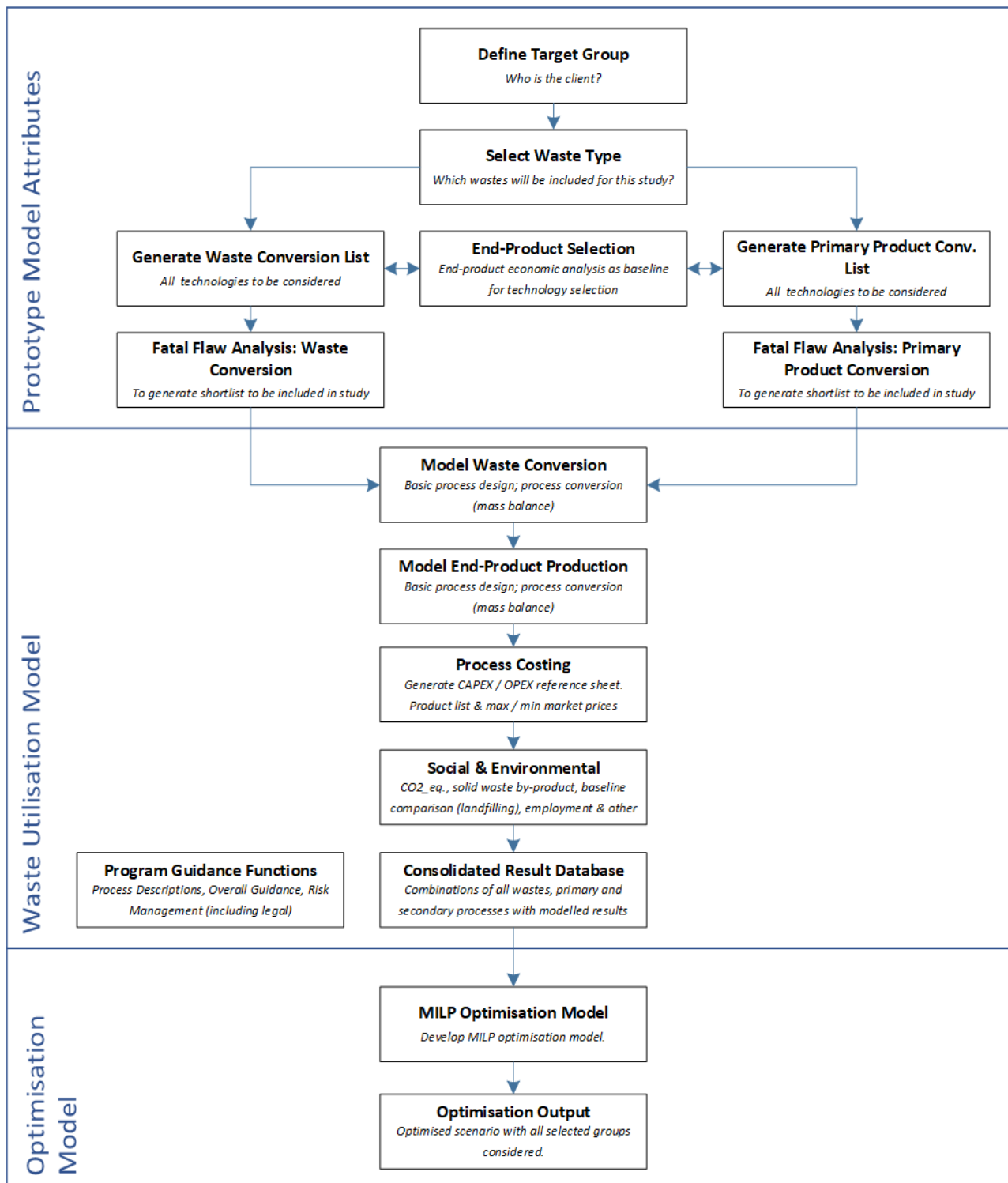


Figure 4-1: Decision Support System synthesis approach

4.3 Decision Support System Problem Domain

This section centres on the selection of feedstock types and processes included in the study. The focus is on the approach followed to select specific inclusions and exclusions.

4.3.1 Feedstock Selection

The waste generated per waste class in South Africa is shown in Table 4-1.

Table 4-1: Percentage of total waste generated in South Africa (SA) per waste type [104]

Waste Type	% of Total Waste Generated in SA
Paper & Cardboard	13%
Glass	4%
Plastics: Hard, Soft	14%
Tetrapak	1%
Multilayer	2%
Metals	2%
E-waste	0%
Nappies	7%
Other: Cleaning, toiletries; Fluorescent bulbs; Batteries	0%
Food Waste: Mixed	9%
Food Waste: Liquids	0%
Food Waste: Starches	1%
Food Waste: Dairy	0%
Food Waste: Fruit or Veg	4%
Food Waste: Meat	1%
Residual Organics	6%
Garden Waste	7%
Residual (Other)	19%
Textile ¹	6%
Other	2%
Construction	2%
Wood	1%

The selection of feedstock to be included in the study is based on South Africa's legal waste classification (Level 1) as well as statistical data on the percentage of waste generated per waste type in South Africa.

¹ Since textile waste is not seen as one of the general waste classes according to the legal classification, this waste stream is not included as one of the selected waste classes for this study.

In terms of waste classification, this study is limited to general waste only and does not consider hazardous waste. In terms of quantities of waste generated, only the waste types generated at higher percentages will be included so that the Decision Support System could appeal to the majority of waste generators. Wastes that make up 4% or more of the total waste generated in South Africa are included in this study, with the exception of nappies, which is a hazardous waste.

Lastly, Municipal Solid Waste (MSW) was included in the list since this waste is a mixture of most of the waste types included in Table 4-1. The final short list of waste types included in this study includes:

- Municipal Solid Waste (MSW)
- Paper & Cardboard
- Plastics
- Food Waste: Mixed
- Residual Organics (RO)
- Garden Waste

For food waste, an analysis of developing countries was used to improve the correlation to expected South African waste compositions. The composition of MSW was calculated based on the percentages of various waste types shown in Table 4-1. This result was compared per category to historical waste composition studies to assure accuracy. The MSW composition used for this study is shown in Figure 4-2.

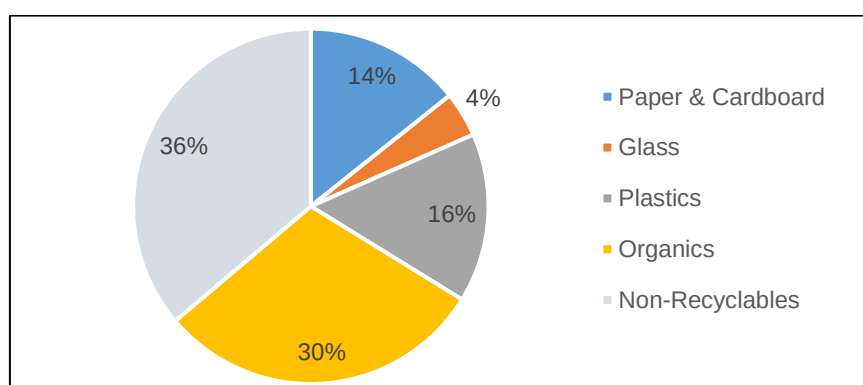


Figure 4-2: Composition of South African MSW

The organic fraction of MSW (OFMSW) is sorted MSW, where all the large fractions of inert materials are removed, for example, glass, metal, construction waste, etc. The main components of OFMSW include paper, food waste, general organic waste and garden waste, as seen in Figure 4-3.

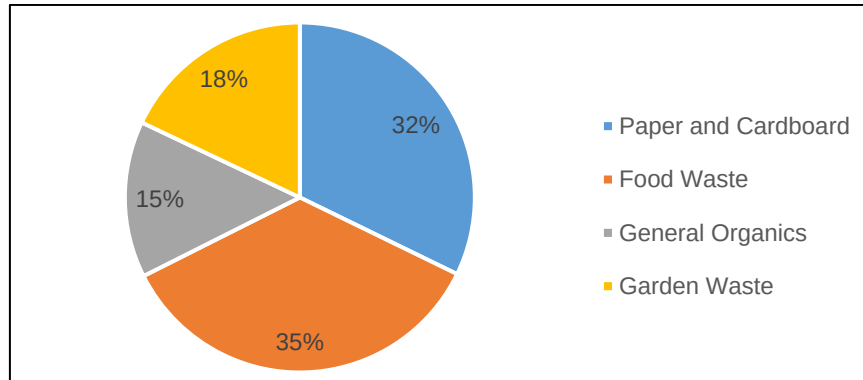


Figure 4-3: Composition of South African OFMSW

The compositions of the waste types included in the study are shown in Table 4-2. These compositions are based on accepted analyses from existing studies.

Table 4-2: Composition, analysis and properties of different waste types ([105], [106], [107], [108], [109], [110])

Waste Type	MSW	Paper & Cardboard	Plastic	Food Waste - Mixed	Organic Fraction of MSW	Garden Waste	RO
Proximate (dry basis)							
Moisture %	17%	5%	1%	41%	25%	22%	2%
Volatile Matter	36%	72%	93%	45%	54%	66%	33%
Fixed Carbon	6%	11%	1%	9%	9%	6%	10%
Ash	41%	13%	5%	5%	13%	7%	55%
Ultimate (dry basis)							
Carbon	18%	33%	77%	21%	27%	36%	21%
Hydrogen	3%	4%	12%	4%	4%	6%	2%
Nitrogen	0.5%	0.0%	0.0%	0.9%	0.7%	0.8%	1.3%
Sulphur	0.1%	0.1%	0.0%	0.1%	0.1%	0.1%	0.5%
Oxygen	21%	46%	5%	28%	31%	29%	18%
Ash	41%	13%	5%	5%	13%	7%	55%
Chemical and Physical Properties							
LHV (MJ/kg)	12.5	22.4	27.8	19.8	18.4	12.6	13.4
Cp Values (kJ/kg.K)	1.21	1.26	2.20	1.72	1.45	1.36	1.36
Density (kg/m ³)	865	689	920	760	669	358	790

4.3.2 End-Product Selection

End-products to be included in this study are selected from a long list of possible products that may be produced either directly from waste processing, as a by-product of waste processing or via an end-product production process. End-product production processes use the product of the primary waste processing step (intermediate product), which could be either a liquid or gas, as feedstock for further processing to a higher value end-product.

The concept of a waste value chain is applied to this study, as described in Chapter 2. In general, the higher up the value chain the end-product is, the following aspects may apply:

- The higher the monetary selling value of the product is;
- The fewer players are active in the market to produce the end-product;
- The smaller the market (specialised products) is.

An economic assessment was undertaken as part of this study to assess potential end-products. The result of the economic assessment is summarised in Figure 4-4, where the values are ranked to show the comparative nature of the commodity costs and estimated market potential, respectively. The bubble size indicates the complexity of market penetration, where a larger bubble represents a higher level of complexity. In general, higher commodity cost, higher market potential, and lower complexity of market penetration are preferable from a commercial point of view.

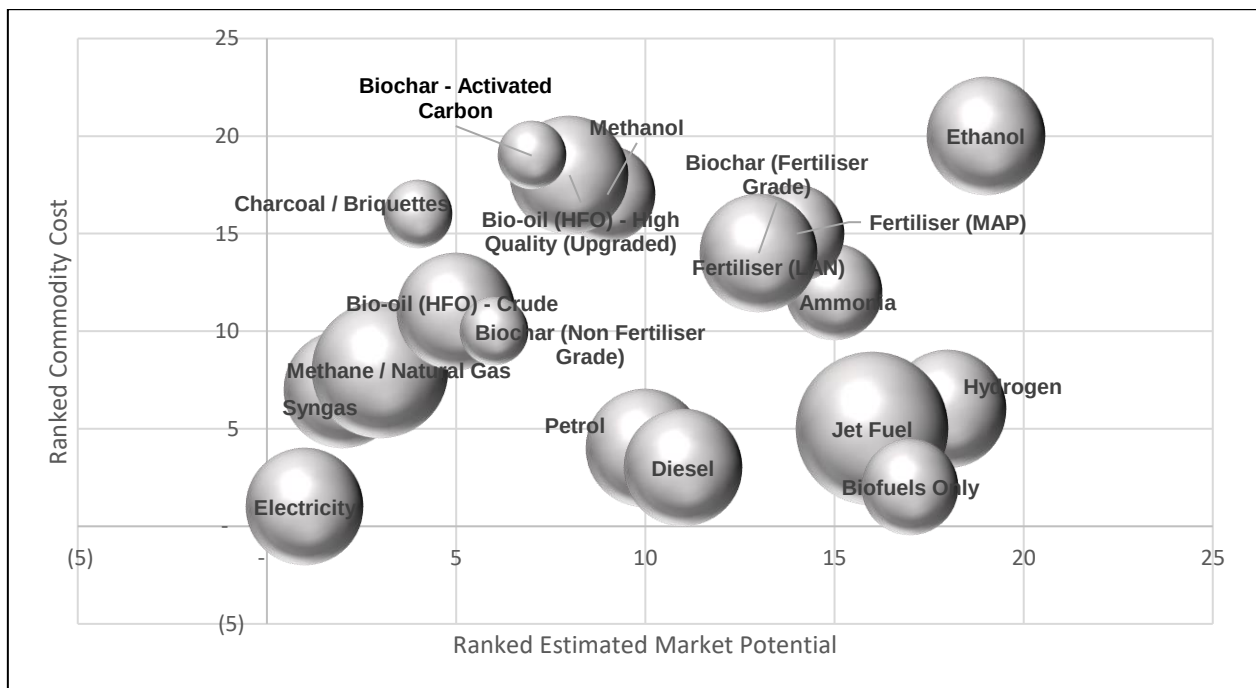


Figure 4-4: Ranked Commodity Bubble Chart (bubble size represents ease of market penetration)

The estimated market potential (EMP) shown in Figure 4-4 was calculated using Equation (4.1).

$$EMP = MS.P.Q \quad (4.1)$$

Where MS is the percentage of the market purchasing the product (market share), P is the selling price and Q is the annual consumption within the overall market. The data used for the estimated market potential calculation is given in Appendix A.

4.3.3 Fatal Flaw Analyses

The fatal flaw analysis for this study was carried out based on set parameters that were selected to fit the decision support system's outcome requirements. Since the goal of this system is to assist SMMEs to select profitable and viable waste management ventures, the three main requirements for the fatal flaw analysis were selected as follows:

- Size Range

The selected system must be operable and financially viable at a small scale. The capacity limit selected for this study is based on a processing throughput of less than the requirement for Waste Management Licencing, as described in GN No. 921 of 29 November 2013.

- Technology Maturity

To minimise the risk to the SMMEs, the technology selected for the waste management system must be commercially proven and reliable. This will also simplify any applications for funding by the SMME.

- Technology Complexity

It is assumed that the target audience for this Decision Support System (SMMEs and start-up companies) will likely not have a large variety of technical resources on staff. For this reason, the ideal waste management system will be relatively simple to operate and maintain.

A General Comments section is also included. In some cases, the specific technology may score positively with regard to all three categories mentioned above. However, there might be a specific reason that renders the technology not viable or applicable for inclusion in this study. These aspects will be mentioned under General Comments.

4.3.3.1 Step 1: Waste Conversion Process Shortlist

A go or no-go approach was used for selecting the shortlist of Waste Conversion Processes to be included in the study. A list of 26 Waste Conversion Processes was considered as part of the selection process (Appendix B). The final shortlist of 16 processes to be included in the Decision Support System is shown in Figure 4-5.

Thermal Processing	Biological Treatment	Sorting and Resale for Recycling	Physical Options
• Gasification • Incineration • Pyrolysis • Catalytic Pyrolysis • Gasification & Plasma Post-Processing • Torrefaction	• Wet Anaerobic Digestion • Dry Anaerobic Digestion • Fermentation	• Sort & Resale: Metal • Sort & Resale: Glass • Sort & Resale: Paper • Sort & Resale: Plastics • Sort & Resale: All Fractions	• Briquetting / Pelletising • Composting

Figure 4-5: Waste Conversion Process shortlist

The selected processes can be applied to most of the waste streams included in the Decision Support System. The shortlisted Waste Conversion Processes and their ability to process the selected waste types are shown in Table 4-3.

Table 4-3: Ability of Waste Conversion Processes to process selected waste streams

Waste Conversion Process	MSW	Paper & Card-board	Plastics	Food Waste	RO & OFMS W	Garden Waste
Briquetting or Pelletizing	√	√	√	√	√	√
Sort & Resale: Metals	√	x	x	x	x	x
Sort & Resale: Plastics	√	x	√	x	x	x
Sort & Resale: Glass	√	x	x	x	x	x
Sort & Resale: Paper	√	√	x	x	x	x
Composting	√	√	x	√	√	√
Incineration	√	√	√	√	√	√
Gasification	√	√	√	√	√	√
Flash Pyrolysis	√	√	√	√	√	√
Gasification & Plasma Post Processing	√	√	√	√	√	√
Fast Pyrolysis	√	√	√	√	√	√
Catalytic Fast Pyrolysis	√	√	√	√	√	√
Slow Pyrolysis	√	√	√	√	√	√
Wet Anaerobic Digestion (AD)	√	√	x	√	√	√
Dry Anaerobic Digestion (AD)	√	√	x	√	√	√
Fermentation	√	√	x	√	√	√
Torrefaction	√	√	√	√	√	√

4.3.3.2 Step 2: End-Product Production Process Shortlist

Using the same approach as described in Section 4.3.3.1, a shortlist of End-Product Production Processes was created to be included in this study. In Figure 4-6, the processes are grouped based on the intermediate product being converted to a final product. A total of 23 processes are included in the shortlist.

Methane Rich Gas (MRG)	Syngas	Low Quality Bio-Oil	Steam
• Internal Combustion Engine (ICE) • Gas Turbine System • Methane Reforming & Pressure Swing Adsorption • Haber Bosch Process • IGCC • Trigeneneration • Cogeneration (Combustion Turbine) • Cogeneration (ICE) • Compression and bottling (CNG)	• Internal Combustion Engine (ICE) • Gas Turbine System • Molecular Sieve / Membranes • Methane Reforming & Pressure Swing Adsorption • Methanol Synthesis • Fischer Tropsch Process • Heterogeneous Catalytic Conversion • Haber Bosch Process • IGCC • Trigeneneration • Cogeneration (Combustion Turbine) • Cogeneration (ICE)	• Distillation	• Steam Turbine System (Steam Cycle)

Figure 4-6: Shortlisted End-Product Production Processes included in this study

4.4 Summary of Prototype Inclusions

The WUDSS includes specific feedstocks, primary Waste Conversion Processes, intermediate products, End-Product Production Processes (secondary processing) and end-products. A complete summary of all possible combinations of inputs, processes and outputs included in the decision support system is shown in

Figure 4-7. In total, the included options allow for more than 600 unique configurations for which all results are calculated and made available as decision support outputs. These results are used as

inputs into the Integrated Optimisation Model and used to select an optimised configuration as the final DSS output.

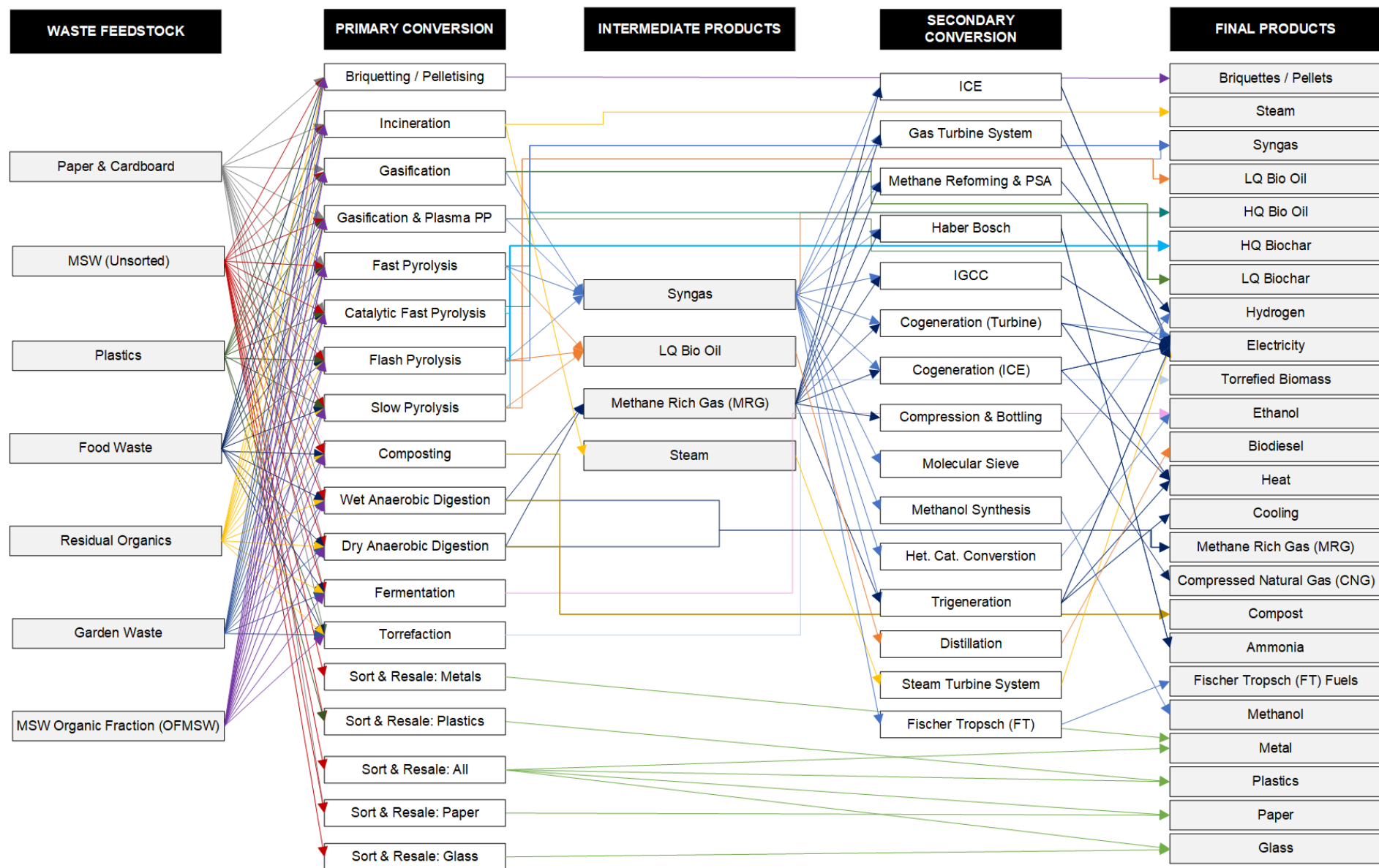


Figure 4-7: Summary of the prototype WUDSS

4.5 Technical Design Basis

As described in Chapter 1, various factors form part of the WUDSS concept, including technical, environmental, legal, financial, social and risk-based considerations. For this section, the focus will be placed on the technical characteristics.

To set the inputs, design conditions, assumptions and outputs of the WUDSS, a baseline process design for each process (Waste Conversion Processes as well as End-Product Production Processes, as shown in Figure 3-3) must be defined. These process designs will act as the technical baseline for the overall decision support system. All technical inputs used for the WUDSS are described in this section. Symbols used in this chapter are defined in detail in the Nomenclature table at the start of the report.

The approach followed to mathematically model all waste utilisation processes for the purpose of this study is based in chemical engineering principles and is called process modelling. Macroscopic modelling [26] is utilised to create balances over each system based on first principle conservation of mass and energy principles [111].

The generalised design philosophy for all processes is shown in Figure 4-8. All designs start with a Block Flow Diagram (BFD) and process description to describe the overall process to be included in the design. Next, certain operating and conversion parameters are defined either by using literature-based inputs, design requirements or logical assumptions. Hereafter, the system mass balance is completed. By setting this mass balance, the overall system performance is set. In some cases, the energy balance is conducted concurrently with the mass balance to balance the reactions or process outputs. Waste by-products, as well as emissions produced, are quantified as part of the mass and energy balance steps. The final outputs of the mass and energy balance are used as the material or energy flows for the Integrated Optimisation Model described in Chapter 3.

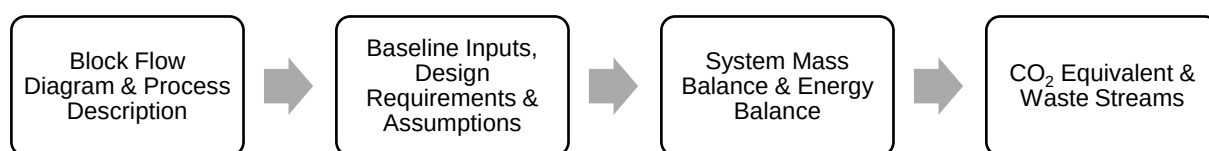


Figure 4-8: Overall design philosophy

Though Figure 4-8 shows a logical stepped approach to the general process design, it should be noted that in some cases the order of the design steps may vary due to specific design requirements.

4.6 Waste Conversion Process Designs

In the context of the decision support system, the Waste Conversion step describes the conversion of the raw waste material into intermediate products – for example, waste gasification to produce syngas or anaerobic digestion to produce a methane-rich gas (MRG). These intermediate products can then be further processed to end-products or sold directly. The Waste Conversion Process is the technological process required to achieve this initial conversion into intermediate products.

Numerous possible variations exist for the process design of each system. However, for each proposed Waste Conversion Process, a single process design was selected. The process design selected for each Waste Conversion Process had to be relatively generic and simple. Equipment that is difficult to source, highly complex or based on designer preference was not selected. Designs were undertaken keeping in mind the targeted users for the WUDSS, namely decentralised users who might not have in-depth expertise in waste processing technologies. For this reason, the system designs must not only be relatively simple but must, as far as possible, not require expert knowledge to operate or maintain.

The following general assumptions or inputs apply to all the technical designs:

- Wastewater treatment is included for all designs where required. Water losses are taken into account, e.g., due to inadequate drying of the final product, evaporative losses, etc.
- Process availability for all processes is calculated based on 20 maintenance days per year. This allows for 8280 hours of operation per year, which falls within the typical design range for availability, as given by Sinnott [25].
- Where solid by-products are produced, the solids are calculated as the inorganic or ash fraction of the waste stream (where applicable).
- Wastewater for the fermentation process is treated and recycled in a closed-loop cycle. This includes process water and steam.
- Cooling water calculations for the thermal processes are done assuming that the cooling water entering the process is heated to 100°C and 10% of the water is lost to evaporation per cooling cycle [112]. The cooling water requirement calculation for thermal processes is done using Equation (4.2), where $\dot{m}$ is mass flow, C_p is specific heat capacity, T is temperature and H_{water}^{vap} is the enthalpy of vaporisation of water.

$$\dot{m}_{cooling\ water} = \dot{m}_{ash} \cdot C_{p(ash)} \cdot (T_{out} - T_{in}) \cdot \left(C_{p(water)} \cdot (T_{out} - T_{in}) + (10\% \cdot H_{water}^{vap}) \right)^{-1} \quad (4.2)$$

Common properties of materials are used in all the calculations. These accepted values are summarised in Table 4-4.

Table 4-4: Material properties ([113], [114], [115])

Property	Unit	Value
Density: Methane (STP)	kg/m ³	0.68
Density: Syngas (STP)	kg/m ³	0.95
Density: Carbon Dioxide (STP)	kg/m ³	1.98
Density: Ethanol (STP)	kg/m ³	697.72
Density: Water (STP)	kg/m ³	1000.00
Density: Biomass (STP)	kg/m ³	789.20
Water H ^{vap}	kJ/kg.K	2260.00
C _p _{water}	kJ/kg.K	4.18
C _p _{ash}	kJ/kg.K	0.96

The process followed to define each system is summarised in more detail in the rest of Section 4.6, with the process design for each Waste Conversion Process shown using a BFD.

4.6.1 Sort & Resale: Metals, Plastics, Glass or Paper

Sorting of waste can be done via various processes. The simpler process includes sorting waste by hand (manual or semi-mechanical process), which is more labour-intensive compared to an automated process, but requires very little in terms of capital investment. For this process (Figure 4-9), the equipment required includes bag openers, conveyor belts and containers for the sorted waste. Operators in full personal protective equipment (PPE) then sort the waste per waste category for downstream recycling at a rate of 5 tonnes of waste per hour per operator [116].

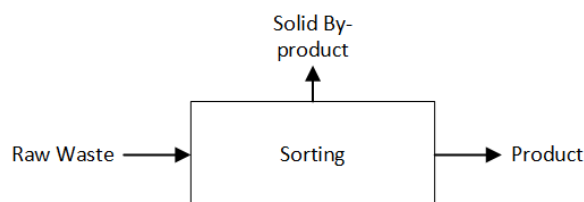


Figure 4-9: Sorting for resale (recycle) process block flow diagram

Automated processes for waste sorting are much more capital intensive and require various units for sorting different waste fractions, either by mass, size, or magneticity. An example of an automated waste sorting process design is shown in Figure 4-10.

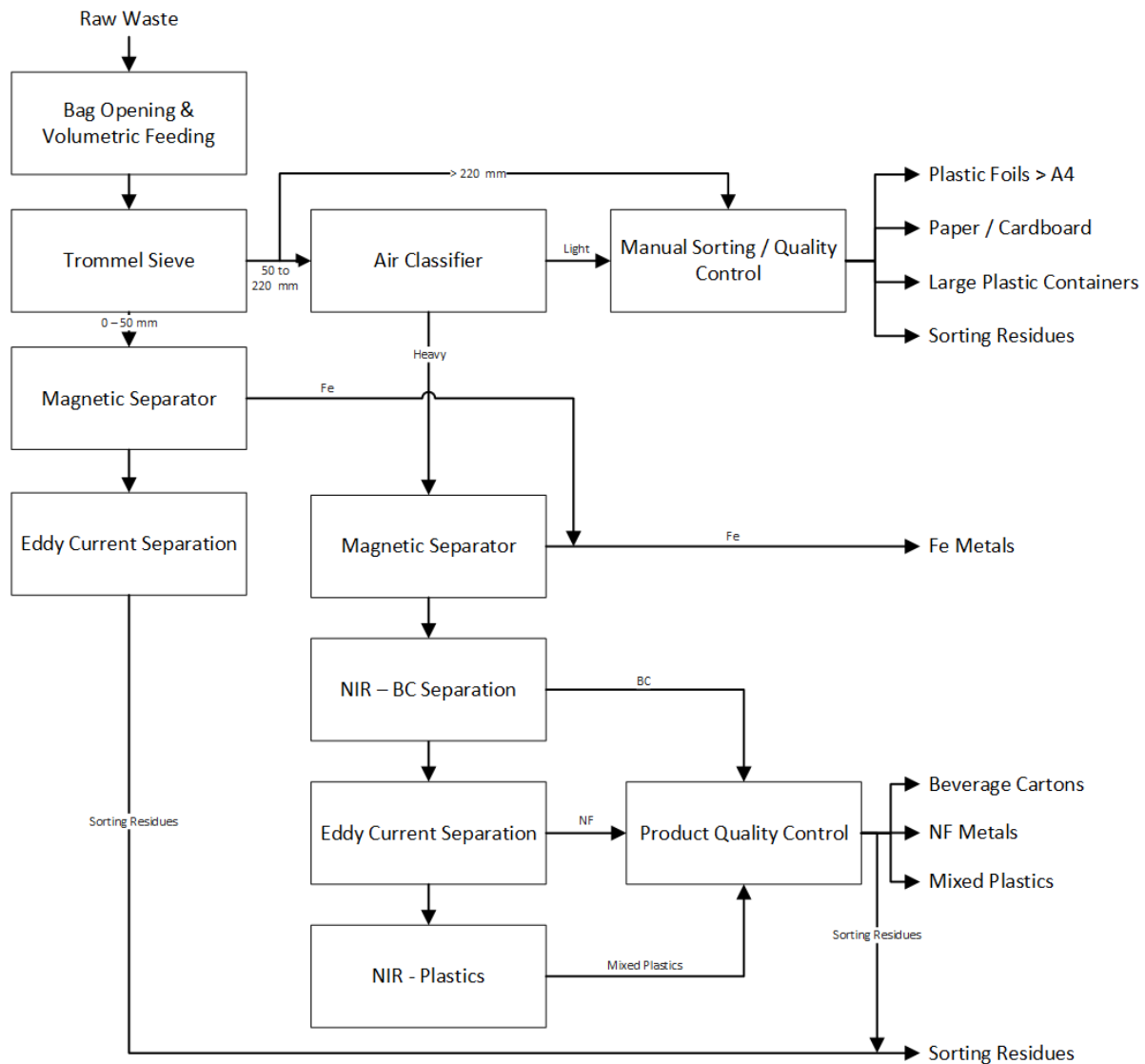


Figure 4-10: Automated sorting for resale (recycle) process block flow diagram (adapted from [117])

4.6.2 Briquetting or Pelletising

Both briquetting and pelletising of biomass follow the same overall process with the main difference being the shape of the final product. For this reason, these two processes can be described by a single process design.

As shown in Figure 4-11, the briquetting process is relatively simple. For certain waste types, e.g. municipal solid waste (MSW), a sorting step is required to remove the incombustible or inorganic

fraction from the feed stream. The solid waste removed during the sorting step is handled as a waste by-product. After sorting, the size of the waste is reduced via a mechanical process such as crushing, shredding or grinding.

The processed feedstock is then dried to reduce the moisture content to below 16% before pelletising or briquetting [118]. This increases the calorific content of the final product. Finally, the feedstock is compressed into the product shape. The increase in pressure and subsequent increase in temperature caused by the compression step result in physical changes in the feedstock – e.g., for wood or biomass, lignin is liberated, acting as a natural binder for the briquette or pellet [118].

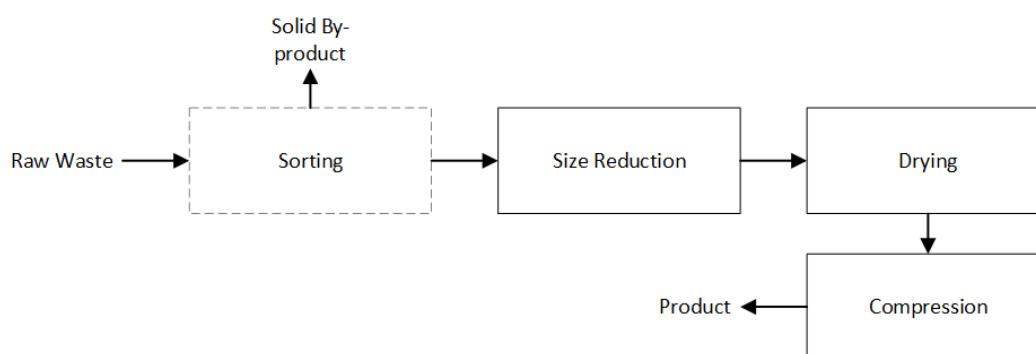


Figure 4-11: Briquetting or Pelletising process block flow diagram

The briquetting or pelletising process can be conducted at various capacities and various levels of automation, depending on the size and sophistication required for the process. Briquettes or pellets can be created using hand-operated presses, where manual labour is used to produce the final product. Alternatively, fully automated turnkey units can be bought to produce the same product at higher throughputs.

4.6.3 Composting

Composting of organic matter produces organic amendments which can be used directly to improve soil quality. The baseline process design for the composting process is shown in Figure 4-12.

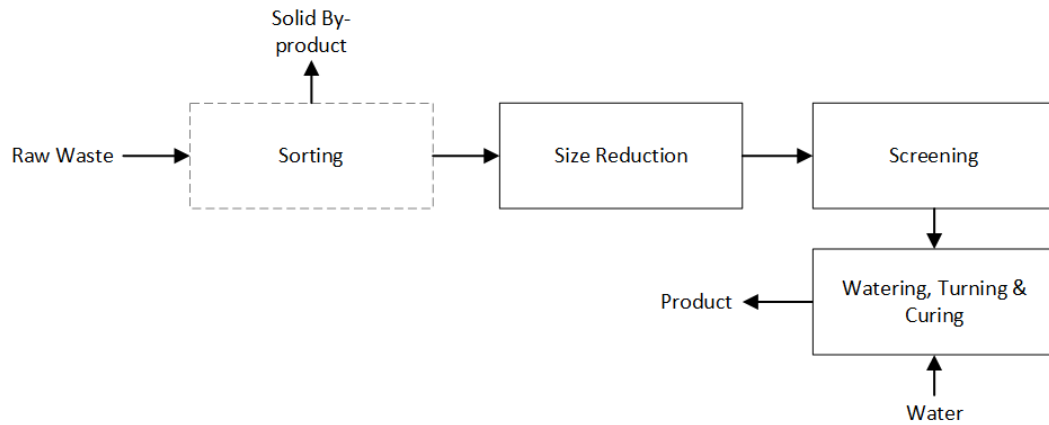


Figure 4-12: Composting process block flow diagram

Starting with raw waste, a sorting step is required for wastes with mixed organic or inorganic contents, such as MSW. The remaining organic fraction of the waste is then ground into small pieces using, for example, a tub grinder or horizontal grinder. During the grinding process, the waste is mixed and screened to around 0.3 to 5 cm pieces [119].

The ground waste is then dumped in windrows. The windrows are typically about 2 to 3 m in height and 3 m apart. Next, the windrows are sprayed with water. This both reduces dust formation and adds to the composting process.

Decomposition of organic matter to compost generally takes place over two to three months, depending on climate. The organic material must be agitated or turned every couple of weeks to expose the material to oxygen (aerobic composting). After each turn, the windrows are once more sprayed with water. The internal temperature of the windrows increases during decomposition (around 10 to 40°C for mesophilic and over 43 to 65°C for thermophilic microbial decomposition) and carbon dioxide is formed (all carbon dioxide formed during composting is biogenic and does not count towards carbon dioxide equivalent emissions [119]).

Curing is the final step in the composting process. Curing is initiated when the windrows no longer reheat after turning. During curing, the raw compost is left as-is for three to four weeks allowing the carbon and nitrogen fractions to reach equilibrium. After curing, the final pH of the compost should ideally be between 6.5 and 8.0, though a range of 5.5 and 9.0 is generally seen as acceptable. A reasonable range for the carbon to nitrogen (C:N) ratio is between 20:1 and 40:1 [119].

4.6.4 Incineration

Incineration is a thermal conversion process where complete combustion takes place in the presence of an oxidiser. Incineration takes place at elevated temperatures (850 to 1000°C). Due to the presence of an excess oxidant, all the reacting fixed carbon is converted to carbon dioxide [120].

Incineration of waste is one of the oldest and most established waste disposal methods. Traditionally, incineration was used for the disposal of waste only, and energy recovery was not included due to the variable nature of the waste feedstock. This can be managed by proper waste pre-treatment but remains one of the largest risks for this process.

Incineration plants traditionally require large investments and are associated with having high operating expenditures. The process itself is relatively complex and skilled staff are required to operate the incineration plant. For this reason, incineration plants are traditionally quite large (economy of scale is vital to make this operation economically viable). Newer technologies such as circulating fluidised bed combustors could be used to make the process viable on a smaller scale [120]. Lastly, the incineration process is known to be environmentally harmful and careful management of the gaseous and solid waste products is required to limit the downstream effects [120]. On the other hand, advantages of incineration processes include drastic volume reduction of waste as well as the ability to produce electricity (substitutes for fossil fuel combustion) [120].

The process used as the baseline for the incineration process design is shown in Figure 4-13.

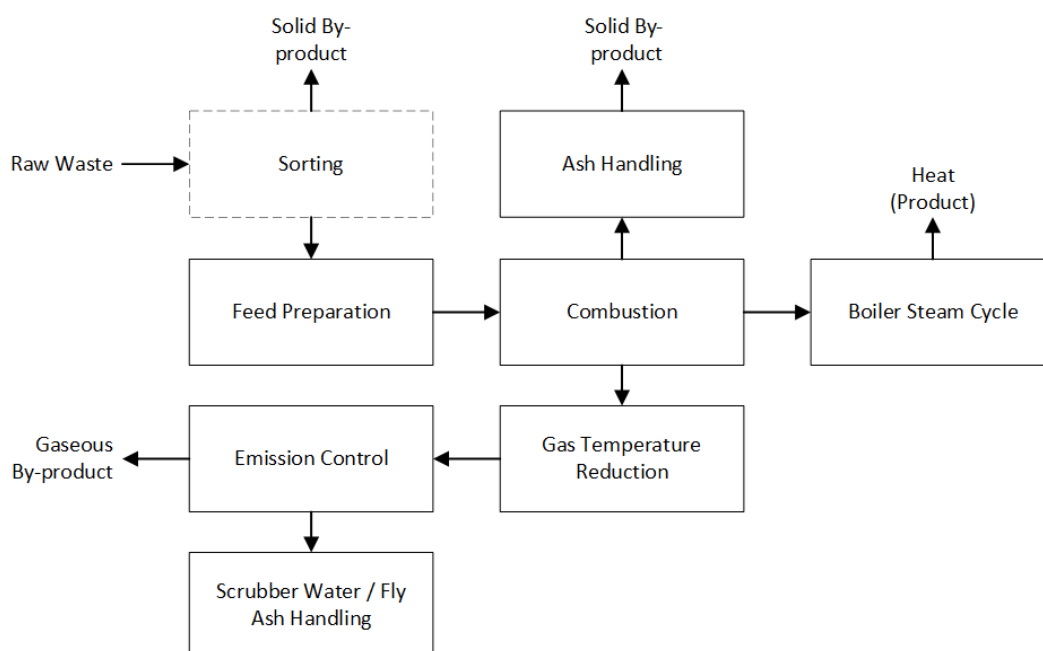


Figure 4-13: Incineration process block flow diagram

Before entering the incineration unit, the feedstock is pre-processed via sorting (removal of incombustibles from the MSW feed stream), size reduction (shredding, crushing, etc.) and preheating. Hereafter, the processed feed is fed into the incinerator, which could be one of several unit types, such as fixed bed, fluidised bed, circulating fluidised bed, moving grate, rotary kiln or multiple-hearth. Waste incinerators are commonly made up of two combustion chambers, namely the furnace (primary combustion) and the secondary combustion chamber (high temperatures for complete combustion) [120].

During incineration, most of the latent energy in the feedstock is converted to heat, which forms the main product of the incineration process. According to Patil *et al.* [120], about 65% to 80% of the organic matter's energy content can be recovered during a waste incineration process. This heat is recovered via steam production (conversion of water to steam in a closed-loop water cycle) and thereafter by recovering the remaining energy in the gas directly, e.g., for feedstock preheating.

Emission controls are applied to the cooled gas to limit the release of pollutants such as SO_x, NO_x, particulate matter, dioxins or furans. This process step includes units such as scrubbers, electrostatic precipitators, cyclone separators, baghouse filters, or adsorption units.

For a well-managed incineration process, the main waste streams produced include captured fly ash, bed ash, as well as a carbon dioxide -rich gas stream (gaseous by-product), as seen in Figure 4-13. Secondary processes such as ash handling and scrubber water handling are included in the design.

For this process design, a typical 80% carbon conversion (X_{carbon}) in the incinerator is assumed [120]. The thermal efficiency ($\eta_{thermal}$) of the boiler is 65%. As seen in Equation (4.3), the energy transferred to the steam from the waste feedstock is dependent on the specific waste's energy content (lower heating value) and composition, as well as the properties of the steam and water, where the water enters the system at 25°C (T_{in}) and the steam exits the boiler at 420°C (T_{out}).

$$\dot{m}_{steam} = \frac{(\dot{m}_{waste} \cdot LHV_{waste} \cdot \eta_{thermal} \cdot X_{carbon})}{(C_{p(water)} \cdot (T_{out} - T_{in}) + H_{water}^{vap})} \quad (4.3)$$

4.6.5 Gasification

Gasification is a thermal conversion process during which waste is converted to a gaseous product under equilibrium oxidant conditions, causing incomplete combustion. The main products of the incomplete combustion process are carbon monoxide and hydrogen (syngas).

The gasification process is shown in Figure 4-14. This process includes a primary sorting step to remove incombustibles, followed by a feed preparation step (size reduction and preheating). Thereafter, the feedstock is fed into the gasifier, where the carbon content of the feedstock is

converted to syngas at an efficiency of around 75 to 80%. Gasification generally takes place in a temperature range of 500 to 1600°C [121].

Uncombusted carbon together with the ash content of the feed is either converted to bed ash and removed sporadically from the gasifier or expelled as minute particles (fly ash) as part of the syngas stream. The bed ash is cooled (direct water cooling) and handled to be sold as biochar. It should be noted that biochar from gasification typically contains less fixed carbon than biochar from pyrolysis, which means that the downstream uses for this product are reserved to lower value applications (e.g. agricultural applications).

The fly ash contained in the syngas stream must be removed to avoid serious consequences to both the environment and human health. Generally, fly ash is removed using a cyclone separator directly downstream of the gasifier, followed by baghouse filters or electrostatic precipitators to remove the smaller particles downstream. Hereafter, major pollutants such as NO_x, SO_x, dioxins and furans, HCl, mercury, etc. are removed from the gas stream using adsorption, absorption or other pollution control units. Heat recovered from the gasification process (from syngas and bed ash) is recycled back into the feed preparation step to preheat the feedstock.

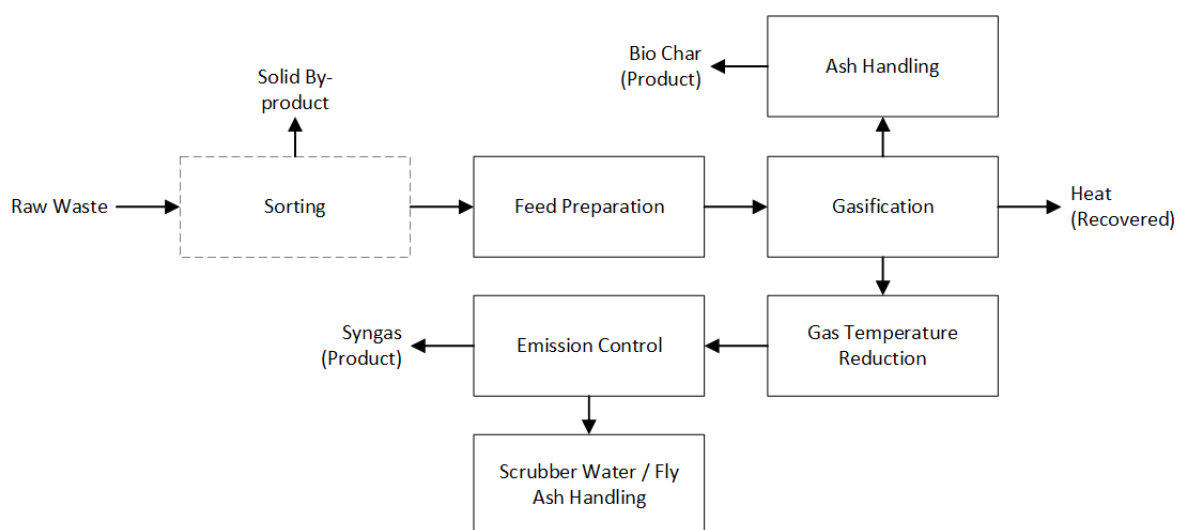


Figure 4-14: Gasification process block flow diagram

Gasification processes can be operated at various throughputs depending on the plant design and gasifier type used. According to Indrawan *et al.* [121], gasifiers generally operate in a range of 0.3 tonnes/day (downdraft fixed bed gasifiers) up to 10,000 tonnes/day (entrained flow gasifiers), though operational throughputs outside of this range are also possible.

4.6.6 Pyrolysis

Pyrolysis is a method of thermochemical conversion, where organic matter is converted to liquid (bio-oil), gas (syngas) and solid (biochar) products in the absence of oxygen. Both bio-oil and biochar are saleable products. Crude bio-oil (bio-crude) can be sold directly as a low-value product or can be upgraded for direct use (higher value product) via distillation or similar post-processes, as explained in detail in Section 4.7.6. Syngas can also either be converted to higher-value end-products or can be combusted as part of the pyrolysis process for heat or energy recovery.

Three main types of pyrolysis processes exist, namely slow, fast and flash pyrolysis. The main differences between the three processes are the fractional distribution of solid, liquid and gaseous products as well as the basic operating conditions, such as operating temperature, heating rate and residence time [122].

Catalytic fast pyrolysis, a subtype of fast pyrolysis, includes the presence of a catalyst in the pyrolysis vessel. Pyrolysis in the presence of a relatively cheap catalyst such as calcium oxide (CaO) could improve the quality of the bio-oil produced while limiting the effect on operating costs.

A general process block flow diagram for a pyrolysis process is shown in Figure 4-15.

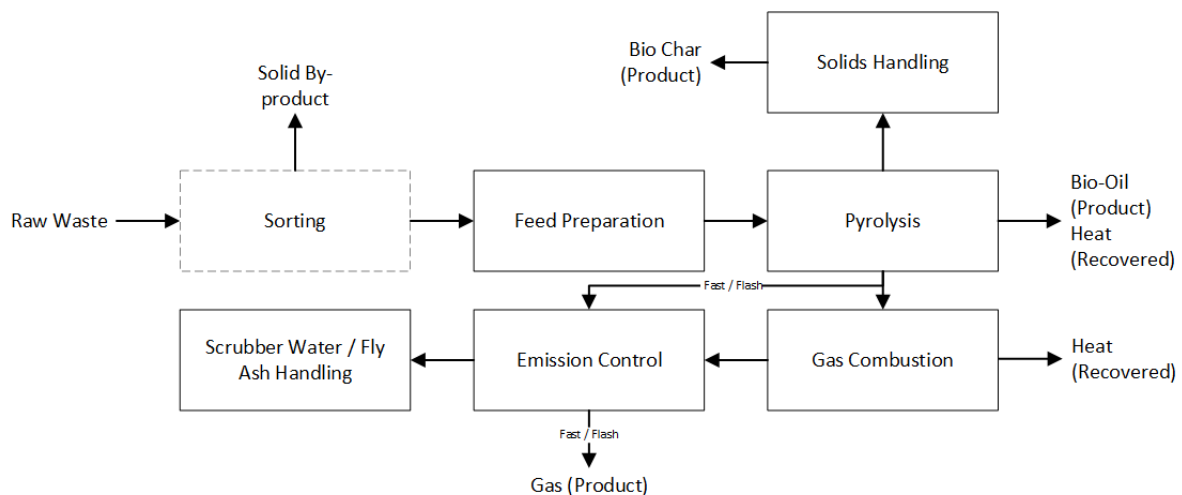


Figure 4-15: Pyrolysis process block flow diagram

For energy balance optimisation, obvious incombustibles must be removed from a mixed pyrolysis feedstock, such as MSW. This includes components such as glass, metal, dirt etc. which will absorb energy to heat, but does not contribute to the heating value of the feedstock. After the sorting step, the feed is prepared by size reduction and preheating. Thereafter, the pyrolysis feedstock is fed into

the reactor. Process conditions in the reactor are governed by the type of pyrolysis process taking place (temperature, residence time, heat rate, etc.), as explained in Table 4-5.

Pyrolysis takes place under oxygen-poor conditions and at lower temperatures compared to gasification and incineration. Due to the partial thermal conversion caused by the lack of oxygen, the bottom ash (biochar) is relatively high in fixed carbon (high quality).

The gaseous stream exiting the pyrolysis reactor contains condensable vapours that can be condensed out as crude bio-oil. The remaining gas is made up of syngas containing mostly carbon monoxide and hydrogen. As seen in Figure 4-15, syngas is seen as a product of the fast and flash pyrolysis processes. For slow pyrolysis, all syngas is combusted for heat recovery (feed preheating and reactor heating) to reduce operating costs.

During the emission control step, fly ash is removed from the gaseous stream and polluting components such as NO_x, SO_x and dioxins and furans are controlled using appropriate technologies, such as scrubbers or adsorption units.

Differences between slow, fast, catalytic and flash pyrolysis are summarised in Table 4-5.

Table 4-5: Comparison of slow, fast and flash pyrolysis processes ([122], [123], [124])

Parameter	Slow Pyrolysis	Fast Pyrolysis	Catalytic Fast Pyrolysis	Flash Pyrolysis
Pyrolysis Temperature	300 to 500°C	500 to 700°C	500°C	700 to 900°C
Residence Time	Vapour Residence Time of 300 to 550 seconds Solid Residence Time: 5 to 50 minutes	Solid Residence Time: 0.5 to 10 seconds Gas Residence Time: 0.5 to 2 seconds	Solid Residence Time: 78 seconds	Residence Time: < 0.5 seconds
Heating Rate	5 to 30°C/s	10 to 200°C/s	10 to 200°C/s	1000°C/s
Product Percentages	Biochar: 35% (25 – 65%) Bio-oil: 30% (10 – 30%) Syngas: 35% (10 – 50%)	Biochar: 12% (15 – 25%) Bio-oil: 75% (40 – 70%) Syngas: 13% (10 – 20%)	Solid product: 81% Liquid product: 19%	Biochar: 10-20% Bio-oil: 15-25% Syngas: 60-80%

4.6.7 Gasification & Plasma Post Processing

The process for gasification with plasma post-processing is shown in Figure 4-16. In general, the process description for this process matches that of normal gasification, the difference being the

addition of a plasma post-treatment unit to treat the syngas leaving the gasifier. During plasma gasification, energy is injected into the process in the form of electricity fed between two electrodes to create highly ionised gas, called plasma. The plasma breaks down all molecules that it comes in contact with into their basic atoms, which allows for complete conversion into products. Due to the extreme temperatures achieved (far above 1000°C), the formation of NO_x, SO_x, dioxins and furans are reduced or eliminated [125].

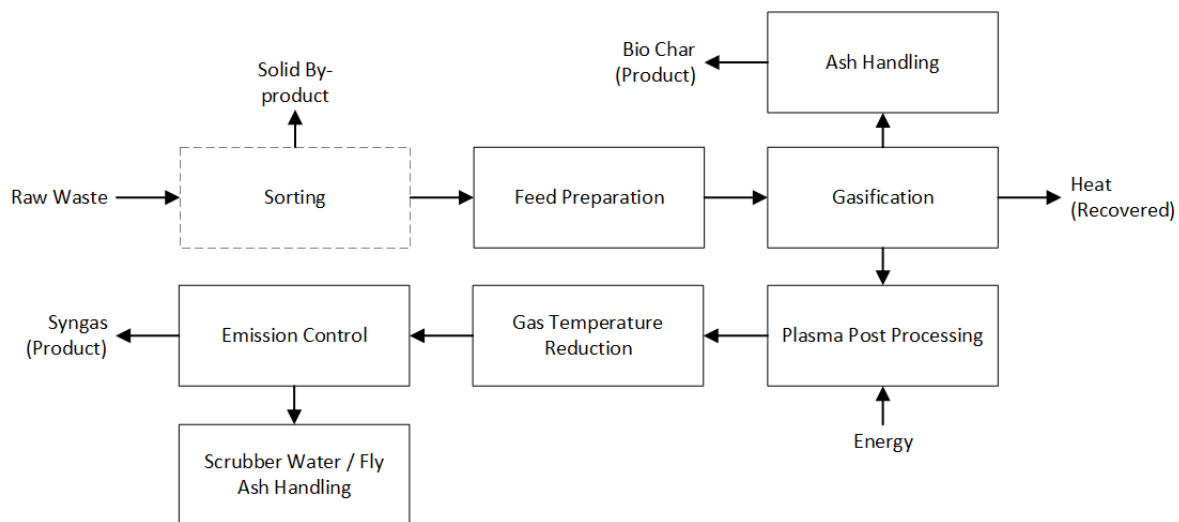


Figure 4-16: Gasification with Plasma Post Processing process block flow diagram

One difficulty with plasma processing is that the plasma ionisation zone is generally quite small (localised) and requires direct contact. For this reason, placing the plasma burners where the gas will naturally pass through the plasma zone is advantageous. An example of this is placing the plasma burners in the gas outlet pipe – a process called plasma post-processing – which allows the plasma burner to avoid direct contact with the solids entering the gasifier. The amount of additional energy required for plasma post-processing is less than for plasma gasification since only the gas is processed. However, for plasma post-processing, the overall conversion is lower compared to direct plasma gasification. Furthermore, the bed ash is not vitrified and must be handled similarly to conventional gasification.

4.6.8 Wet or Dry Anaerobic Digestion (AD)

During anaerobic digestion, a diluted mixture of solids in water is decomposed into biogas or methane-rich gas (MRG) and digestate. The digestate can be sold directly as liquid fertiliser or dried and sold as a dry fertiliser. Anaerobic digestion takes place within specific temperature ranges (mesophilic conditions: 30 to 40°C, or thermophilic conditions: 45 to 60°C) and preheating is required

to achieve these temperatures. To optimise the energy balance, a portion of the biomass or MRG could be combusted to heat the incoming streams [126].

For the anaerobic digestion process seen in Figure 4-17, waste is first sorted so that the waste fed into the anaerobic digestion process is mostly organic. After being sorted, the size of the waste is reduced (shredded or pulverised) and the stream is fed into a mixing vessel to create a slurry. For wet AD, water generally makes up more than 84% of the slurry by mass. For dry AD, the solid fraction in the slurry is higher, with water making up around 60% of the slurry fraction by mass [126].

After pretreatment, the slurry stream is fed into the digester where it undergoes various chemical and physical conversion phases (hydrolysis, acidogenesis, acetogenesis and methanogenesis) and is converted into the final AD products. This conversion is a timely process, with a retention time of between 10 to 40 days, depending on the pH, temperature, particle size, organic load rate (ORL) and composition of the waste [126].

For both wet and dry AD, various digester setups exist, including single or multistage, stirred or unstirred, continuous or batch.

For this specific process, the biogas produced via the AD process is treated before being considered as the final product. The digestate leaving the AD process is dehydrated to produce dry compost, and all wastewater is recycled back into the slurry premixing stage. This process is shown in Figure 4-17.

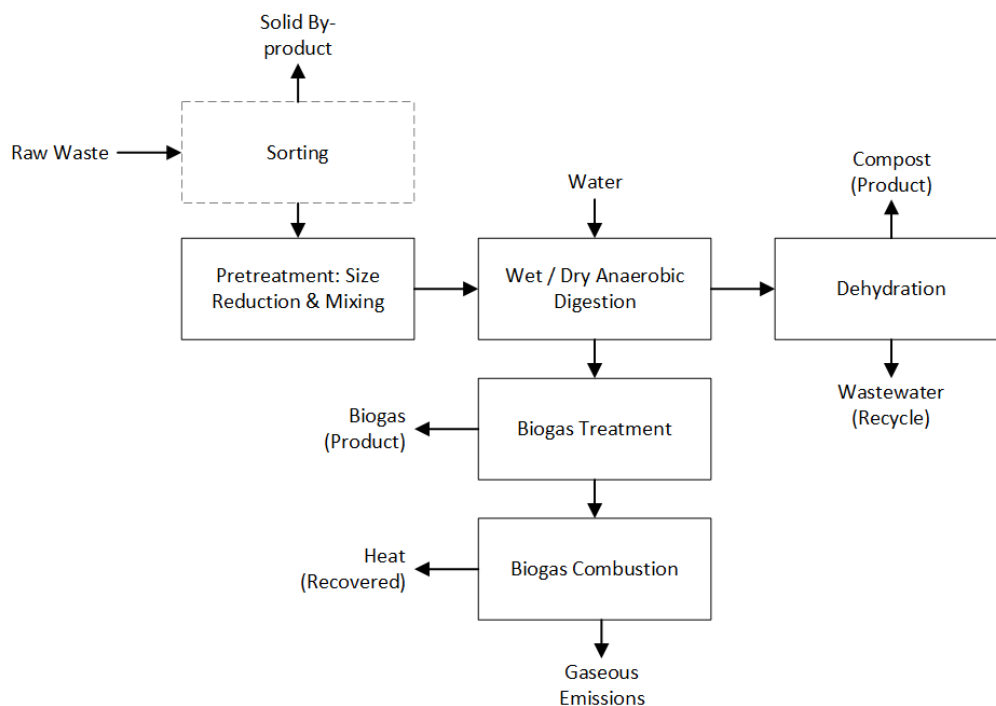


Figure 4-17: Wet or Dry Anaerobic Digestion process block flow diagram

4.6.9 Fermentation

Fermentation decomposes glucose in an organic feedstock into alcohols or acids via an anaerobic process that uses bacteria or yeast. The feedstock size must be reduced to the point where the sugars are easily accessible for decomposition, which commonly requires a pulping process. Pre-treatment, such as premixing, acidic pre-processing, steam pre-processing, washing etc. is vital to increase the overall product yield as well as reduce the number of non-structural components (NSC), such as extractives and ash [127].

After sorting, pulping and pretreatment, the premixed biomass feed stream (slurry with a 4:1 liquid to biomass ratio) is sent to the fermentation unit where it is fermented, generally over a period of 3 days. The main fermentation product is bioethanol, which is produced as a diluted solution. Ethanol is produced at an assumed ethanol yield of 23% per kilogram of fermentable feedstock, as per Pascoli *et al.* [127]. The ethanol solution is then distilled to increase the product concentration to the required alcohol percentage and purity. The heavy liquid stream from the distillation column bottom (stillage) is sent to an evaporator. Evaporated water is recovered in a closed-loop system and reused for mixing with the pulped waste feedstock. The solid by-product left over after the evaporation process is completed, is sent to a combustor for heat recovery. The overall process is shown in Figure 4-18.

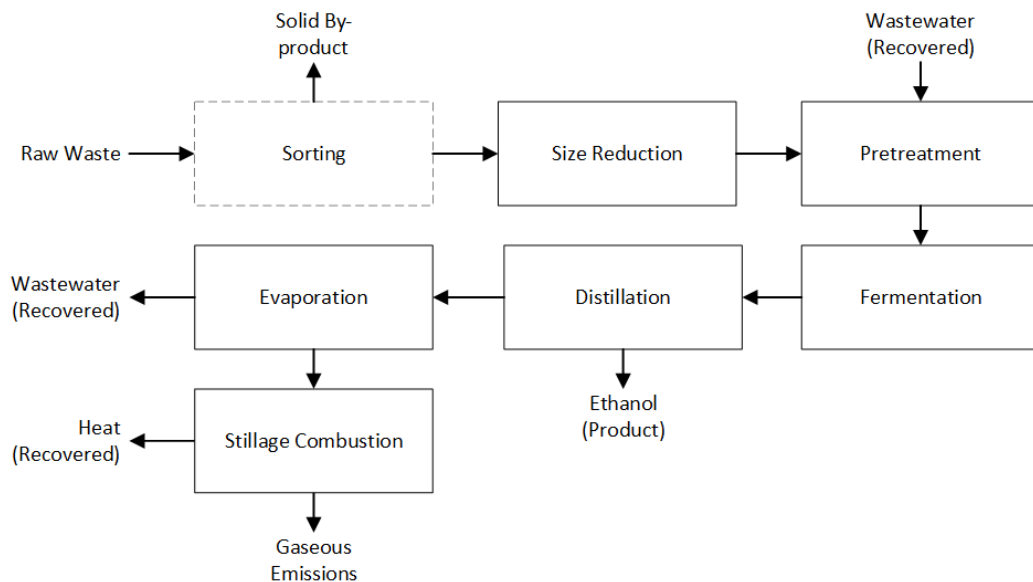


Figure 4-18: Fermentation process block flow diagram

4.6.10 Torrefaction

Torrefaction is a method of upgrading a solid fuel's thermal conversion properties by increasing the fuel's lower heating value while simultaneously decreasing the moisture fraction and volatile content. Biomass has a relatively low calorific content compared to fossil fuels such as coal. Through torrefaction, the main components of biomass, namely lignin, hemicellulose and cellulose, are thermally broken down [128]. According to Anukam *et al.* [129], normal biomass typically has an HHV of around 15 MJ/kg, which increases to around 16 to 29 MJ/kg (depending on the biomass type) by application of torrefaction. For torrefied biomass, the H/C and O/C ratios approach that of coal.

Torrefied biomass can either be used as an upgraded industrial fuel for gasification or it can be briquetted or pelletised for use as an upmarket, smoke-free fireplace fuel for domestic consumption.

Torrefaction is conducted by heating biomass to a temperature in the range of 220 to 320°C in the absence of oxygen. Torrefaction requires relatively long residence times and even temperature distribution. Popular reactors for torrefaction include rotary kilns (indirect heating) or rotary drum reactors (direct heating) [128].

A block flow diagram for the torrefaction process is shown in Figure 4-19.

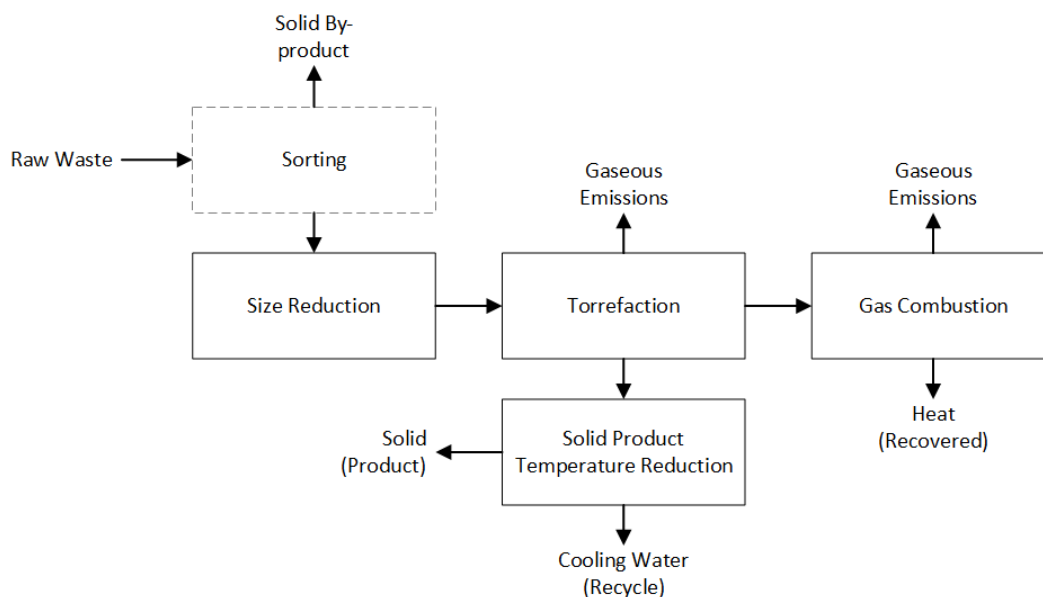


Figure 4-19: Torrefaction Process block flow diagram

For the process shown in Figure 4-19, the waste is sorted so that only organic or biomass-based waste is left as process feedstock. The feedstock undergoes a size reduction step such as shredding to reduce the size of the larger fractions of the waste stream. The shredded waste is then fed into

the torrefaction reactor for low-temperature thermal processing. During the torrefaction process, both a solid and gaseous product is formed. The gaseous product is fed into a gas combustor for complete combustion to carbon dioxide. The heated flue gas stream is fed back into the torrefaction reactor for heat transfer, thus lowering the electrical energy input required for the torrefaction process. After the torrefaction process is complete, the solid product is removed from the reactor. The torrefied product is then cooled to the outlet temperature (around 40°C) using water in a pumped closed-loop system.

4.7 End-Product Production Process Designs

The End-Product Production step, as described in Figure 3-3, describes the conversion of the intermediate products into final end-products – for example, conversion of MRG into ammonia or production of electricity from syngas. These end-products can be sold directly to generate revenue. The End-Product Production Process is the technological process required to achieve this conversion of intermediate products into end products.

As was done for the Waste Conversion Processes, a single process design was selected to represent the selected End-Product Production Processes. These designs were selected by considering various process design options for each process. The goal was to keep the designs generic and simple for comparative purposes. For the same reason, the compositions of the gaseous intermediate products used as feedstocks for the End-Product Production Processes were set based on accepted literature ranges, as shown in Table 4-6.

Table 4-6: Gaseous intermediate product characteristics [130]

Description	Syngas	Methane Rich Gas (MRG)
Hydrogen (H ₂)	25%	-
Carbon Monoxide (CO)	40%	-
Methane (CH ₄)	2%	90%
Carbon Dioxide (CO ₂)	9%	10%
Lower Heating Value (LHV) (MJ/kg)	10.4	47.1

The process followed to define each system is summarised in more detail in the rest of Section 4.7, with the process design for each End-Product Production Design shown using a BFD.

4.7.1 Internal Combustion Engine (ICE)

Syngas or MRG can be fed directly into an ICE adapted to handle this fuel using a pressure reducer. As part of the primary Waste Conversion Process, the gas is cleaned to the correct quality required by the ICE, which implies a particulate matter concentration of less than 50 mg/Nm³, with remaining particles being less than 10 µm in size, and a tar concentration of less than 100 mg/Nm³ [131]. The clean gas enters the ICE which is coupled to a generator unit. Electricity is produced as product, as seen in Figure 4-20.

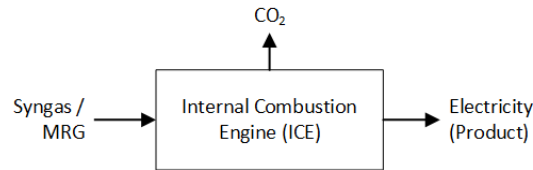


Figure 4-20: Internal combustion engine (ICE) process block flow diagram

The efficiency of the ICE unit is dependent on the engine baseload capacity and lower heating value of the gaseous feed [132], as shown in Figure 4-21.

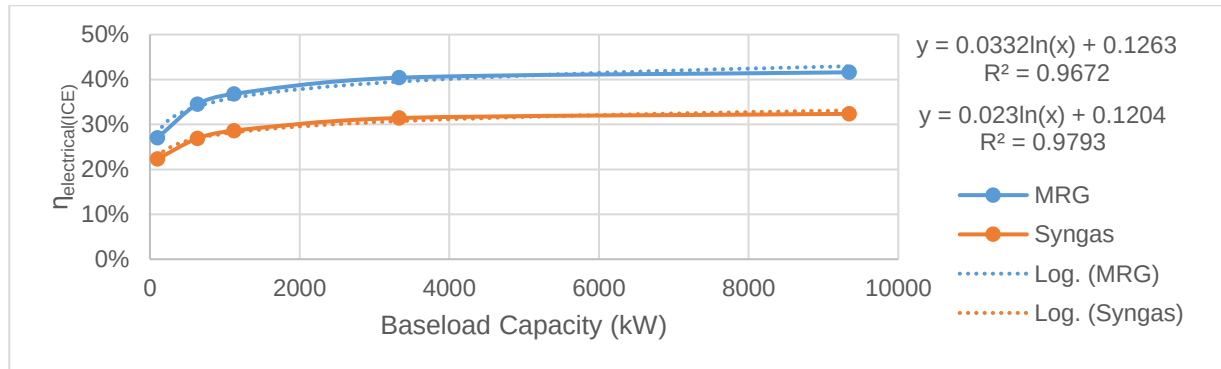


Figure 4-21: Efficiency versus baseload electric capacity for an ICE [132]

The electricity generated via the ICE unit is calculated as shown in Equation (4.4) using the mass flow rate of the feed gas ($\dot{m}_{feed\ gas}$), the Lower Heating Value of the feed gas ($LHV_{feed\ gas}$) and the ICE system efficiency ($\eta_{electrical(ICE)}$), where the efficiency is sourced from the relationship shown in Figure 4-21.

$$E_{(ICE)} = \dot{m}_{feed\ gas} \cdot LHV_{feed\ gas} \cdot \eta_{electrical(ICE)} \quad (4.4)$$

4.7.2 Gas Turbine System

Gas turbines are available in various sizes, though their application is usually for slightly larger power loads than internal combustion engines. Simple cycle gas turbines can be sourced in sizes from smaller than 1 MW (microturbines) to 300 MW or larger. Turbines can also operate at part load, though only base load (ideal full load) operations were considered for the process design calculations.

Figure 4-22 shows a simple gas turbine system (Brayton cycle operation [133]). The turbine system includes a compressor, combustion chamber and turbine.

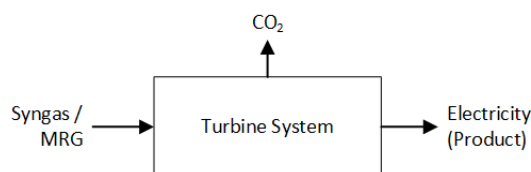


Figure 4-22: Gas turbine process block flow diagram

Air is compressed and heated by the compressor before being sent to the combustion chamber [134]. Here it is mixed with the high-temperature clean, dry gas (feedstock) and combustion takes place. The combustion product – high-pressure, high-temperature flue gas – is sent to the turbine, where mechanical work is produced from the change in flue gas enthalpy due to expansion. The turbine shaft is coupled via a gearbox to the synchronous generator, and electricity is produced as product [135].

The turbine efficiency is dependent on the lower heating value of the gaseous feed, the system size as well as the gas temperature. For the process calculations, the gas temperature is assumed to be constant, but changes in both the feed characteristics and system size are considered. The effect of system size on the turbine efficiency is shown in Figure 4-23.

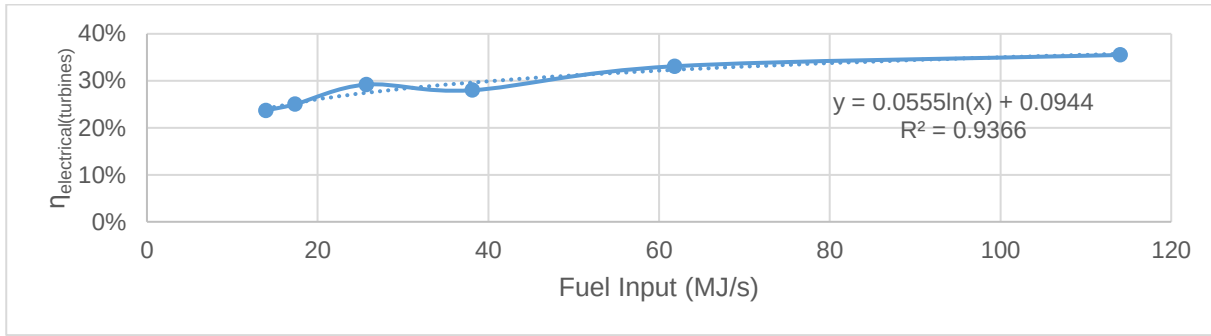


Figure 4-23: Efficiency versus baseload electric capacity for a simple turbine system [134]

The electricity generated via the gas turbine system is calculated as shown in Equation (4.5), where the system efficiency is sourced from the relationship shown in Figure 4-23.

$$E_{(Gas\ Turbine\ System)} = \dot{m}_{feed\ gas} \cdot LHV_{feed\ gas} \cdot \eta_{electrical(Gas\ Turbine\ System)} \quad (4.5)$$

4.7.3 Steam Turbine System (Steam Cycle)

For the process design, the steam generation step is seen as part of the primary Waste Conversion Process (incineration). The steam turbine system included in the End-Product Production Process consists of the following main components, as seen in Figure 4-24: steam turbines, generator unit, condenser, and feedwater pumps. Depending on the system, intercoolers, a deaerator, and low-pressure feedwater heaters may be included for optimisation of the Rankine cycle.

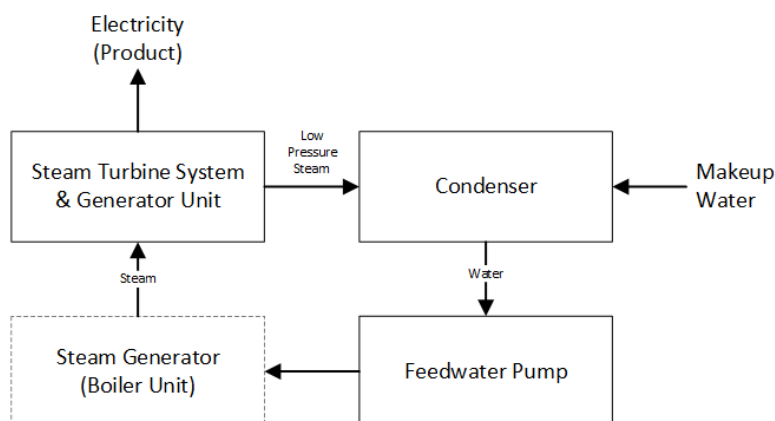


Figure 4-24: Steam turbine system (steam cycle) process block flow diagram

Water is used as process fluid in the steam turbine system. The water is pumped through the boiler tubes by the feedwater pumps, and heated or superheated steam exits the steam generation unit. The amount of energy that can be extracted from the steam by the turbine expansion is based on the enthalpy of the steam, which is a function of temperature and pressure. Therefore, high temperature, high-pressure steam requires smaller steam volumes to generate the same amount of electricity than large volumes of lower temperature, lower pressure steam. This balance is usually a primary input for the steam cycle design [135].

The generated steam is then sent to the downstream steam turbine system which is coupled to a generator to convert the energy from the steam's enthalpy change to mechanical energy and finally to electricity. For small systems, the generator is coupled via reduction gear to the turbine, while mid and large-scale applications can be directly coupled.

For the process calculation, the inlet temperature for the steam is taken as per the Waste Conversion Process calculation design output, namely 420°C. The outlet temperature from the steam turbine system is 110°C and the efficiency of the turbine and generator unit is taken as 55% [135]. The energy recovered from the steam turbine system ($E_{(Turbine\ System)}$) is calculated using a simple enthalpy balance calculation, as shown in Equation (4.6), where $\dot{m}_{steam}$ is the mass flowrate of the steam, Cp_{steam} is the specific heat capacity of the steam and $\eta_{turbine \& generator\ unit}$ is the overall efficiency of the system, which includes the turbine and generator unit.

$$E_{(Turbine\ System)} = \dot{m}_{steam} \cdot Cp_{steam} \cdot \Delta T_{steam} \cdot \eta_{turbine \& generator\ unit} \quad (4.6)$$

4.7.4 Molecular Sieve or Membranes

For this study, membranes are used to recover high-purity hydrogen as end-product. Though various types of membrane systems exist, the operating principle is generic: mixtures are sent through a semi-permeable layer and separated based on the components' molecular size. The separation can occur via sieving, sorption-diffusion, or a combination of these mechanisms. The type of membrane used is dependent on the component to be removed from the mixture and its molecular size.

The process shown in Figure 4-25 describes a simple two-phase membrane system for high-purity hydrogen separation. The process utilises a hollow fibre carbon membrane, also called a carbon molecular sieve membrane (CMSM), for the first stage followed by a selective surface flow carbon membrane (SSF) for the second stage.

The cleaned syngas or methane rich gas (MRG) from the Waste Conversion Process is compressed to around 5 to 20 bar and cooled to a temperature of 100 to 150°C before entering the CMSM [136]. The purified hydrogen stream is then recompressed to 20 bar and cooled to 20°C before entering the SSF carbon membrane. After the second stage separation, high purity (>99%) hydrogen is

recovered as product. While the offgas from the first stage membrane (CMSM) is flared or vented, the by-product from the second stage membrane is recycled back to the first cooling stage to optimise the overall hydrogen recovery [136].

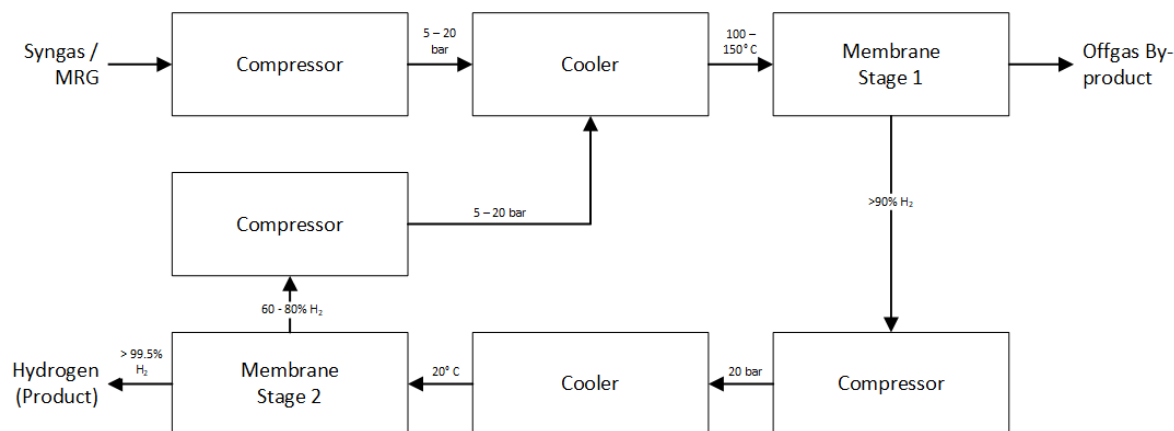


Figure 4-25: Membrane or molecular sieve process block flow diagram

4.7.5 Methane Reforming and Pressure Swing Adsorption

The methane reforming process consists of the following steps: reforming of steam into methane, water-gas shift (WGS), carbon dioxide removal and methanation. A high-level process for methane reforming and pressure swing adsorption is shown in Figure 4-26.

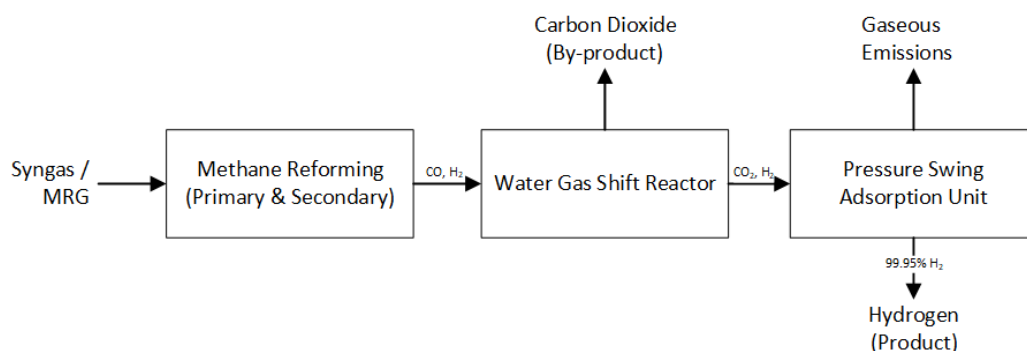


Figure 4-26: Methane reforming and pressure swing adsorption process block flow diagram

Steam methane reforming is split into primary and secondary. Primary reforming takes place at around 850 to 900°C and 25 to 35 bar via Equation (4.7). To supply the energy required for the endothermic reaction, a fraction of the feed gas is combusted in external furnace tubes that run through the catalyst bed [137].



Next, partial oxidation takes place at 900 to 1000°C in the second reactor (secondary reforming) using compressed air as oxidant, as shown in Equation (4.8). Furthermore, waste heat from the exothermic reaction is used to produce a steam stream that is used for general internal energy production [137].



The product of the steam methane reforming process is next fed into the WGS reactors, where the carbon monoxide is converted to hydrogen via an exothermic reaction, as per Equation (4.9). Heat is removed to maximise equilibrium conversion and recovered as waste heat (steam production).



In some cases, carbon dioxide removal is included in the process for optimisation and reduction of the environmental impact. carbon dioxide removal can be conducted via the Selexol or Benfield process, after which any remaining carbon monoxide is recycled back to the methanation process and converted back to methane to prevent catalyst poisoning [137].

After the amount of hydrogen in the feed gas stream is optimised, the gas is sent to a pressure swing adsorption (PSA) unit to separate the hydrogen. In the PSA, all species except hydrogen are adsorbed at elevated pressure. The adsorption binding force differs per species – in general, species with higher polarity and lower volatility are easily adsorbed which allows high-purity hydrogen (99.95% H₂) to pass through (product stream) [138].

Eventually, the adsorption medium in the PSA becomes saturated and must be depressurised, regenerated and repressurised. For continuous operation, more than one PSA unit is required to assure that one unit is operational while the other unit(s) are offline. This sequence is usually pre-programmed to allow for uninterrupted hydrogen production [139].

4.7.6 Distillation

To upgrade the crude bio-oil that is produced as a product of various Waste Conversion Processes, catalytic reactive distillation can be used as shown in Figure 4-27. This process includes the esterification of bio-oil over a solid acid catalyst.

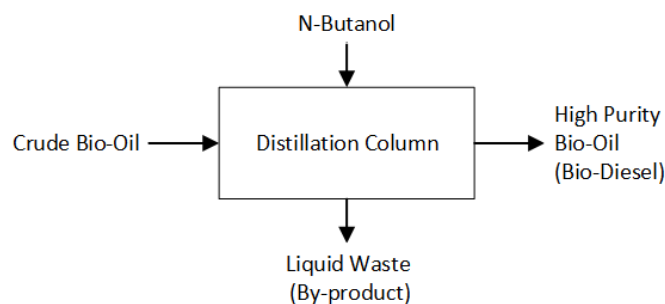


Figure 4-27: Distillation process block flow diagram

The calculations for this process are based on the conditions, conversions and design values attained by Khan and Adewuyi [140] who conducted optimised simulations of catalytic reactive distillation of simple bio-oil.

The crude feedstock is a simple bio-oil composed of 75% acetic acid and 25% water. N-butanol is used as reactant for the esterification reaction at a molar ratio of 1:1 n-butanol to acid. The feed stream enters the distillation column at a pressure of 1.65 bar and a temperature of 110°C. At a distillate to feed ratio (D:F) of 0.53, the distillation process produces a liquid waste stream that consists mostly of water (top product) and a high purity bio-oil stream (bottom product). The bottom product is made up of 11% butanol, 21% acids and 68% esters. For simplification of the calculation, all esters were taken as butyl acetate and all acids were taken as acetic acid.

4.7.7 Fisher Tropsch Process

The Fischer Tropsch (FT) process is a well-understood technique for producing fuels from hydrocarbon gases and is widely used in industry. The process produces a wide array of alkanes (C_1 to C_{60+}) from a carbon monoxide and hydrogen feedstock. It is possible to adapt the range of products produced via FT synthesis by changing the operating conditions and catalyst type, or by adding various post-processing steps [141].

The highly exothermic reaction occurring during the FT process is shown in Equation (4.10).



Since the FT reaction is dependent on the ratio of hydrogen to carbon monoxide, the methane reforming, water gas shift and pressure swing adsorption processes are used to optimise the feedstock composition. During these processes, the hydrogen fraction in the gas is increased and unwanted components such as methane, carbon dioxide, nitrogen, and water are removed.

The purified gas then enters the FT reactor. Due to the exothermic nature of the FT reaction, heat removal from the reactor is vital for preserving the life of the catalyst. Waste heat from the FT reactor is recovered and used for onsite power generation. Depending on the scale of the operation, the FT process can produce net electricity as a by-product after covering all internal energy requirements [141].

The selection of the FT catalyst is a vital step in the FT process design. The product distribution produced in the FT reactor is controlled by the Anderson-Schulz-Flory (ASF) distribution, which is a characteristic of the catalyst. Typical catalyst ASF ranges fall between 0.75 to 0.9. Catalysts with high α values (more than 0.9) are generally preferred in commercial operations to limit the formation of low-value gaseous products. This includes iron and copper-based FT catalysts. However, high α -value catalysts increase the hydrocarbon chain growth in the reactor which causes a higher formation of unwanted heavy waxes (C_{20+}) which must be further processed [142].

After leaving the FT reactor, the crude FT products are purified. Water is removed from the product, producing a wastewater by-product. Next, the heavy waxes are sent to the hydroprocessing operations where they are mostly broken down to transport fuel range hydrocarbons (C_5 to C_{20}) [142]. The overall FT process is shown in Figure 4-28.

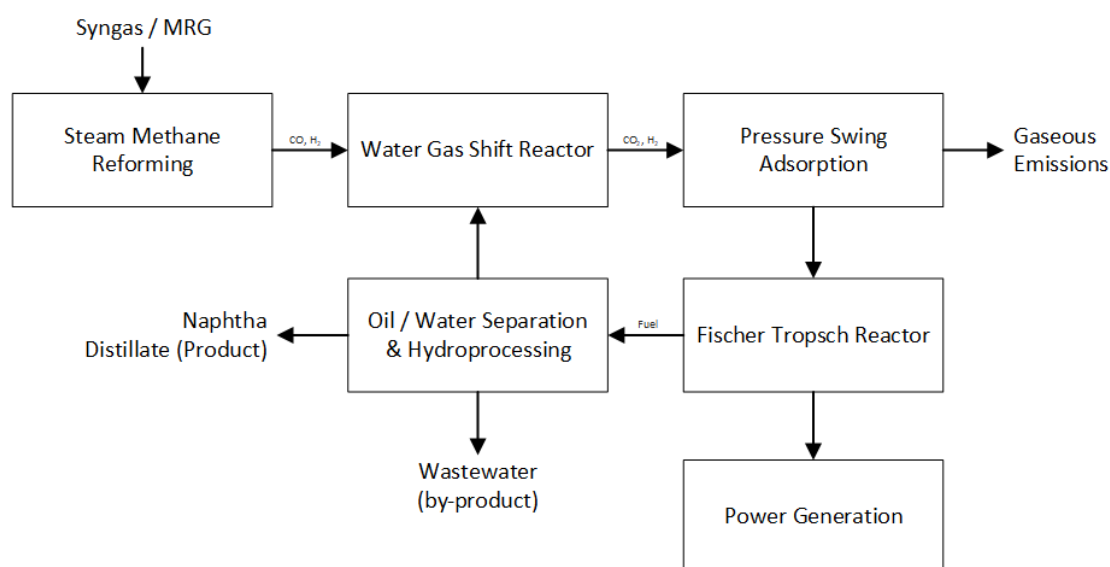


Figure 4-28: Fischer Tropsch process block flow diagram

For the process calculations, a carbon monoxide conversion to FT fuels of 66% was used based on available process simulations (gas recycle ratio of 1.95). The reaction temperature is set to 200°C and a cobalt catalyst is used (α of 0.9). This causes a 30% wax formation, which necessitates a

hydrocracking and distillation step (hydroprocessing). Based on these inputs, the mass fraction distribution of the final FT product is 3% methane, 9% LPG, 26% gasoline and 62% diesel [141].

4.7.8 Methanol Synthesis

Methanol synthesis from syngas is a process that is widely used in industry. Carbon monoxide and carbon dioxide are used as primary feedstock for methanol production via Equations (4.11) and (4.12) [143].



This catalytic, exothermic hydrogenation process is reversible, meaning that heat must continuously be removed to keep the reactor within the required temperature ranges. Adequate heat transfer is also required for the preservation of the Cu/ZnO/Al₂O₃ catalyst. The feed gas is compressed to keep the operating conditions within the reactor at around 210°C and 6 MPa, as shown in Figure 4-29. After leaving the reactor, the product stream is cooled to around 40°C at 5.6 MPa and partially condensed [144]. Conversion of the feedstock to methanol is optimised by recycling a fraction of the cooled product stream back to the methanol synthesis reactor. The remainder of the product stream enters a separation and distillation process, wherein the methanol stream is depressurised, and contaminants are removed. The final methanol product stream is then sent to local storage.

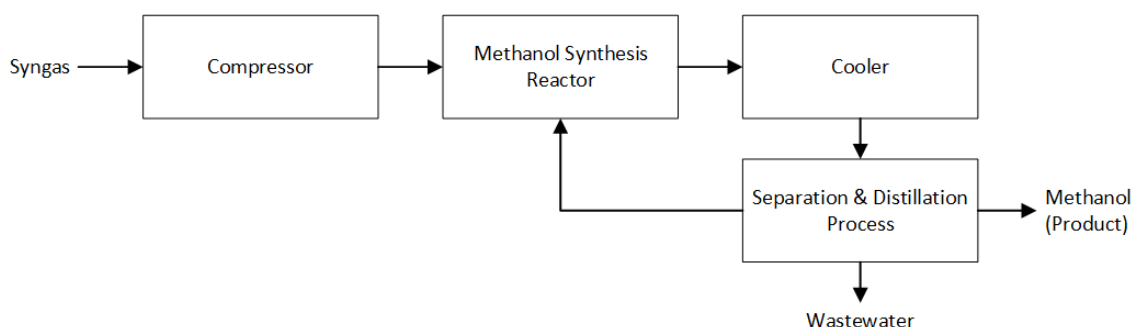


Figure 4-29: Methanol synthesis process block flow diagram

4.7.9 Heterogeneous Catalytic Conversion

Heterogeneous Catalytic Conversion describes the conversion of syngas to ethanol via a larger process that includes the methanol synthesis process described in Section 4.7.8. After methanol has been produced from syngas, the methanol is sent to a carbonylation and esterification reactor where it is reacted with carbon monoxide. Methyl acetate is formed as product. In the hydrogenolysis

reactor, the methyl acetate is reacted with hydrogen to form methanol and ethanol. Hereafter, the product stream is purified to split out the ethanol product, while the methanol is recycled back into the process [145], as shown in Figure 4-30.

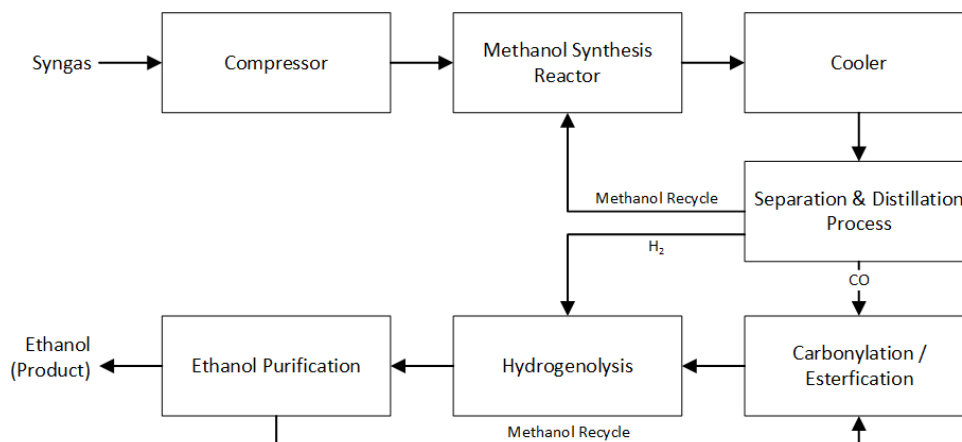


Figure 4-30: Heterogeneous catalytic conversion block flow diagram

The primary alcohol synthesis reaction is highly dependent on temperature, with various alcohols forming at various temperature ranges. The highest syngas conversion is found at low temperatures (below 350°C). Furthermore, catalyst type plays a significant role in product formation. For this process, a copper-based catalyst was used as baseline, which allows for a feed gas conversion of 84% with a product distribution of around 26% methanol, 38% ethanol, and additional fractions of heavier alcohols forming as by-products. For this design, only methanol and ethanol formation are considered, and all methanol is recycled [145].

The formation of ethanol, simplified using Hess's Law [146], is shown in Equation (4.13), while the by-product formation reactions (methanation and hydrocarbon formation [145]) are shown in Equations (4.14) and (4.15).



4.7.10 Haber Bosch Process

Figure 4-31 shows the Haber Bosch process with pre-processing of the gaseous feed stream (steam reformation) to optimise the overall process efficiency. Haber Bosch is a thermocatalytic process that is used to produce ammonia on an industrial scale. More than 150 million tonnes of ammonia is produced internationally using the Haber Bosch process, of which 85% is used to create fertilisers. One disadvantage of the Haber Bosch process is its dependency on economy of scale due to the requirement for high operating temperature and pressures, leading to high capital costs [147].

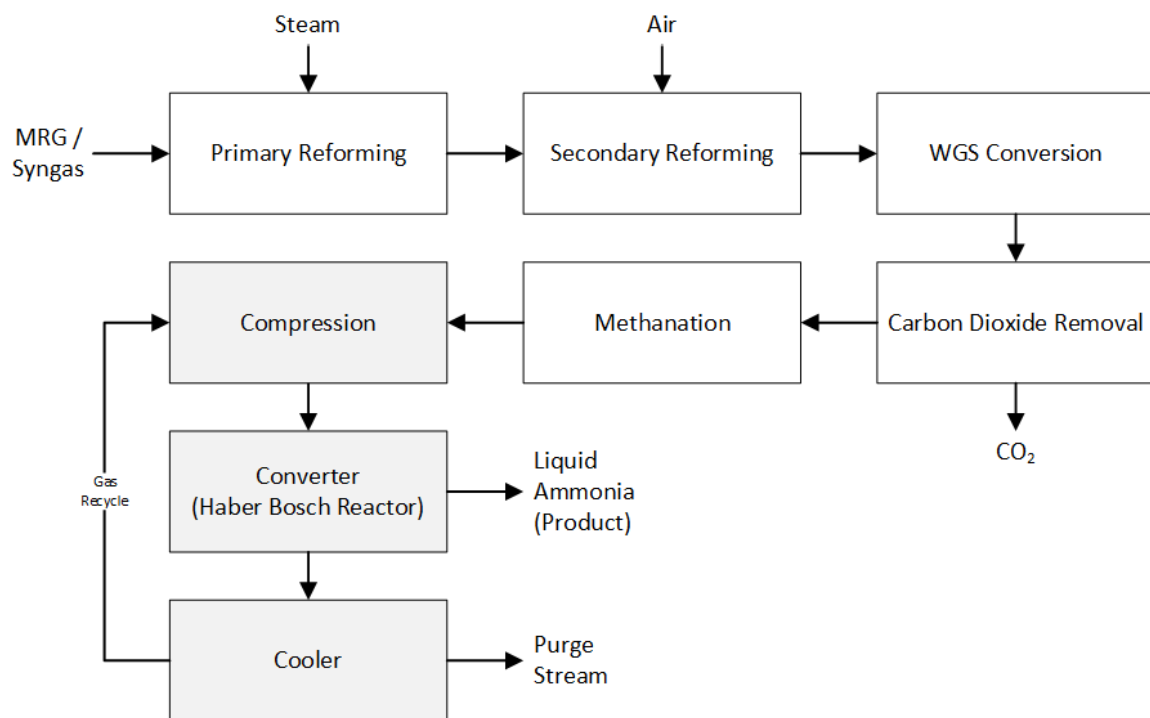


Figure 4-31: Haber Bosch process block flow diagram

The principle of the Haber Bosch process is the production of ammonia from hydrogen and nitrogen. The overall process can be broken into two main steps: hydrogen production followed by ammonia synthesis. Hydrogen is produced via steam reforming of methane, followed by water-gas shift (WGS), carbon dioxide removal and methanation. This process is described in detail in Section 4.7.5.

After the steam reforming process is completed, the gas is compressed and fed into the Haber Bosch reactor (shown in grey in Figure 4-31). Nitrogen is already present in the gas stream since compressed air was used as oxidant in the secondary methanation process. The hydrogen and nitrogen react at 400 to 450°C and 15 to 25 MPa according to Equation (4.16). The gas is recycled to increase the overall conversion (single-pass conversion is around 15%). The ammonia product is

removed between recycling passes by condensation, while inerts are purged back to the steam methane reforming reactors [147].



4.7.11 Compression and bottling

The compression and bottling process considers the direct bottling of MRG, effectively producing a compressed natural gas (CNG) product. In terms of gas quality, raw biogas typically has a methane content of between 55 to 65% and can be used for cooking with biogas stoves, electricity production (biogas engine) or heating [148]. Upgraded biogas with a methane content of more than 90% can be used as a direct replacement for natural gas [149].

Small-scale MRG bottling systems typically include compression of gas via a high-pressure compressor. The gas is then dispensed through a nozzle system into the storage cylinders. Various types of CNG cylinders exist, though Type 1 (metal cylinders) are most commonly used [149]. A high-level representation of this process is shown in Figure 4-32.

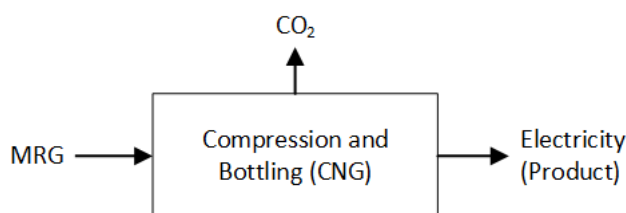


Figure 4-32: Compression and bottling process block flow diagram

4.7.12 Integrated Gasification Combined Cycle (IGCC)

The IGCC process is a well-understood, high-efficiency power generation method. The IGCC process is a combination of the steam cycle and gas turbine system and is made up of a topping cycle and a bottoming cycle [135].

The topping cycle is the section in which the syngas or methane rich gas is sent through a combustion turbine and the energy is extracted (gas turbine system). Looking at the topping cycle in more detail, the gas is first compressed, then combusted in the combustion turbine's combustion chamber, after which the expanding gas is sent through the turbine unit. The enthalpy change in the gas is converted to electricity using a synchronous generator unit attached to the turbine [135].

The hot flue gas (530°C) from the combustion turbine enters the bottoming cycle (steam cycle). Heat is recovered from the flue gas in the heat recovery steam generator (HRSG) using steam as heat-carrying medium. The HRSG is usually made up of three interconnected units, namely the economiser, evaporator and superheater. The steam is then sent to the steam turbine process where the energy is extracted and converted to electricity using a second generator unit. The expanded steam is then condensed and sent back to the HRSG in a closed-loop system [135].

The topping and bottoming system designs for this process are a combination of the gas turbine and steam cycle system designs described in Sections 4.7.2 and 4.7.3. The block flow diagram for this process can be seen in Figure 4-33.

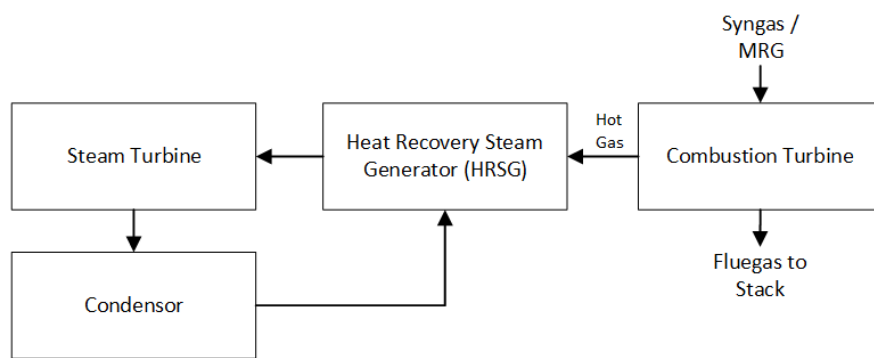


Figure 4-33: IGCC process block flow diagram

4.7.13 Cogeneration

Cogeneration, also called Combined Heat and Power (CHP), describes the process of simultaneously generating electricity and heat. Electricity can be generated using either an ICE or combustion turbine, as shown in Figure 4-34. To recover the waste heat, the high-temperature outlet stream from the turbine or ICE is sent to an HRSG unit to generate steam for use in a local process [134], e.g. as a utility stream (negating the need to generate process steam using an onsite boiler) or as a feed stream for district heating.

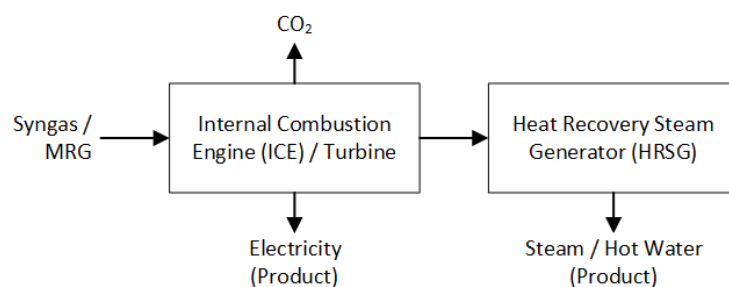


Figure 4-34: Cogeneration process block flow diagram

The biggest advantage of cogeneration is the increased efficiency of the process. Where separate generation of steam and electricity could realistically reach efficiencies up to around 40% (depending on process size), cogeneration processes can recover energy at an overall efficiency of up to 70% for gas turbine-based systems [134]. According to the official publication on cogeneration and trigeneration by the Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) [150], larger cogeneration processes could attain efficiencies of up to 90%.

For this process design, the electricity production process is described in Sections 4.7.1 and 4.7.2 for ICE and gas turbine systems. The thermal efficiencies for the ICE system are taken as 44.2% of the gas LHV, and the thermal efficiency of the turbine system is calculated within a range of 34.4% to 48.0% based on system size [134].

4.7.14 Trigeneration

The trigeneration process is very similar to cogeneration with a cooling step added to produce cool water for heating, ventilation and air conditioning (HVAC) or process cooling requirements. Various technological options exist for the cooling step, though absorption coolers are the most commonly used at present in the industry and therefore seen as the best-established technology [150].

The absorption chiller's working principle is similar to the standard vapour-compression refrigeration cycle. In the absorption chiller, the hot feed gas is used to heat the weak lithium bromide solution (LiBr) which is used as a refrigerant. The solution is heated to boiling point, producing a water vapour stream as well as a high concentration LiBr stream. The water vapour from the solution enters the condenser, where heat is removed. The solution is then expanded and sent to the evaporator, where the cold water is evaporated to provide the required cooling effect. The liquid water is then sent back to the absorber to dilute the LiBr solution in a closed-loop system [151].

The process design shown in Figure 4-35 uses a COP of 1.5 based on industry data (absorption unit technical datasheet [152]), with 30% of the gas stream redirected for cooling.

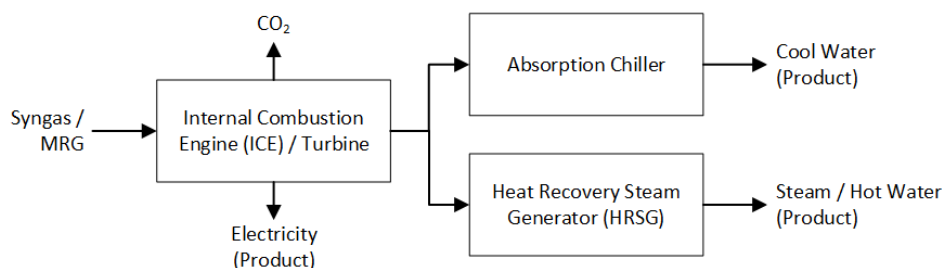


Figure 4-35: Trigeneration process block flow diagram

4.8 Summary of Process Design Inputs

This chapter defined the problem domain for this study, which included the approach followed for the selection of each process (Steps 1 and 2), the logic behind the selection of each included waste type, as well as the composition of each selected waste stream.

This chapter also provides a detailed description of the process design inputs for the WUDSS. The technical characteristics explained in this chapter for both the waste conversion processes and end-product production processes act as baseline for the model defined as part of the study.

To quantify the system mass balances over the processes described in Sections 4.6 and 4.7, specific inputs are necessary as high-level design requirements or set points. These inputs are based on either accepted values or value ranges from literature for the specific process (empirical), design assumptions, or requirements or constraints. These requirements or constraints can be governed by regulatory limits, product quality, or various other factors.

A summary of the technical design inputs used to define the WUDSS can be seen in Table 4-7. The inputs below are given as general, high-level or percentage-based inputs to be applied to the various waste types per unit feed.

Table 4-7: Summary of waste conversion process and end-product production process design inputs

Process	Conversion	Inputs or Feed	By-products
Briquetting or Pelletising	100% conversion of organic waste fraction Volume Change: Raw waste to product, 20 times volume reduction [118]	Incombustibles to be removed from feed (sorting).	Incombustibles (solids) are handled as solid waste.
Composting	MSW to be sorted for composting. Carbon Conversion: 98% to Product, 2% to CO ₂ . Volume Change: Raw waste to product, 20 times volume reduction [153].	MSW to be sorted. Water: Product moisture content to be kept above 40% [153]. Water is added every 2 weeks.	Incombustibles (solids) are handled as solid waste.
Incineration	Overall Carbon Conversion: 80% Steam production: 65% incinerator heat efficiency Incineration temperature: 1000°C [120].	Incombustibles to be removed from feed (sorting). Steam cycle water to be replaced monthly (assumption). Ash cooling water: 10% evaporation loss.	Incombustibles (solids) are handled as solid waste. Ash exits the boiler at 1000°C. Ash cooled to 120°C.

Process	Conversion	Inputs or Feed	By-products
Gasification	Overall Carbon Conversion: 80%	Incombustibles to be removed from feed (sorting). Ash cooling water: 10% evaporation loss.	Ash exits the boiler at 800°C [121]. Ash cooled to 120°C.
Flash Pyrolysis	Overall Carbon Conversion: 75% Of which the following product fractions are produced [154]: Gas (Syngas): 75% Liquid (Bio-oil): 12% Solid (Biochar): 13%	Incombustibles to be removed from feed (sorting). Cooling water required is 20% of biochar produced	1% fly ash produced.
Fast Pyrolysis	Overall Carbon Conversion: 75% Of which the following product fractions are produced [154]: Gas (Syngas): 30% Liquid (Bio-oil): 50% Solid (Biochar): 20%	Incombustibles to be removed from feed (sorting). Cooling water required is 20% of biochar produced	1% fly ash produced.
Slow Pyrolysis	Overall Carbon Conversion: 75% Of which the following product fractions are produced [154]: Gas (Syngas): 35% Liquid (Bio-oil): 30% Solid (Biochar): 35%	Incombustibles to be removed from feed (sorting). 100% of gas used for process heat generation Cooling water required is 20% of biochar produced	1% fly ash produced.
Catalytic Fast Pyrolysis	Of total carbon conversion, the following product fractions are produced [122]: Solid product: 81% Liquid product: 19%	Cooling water required is 20% of biochar produced.	1% fly ash produced. All gaseous and liquid waste products are based on conversions from previous previously simulated results. CaO is added to the process as feedstock [122].
Gasification & Plasma Post Processing	80% carbon conversion	Incombustibles to be removed from feed (sorting). Ash cooling water: 10% evaporation loss. Gasification temperature: 800°C.	Ash exits the boiler at 800°C. Ash cooled to 120°C. 1% fly ash produced (assumption).
Wet AD	Methane yield is adapted from the dry AD methane yield (0.47 kg methane kg total solids) [155].	MSW to be sorted. The feed stream (slurry) contains 15% total solids [155]. The process is mesophilic (35°C). 30% of the biogas produced is used for heat production.	15% of water is lost per digestion cycle (evaporation, water left in the compost product, etc.)

Process	Conversion	Inputs or Feed	By-products
Dry AD	Methane yield is taken as 0.5 m ³ methane per kg total solids fed (0.33 kg methane/kg total solids) [155].	The feed stream (slurry) contains 40% total solids [155]. The process is mesophilic (35°C). 30% of the biogas produced is used for heat production. MSW to be sorted.	15% of water is lost per digestion cycle (evaporation, water left in the compost product, etc.)
Fermentation	Based on literature, feedstock with 4% ash content can achieve an ethanol yield of 23% (mass) [127]. Distillation to high-purity ethanol is included in this process.	MSW to be sorted.	Stillage is combusted to gas and heat [127]. All water is treated in a closed-loop system. 10% of feed equivalent water loss is assumed per cycle. Combusted stillage carbon content is converted to 100% CO ₂
Torrefaction	Conversion to product moisture percentage: 3% Product volatile content: 30% [128]	MSW to be sorted. Gas with CO to CO ₂ Ratio of 30:70 Ash cooling water: 10% evaporation loss.	Ash exits the boiler at 230°C. Ash cooled to 80°C.
Sort and Resale	All recyclable fractions based on MSW composition: Paper and cardboard: 14% Glass: 4% Plastics: 15% Metals: 2%	No pre-processing.	The fraction of the waste stream that is not included in the sorted fraction is seen as solid waste.
Distillation	Mass balance is based on D:F of 0.53, where the bottom product is made up of 11% butanol, 21% acids and 68% esters [140].	Low-quality bio-oil composed of 75% acetic acid and 25% water. N-butanol reactant is fed into the system at a molar ratio of 1:1 n-butanol to acid [140].	Top product: Liquid waste stream that consists mostly of water.
Trigeneration	Energy balance is based on a COP of 1.5 with 30% of the waste stream redirected for cooling [152].	MRG or syngas	CO ₂
Cogeneration	Thermal efficiencies [134]: ICE system: 44.2% of the gas LHV Turbine system: calculated within a range of 34.4 to 48.0% based on system size	MRG or syngas	CO ₂
Compression and bottling (CNG)	100% of the feed gas is compressed and bottled [149].	MRG	None

Process	Conversion	Inputs or Feed	By-products
Gas Turbine System	Calculated depending on the LHV, system size and gas temperature [134].	MRG or syngas	CO ₂
Haber Bosch Process	Hydrogen conversion is based on mass balance outputs, with 45% conversion of nitrogen to ammonia [147].	MRG or syngas Steam	CO ₂ Purge gas
ICE	Calculated based on the engine baseload capacity and LHV of the gaseous feed [132]	MRG or syngas	CO ₂
IGCC	Based on efficiencies calculated for the topping and bottom cycles (gas [134] and steam turbine cycles [135]).	MRG or syngas	CO ₂
Methane Reforming & Pressure Swing Adsorption	Mass balance over process steps with 80% hydrogen recovery over the PSA [138].	MRG or syngas Compressed air	Gaseous emissions from PSA CO ₂ from the WGS process.
Steam Turbine System (Steam Cycle)	Mass balance-based conversion at turbine and generator unit efficiency of 55% [135]	Steam	-
Fisher Tropsch	Carbon monoxide conversion of 66% for a gas recycle ratio of 1.95. Fractional distribution ratio of FT fuels are 3% methane, 9% LPG, 26% gasoline and 62% diesel [141].	MRG or syngas Cobalt catalyst [142]	Gaseous emissions Wastewater
Heterogeneous Catalytic Conversion	Carbon conversion of 84%. Product distribution of around 26% methanol, and 38% ethanol [145].	Syngas Copper-based catalyst [145]	Wastewater Methanol (recycled internally)
Methanol Synthesis	Methanol synthesis efficiency of 80% [144].	Syngas Cu/ZnO/Al ₂ O ₃ catalyst [144]	Wastewater
Molecular Sieve / Membranes	Mass balance-based hydrogen production with 99.5% recovery efficiency over the membrane system [136].	MRG or syngas	Offgas

Chapter 5: Additional Modelling Requirements

5.1 Introduction

After outlining the problem domain and establishing the technical design basis for the Waste Utilisation Decision Support System (WUDSS) in Chapter 4, Chapter 5 explores the additional modelling requirements. This chapter covers the essential components for enhancing decision support in the WUDSS. This includes describing the process costing and financial analysis, social, environmental and other considerations, legal and regulatory considerations, as well as guidance and risk analysis. Where the legal and risk-based considerations are used as guidance for the user inputs, the financial considerations described in this chapter are used as inputs to the cost components of the Integrated Optimisation Model objective function provided in Chapter 3. Furthermore, the land and social considerations are used as constraints to the model.

5.2 Process Costing and Financial Analysis

The methodology around the process costing is based on the WUDSS's requirements and planned use. The goal of the system is to provide decision support to SMMEs for project/business development within the decentralised waste utilisation sector. The focus of the system is therefore on the early project development stage. The WUDSS must provide guidance in selecting the most appropriate process to create value from a certain waste stream. The information provided as output of the WUDSS must be usable as a basis to approach investors or plan a funding approach. The financial outputs from the decision support system must therefore be adequate for:

- Option comparison and analysis
- Preliminary costing (FEL 1)

The accuracy of the costing can therefore be expected to be around 30%, based on the FEL methodology, for which the theoretical foundations are explained in Section 1.7. As part of a detailed design phase, an itemised costing must be developed to improve the accuracy of the estimate.

The estimate is based on certain centralised input values that can be easily adapted in the future but create a baseline for the estimation. This includes the baseline year of estimate, which for this study is taken as 2020. It also includes the various exchange rates for the South African Rand (ZAR), which can be summarised as follows:

- United State Dollar (USD) to ZAR: 15
- Pound Sterling to ZAR: 20

- Euro to ZAR: 18
- Malaysian Ringgit to ZAR: 3.5
- Indian Rupee to ZAR: 0.19

5.2.1 Capital Expenditure (CAPEX) and Operating Expenditure (OPEX)

Capital expenditure (CAPEX) quantifies the expected cost of the main equipment that makes up the plant. Operating expenditure (OPEX) quantifies the annual expenses associated with operating the plant, usually including specific inputs such as labour costs, utilities (water, electricity, chemicals, etc.), repair and maintenance costs, etc.

The cost accuracy requirements for this project allow for factorial cost estimations based on existing cost analyses (historical data), corrected for both process size and base year. For process size (capacity) correction, the Six Tenth Rule, an accepted method [25], is used as shown in Equation (5.1), where C_2 and C_1 are the cost for the existing system and referenced system respectively, and S_2 and S_1 is the size of the existing system and referenced system respectively. Traditionally, n is taken as 0.6 [25].

$$C_2 = C_1 \cdot \left(S_2 / S_1 \right)^n \quad (5.1)$$

For cost escalation, Equation (5.2) is used [25]. South Africa's cost index information between 1961 and 2020 is used as input (Appendix C).

$$Cost_{2020} = Cost_{Reference} \cdot \left(\frac{Cost\ Index_{2020}}{Cost\ Index_{Reference}} \right) \quad (5.2)$$

Data for the decision support system is gathered in a consolidated CAPEX or OPEX database. The data comes from a large number of studies on the costs of the specific processes considered. Though various process designs are considered for each process, it is specifically ascertained that the required process sections are included in all costings considered (e.g., wastewater treatment or electricity generation must be included in the costing, where this is considered for the design case). To attain a good representation of actual plant costs, between two to four costings for each process (primary and secondary) are included in the final costing sheet. All cost data included in the costing database is further adapted for location based on internationally accepted country factors. These published index-based country factors show differences in the general price-levels of various countries [156]. The country factors are applied to a percentage of the CAPEX and OPEX values determined as part of the verification process. This also allows for the establishment of a high and low-cost indication (CAPEX and OPEX).

In general, CAPEX and OPEX values for a specific process can be expected to vary within the accepted FEL 1 range (30% to 50%) due to basic differences in design, level of automation, material

of construction, or other aspects that might influence the final price. For example, a gasification process may be completely automated, in which case the CAPEX will typically be high and the OPEX low compared to a more manually operated process. Similarly, some vessels could be constructed from stainless steel, which will result in a higher CAPEX, but a lower OPEX since very little maintenance is required when compared to a carbon steel vessel that might need to be recoated as part of its planned maintenance. For this reason, both high and low CAPEX and OPEX values are provided, which may be selected for further scenario analysis, as well as a median cost which is typically used as the final CAPEX or OPEX value for the decision support system.

5.2.2 Total Capital Investment (TCI)

Though the plant CAPEX shows the cost of the main production units, various costs are not included in this first estimation. For this reason, it is required to obtain the Total Capital Investment (TCI), which is the total cost of the project. Both total Purchase Cost (PC) and Physical Plant Cost (PPC) are included in the overall TCI. The TCI can be obtained using the Detailed Factorial Method [25], which allows for management of the cost contribution of each plant factor as a percentage of the CAPEX cost.

Balance of plant costs (including piping, instrumentation, buildings, etc.) must be included to calculate the PC. Land costs form a part of the PC but are calculated directly based on cost per m². Hereafter, the PPC can be calculated to include the project costs, such as design and engineering and contractor's fees. The equations for the general TCI calculation are shown in Equations (5.3) and (5.4), where *cf* represents the cost factors given in Table 5-1 [25]. The general TCI value is then adapted for South Africa using the internationally accepted country factors, as per Equation (5.5) (developed iteratively to fit to actual industry data as part of the verification process of this study).

$$PC = CAPEX(1 + cf_1 + \dots + cf_9) \quad (5.3)$$

$$TCI_{general} = PC(1 + cf_{10} + \dots + cf_{12}) \quad (5.4)$$

$$TCI = TCI_{general}(0.5 + 0.7.Country\ Factor) \quad (5.5)$$

All cost percentages shown in Table 5-1 can be edited as input to the model to allow for specific project requirements. However, the given percentages are based on internationally accepted values [25] and will be proposed by the model as a first estimation to guide the decision-making process.

Table 5-1: TCI input values for the decision support system [25]

Total Capital Investment		Unit	Cost Input
<i>Total Purchase Cost (PC) Inputs</i>			
cf₁	Equipment Erection	% of CAPEX	45%
cf₂	Piping	% of CAPEX	45%
cf₃	Instrumentation	% of CAPEX	15%
cf₄	Electrical	% of CAPEX	10%
cf₅	Buildings & Process	% of CAPEX	10%
cf₆	Utilities	% of CAPEX	45%
cf₇	Storage	% of CAPEX	20%
cf₈	Site Development	% of CAPEX	5%
cf₉	Land Cost	ZAR/m ²	R 50.00
<i>Physical Plant Cost (PPC) Inputs</i>			
cf₁₀	Design and Engineering	% of CAPEX	25%
cf₁₁	Contractor's Fee	% of CAPEX	5%
cf₁₂	Contingency	% of CAPEX	10%

Furthermore, to calculate the total cost of a process that includes both a Primary Waste Conversion and an End-Product Production process, the two costs must be added together. However, since some existing services or balance of plant processes can be shared between the two processes, the overall TCI can be reduced. The integration factor (β) included in this work is taken as 0.9, as shown in Equation (5.6) [157].

$$Cost_{Total} = Cost_{Waste\ Conversion\ Process} + (Cost_{End-Product\ Production\ Process})^{\beta} \quad (5.6)$$

Lastly, to provide decision support regarding the economy of scale considerations for a specific process and waste type considered, an economy of scale graph is generated for each configuration that can be selected. An example of the economy of scale graph can be seen in Figure 5-1, which shows the waste throughput versus average TCI for a fast pyrolysis plant processing food waste. The economy of scale graph is presented as part of the visual guidance aids.

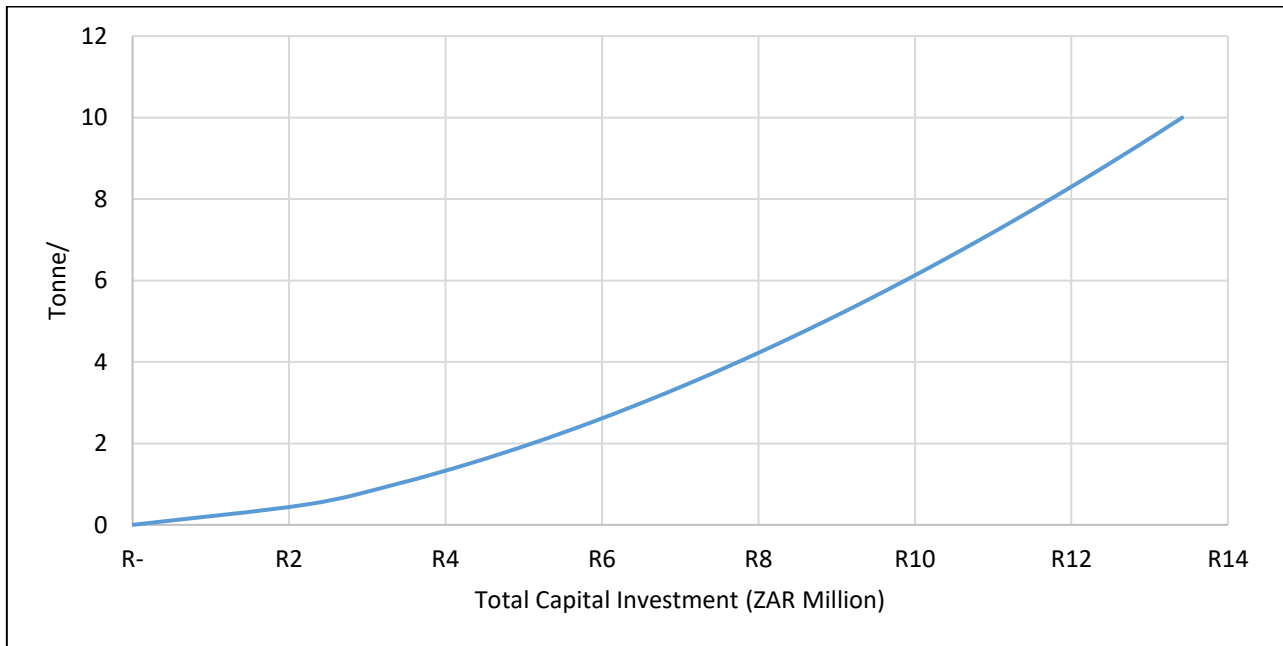


Figure 5-1: Economy of scale graph for a fast pyrolysis plant processing food waste

5.2.3 Total Production Cost per Annum (TPC/a)

The OPEX estimate for the plant included in the consolidated CAPEX or OPEX sheet includes all main OPEX items, excluding the cost of waste. Since the cost of waste has a large impact on the overall financial model based on feedback from various studies (including, amongst others, Swanson *et al.* [141], Indrawan *et al.* [121], Pascoli *et al.* [127], and Campbell *et al.* [158]), this cost item was removed from the reference OPEX inputs and must be provided as inputs to the model for the specific project and waste stream.

The TPC/a includes indirect annual expenses such as taxes, insurance, etc., and is calculated from the fixed cost based on percentages (or cost factors, *cf*) using Equation (5.7), which was adapted from Sinnot [25] to include the country factor adaptations for South African projects.

$$\begin{aligned} \frac{TPC}{a} = & OPEX(0.95 + 0.05 \cdot \text{Country Factor}) + TCI(cf_{14} + \dots + cf_{17}) \\ & + (OPEX(0.95 + 0.05 \cdot \text{Country Factor})(cf_{18} + cf_{19})) \\ & + \left(\frac{\text{Feedstock}}{\text{annum}} \cdot cf_{13} \right) \end{aligned} \quad (5.7)$$

All cost factor percentages used for the TPC/a calculation is shown in Table 5-2.

Table 5-2: TPC/a input values for the WUDSS [25]

Production Costs	Unit	Cost Input
Variable Costs		

	Production Costs	Unit	Cost Input
cf₁₃	Waste Feed Cost	ZAR/ton	Model Input
	<i>Fixed Costs (FC)</i>		
-	Maintenance	Incl.	-
-	Operating Labour	Incl.	-
cf₁₄	Capital Charges	% of TCI	10%
cf₁₅	Insurance	% of TCI	1%
cf₁₆	Local Taxes	% of TCI	2%
cf₁₇	Royalties	% of TCI	1%
	<i>Additional Costs</i>		
cf₁₈	Sales Expense	% of OPEX	20%
cf₁₉	R&D	% of OPEX	0%

5.2.4 Income Streams

Income streams describe the various possible ways for the company to earn revenue. The primary income streams come from the sale of products produced from the waste utilisation or valorisation processes. The potential incomes are calculated by the model based on the amount of each product produced (tonnage or kWh), as well as the market or sale value of the specific product. The actual product sale value is dependent on the project location, off-taker, negotiations, as well as appetite of the market. For products such as heat and cooling, the cost offset from producing these streams is calculated, based on the assumption that the company is currently paying for steam production via an industrial boiler (heat) or for cooling using electricity.

To provide decision support in terms of typical market prices, both a minimum and maximum market price is given, as shown in Table 5-3. An indicative value that falls within this range is provided as the primary input value (Market Price). This value can be adapted as appropriate.

Table 5-3: Primary income streams for the decision support system

Product Sale Values	Unit	Market Price	Min Market Price	Max Market Price	Source
Compost	ZAR/ton	R599	R469	R728	[159]
LQ Biochar	ZAR/ton	R5 723	R5 723	R6 638	[122]
HQ Biochar	ZAR/ton	R9 793	R2 448	R77 250	[122]
Briquettes / Pellets	ZAR/ton	R3 057	R2 588	R3 526	[160]
Sorted Fractions	ZAR/ton	R2 584	R1 595	R3 572	[161], [162]
Glass	ZAR/ton	R300	R270	R330	[162]
Metal	ZAR/ton	R23 915	R10 770	R37 060	[161]
Paper	ZAR/ton	R812	R731	R893	[162]
Plastics	ZAR/ton	R2 165	R1 624	R2 707	[162]
Torrefied Biomass	ZAR/ton	R5 104	R3 708	R6 500	[122]
LQ Bio Oil	ZAR/ton	R2 871	R2 610	R3 132	[122]
HQ Bio Oil	ZAR/ton	R3 132	R18 961	R22 754	[122]
Ethanol	ZAR/ton	R6 000	R2 984	R57 164 860	[163]

Product Sale Values	Unit	Market Price	Min Market Price	Max Market Price	Source
Steam	ZAR/ton	R1.46	R1.41	R1.51	[164]
Biodiesel	ZAR/ton	R18 240	R15 960	R21 660	[163]
Electricity	ZAR/kWh	R1.70	R0.98	R2.42	[122]
Heat	ZAR/kWh	R1.59	R1.53	R1.65	[164]
Cooling	ZAR/kWh	R1.69	R1.52	R1.86	[165]
Syngas	ZAR/ton	R676	R608	R744	Quote
Methane Rich Gas	ZAR/ton	R166	R149	R182	Quote
CNG	ZAR/ton	R27 222	R24 500	R29 944	Quote
Ammonia	ZAR/ton	R7 028	R4 686	R9 371	[166]
FT Fuels	ZAR/ton	R16 711	R14 623	R19 841	[163]
Methanol	ZAR/ton	R13 410	R7 020	R19 800	[163]
Hydrogen	ZAR/ton	R18 240	R3 000	R109 800	[167]

Since the processes that form part of the decision support system are focused on waste management and production of green products, various alternative income streams exist to support these types of businesses. These income streams are seen as secondary incomes and are summarised in Table 5-4.

Table 5-4: Secondary income streams for the decision support system

Income	Unit	Cost Input
Carbon Credits [168]	ZAR/ton-CO ₂ (eq)	R100.00
Carbon Credits Sold	% of Total	50%
Tipping Fees [169]	ZAR/ton	R200.00
Biodiesel Producer Incentive [170]	ZAR/ton	R317.44
Ethanol Producer Incentive [170]	ZAR/ton	R211.66

The viability of selling carbon credits is given as an output of the decision support system since the project must have a negative carbon footprint for this income stream to become feasible. This output acts as a general guidance function to assist in understanding which income streams can be generated for a specific configuration.

Guidance is also provided with regards to the tipping fees item since the value of this item varies based on the municipality and must be adjusted based on project location. Tipping fees might not always be awarded, and this income item is highly dependent on negotiation outcomes. For this reason, a list of existing tipping fee values is given for major municipalities, but the actual tipping fee input value to be used as input to the model must be selected. The value of the tipping fee charged by the project should be lower than the value charged by the municipality since open market principles can be expected to dictate the waste sellers' behaviour. The list of tipping fee values per municipality is provided in Table 5-5.

Table 5-5: Tipping fees per municipality (excluding VAT) [169]

Municipality	Tipping Fee
City of Cape Town	R508.00
eThekweni	R362.00
Mangang	R322.00
Buffalo City	R293.00
City of Ekurhuleni	R262.00
City of Johannesburg	R232.00
City of Tshwane	R200.00
Nelson Mandela Bay	R153.00

5.2.5 Financial Analysis

A simple financial model was created for the decision support system to provide capital budgeting metrics to assess the expected financial performance of a specific business case. As inputs to the financial model, the project duration is taken as 20 years, a straight-line depreciation method is used, a discount rate of 8% is applied and all loan or other financing costs are excluded since capital charges (which cover loan costs) are included in the TPC/a calculation.

Some of the input values for the financial model can be provided as input to the model, though guide values are given by the decision support system, as shown in Table 5-6. These values include price escalations, expected annual increases in OPEX as well as the applicable corporate tax percentage.

Table 5-6: Financial model inputs for the decision support system [25]

Product Sale Values	Input
Annual Price Escalation	6%
OPEX increase per annum	6%
Corporate tax (%)	28%

The result of the financial analysis includes three capital budgeting metrics, namely Net Present Value (NPV), which is the present value of all the cash flows generated by the project over its lifecycle (including capital investment); Internal Rate of Return (IRR), which is the percentage return without considering external factors and which can be used to indicate the profitability of a project; and Pack Back Period (PBP), which is the time required to pay back the initial investment required for the project.

The financial model is used to generate a cash flow graph, which shows the summary of project incomes and expenses over time. The cash flow graph also acts as a visual aid, showing the difference in the initial investment versus the project gains over the lifetime of the project.

5.3 Social, Environmental and Other Considerations

The social, environmental and other considerations included in the WUDSS include the following:

- Social considerations:
 - Direct job creation
 - Construction-phase job creation
- Environmental considerations:
 - Liquid waste
 - Solid waste
 - Gaseous emissions (carbon dioxide equivalent)
 - Reduction in gaseous emissions compared to waste landfilling
- Other considerations:
 - Land area required per process (ha²)

Calculations of the social considerations are adapted from existing studies for waste management processes in South Africa. A study done by Maia *et al.* [171] summarises the direct job creation potential of a South African green economy. Various processes are considered with case studies included. Based on these case studies, the job creation estimates were calculated for this study using the Six Tenth Rule to adapt for process size. Table 5-7 shows the inputs used for the decision support system based on a 10 tonne/day process.

Table 5-7: Employment calculations for a 10 tonne/day process [171]

Process	Direct Jobs Creation	Construction Job Creation
Briquetting or Pelletising	2	17
Sort & Resale Processes	2	17
Composting	3	17
Thermal Processes	7	40
Anaerobic Digestion (AD)	12	29
Fermentation	38	75

The environmental considerations were calculated for each process as part of the mass balance (technical process design) step of the decision support system synthesis. Gaseous emissions were calculated as carbon dioxide equivalent for the specific component based on its molar mass (MW), as shown in Equation (5.8).

$$CO_{2_eq. (component)} = \frac{MW_{carbon\ dioxide}}{MW_{component}} \quad (5.8)$$

For the reduction of gaseous emissions compared to waste landfilling, the assumption is made that 50% of the landfilled waste would have been converted to carbon dioxide and 50% to methane, which falls within the accepted ranges for biogas [148]. The formula used to calculate the emission reduction is shown in Equation (5.9).

$$CO_{2_eq. (landfill)} = \left((50\% \cdot \dot{m}_{waste} \cdot CO_{2_eq. (methane)}) + (50\% \cdot \dot{m}_{waste}) \right) \cdot (100\% - mass\%_{ash}) \quad (5.9)$$

5.4 Legal and Regulatory Considerations

In terms of legal and regulatory inputs, the following categories of permits, authorisations or requirements were considered: standard environmental permits, land use permits, grid connections, gas-specific regulations, health and safety regulations and other permits. The most relevant items under each of these categories are included in the system for further pursuit. These legal inputs are taken from the National Environmental Management Act, 1998 (Act No 107 of 1998), National Environmental Management: Waste Act, 2008 (Act No 59 of 2008), National Environmental Management: Air Quality Act (Act No 39 of 2004), National Environmental Management: Integrated Coastal Management Act of 2008, and the Heritage Resources Act (Act No 25 of 1999).

5.5 Guidance and Risk Analysis

Various guidance and risk analysis functions are included in the WUDSS to provide assistance with regards to inputs, interpretation of outputs or general decision-making. General assistance functions, more specifically, are included to afford guidance in selecting the most preferred waste type, Waste Conversion Process and End-Product Production Process combination (configuration). Information for the general guidance functions is largely sourced from the centralised results summary database of the decision support model, which summarises the results of the Process Calculations to be used as inputs to the Integrated Optimisation Model. The process descriptions and block flow diagram content are based on the descriptions given under Chapter 4 and summarised for inclusion in the decision support system.

More focused guidance functions, such as the Risk-based Guidance Section, is intended to provide more outcome-specific guidance and are explained in more detail in the sections below.

5.5.1 Synthesis of the Guidance and Overview Section

The general Guidance and Overview section provides visual decision support by presenting specific results from the decision support system's consolidated results database. The graphs generated can be used to compare the specific aspects of the results for various processes, feedstocks or end-products, where any combination of waste feed type, waste conversion process and end-product production process can be selected. Specific outputs are then given graphically for ease of comparison.

The outputs are presented by category, with Input Selection being the first category. The second category is General, which includes information on costs and products produced. An example of the products produced graphical output is shown in Figure 5-2 considering randomly selected waste types and processes.

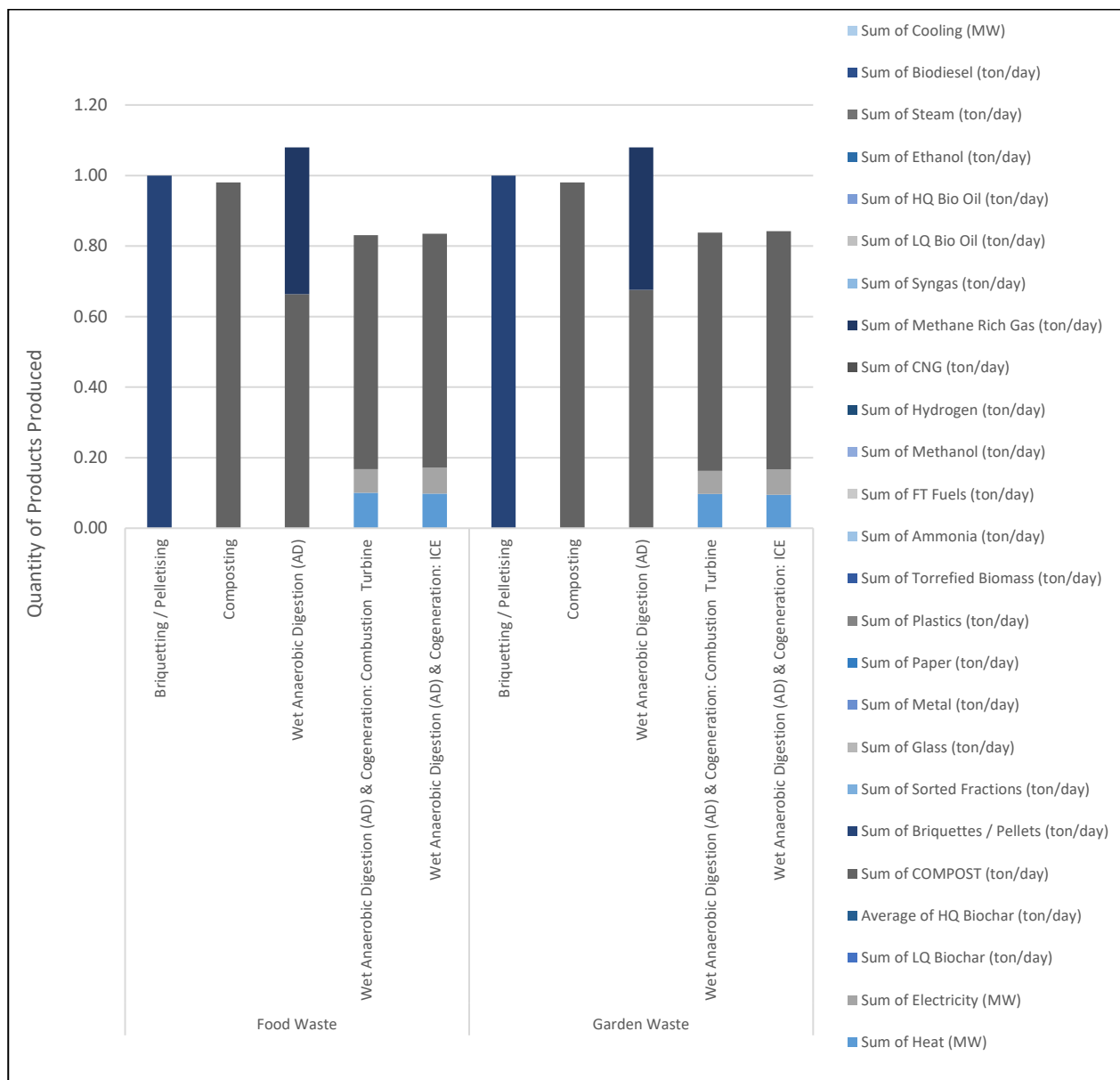


Figure 5-2: Example of the prototype system Guidance and Overview: Products Produced

An example of the cost information graphs general Guidance and Overview section is shown in Figure 5-3.

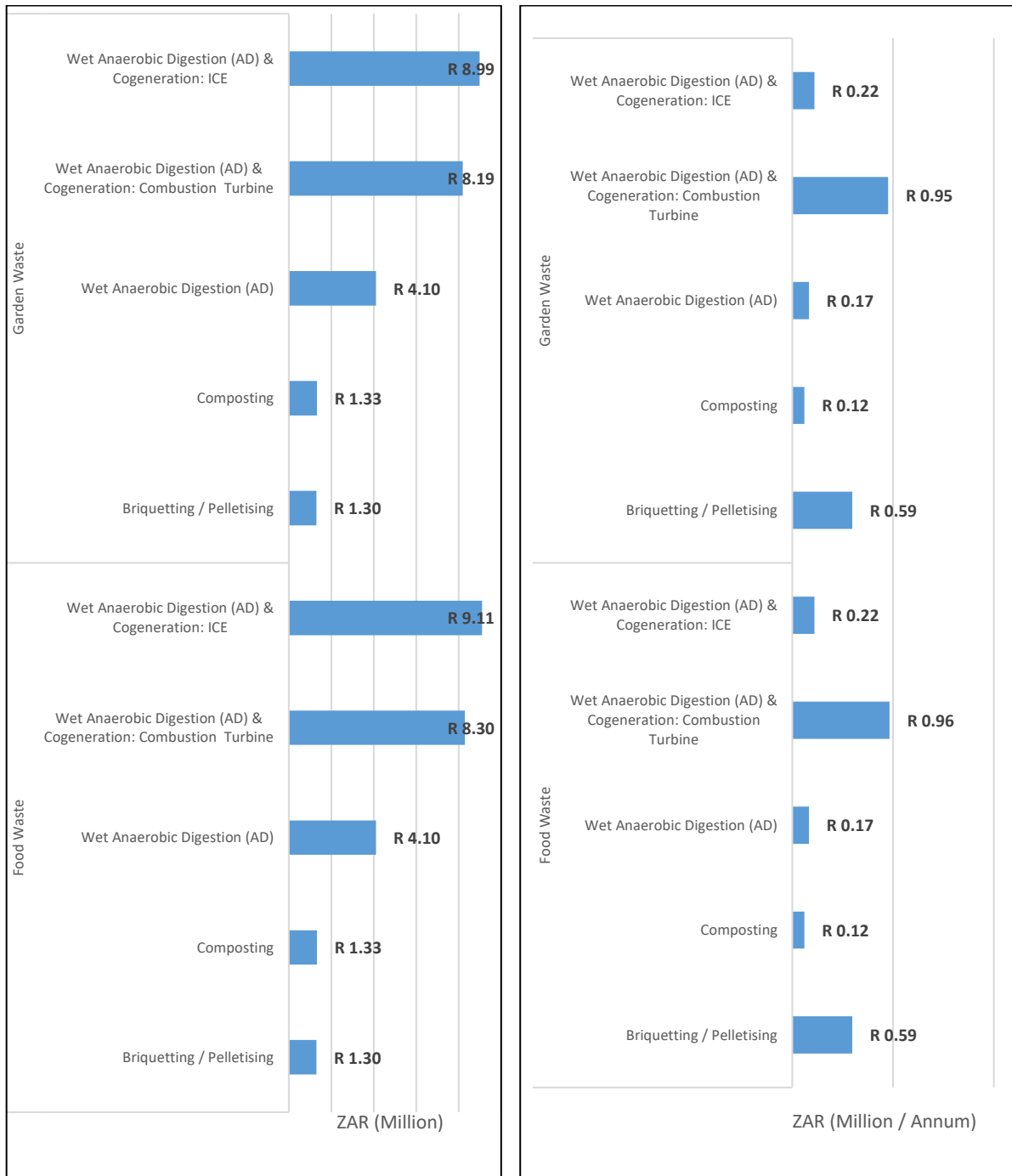


Figure 5-3: Guidance and Overview: Mean TCI (left) and TPC/a (right)

The third category that forms part of the general Guidance and Overview section is the Environmental & Social section, including information on carbon dioxide reduction, employment, and waste (by-products) generated. Examples are shown in Figure 5-4 to Figure 5-6.

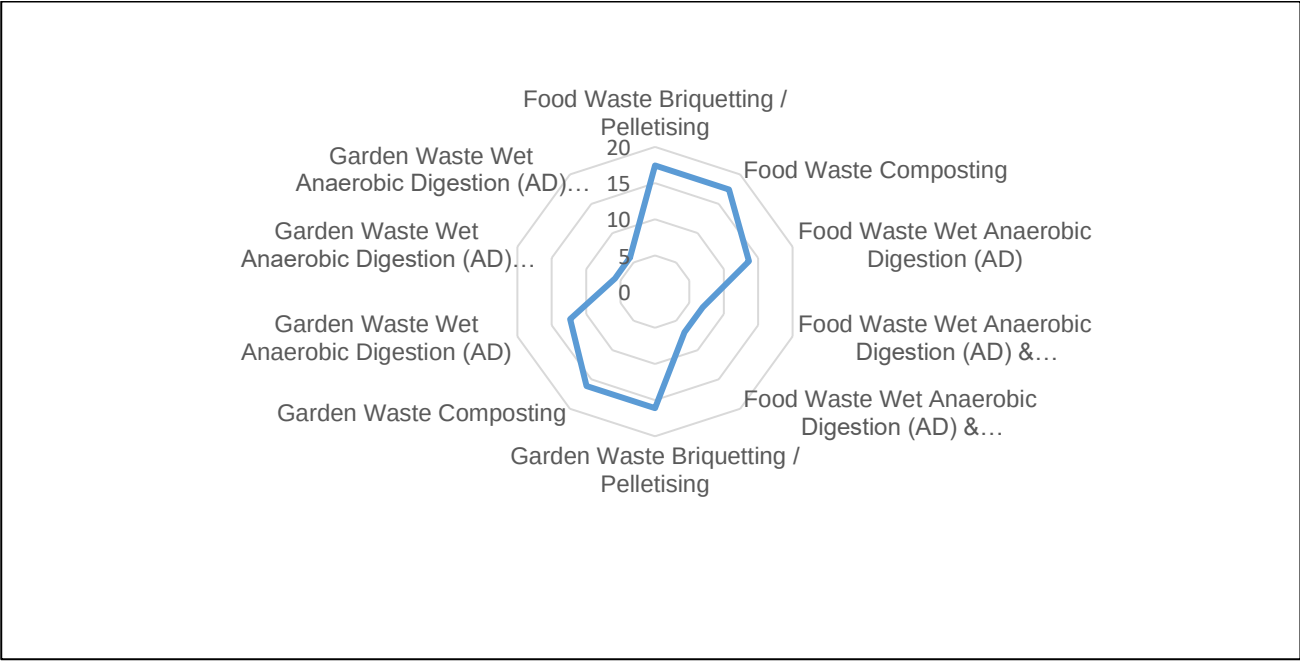


Figure 5-4: Guidance and Overview: Carbon dioxide reduction in tonne/day

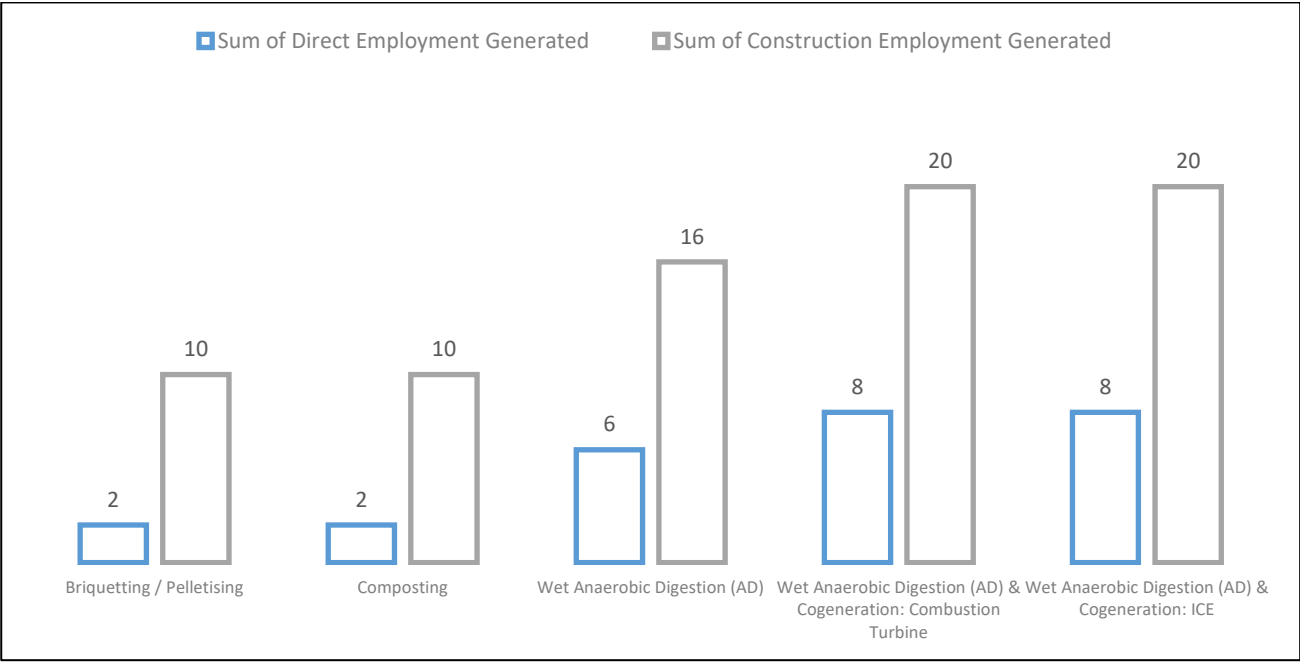


Figure 5-5: Guidance and Overview: Employment generated

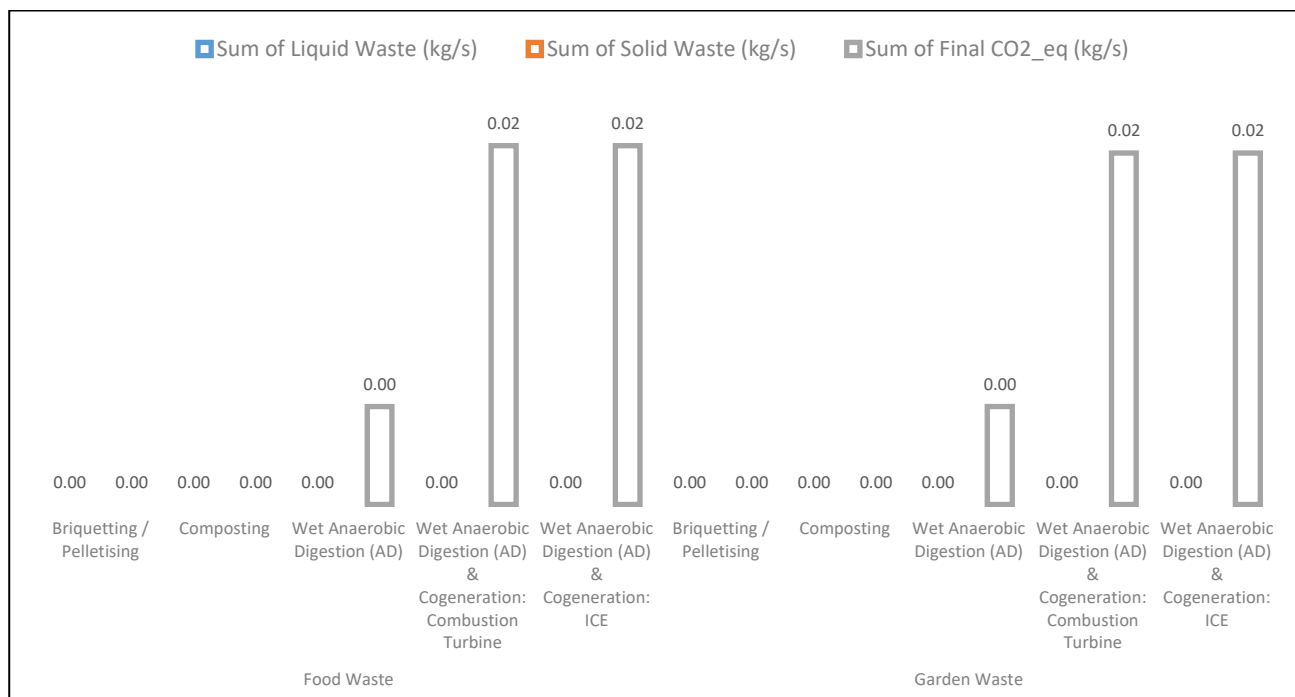


Figure 5-6: Guidance and Overview: Waste generated

5.5.2 Synthesis of the Risk-based Guidance Functions

The Risk-based Guidance functions are made up of specific Risk-based Considerations as well as Regulatory Considerations. The synthesis of these aspects are discussed in more detail in this section.

5.5.2.1 Specific Risk-based Considerations

The Specific Risk-based Considerations section provides prompts to consider certain risks related to certain aspects of the project or process. To provide prompts, specific questions are asked based on the sustainability assessment success factors for development projects, as given by Zurbrügg *et al.* [21]. Answers may be selected from a drop-down list. Based on the answer, risks and recommendations are provided as outputs of the decision support system model, as shown in Figure 5-7.

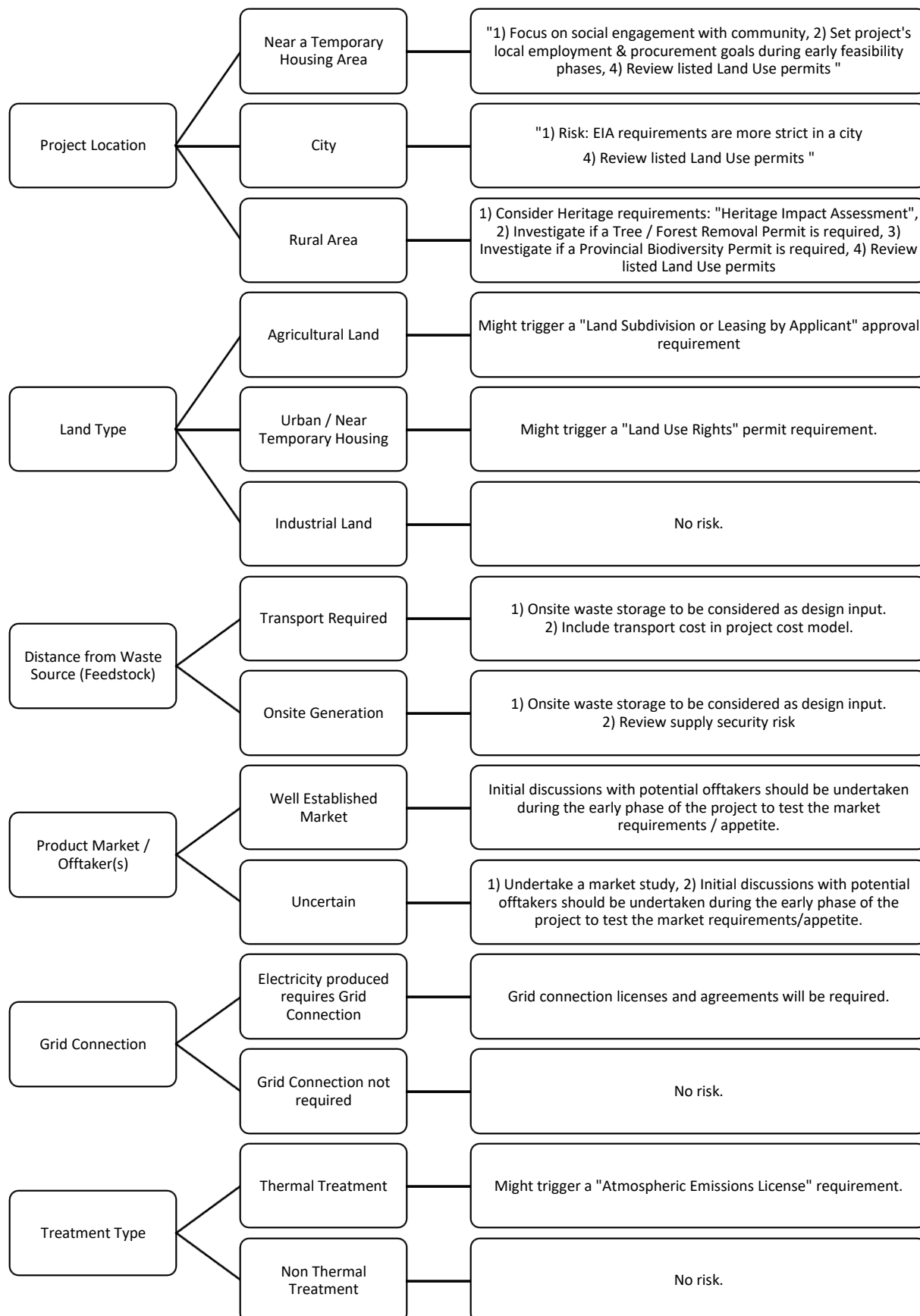


Figure 5-7: Specific Risk-based Considerations input and response options (left: category; middle: potential responses; right: risk outputs and recommendations)

To assist with risk mitigation (even though most of the recommendations can only be addressed to the required level of accuracy during the later project phases), the cost implication of the risk outputs is calculated by the decision support system. This allows for the inclusion of the required provisions to address the risks in the project's financial planning. The costs are included by adding to the standard contingency (percentage-based allowance) recommended by the decision support system. To calculate the financial implications of the risks, both the preparation costs and administration costs for licences, approvals, tests, studies or authorisations are included in the model based on cost baselines given in the applicable regulations as well as industry-based preparation costs.

An example of a Specific Risk-based Considerations scenario as well as the resultant contingency recommendation is shown in Table 5-8.

Table 5-8: Example of results of the Specific Risk-based Considerations section

Category	Inputs:	Risks and Recommendations:
Project Location	Rural Area	1) Consider Heritage requirements: Heritage Impact Assessment 2) Investigate if a Tree or Forest Removal Permit is required 3) Investigate if a Provincial Biodiversity Permit is required 4) Review listed Land Use permits
Land Type	Industrial Land	No risk.
Distance from Waste Source (Feedstock)	Transport Required	1) Onsite waste storage to be considered as design input. 2) Include transport cost in the project cost model.
Product Market / Offtaker(s)	Uncertain	1) Undertake a market study 2) Initial discussions with potential off-takers should be undertaken during the early phase of the project to test the market requirements or appetite.
Grid Connection	Grid Connection is not required	No risk.
Treatment Type	Thermal Treatment	Might trigger an Atmospheric Emissions License requirement.
Recommendation:	Include risk mitigation actions in the project contingency. Contingency percentage to be increased to:	15%

5.5.2.2 Regulatory Considerations

The regulatory considerations include a list of regulations that are given for consideration [172]. This includes the most relevant regulations that are likely to apply to the processes/operations that are included in the decision support system. With guidance from the Specific Risk-based Considerations section, the listed regulations may be further investigated (Figure 5-8), if required.

Standard Environmental Permits
•Atmospheric Emissions - Basic Assessment - Heritage - Protected Species Removal - Protected trees and forests - Scoping and Environmental Impact Report - Use of coastal zone property - Waste discharge from land to marine environment - Waste Management - Water Use
Land use permits
•Building plan approvals and permits - Land subdivision / leasing by applicant - Land use rights application
Other Permits
•Hazardous Substances - Permit for Abnormal Loads
Grid Connection
•Commissioning Tests - Customer Use of System Agreement - Dry run test results - Final Grid Code compliance testing - Generation licence - Grid Code compliance matrix - Grid Code compliance simulation study - Grid Connection Budget Quotation - Grid Connection Cost Estimate Letter - Operating Agreement - Power Purchase Agreement (PPA)
Gas
•Gas Acts - Petroleum Pipeline Levies Act - Petroleum Products License - Regulations (IPP) - Regulations relating to Licence Fees
Health and Safety
•Compensation for Occupational Injuries and Diseases Act - MHSA: Code of Practice - MHSA: Form 1 Application for Prospecting Permit - MHSA: Form 2 Application for Mining Authorisation - Occupational Health and Safety Act and regulations - OHSA: Construction Regulations Section 3 / Section 4 - OHSA: Electrical Installation Regulations & Annexures - OHSA: Major Hazard Installation Regulations

Figure 5-8: Regulatory considerations included in the decision support system

5.6 Summary

As explained in this chapter, the WUDSS was synthesised around a specific set of requirements to address the gap in the literature. The calculations for the problem domain of the theoretical model that forms part of the waste utilisation decision support system is explained in detail in this chapter. The system is designed to be used to test and compare the overall viability of South African decentralised business development within the waste utilisation environment at concept level. The system takes into account technical, environmental, legal, financial, social and risk-based aspects to allow for a complete overview of the scenario being considered. The intended users for the decision support system are SMMEs and the outputs of the system can be used as direct input into the next phase of project development (pre-feasibility or feasibility).

Chapter 6: Results and Discussion

6.1 Introduction

The mathematical modelling framework of the WUDSS is explained in some detail in Chapter 3, while the detail of the problem domain as well as the calculations are explained in Chapters 4 and 5. The goal of this chapter is to evaluate the Waste Utilisation Decision Support System (WUDSS) described in the previous chapter. To evaluate the proposed decision support system, a prototype system was created as a final product of the study.

The main outputs of this prototype system, including the outputs of both the Process Calculations and the Integrated Optimisation Model, will be analysed and compared to information from literature and case studies to test the accuracy of the results. All evaluations were performed within the context of the system’s development, keeping in mind the intended users as well as the goal of the system. Lastly, the system will be assessed against the criteria set for decision support tools or systems.

6.2 Evaluation Methodology and Approach

To evaluate the overall performance of the decision support system, a two-tier approach will be used. This will include verification and validation, as shown in Figure 6-1.

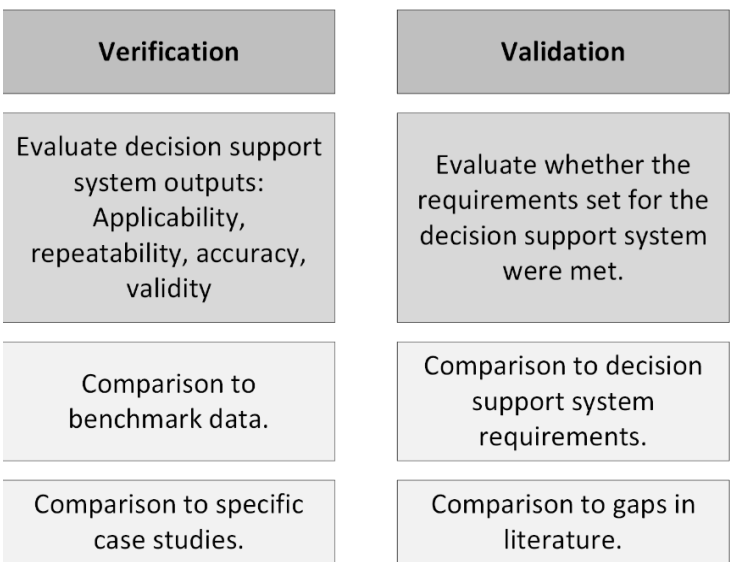


Figure 6-1: Methodology for verification and validation of results

Firstly, verification will be accomplished by testing the accuracy of the decision support system outputs for the Process Calculations against literature data as well as real project data as follows:

1. Comparison of the prototype system's outputs against benchmark data, including:
 - a. Accepted specific cost ranges
 - b. Specific cost values from historical projects, literature, or case studies
 - c. Accepted parameters for specific outputs, e.g., employment generation or labour, carbon dioxide equivalent, land requirements, etc.
2. Comparison of the prototype system's outputs against case studies, including:
 - a. Simulation of case study scenarios and direct comparison of results.
 - b. Sensitivity analysis on scenarios and results.

South African data and case study scenarios will be used in all cases to provide valid evaluation outcomes. For the decision support system to be adequate for concept level comparison and investment decision making, the financial outputs of the Process Calculations should fall within a 30 to 50% accuracy range.

Verification for the Integrated Optimisation Model will be accomplished by running specific scenarios through the optimisation model and comparing the outputs to first principle calculation results. Since this includes a direct comparison, the selected configuration from the Optimisation Model and first principle results (ideal case) must be the same.

For both the Process Calculations and the Integrated Optimisation Model, the test verification method is used as basis of the verification process, as explained in the System's Engineering Guidebook [173].

6.3 Verification of the Study

To evaluate the performance of the decision support system developed as part of the previous chapters, a circular approach will be used as shown in Figure 6-2. This approach will include testing the prototype system's outputs against general data as well as specific test scenarios. Where gaps are identified, updates will be made to the decision support system assumptions or calculations until the results fall within the expected error margin.

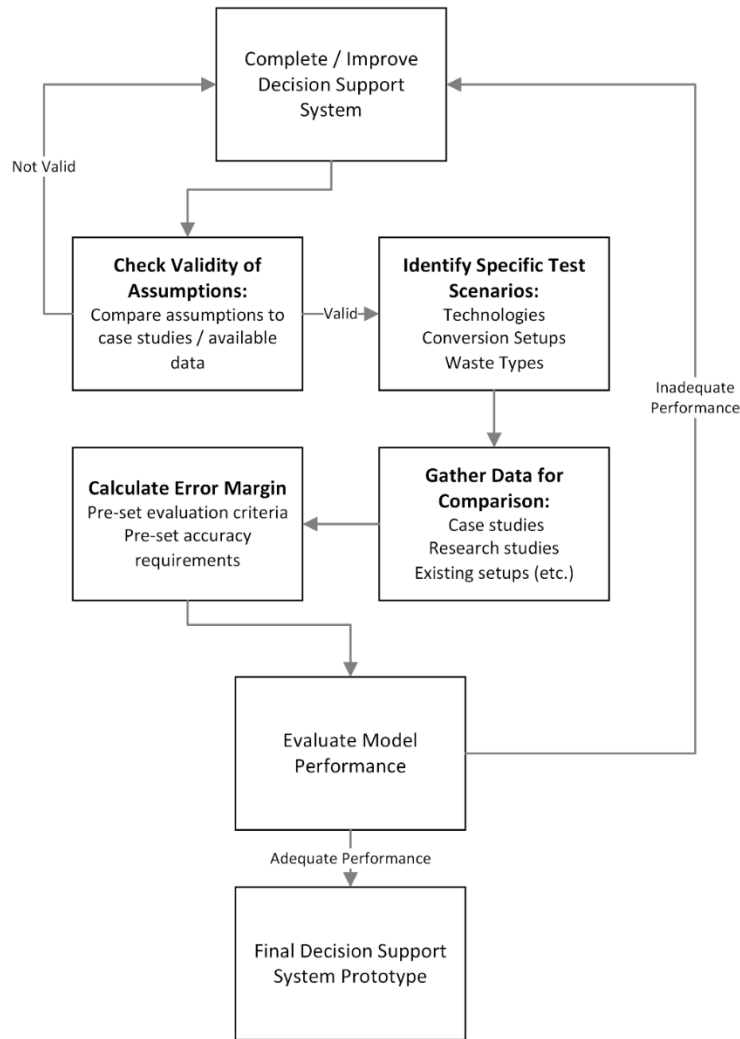


Figure 6-2: Decision support system evaluation and optimisation procedure

6.3.1 General Decision Support System Verification

The general verification of the decision support system's Process Calculations focuses on the two most important measurable and comparable outputs, namely mass balance outputs and financial verification (CAPEX). These outputs are selected for the following reasons:

- Verifying the mass balance tests the accuracy of the technical outputs of the Process Calculations. Though mass balance results are expected to vary depending on feedstock composition as well as numerous design and process-specific factors, a general expected range of outputs can be identified for each configuration by considering results from various literature-based sources.
- Verifying the financial results for the Process Calculations is vital for evaluating the accuracy of business case outputs. The general financial verification is limited to a specific cost (CAPEX) comparison of the decision support system outputs to literature outputs. Due to the requirement for local (South African) literature outputs, configuration comparisons were limited based on data availability.

6.3.1.1 Mass and Energy Balance Verification

To verify the mass and energy balance outputs of the decision support system, the product fractions produced per tonne of waste or intermediate product input are compared to accepted literature and benchmark data. The result of this comparison is shown in Figure 6-3.

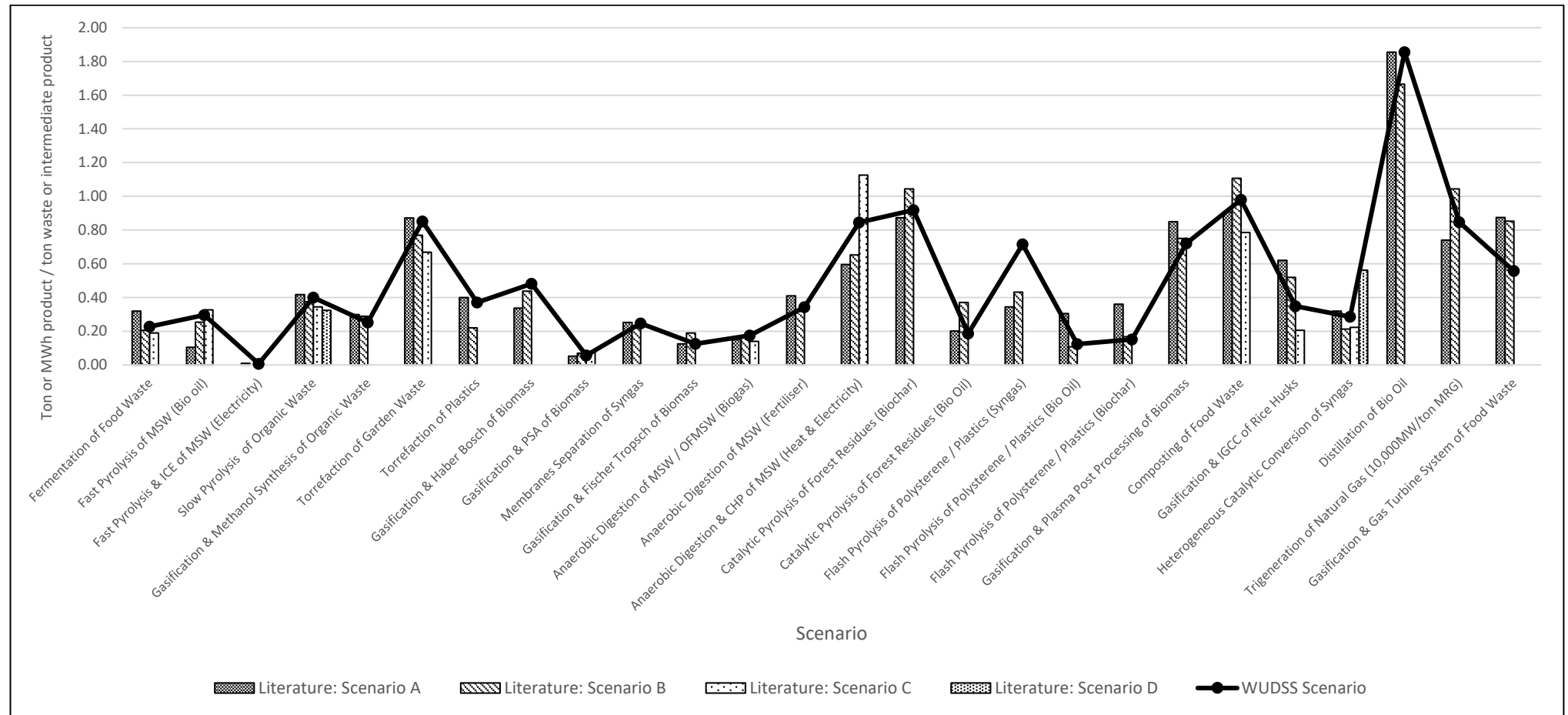


Figure 6-3: Mass and energy balance comparison to literature data

All data used for the verification is given in Appendix E with reference to the original sources.

Differences in the mass balance outputs are expected when comparing the literature scenarios and the decision support system scenarios due to:

- Differences in feedstock compositions for mixed waste streams
- Differences in process designs, which could lead to differences in conversion, product quality or product fractional distributions
- Differences in base assumptions or prioritisation (e.g., the inclusion of recycle streams, water recovery, and emission management, which could lead to improved or reduced conversion)

Allowing for the above-mentioned variations, it is nevertheless expected that the decision support system outputs be within the correct general range. In this case, the expectation of accuracy is within 30 to 50% as per the concept level requirement, with underestimated results being preferred to allow for a conservative approach.

Of the scenarios shown in Figure 6-3, 94% of the 63 values fall within the required accuracy limits. Of the 6% of the total data points that fall outside the required accuracy ranges, 3% are underestimated, adding to the conservative approach, and 3% are overestimated. This equates to two data points being overestimated, which include the flash pyrolysis of polystyrene and the fast pyrolysis for MSW to bio-oil. In both cases, the inaccuracy can be attributed to significant compositional differences between the feedstock considered by the literature scenario and the feedstock considered by the decision support system. Furthermore, for both cases, other literature scenarios are included that correlate better to the decision support system outputs. For this reason, these two data points can be seen as outliers.

6.3.1.2 Financial Verification

To verify the financial outputs of the prototype WUDSS, the CAPEX information provided by the system is compared to benchmark data for accepted ranges as well as similar projects and facilities in South Africa. This comparison is dependent on data availability for South Africa specifically, therefore fewer scenarios are modelled. For ease of comparison, the CAPEX values are converted to specific costs and MSW organic fraction is used as reference feedstock. The results of the analysis can be seen in Figure 6-4.

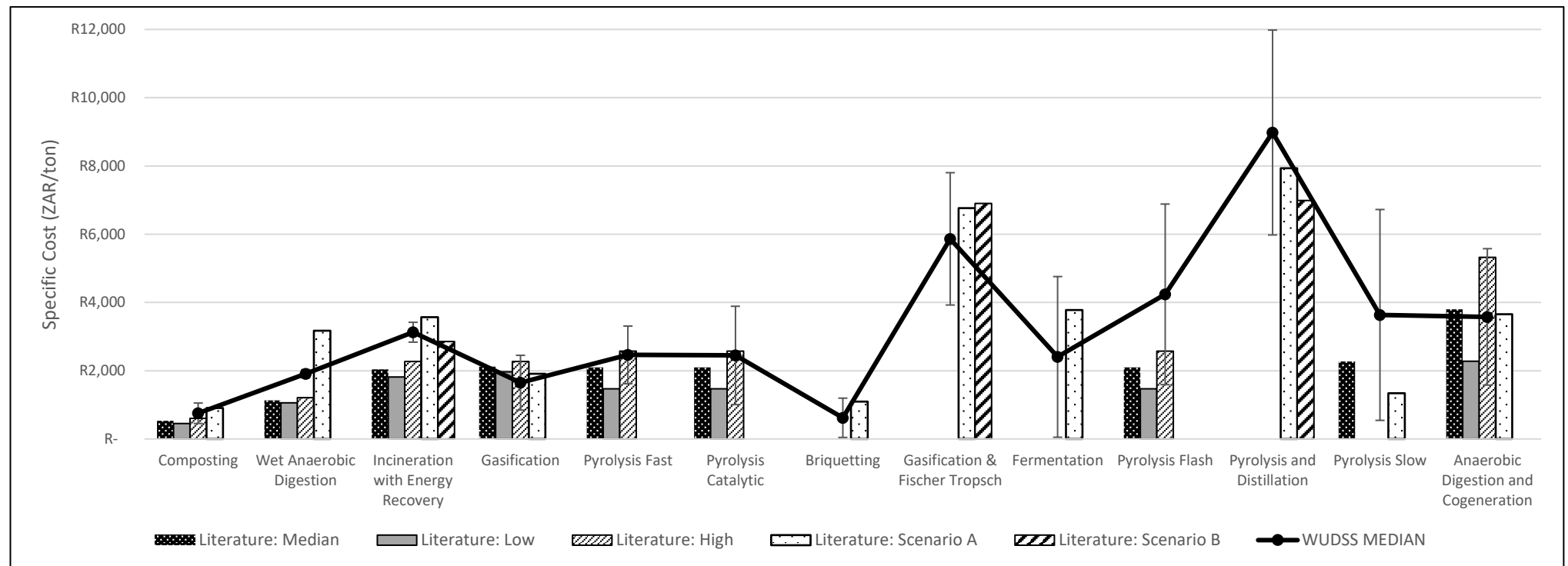


Figure 6-4: Specific cost comparison based on benchmark data

Further analysis of the prototype's specific cost outputs in comparison to the benchmark data showed that a total of 82% of the available data points fell within the CAPEX ranges predicted by the decision support system. The data points falling outside the predicted ranges belonged to two processes, namely anaerobic digestion and incineration with energy recovery. In both cases, the median cost predicted by the decision support system fell within the range predicted by the benchmark data, which shows a strong correlation between the decision support system results and existing data.

However, for both anaerobic digestion and incineration with energy recovery, the difference between the maximum expected CAPEX and minimum expected CAPEX given by the system is relatively small. Increasing this range might lead to more accurate results as well as a better representation of the varying technology or process design options.

Further analysis of the anaerobic digestion scenario was conducted to verify the outputs. Anaerobic digestion with cogeneration was selected because of the availability of reliable information related to these technologies. Biogas-related technologies have been investigated in detail in South Africa in recent years due to international interest and local governmental push (including, but not limited to, interest caused by the Renewable Energy Independent Power Producer Procurement Programme). Numerous projects have been developed around biogas technologies in South Africa when compared to other technology types which form part of this prototype's configurations.

Based on a long history of investing in biogas projects, the Industrial Development Corporation of South Africa (IDC) has developed a benchmark range for facility costs per MW. The specific cost outputs of the decision support system compared to the IDC's benchmark expected cost range [174] is shown in Figure 6-5. This includes decision support system outputs for wet and dry anaerobic digestion of various waste feedstocks, combined with ICE and combustion turbines.

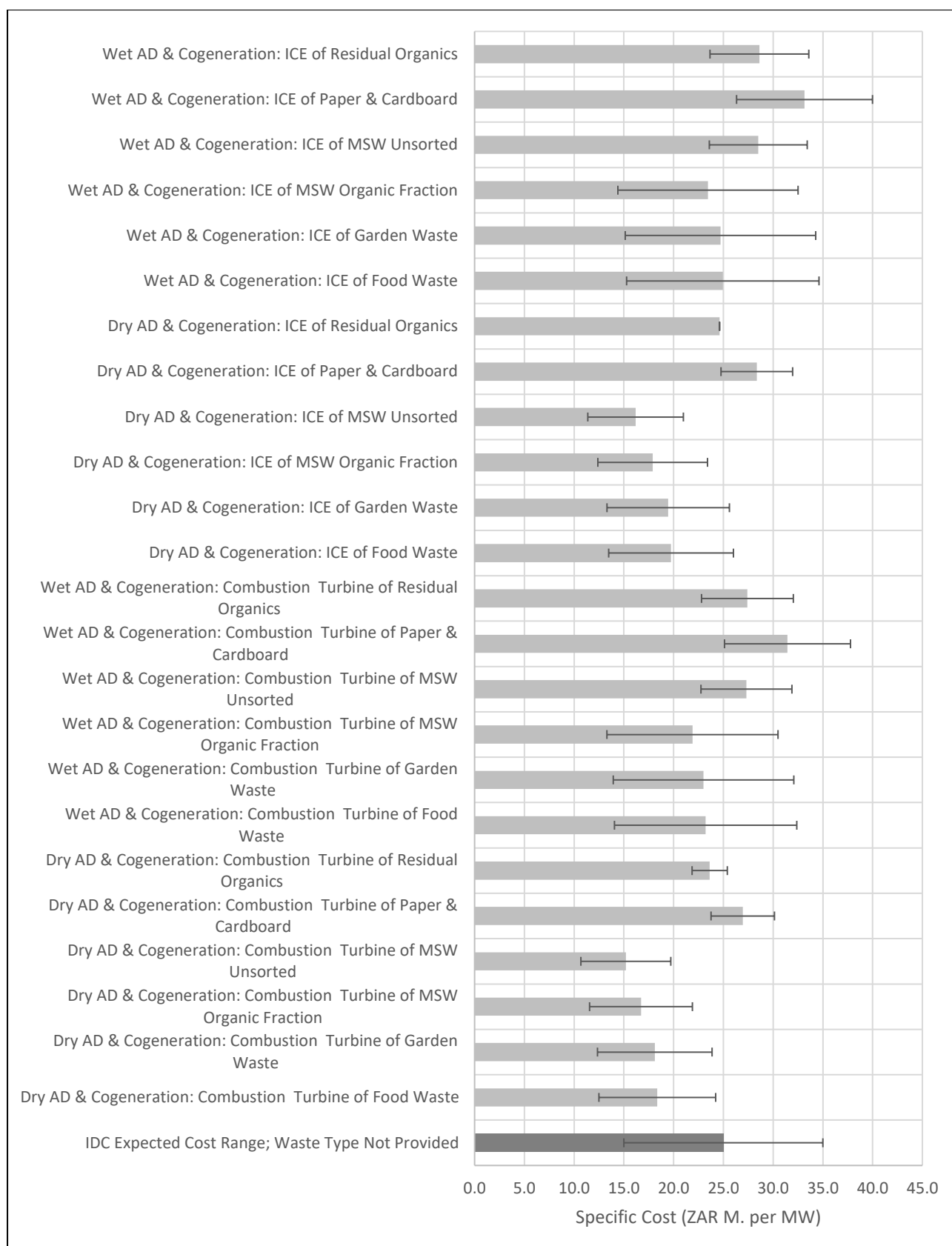


Figure 6-5: IDC expected benchmark cost range for biogas facilities versus WUDSS outputs

6.3.2 Verification of System Outputs using Case Studies

In this section, case studies are considered to evaluate the performance of the decision support system. To allow for an accurate comparison, the case study scenarios are replicated as closely as possible by the prototype system without changing any process design or technical assumptions. The case studies selected must abide by a specific criterion, namely that considered cases must fall within the specification of the decision support system, including only:

- Locally based (South African) facilities or scenarios
- Facilities processing less than 10 tonnes/day of waste
- Facilities processing general solid waste (not hazardous or construction waste)
- Decentralised facilities

Due to the limited nature of small-scale waste utilisation projects in South Africa, three case studies were selected for the system verification. This limited availability of data in this field once again proves the gap in the research, since very little attention has been given to small-scale, decentralised waste utilisation in South Africa up until the present. It should be noted that more data is available regarding small-scale anaerobic digestion facilities, due to the recent positive attention given to this technology. However, little value was seen in adding additional case studies considering this technology, since anaerobic digestion is already well-studied in the cases considered.

6.3.2.1 Case Study 1: Anaerobic Digestion and Internal Combustion Engine (ICE)

A study done by Purser [175] considered a small-scale anaerobic digestion plant for the City of Cape Town. Data was collected from AGAMA Energy on their anaerobic digestion facility which included a screening system, 230 m³ non-stirred digester and a setup for electricity generation. The facility processes 3 tonnes/day of organic waste which is either source-separated or separated from MSW via the screening system on site.

For the case study comparison, the waste type selected as input is MSW Organic Fraction. The case study conditions considered as input to the prototype are shown in Table 6-1.

Table 6-1: Case study 1: Anaerobic digestion and ICE inputs

Description	Value
Base Year	2010
Feed Type	MSW Organic Fraction
Throughput (tonne/day)	3
Carbon Credits Sold (ZAR/tonne CO ₂ _eq)	65 (100% sold)
Tipping Fees (ZAR/ton)	303.88
Land Cost & Construction Cost (ZAR/ha)	1,150,000
Facility Lifespan (years)	10
Annual Inflation	5%
Product Selling Price (Electricity, ZAR/kWh)	0.23
Product Selling Price (Compost, ZAR/ton)	300
Working Capital	Case Study: 5% of Fixed Capital DST: Fixed Costs set to 5% of Fixed Capital to adapt OPEX to TPC/a (insurance, local taxes, royalties included)

The results obtained from the replication of the case study are given in Figure 6-6. Since the anaerobic digestion process type is not given as part of the case study description, the results from both wet anaerobic digestion and dry anaerobic digestion configurations are provided for comparison.

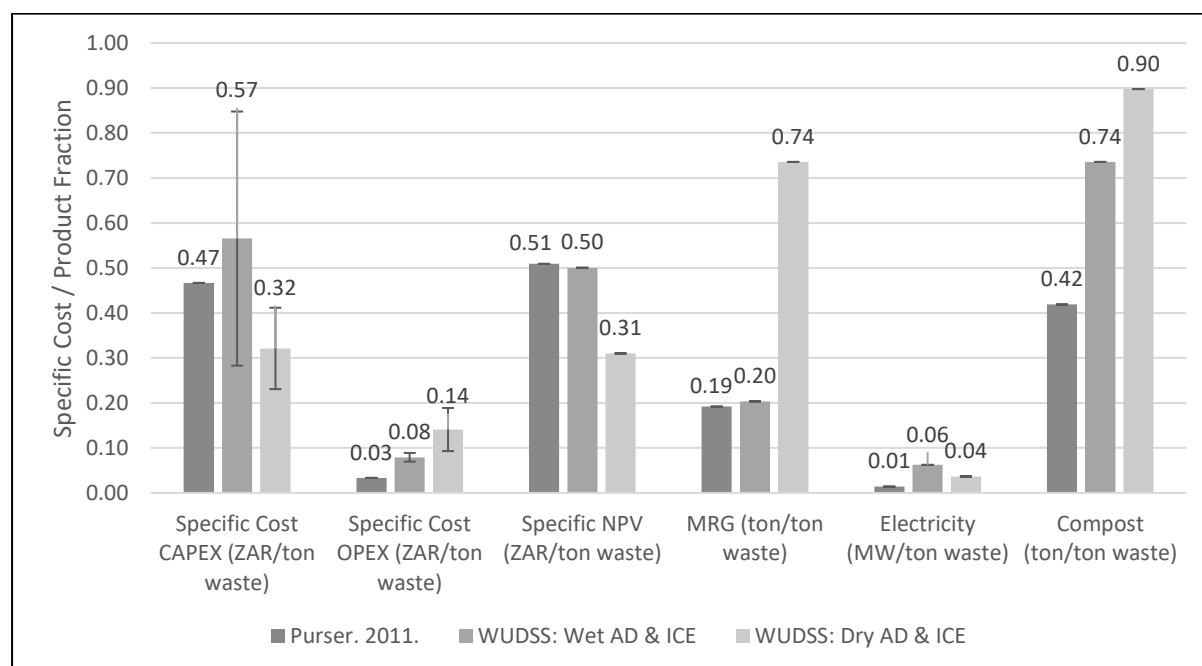


Figure 6-6: Specific cost and product fraction results from case study 1

The results from the wet anaerobic digestion of MSW organic fraction waste correlated better with the case study outputs compared to the results of the dry anaerobic digestion process. The following should be noted:

- Both the CAPEX, NPV and MRG product fraction results compare accurately to the case study data, with error values falling within the required bounds.
- Some inconsistencies are interesting to note, such as the difference in specific OPEX, electricity and compost production. This is due to the process design differences between the two systems. In the case study process, a fraction of the product stream is used for internal energy to reduce the OPEX requirements, which also reduces the saleable product quantity. This in turn reduces the product stream outputs. Interestingly, over the 10-year period being considered for this scenario, the difference in OPEX (higher for DST) and saleable products produced (higher for DST) results in a similar financial model output.

Though further financial metrics are not available for the case study, additional information is generated by the prototype for the wet anaerobic digestion scenario as follows:

- IRR: 17%
- PBP: 5 years
- Expected TCI cost: ZAR 2.23 M to ZAR 3.93 M
- Expected TPC/a: ZAR 0.21 M to R0.27 M per annum
- Direct job creation is expected to be around 8 jobs with an additional 18 jobs being created during the construction period.
- The cost of the anaerobic digestion process contributes around 75% of the total cost, with the post-processing (ICE) contributing the remainder of the costs.
- Using the Guidance – Risk Management function of the decision support system, it is found that the contingency required to manage perceived risks for the project is 20%. This approach assumes that the project is in its early stages and that certain inputs are unknown, for example, the EIA requirements for the city-based location. If included, this increase in contingency changes the capital metrics of the project as follows:
 - NPV: ZAR 1.37 M.
 - IRR: 16%
 - PBP: 6 years

Since the NPV produced by the prototype correlates well with the case study value (ZAR 1.527 M. for the case study compared to ZAR 1.501 M. predicted by the decision support

system), an analysis was done around the sensitivity of the decision support system capital budgeting metrics to specific input parameters. The selected parameters include the cost of tipping fees, the contingency percentage allowed for as per the risk-based approach, the waste throughput value, and the selling price of electricity. The values for each parameter were varied based on percentage to allow for direct comparison of outputs, as seen in Table 6-2.

Table 6-2: Input values per parameter used for the sensitivity analysis

Percentage of Base Case Input Value	Tipping Fees (ZAR/ton)	Risk-based Approach (Contingency %)	Throughput (Tonne/day)	Selling Price of Electricity (ZAR/kWh)
60%	182	12%	1.80	0.14
80%	243	16%	2.40	0.18
100%	304	20%	3.00	0.23
120%	365	24%	3.60	0.28
140%	425	28%	4.20	0.32

Figure 6-7 shows the results of the sensitivity analysis for NPV and IRR based on the percentage change of the specific input parameter values when compared to the base case.

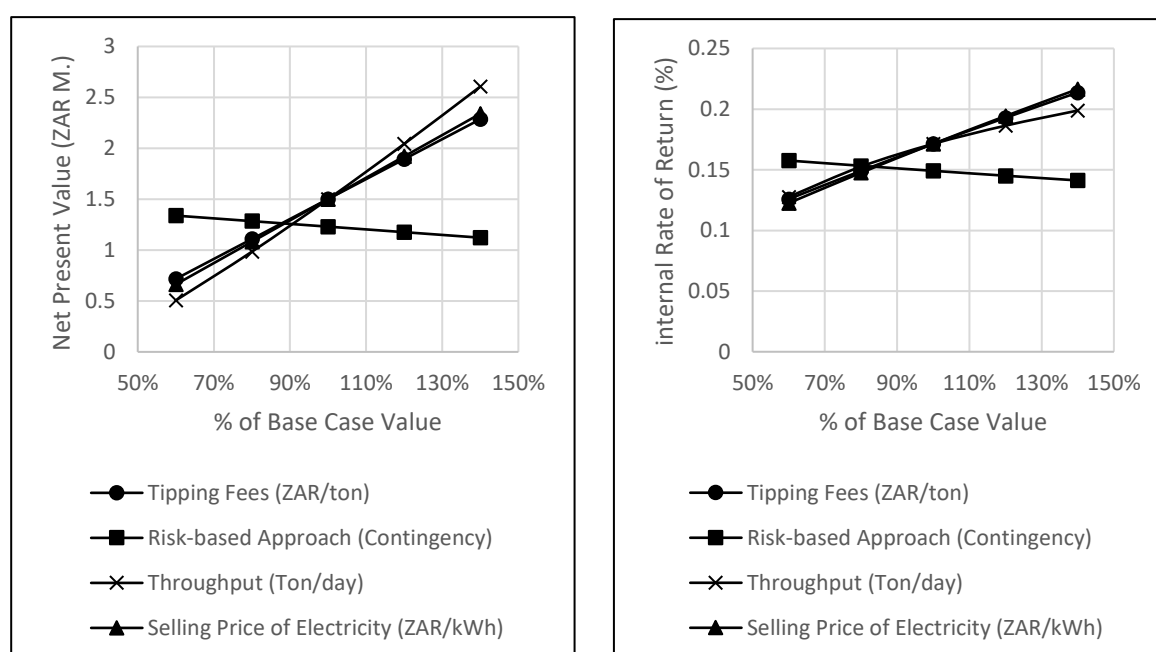


Figure 6-7: Sensitivity analysis results per parameter for NPV (left) and IRR (right)

As seen in Figure 6-7, the changes in parameter input values have a more pronounced effect on the NPV output compared to the IRR output. This is reiterated in Table 6-3, which shows the slope values for the sensitivity analysis results. The highest sensitivity for the NPV value is towards changes in the waste throughput, followed by changes in the selling price of electricity. For the IRR value, the highest sensitivity is towards the selling price of electricity, followed by the number of tipping fees allowed for processing the waste stream. The lowest sensitivity for both the NPV and IRR values is toward changes in the contingency included in the cost, which implies that the risk-based approach for capitalising on the risk costs during the early phases of the project has a small effect on the capital budgeting metrics when compared to the other parameters.

Table 6-3: Line slope values for the sensitivity analysis results

Input Parameter	IRR Slope	NPV Slope
Tipping Fees (ZAR/ton)	0.11	1.96
Risk-based Approach (Contingency)	-0.02	-0.27
Throughput (Tonne/day)	0.09	2.63
Selling Price of Electricity (ZAR/kWh)	0.12	2.10

6.3.2.2 Case Study 2: Biochar Production from Garden Waste

This case study considers the production of high carbon biochar (torrefied biomass) from garden waste. The overall analysis is based on a study by Konz *et al.*, [176] on the potential to produce biochar in South Africa. Though this study summarises various value chains for producing biochar under the general category of pyrolysis processes, it should be noted that the specific configuration considered for this case study is a torrefaction process. This configuration considers the mobile kiln technology developed by Vuthisa, where agricultural waste is used to produce high carbon biochar via low-temperature conversion using extended residence times (12 hours for the case being considered), and no liquid product (bio-oil) is produced.

The case study considers the scenario where Vuthisa's mobile process is used to produce biochar using agricultural waste at the harvesting site (no transport costs). For simulation of the case study scenario via the prototype system, garden waste was used as feedstock. Input values used are shown in Table 6-4.

Table 6-4: Case study 2: Biochar production inputs

Description	Value
Base Year	2015
Feed Type	Garden Waste
Technology	Torrefaction
Throughput (tonne/day)	0.125
Carbon Credits Sold (ZAR/tonne CO ₂ -eq)	None
Tipping Fees (ZAR/ton)	None
Capacity Factor	68%
Facility Lifespan (years)	15
Annual Price Escalation	5.5%
Annual OPEX Increase	8.0%
Harvesting Cost (ZAR/annum)	41,367
Product Selling Price (ZAR/ton)	6,600
Capital Charges	23.33%, calculated from the debt-equity ratio, cost of equity and interest rate on debt (case study)

Results for the biochar production scenario are shown in Table 6-5. For this scenario, a strong correlation was found between the output values from the prototype compared to the case study outputs. The largest error was found for the carbon dioxide reduction calculation, which had to be recalculated for the prototype system due to baseline differences in the definition of CO₂ Reduction. In this case, the reduction in carbon dioxide equivalent is calculated based on the carbon dioxide potential that is fixed in the biochar instead of the emissions avoided compared to landfilling, which includes the production of methane. The final result comparison produced an error value of 8%, which is well within the requirements for concept design.

Table 6-5: Case study 2 results comparison

Scenario	Konz <i>et al.</i> , 2015.	WUDSS: Torrefaction of Garden Waste	Error (%)
Biochar Production (tonne/day)	0.075	0.080	6%
CAPEX (ZAR)	R21 514	R20 657	4%
Employees (Direct Job Creation)	1	1	0%
CO ₂ Reduction (tonne CO ₂ -eq/tonne product)	1.97	1.82	8%

Results of the financial analysis conducted as part of the case study stated that the given scenario allowed for an IRR value of higher than 15%. From the prototype's outputs, an IRR value of 28% was determined. Furthermore, the following additional results were calculated:

- OPEX: ZAR 54,860/annum
- NPV: ZAR 53,636
- PBP: 4 years
- Job creation during construction: 3

Lastly, equipment cost data provided by the Vuthisa supplier led to a more detailed cost comparison analysis. Actual costs provided for three Vuthisa systems were compared to the outputs of the prototype system. These systems included the BKUI Mini Mason which produces 60 kg/day of biochar, the RING17 which produces 100 kg/day of biochar and the RING20 which produces 125 kg/day of biochar. The cost comparison for these three scenarios can be seen in Figure 6-8, with error values of 4%, 1% and 6% for the abovementioned comparisons respectively.

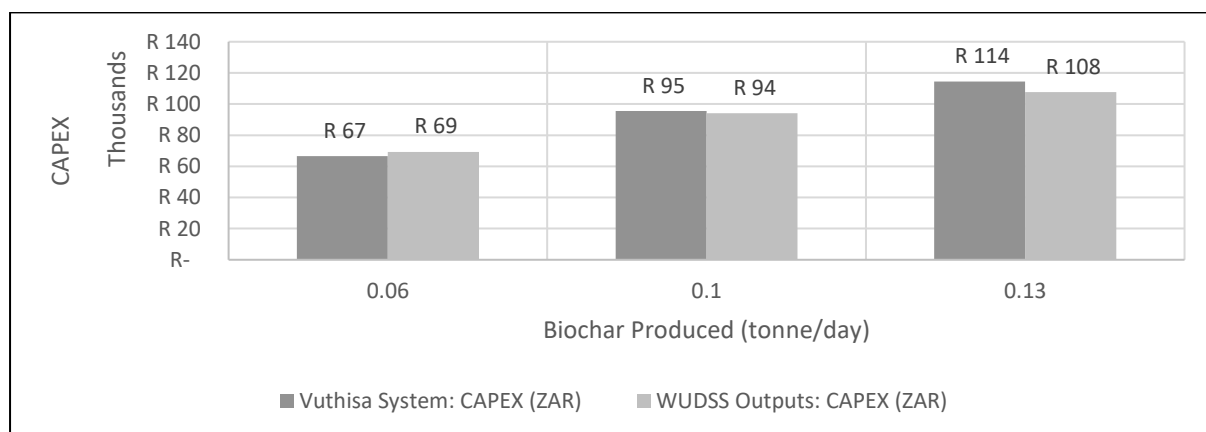


Figure 6-8: Cost comparison results for Vuthisa systems versus prototype outputs

6.3.2.3 Case Study 3: Anaerobic Digestion and Cogeneration (ICE)

As described in Section 6.3.1.2, reliable local information on small-scale anaerobic digestion scenarios is more commonly available due to recent interest in biogas projects in South Africa. For this reason, a second scenario was selected which focuses on anaerobic digestion. In this case, anaerobic digestion coupled with a cogeneration system is being investigated based on both a case study and a generated base case provided by GreenCape in their investigation into the business case for biogas from solid waste projects in the Western Cape [177].

The first case considers a case study of the Bayside Mall anaerobic digestion and cogeneration system. The system, which has since been decommissioned, processed 570 kg/day of food waste generated by the mall and produced electricity and heat, which were

in turn used by the mall to reduce grid electricity requirements. The digester produced about 30,500 m³/annum of biogas using a mesophilic digestion process (35°C to 39°C) requiring a 21-day retention time [177].

The second case used for the anaerobic digestion and cogeneration (ICE) comparison is a Generated Base Case created by GreenCape as a general business case example for a commercial small-scale anaerobic digestion and cogeneration installation. The Generated Base Case is relatively similar to the Bayside Mall case study in that it considers the use of food waste onsite by the waste generator (e.g. mall, hotel or restaurant) [177].

The inputs for the prototype simulations of the two cases respectively are shown in Table 6-6.

Table 6-6: Case study 3: anaerobic digestion and cogeneration (ICE) inputs

Description	Case Study Value	Generated Base Case Value
Base Year	2016	2016
Feed Type	Food Waste	Food Waste
Throughput (tonne/day)	0.57	1.3
Carbon Credits Sold (ZAR/tonne CO ₂ _eq)	0	0
Tipping Fees (ZAR/ton)	395	395
Facility Lifespan (years)	20	15
Annual Inflation	6%	6%
Product Selling Price (Electricity and Heat, ZAR/kWh)	1.47	1.10
Discount Rate	8%	15%
Working Capital	Brownfield project: TPC/a inputs reduced by removing cost addition for items Building and Process, Storage, Site Development. Utilities reduced to 20% of CAPEX. Compost sales removed to match the case study. Half of the heat produced is used to preheat feedstock (reduced sale output). Sales expenses are removed since all electricity and heat are used onsite. For CAPEX: A risk-based approach was applied where the likely requirement for an addendum to the EIA is taken as half the cost of the EIA.	Brownfield project: TPC/a inputs reduced by removing cost addition for items Building and Process, Storage, Site Development. Compost sales removed to match the literature case. Sales expenses are removed since all electricity and heat are used onsite. The cost for the avoidance of diesel fuel (R266,000 per annum) is included as an income stream as per the literature case.

Using the inputs shown in Table 6-6, the two cases were simulated using the prototype.

For the Bayside Mall Case Study, a mass balance comparison is done for product outputs and the results are shown in Figure 6-9. Error-values of between 12% to 31% for the outputs are within the level of accuracy required for concept analysis. Differences are noted due to differences in feedstock compositions as well as the overall process designs of the systems.

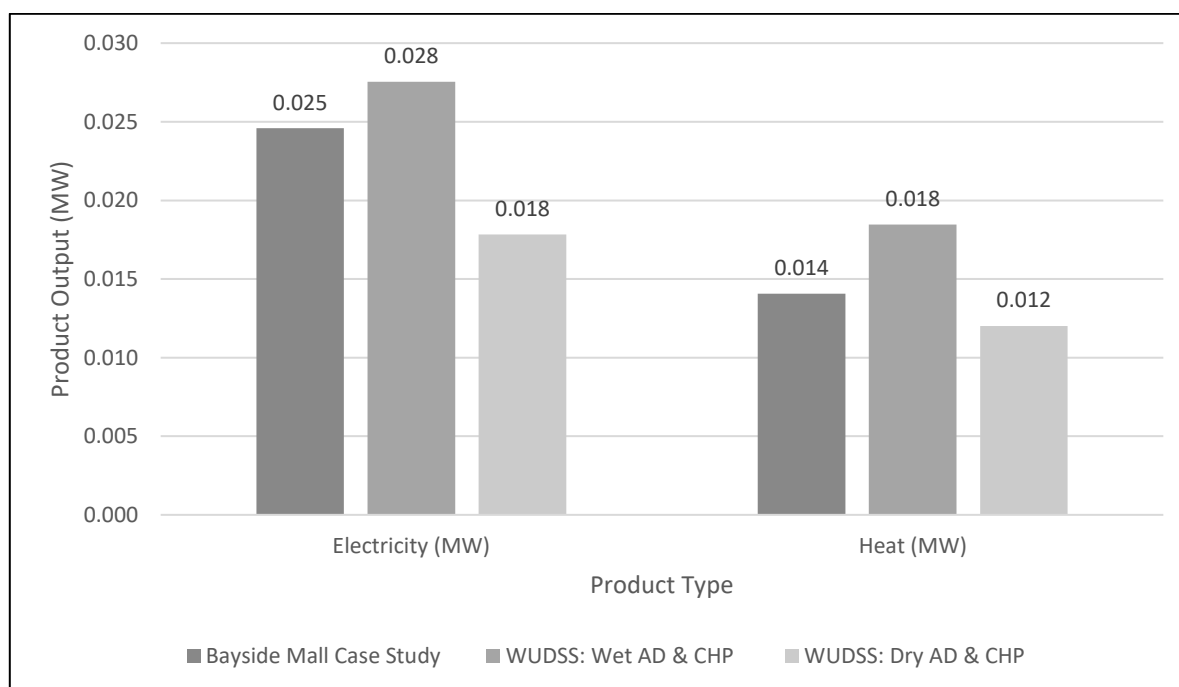


Figure 6-9: Product output for the Bayside Mall case study and the prototype scenarios

Specific cost results for the two cases compared to the outputs of the prototype system for the wet anaerobic digestion and cogeneration (ICE) scenario are shown in Figure 6-10. Though GreenCape's Generated Base Case is in general more pessimistic compared to the case study findings, both cases were found to compare well to the outputs of the decision support system, falling between the minimum and maximum expected values. The error values for the two cases compared to the median specific cost predicted by the prototype system were found to be 0.4% for the Bayside Mall Case Study and 3.8% for GreenCape's Generated Base Case.

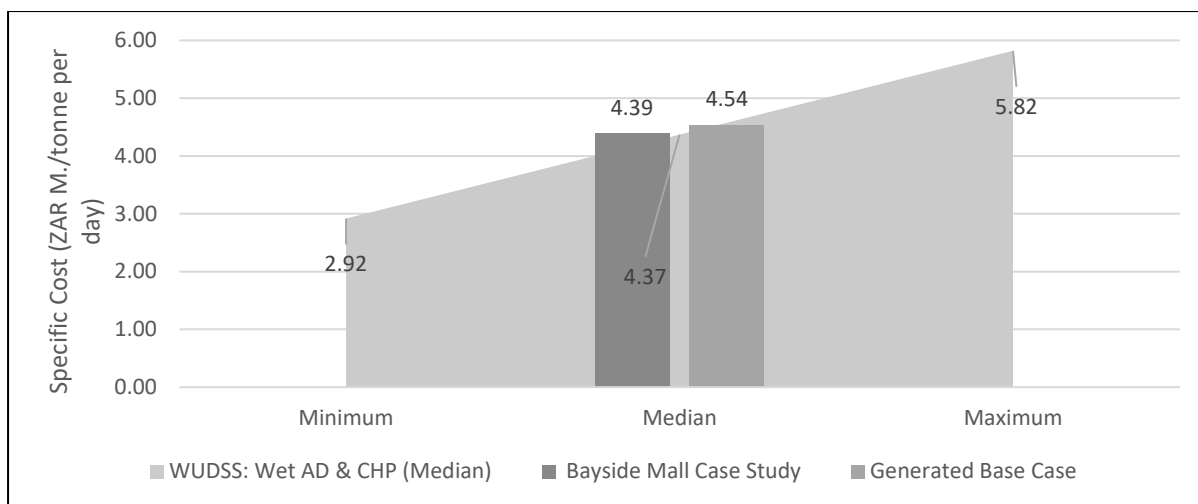


Figure 6-10: Specific cost comparison between WUDSS outputs and reported cases

Furthering the analysis, an economy of scale graph was created for the Bayside Mall Case Study and GreenCape's Generated Base Case using the six-tenth rule. The outputs were compared to the predicted TCI economy of scale graph generated as part of the prototype's outputs.

The results can be seen in Figure 6-11, where both the Bayside Mall Case Study and GreenCape's Generated Base Case fall within the range predicted by the decision support system for both wet and dry anaerobic digestion. For both scenarios, the prototype system median TCI values were again more pessimistic than the studies cases.

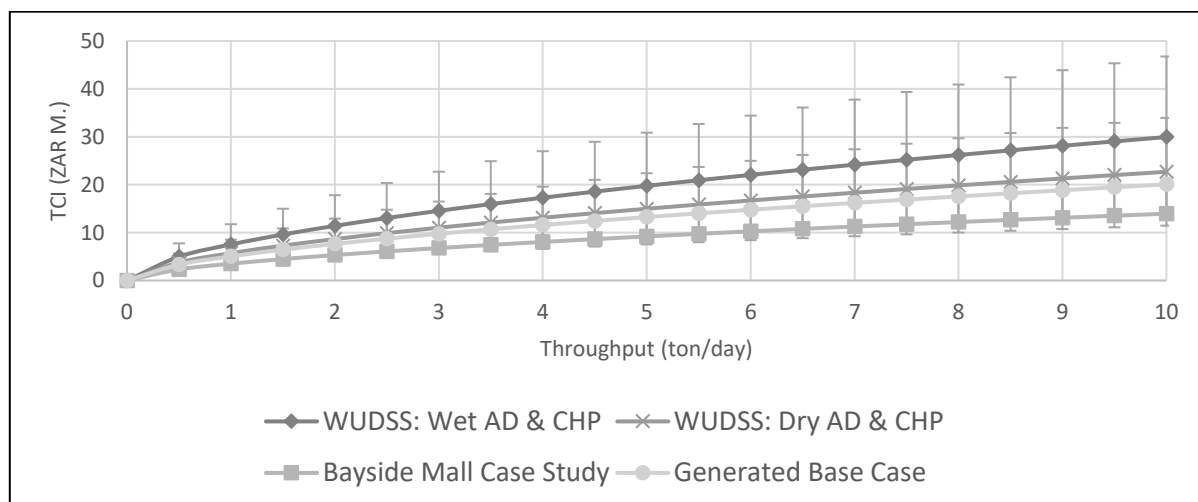


Figure 6-11: Economy of scale graphs for WUDSS configurations versus reported cases

The capital budgeting metrics for the two cases compared to the decision support system outputs are shown in Table 6-7. As seen, the outputs of the configuration for wet anaerobic digestion and cogeneration (ICE) from the prototype compare well to the Bayside Mall Case Study data. For the GreenCape Generated Base Case, the comparison is less accurate, though the accuracy still falls well within the required ranges for a concept study.

Table 6-7: Capital budgeting metric comparison for considered cases

Description	Bayside Mall Case Study			Generated Base Case		
	Case Study	WUDSS: Wet AD & CHP	WUDSS: Dry AD & CHP	Generated Base Case	WUDSS: Wet AD & CHP	WUDSS: Dry AD & CHP
Net Present Value (ZAR M.)	-	1.2	0.9	-1.3	-1.8	-2.6
Internal Rate of Return (%)	10.3%	10.4%	5%	10.0%	12.3%	9.5%
Payback Period	10 years	10 years	14 years	-	8 years	9 years
Direct Job Creation	-	4	4	-	5	5
Construction Job Creation	-	7	7	-	11	11

Lastly, the negative business case presented by GreenCape's Generated Base Case was analysed to test the business viability for two different selling prices of electricity [177]. As seen, the difference between the Generated Base Case and the decision support system outputs for both the IRR and NPV improves as the selling price of electricity increases.

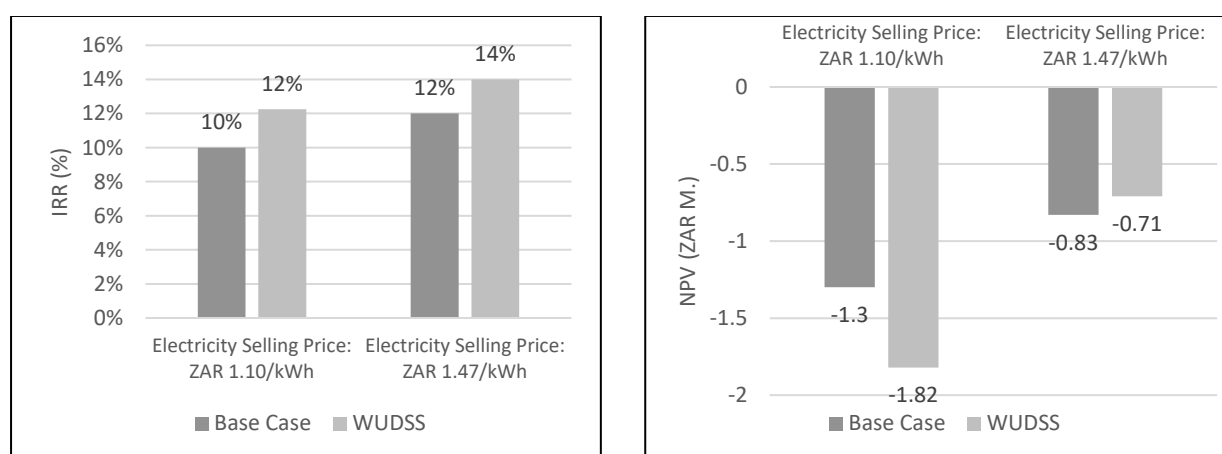


Figure 6-12: Comparison of Generated Base Case and WUDSS outputs for IRR (left) and NPV (right) at different electricity selling prices

Finally, the comment is made by GreenCape that an electricity selling price of around ZAR 2.20 per kWh is required for a financially viable business case. The outputs of the prototype system show a similar conclusion, with the IRR improving to 17% and the NPV improving to ZAR 1.48 M. at the above-mentioned electricity selling price.

6.3.3 Verification of the Integrated Optimisation Model

This section discusses the verification of the MILP Integrated Optimisation Model that is presented in Section 3.4. The verification process is conducted by comparing the results of the optimisation model with the results obtained from a first principle calculated configuration. Both the model results and first principle calculations are discussed in this section.

The number of configurations is limited to simplify the proof of concept of the MILP model. Two cases are considered for verification purposes. The first case considers only the combustion process and its potential end-products, namely steam or electricity, and considers a simplified economic scenario. The second case compares the combustion pathways to briquetting and includes a more realistic and robust economic analysis. Both these cases are discussed in the sections below.

To successfully verify the model, the following conditions must be met:

- Flow conservation must be maintained for the Integrated Optimisation Model, which means the sum of all inputs to a node must equal the sum of all outputs from a node, for all nodes.
- The Integrated Optimisation Model objective function results must exactly equal the results of the first principle calculations.
- The Integrated Optimisation Model must select the superior configuration within the set constraints, as verified using the results of the first principle calculations.
- Both the flow conservation and objective function results must match the first principle calculation results when a constraint is applied to the model.

6.3.3.1 Case 1: Combustion to Steam or Electricity

For the first case, the economic optimisation results are calculated for two configurations that consider the thermal treatment of unsorted MSW via a combustion process to produce steam from water. The steam can then either be sold or utilised directly as an end-product, or it can

be converted further to electricity to be sold as an end-product. Finally, gaseous emissions, solid waste and water are produced as by-products.

The integrated optimisation graph for these configurations is shown in Figure 6-13. For this graph, the included nodes are unsorted MSW ($z_{1,i}$), water ($z_{2,i}$), a dummy node ($z_{3,i}$), steam ($z_{4,i}$), electricity ($z_{5,i}$), solid waste ($z_{6,i}$), gaseous waste ($z_{7,i}$) a dummy energy node ($z_{8,i}$), the incineration process ($\sigma_{1,i}$) and the steam turbine process ($\sigma_{2,i}$).

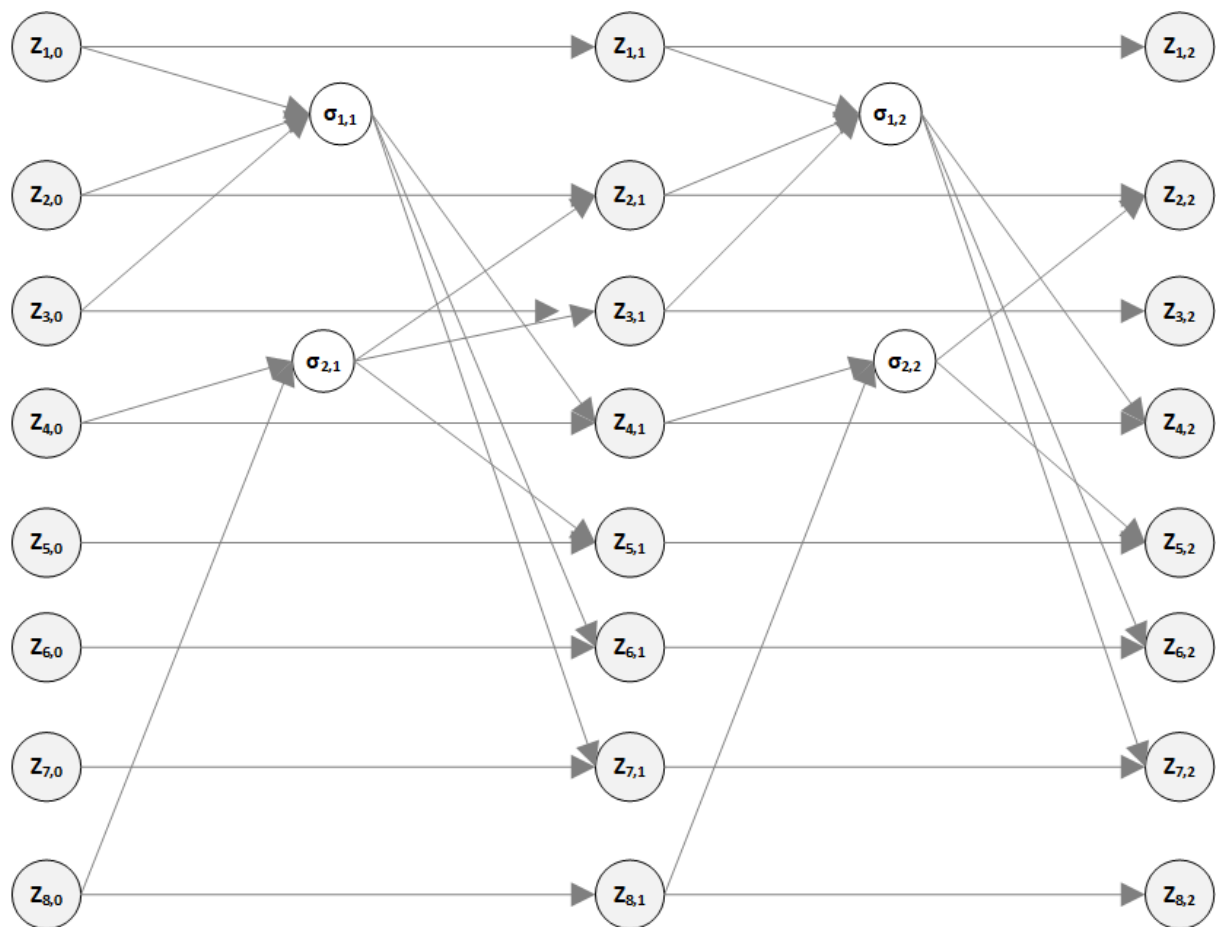


Figure 6-13: Combustion optimisation graph (Case 1)

For this optimisation model, flow conversion governs the balance over the nodes. An energy dependency is included to balance the electricity produced from steam via the steam turbine process. A dummy node ($z_{3,i}$) is included to balance the combustion air as well as the emissions, which are calculated in terms of carbon dioxide equivalent. A dummy energy node ($z_{8,i}$) is also included as an input to balance the electricity production output over the nodes

and to allow for efficiency losses, as explained in more detail in Chapter 3. Finally, the energy and material flows are inserted into the MILP model as two separate groups with a dependency defined over the steam turbine process of 0.18 of energy produced per unit input of steam.

The pre-processed results taken directly from the Process Calculations and used as inputs for the optimisation case are given in Table 6-8.

Table 6-8: Integrated Optimisation Model inputs for Case 1

Arc	Description	Value
X _{1,1,0,1}	MSW (unsorted) to Incineration	0.42
f _{4,1,0,1}	Incineration to Steam	0.46
X _{4,2,0,1}	Steam to Steam Turbine System	1.00
f _{5,2,0,2}	Steam Turbine System to Electricity	1.00
X _{2,1,0,1}	Water to Incineration	0.46
X _{3,1,0,1}	Dummy Node to Incineration	0.12
f _{6,1,0,1}	Incineration to Solid Waste	0.19
f _{7,1,0,1}	Incineration to Gas Waste	0.35
f _{2,2,0,1}	Steam Turbine System to Water	1.00
X _{8,2,0,1}	Dummy Energy to Steam Turbine System	1.00

For the first optimisation case, only the supply and demand cost information are taken into account to guide the model's selection. The supply price of unsorted MSW is taken as R50 per ton, while the demand prices (selling prices) are taken as R1100.00 per MWh for electricity and R1.46 per tonne of steam based on the ranges given in Table 5-3.

The optimisation case results are shown in Figure 6-14. This shows the optimised configuration including flow variables for the optimum throughputs considering both mass and energy. In this case, the production of electricity pathway is selected as economically superior to the pathway considering direct sale/use of steam, with an objective function (profit) value of R147.74. Figure 6-14 also shows the conservation of flow that was maintained over the nodes, where the sum of all inputs into the node is equal to the sum of all outputs of the node for each node.

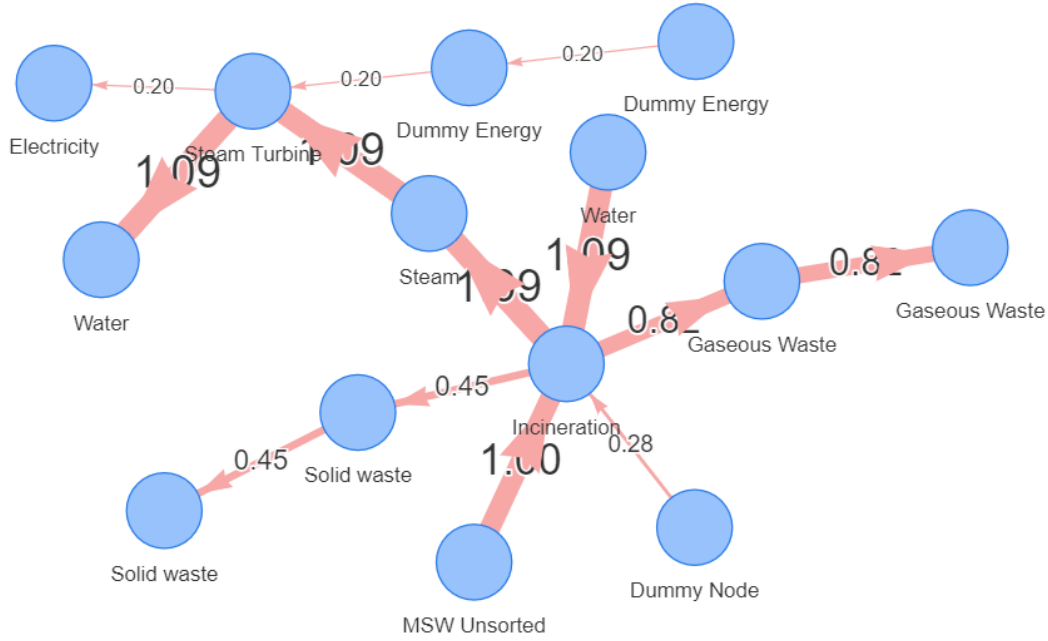


Figure 6-14: MILP optimisation model results for Case 1

The same calculation can be done using first principles with the aim of verifying the flow conservation presented as part of the MILP model results (Figure 6-14). This includes the calculation of the combustion mass balance from first principles.

Firstly, the waste is sorted before being sent to the incinerator and only the combustible fraction is combusted. The combustible feedstock fraction ($x_{combustible}$) is calculated using the composition of South African waste (Figure 4-2), where $x_{paper \& cardboard}$, $x_{plastics}$ and $x_{organics}$ are the compositional fractions of paper and cardboard, plastics and organics in unsorted MSW respectively, as shown in Equation (6.1).

$$x_{combustible} = x_{paper \& cardboard} + x_{plastics} + x_{organics} \quad (6.1)$$

Next, the mass flowrate of steam produced (m_{steam}) per mass flowrate of waste (m_{waste}) is calculated using Equation (6.2). This calculation takes into account the lower heating value of the waste (LHV_{waste}), the carbon conversion (X_c), the boiler efficiency (η_{boiler}), the specific heat capacity of water (C_p), the temperature change of water (ΔT) and water's heat of vaporisation (H_{water}^{vap}). The calculated mass flowrate of steam is used as an input into the steam turbine energy production calculation given in Equation (4.6).

$$m_{steam} = m_{waste} \cdot x_{combustible} \cdot \left(\frac{LHV_{waste} \cdot X_c \cdot \eta_{boiler}}{C_p \cdot \Delta T + H_{water}^{vap}} \right) \quad (6.2)$$

Lastly, the solid waste produced as by-product of the combustion process as well as the gaseous waste by-product is shown in Equations (6.3) and (6.4). The carbon dioxide equivalent ($CO_{2_eq\ carbon}$) is calculated as per Equation (5.8).

$$m_{solid\ waste} = m_{waste} \cdot (1 - x_{combustible}) \quad (6.3)$$

$$m_{gaseous\ waste} = m_{waste} \cdot (x_{volatile\ matter} + x_{fixed\ carbon}) \cdot X_c \cdot CO_{2_eq\ carbon} \quad (6.4)$$

Hereafter, the simplified economic configuration calculations can be done using Equations (6.5) and (6.6) to find the profit for each configuration.

$$Profit_{steam} = m_{steam} \cdot Selling\ Price_{steam} - m_{MSW\ Unsorted} \cdot Cost_{MSW\ Unsorted} \quad (6.5)$$

$$Profit_{electricity} = m_{electricity} \cdot Selling\ Price_{electricity} - m_{MSW\ Unsorted} \cdot Cost_{MSW\ Unsorted} \quad (6.6)$$

The results of the calculations are shown in Figure 6-15. As seen, the profit per tonne of waste for the electricity production scenario (R147.74) exactly matches the Integrated Optimisation Model objective function value and is far superior to the profit (or loss) made by the steam production scenario. The electricity production scenario should therefore be selected. Based on this analysis, it is found that the first principle calculations match the results from the Integrated Optimisation Model for Case 1.

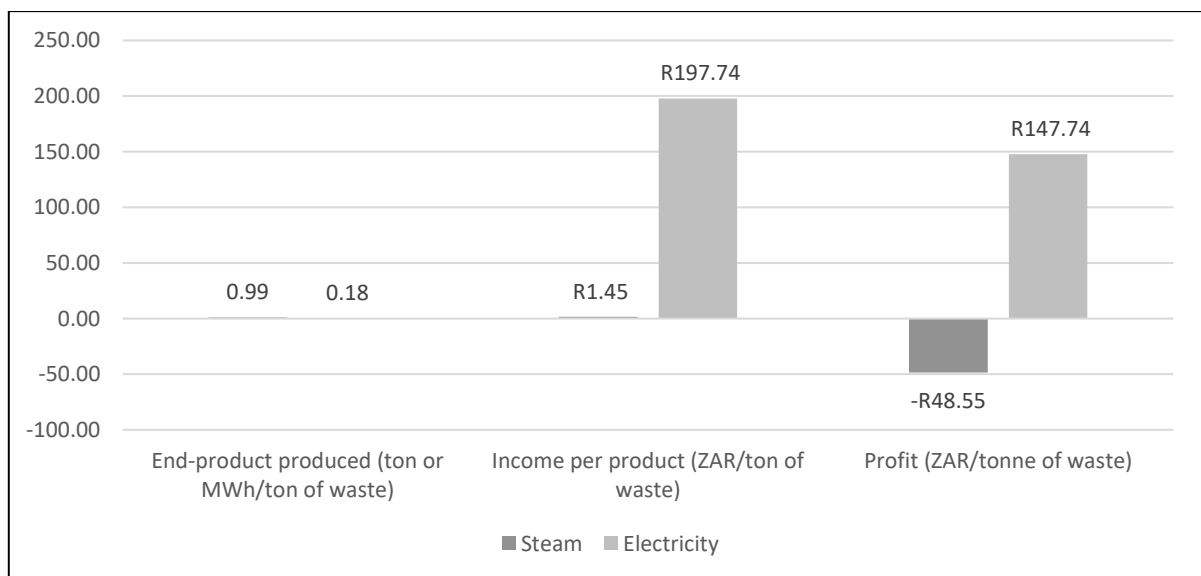


Figure 6-15: First principle calculation results for Integrated Optimisation Model Case 1

6.3.3.2 Case 2: Combustion and Briquetting

For Case 2, the economic optimisation results are calculated for three configurations, namely (1) the combustion process to produce steam, (2) the combustion and steam turbine cycle processes to produce electricity, and (3) a briquetting process to produce briquettes. All three configurations consider the use of unsorted MSW as feedstock and include all products and by-products. As seen in the integrated optimisation graph (Figure 6-16), Case 2 is similar to Case 1 with the addition of the briquetting process ($\sigma_{3,i}$) as well as the resulting briquettes ($z_{9,i}$).

A third group is added to the case, namely available land, which is represented by land ($z_{10,i}$) and the land dummy node ($z_{11,i}$). The land node is used to define the available land and the land dummy node is used to constrain the land availability. The land required per process is set using a dependency of land area (ha^2) per unit of mass flow (tonne) for each process (0.232 for incineration, 0.003 for steam turbines and 0.017 for briquetting).

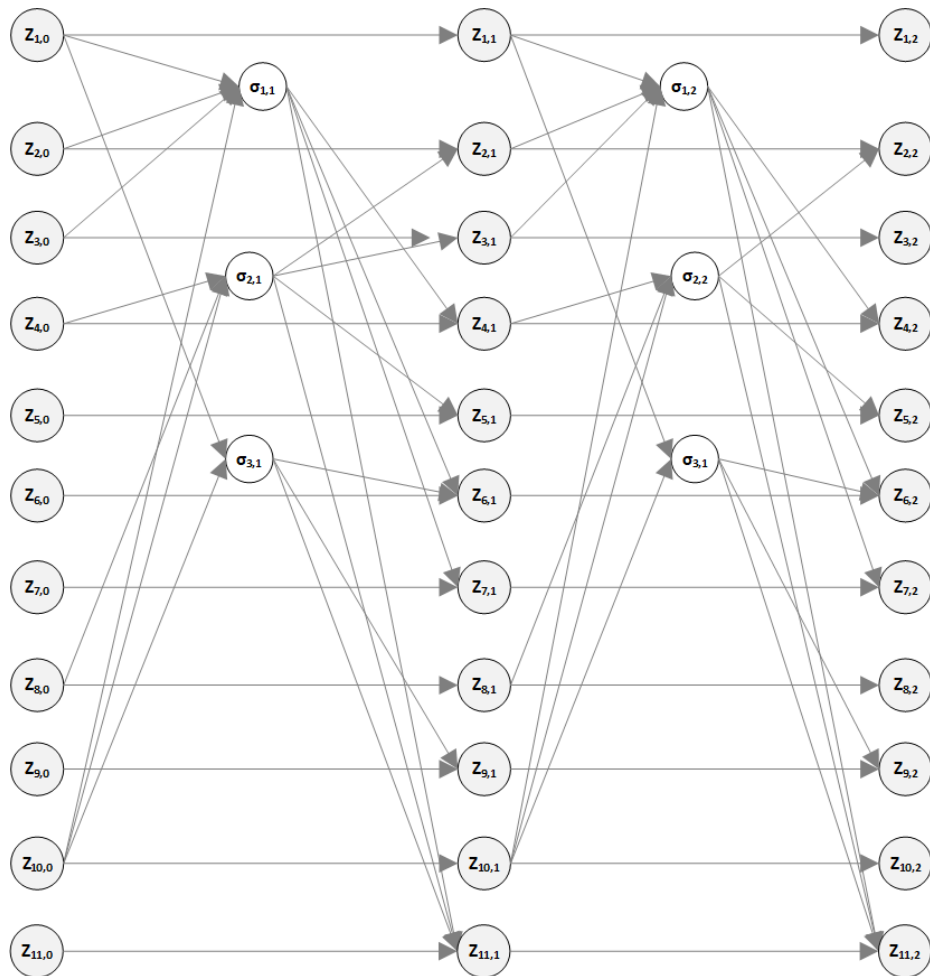


Figure 6-16: Combustion and briquetting optimisation graph (Case 2)

The model inputs are taken directly from the Process Calculations and are used as inputs for the optimisation case, as per Table 6-9.

Table 6-9: Integrated Optimisation Model inputs for Case 2

Arc	Description	Value
X _{1,1,0,1}	MSW (unsorted) to Incineration	0.42
f _{4,1,0,1}	Incineration to Steam	0.46
X _{4,2,0,1}	Steam to Steam Turbine System	1.00
f _{5,2,0,2}	Steam Turbine System to Electricity	1.00
X _{2,1,0,1}	Water to Incineration	0.46
X _{3,1,0,1}	Dummy Node to Incineration	0.12
f _{6,1,0,1}	Incineration to Solid Waste	0.19
f _{7,1,0,1}	Incineration to Gas Waste	0.35
f _{2,2,0,1}	Steam Turbine System to Water	1.00
X _{8,2,0,1}	Dummy Energy to Steam Turbine System	1.00
X _{1,3,0,1}	MSW (unsorted) to Briquetting	1.00
f _{9,3,0,1}	Briquetting to Briquettes	0.66
f _{3,3,0,1}	Briquetting to Solid Waste	0.34
X _{10,1,0,3}	Land to Incineration	1.00
X _{10,2,0,3}	Land to Steam Turbine	1.00
X _{10,3,0,3}	Land to Briquetting	1.00

For this case, however, a more complete economic analysis is considered which takes into account the TCI, TPC/a, as well as the costs and incomes associated with the process over a period of 20 years for a 1 ton/day process. The TCI costs were calculated based on the methodology shown in Section 5.2.2, and the TPC/a values were calculated based on the methodology shown in Section 5.2.3. These values were used as input into the model as follows:

- TCI and TPC/a for incineration process: R5.81 million and of R0.61 million per annum respectively
- TCI and TPC/a for incineration and steam turbine processes: R8.21 million and R0.81 million per annum respectively
- TCI and TPC/a for briquetting process: R2.14 million and R0.57 million per annum respectively

The supply price of unsorted MSW was taken as R50 per ton, while the demand prices (selling prices) were taken as R1100.00 per MWh for electricity, R1.46 per tonne of steam and R2500

per tonne of briquettes based on the ranges given in Table 5-3. All these prices were summed over a period of 20 years to account for plant life.

The optimisation case was calculated by the Integrated Optimisation model, as shown in Figure 6-17. For Case 2, the briquetting configuration is found to be economically preferable to the incineration configurations calculated previously with an objective function value of R5,753,108. Figure 6-17 also shows the conservation of flow that was maintained over the nodes, where the sum of all inputs into the node is equal to the sum of all outputs of the node for each node.

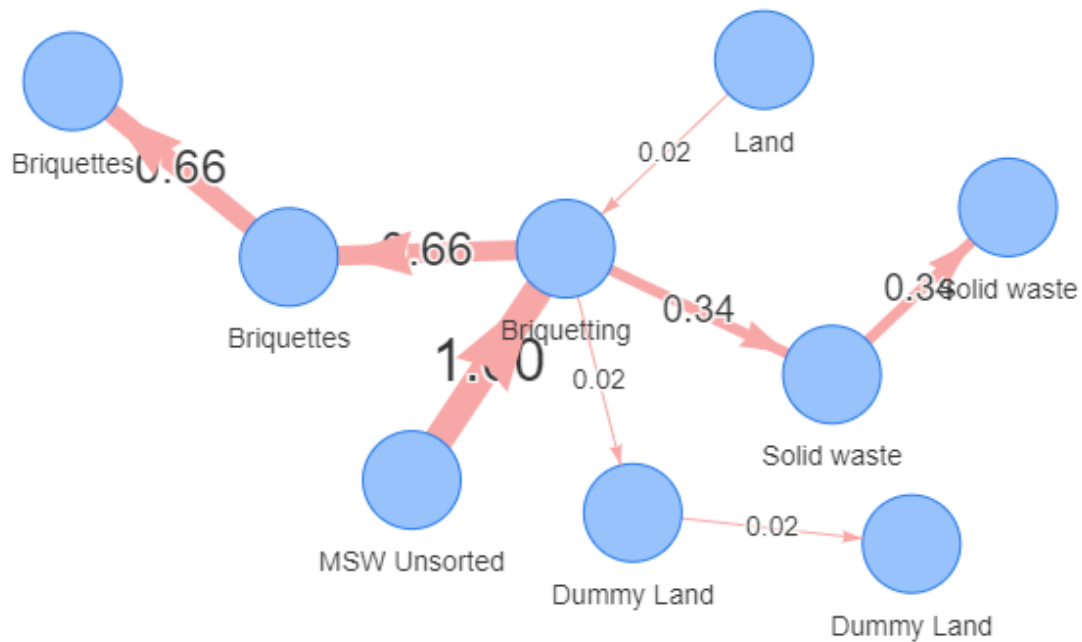


Figure 6-17: Integrated Optimisation Model results for Case 2

Once more, the same calculations can be done from first principles to verify the flow conservation of the Integrated Optimisation Model. Where the combustion mass balance remains the same, the mass balance for the briquetting process can be calculated as per Equations (6.7) and (6.8).

$$m_{briquettes} = m_{waste} \cdot x_{combustible} \quad (6.7)$$

$$m_{solid\ waste} = m_{waste} \cdot (1 - x_{combustible}) \quad (6.8)$$

The economic calculations can be done using Equations (6.9) to (6.11) to find the profit for each configuration.

$$Profit_{steam} = m_{steam} \cdot Selling\ Price_{steam,20\ years} - TCI_{incineration} - m_{MSW\ Unsorted} \cdot Cost_{MSW\ Unsorted,20years} - TPC_{incineration,20\ years} \quad (6.9)$$

$$Profit_{electricity} = m_{electricity} \cdot Selling\ Price_{electricity,20\ years} - TCI_{incineration\ \&\ ST} - m_{MSW\ Unsorted} \cdot Cost_{MSW\ Unsorted,20years} - TPC_{incineration\ \&\ ST,20\ years} \quad (6.10)$$

$$Profit_{briquettes} = m_{briquettes} \cdot Selling\ Price_{briquettes,20\ years} - TCI_{briquetting} - m_{MSW\ Unsorted} \cdot Cost_{MSW\ Unsorted,20years} - TPC_{briquetting,20\ years} \quad (6.11)$$

Finally, the land requirements per process are given in Equations (6.12) to (6.14).

$$Land\ Required_{incineration} = 0.232 \cdot m_{waste} \quad (6.12)$$

$$Land\ Required_{turbines} = 0.003 \cdot m_{waste} \quad (6.13)$$

$$Land\ Required_{briquetting} = 0.017 \cdot m_{waste} \quad (6.14)$$

The results of the economic and throughput analyses are shown in Figure 6-18. Similar to the results of the Integrated Optimisation model, the first principle calculations show the profit for the briquetting configuration to be superior to the two incineration configurations when TCI and TPC over 20 years are taken into account. The first principle calculated profit over 20 years for the steam production case was found to be R5,753,108, which exactly matches the objective function value of the Integrated Optimisation Model.

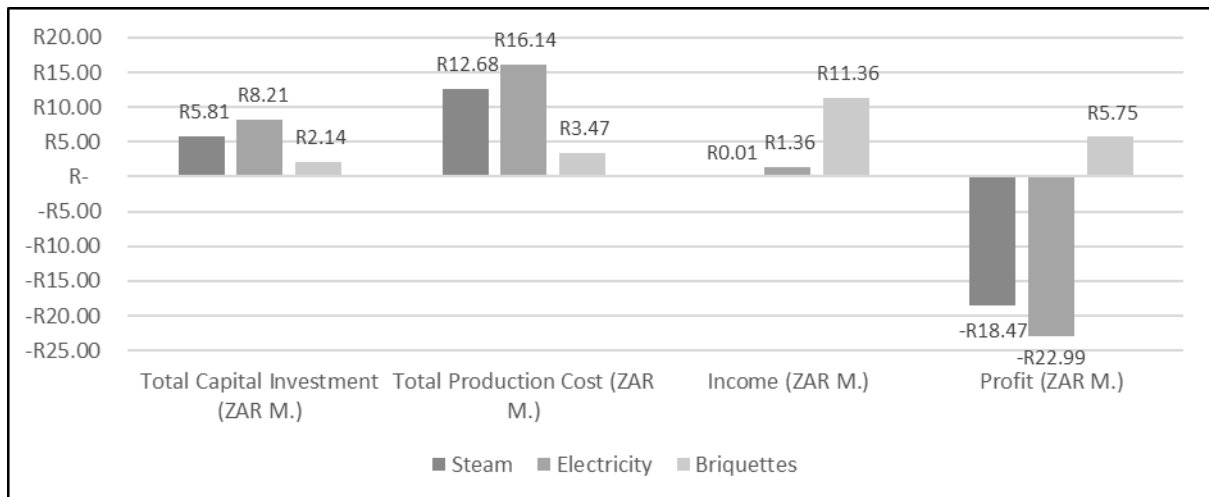


Figure 6-18: First principle calculation results for the Integrated Optimisation Model Case 2

In order to verify the Integrated Optimisation Model group constraint, a constraint is applied to the land availability for Case 2. The availability of land for the briquetting process is constrained to 0.01 ha² per tonne of feedstock. With the constraint in place, the mass throughput for the briquetting process is reduced to 0.53 tonnes/day and the objective function result of the Integrated Optimisation Model changes to R3,049,147. This value once more exactly matches the first principle results.

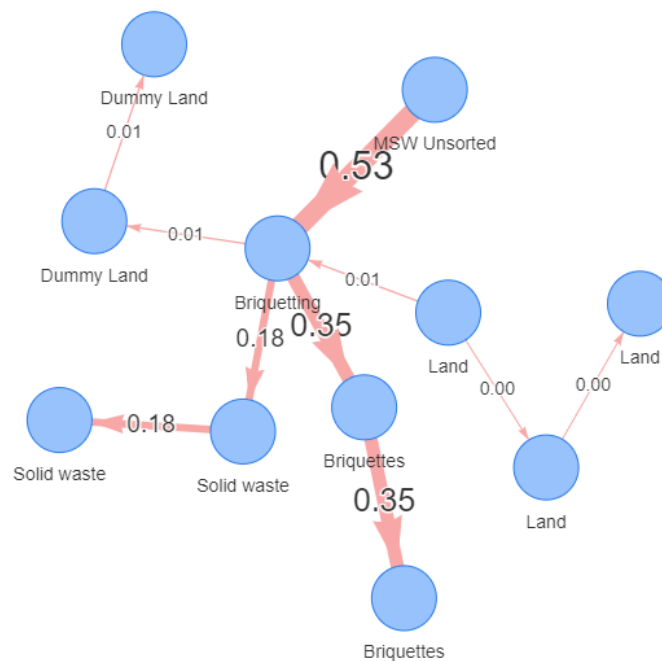


Figure 6-19: Integrated Optimisation Model results for Case 2 with land constraint applied

Thus, the Integrated Optimisation model which forms part of the WUDSS is successfully verified by:

- Proving that flow conservation was maintained for both cases.
- Finding an exact match between the results of the Integrated Optimisation Model objective function and the results of the first principle calculations.
- Selecting the economically superior configuration by the Integrated Optimisation Model within the set constraints, as verified using the results of the first principle calculations.
- Proving that both the flow conservation and objective function results match the first principle calculation results when a constraint is applied.

6.4 Validation of the Study

The validation approach is divided into four aspects, namely validation of the WUDSS function compared to other decision support systems, validation against the user needs, validation against gaps in the research and validation of the study outputs. In all cases, the outputs achieved are compared to the specification or requirements set out at the start of the study to evaluate whether the required results have been achieved.

6.4.1 Validation of the WUDSS compared to Decision Support System Requirements

As part of Chapter 2, various requirements for decision support systems were identified from the literature. The requirements were summarised according to the main goals of decision support systems, namely to be adjustable to changes in end-user requirements, to be easy to use, to provide concise outputs, respond rapidly, provide an intuitive user interface and to visualise the results to be easily understood ([72], [71]).

The WUDSS was developed keeping in mind the target audience, goals of the system, environment in which it will be used, as well as the specific required outputs. The prototype developed for this study is believed to have achieved its required objectives. In summary, the system:

- Provides the required level of detail for investment decisions and process comparison at a concept level.

- Speaks to a specific audience, which is well-defined. The needs of the audience are considered and well-understood.
- Provides feedback rapidly.
- Is easy to use, since the optimisation model selects a single configuration for ease of interpretation.
- Has a database of information that can be updated (e.g., yearly for costing).
- Gives enough information to assist the user to reach an informed decision, but is not deluging (e.g., legal considerations are given, but the system does not give the details of every applicable law).
- Includes guidance to assist the user with inputs and guide the user's thinking.

6.4.2 Validation of the WUDSS against the User Needs

Various requirements for the WUDSS system were identified in Chapter 1 based on the needs of SMME users. The needs analysis given in Section 1.2 identified access to funding ([5], [6], [7], [8], [9]), early project planning and business concept development [10], as well as knowledge of the industry ([5], [7]), as the main factors influencing SMME development and success. Additionally, SMME performance measurement was found to be based on economic, social and environmental performance [10].

All these factors were taken into accounts during the development of the WUDSS as follows:

- The WUDSS outputs were selected based on typical funding minimum requirements to assist SMME users in selecting projects that could be eligible for funding. Basic information required to apply for funding is given as output by the system, such as process design information, project economic considerations, environmental concerns and benefits, facility footprint and job creation potential. These WUDSS outputs can act directly as funding application inputs.
- In terms of early project planning and business concept development, the WUDSS assists the user in selecting model inputs (as per the general guidance functions) as well as providing specific design information, such as process descriptions and block flow diagrams. Financial metrics such as payback period, IRR and NPV provides the user with information to ascertain commercial feasibility and to make business planning decisions. Basic information around product selling cost ranges and potential additional inputs such as incentives or carbon credits are provided. In summary, all

outputs of the WUDSS are designed to aid SMMEs in comparing project options and developing a sound business concept on a FEL 1 level.

- Lastly, the WUDSS assists SMMEs with basic knowledge of the waste utilisation industry by providing a risk-based guidance function and providing information with regards to typical legal requirements, licences and permits.

Considering the above response to the user need identification as well as the initial design specification, the WUDSS has successfully fulfilled its requirements.

6.4.3 Validation of the Study against Gaps in the Research

In the context of the study, the decision support system developed for this work is believed to address the gaps in current research with regards to waste management in South Africa, decision support systems for waste management, and the decentralised approach, as seen in Table 6-10.

Table 6-10: How the decision support system addresses the gaps in the current research

No.	Gap in the current Research (Chapter 2)	How this study addresses the gap
1.	Most decision support tools are focused on providing strategic advice to specific role players, such as municipalities, national governments or planning decision-makers. Little work has been done towards addressing the private sector, specifically SMMEs. No studies were found on business development decision support for decentralised waste utilisation.	The WUDSS is aimed forwards business development and SMME participation. The goal of the WUDSS is to evaluate a potential project's overall viability, including its business case, risk profile, the potential for job creation and environmental impact. The outputs were selected to guide SMME's in ascertaining whether the selected configuration is eligible for project funding and to provide basic information that can be used as input into the funding application.
2.	Waste management decision support for developing countries requires addressing.	This study addressed waste utilisation in South Africa from a private sector or SMME point of view.
3.	All waste-related decision support tools in South Africa are aimed to provide strategic advice to municipal stakeholders. Decision support aimed towards decentralisation, business development and SMME development has not been addressed."	This system addresses the decentralisation of waste utilisation by addressing the project-related needs of an SMME or private sector user. The basis of the system is the concept of waste utilisation at the source of waste generation.

No.	Gap in the current Research (Chapter 2)	How this study addresses the gap
4.	The use of a market-based or a value chain approach to waste valorisation in South Africa has not been considered.	The selection of end-products for the WUDSS is based on a market and value chain approach within the selected problem domain. A review of estimated market potential was done for each product to estimate the viability of creating a new business around a certain product.
5.	Solid waste management planning in terms of technology mapping – considering sustainability and techno-economic parameters – has not been addressed for South Africa.	Technology mapping was done in some detail within the problem domain of this study, starting with the creation of a long list of options for primary waste management and fatal flaw analyses to select the most viable options. From there, the potential technology pathways were mapped for each waste type in terms of primary conversion, intermediate products, and end-product production based on the selected end products.
6.	Decentralisation, in terms of shifting the focus to the South African private sector, is currently not addressed by literature.	This decision support system is aimed toward the development of new decentralised waste utilisation facilities. The goal of the system is achieving true decentralisation, where the waste is managed at or near the source of generation by a private (non-centralised) facility on a scale fitting the typical expected waste generation volumes (small or medium scale).
7.	Risk-based approaches have not been included in any waste decision support frameworks for South Africa. Integration of risk management into the cost model for waste management decision support has not been addressed on a national or international level.	Risk-based approaches are included in the decision support system, as explained in Section 5.5. Risk-based contingency recommendations are given by the system for input into the costing.
8.	A need exists for guidance with regards to legal requirements for new waste management companies.	Guidance with regards to relevant legal authorisations, permits or requirements is given as part of the decision support system.
9.	An integrated approach to waste utilisation (considering waste end-product value chain, technology considerations, environmental impacts, risks and legislative influences) for the private sector has not been undertaken in the South African context.	This system provides an integrated approach with specific guidance regarding the South African environment. Aspects addressed by the decision support system include technical, environmental, legal, financial, social and risk.

6.4.4 Validation of the Study Outputs

For the study outputs to be successfully validated, the completed work must be compared to the research objectives identified in Chapter 1. These objectives were achieved as follows:

- Objective 1: Defining the concepts surrounding decentralisation of waste utilisation in South Africa.
 - These concepts were defined in Section 1.6 as part of the design specification and more detailed explanations are given in Chapter 2 as part of the literature study.
- Objective 2: Defining the conceptual requirements for a decentralised waste utilisation decision support system for SMME business/project development.
 - A needs analysis for SMMEs was undertaken. These user needs were then used, together with typical project funding screening requirements, to generate the output requirements for the system.
- Objective 3: Developing the mathematical modelling framework for a decision support system aimed at SMME business development in South Africa within a decentralised waste utilisation field.
 - The mathematical modelling framework was described in detail in Chapter 3.
- Objective 4: Creating a prototype model of the decision support system for concept demonstration purposes.
 - The development of the prototype WUDSS is explained in Chapters 4 and 5.
- Objective 5: Evaluating the working of the prototype decision support system by comparison of its outputs to benchmark and literature data (verification).
 - Both general and case study-based verification steps are undertaken to evaluate the working of the WUDSS. The verification process was applied to both the Process Calculations and the Integrated Optimisation Model. The verification process as well as its results are shared in Chapter 6.
- Objective 6: Evaluating whether the study addressed the objectives set as well as the gaps identified in literature (validation).
 - The validation process followed for this work is completed based on decision support system requirements, user experience, gaps identified and study objectives (Chapter 6).

Chapter 7: Summary and Conclusion

This study introduced the concept of decentralised waste management, where waste is managed at the source of waste production before ownership of the waste is carried over to the municipal stakeholders. At this point, true decentralisation of waste management is possible, and opportunity exists for business development by private sector stakeholders.

This study proposed a novel decision support system for decentralised waste utilisation to assist business development around general waste in South Africa. The focus of the study is on private sector and SMME development, thus investigating the business cases around small waste utilisation systems for onsite waste management and downstream resource utilisation.

This concept addresses a gap in the existing research, where waste utilisation decision support for small company development (decentralised) is yet to be addressed [82]. Furthermore, a market-based value chain approach [52] is followed to identify end-products to be included in the system, which is a novel approach for waste management decision support in South Africa. The study also addresses the need for an integrated approach to waste utilisation decision support ([20], [21]) aimed at the private sector (“project” approach) and includes a risk-management-based decision support function, which is a gap not addressed by any of the existing tools.

Finally, emphasis is placed on the use of a mathematical framework as the foundation of the proposed decision support system. This mathematical framework encompasses the detailed chemical process calculations, the financial drivers, the regulatory requirements and other user-specific constraints, into an overarching optimisation model. The outputs provided by this optimisation model are essentially the prescriptive features that qualify the resulting artefact as a decision support system.

7.1 Chapter Summaries

Chapter 1 introduced the background and focus of this study. The focus was placed on the needs of SMMEs, the methodical approach, the study purpose (including inclusions and exclusions), research objectives as well as a summary of the main study conclusions.

Chapter 2 provided an overview of the existing literature as well as the background relevant to this study. This chapter introduced important concepts in modern waste management and utilisation such as industrial ecology, the waste triangle, circular economies and waste value chains. International, as well as national waste statistics and the waste management status

quo, were introduced to explain the environment in which the decision support system needs to operate. This included background on the socio-economic impact of waste, the legal framework as well as waste economics in South Africa. Next, the decentralised approach to waste management was introduced as well as the current status of decentralised waste management and SMME participation in South Africa. Though recommendations have been made in past studies to improve decentralised waste management in South Africa, very little work has been done around the implementation of the concept [14]. This was identified as a primary gap in the existing research. Lastly, decision support systems were introduced and explained in terms of goals (success factors) as well as types of decision support tools which have been developed internationally. To prove the gap in the research, a systematic literature review was undertaken utilising the PRISMA method. A review of South African waste management decision support tools was also conducted to ascertain that the system developed as part of this study is indeed novel, relevant and unique.

Chapter 3 introduced the decision support system mathematical modelling framework. This included explaining the relation between the Process Engineering Calculations and the Integrated Optimisation Model. The required inputs, calculation steps and intended outputs of the overall model were explained. The guidance functions were defined with a focus on their goals and working in the context of the overall model. Finally, the Integrated Optimisation Model was provided.

In Chapter 4, the problem domain as well as the methodology and approach for developing the prototype WUDSS were provided. The included waste types were characterised and the value-chain approach to end-product selection was explained. Finally, a fatal flaw analysis was then conducted to select the processes to be included in the prototype system and a summary was given of all study inclusions, listing the waste types, Waste Conversion Processes, End-Product Production Processes and final end-products, as well as all possible pathways that can be followed to create individual “configurations”.

Next, the technical development of the WUDSS was described for all processes included in Step 1 and Step 2 tiers of the Process Calculations. This included all supporting design basis assumptions, baseline conditions, supporting data, calculation methodologies and factors.

Chapter 5 continued the description of the overall WUDSS abstraction by quantifying all remaining components included in the decision support system, namely financial, social, environmental, legal and regulatory, as well as guidance and risk.

The focus of Chapter 6 was the evaluation of the developed decision support system using the prototype. The methodology was broken up into two parts, namely verification of the WUDSS and validation of the study. While the verification process focused on assessing the accuracy of the prototype system's outputs, the validation process focused on assessing whether the requirements set for the decision support system as well as for the overall study were met.

As part of the general validation, the outputs of the prototype system were compared to literature data. The mass and energy balance outputs were compared to international data at the configuration level, while the financial outputs were compared to available South African data only, due to the location dependency of financial results. In both cases, specific cost or specific throughput values (per tonne waste throughput) were compared and found to be within the required accuracy ranges. For anaerobic digestion, the accuracy of specific cost values based on the total energy value of the products was also found to fall within in expected benchmark range for South African projects. The outputs of the prototype system were further analysed by comparison to case study outputs for small projects in South Africa. In this case, the capital budgeting metrics were found to compare well to the case study values. In-depth sensitivity analyses further proved the accuracy of the prototype system's results.

Verification of the Integrated Optimisation Model included comparing the outputs of the model to first principle results. The flow conservation results, objective function results, configuration selection and objective function results under constraints were verified.

Lastly, the validation of the system was undertaken based on specific decision support system requirements defined in Chapters 2, as well as based on set user needs. The prototype system was found to comply with the requirements and was therefore found to be fit for use.

Next, the study itself was evaluated to determine whether the gaps identified in the research were addressed and the study outcomes were achieved. Both these items were proved to be successfully validated.

7.2 Limitations and Future Research

In order to clearly define the scope and address the specific outcomes of this study, certain limitations were required. These limitations of the study are as follows:

- The WUDSS is designed for decision support for project selection during the early project phases (concept design or FEL 1). It is not intended to provide decision support

throughout the project. Keeping this in mind, various aspects that can be expected to be routinely addressed as part of the FEL project lifecycle is not included in the WUDSS, such as quality requirements, project controls, project execution systems, operational readiness factors or safety assessments. These items, as well as typical decision support for later project phases, can be addressed as part of future studies.

- The WUDSS prototype developed as part of this study is intended to demonstrate the working of the system and to evaluate the concept. With this goal in mind, a limited list of waste types, processes and end-products are included in the study based on a structured selection process. However, the possibility exists to add to this list of processes and feedstocks as part of future work. The same should be noted for the contents of the guidance functions (Specific Risk-based Considerations, legal guidance, etc). All WUDSS prototype inputs were limited in order to make it viable to create a working prototype of the complete system.
- The goal of the WUDSS is to provide decision support to SMME users to promote project/business development in the decentralised waste utilisation environment. The goal is therefore not to provide strategic decision support for use in policy-making, city planning, strategic facility location selections, etc. This consideration intrinsically changes the way the WUDSS operates and sets it apart from other decision support systems in the waste management field which addresses the abovementioned aspects.
- It should be noted that direct stakeholder engagement was not considered as part of this study. Thus, both the stakeholder analysis and the evaluation of the WUDSS were completed using literature data. The decision support system developed as part of the study is therefore theoretical in nature and has not been applied. Application of the WUDSS should form part of future research.
- Since the WUDSS is aimed at providing decision support for the utilisation of general solid waste, the study as well as the usage of the system is limited to exclude other waste types. This includes specialist or hazardous wastes, such as medical waste, nuclear waste or construction waste. It also excludes wastewater management, since decentralised wastewater management has been well addressed in current literature.
- Though education and skill development in SMMEs are noted as a potential risk area for SMME success, these factors are not addressed by the WUDSS. Furthermore, business management and operational factors are not included. The focus of the WUDSS is thus limited to the project-approach, which focusses on the development of the business concept and the project itself.

- Location selection is not considered as part of the work, though guidance is provided with regards to potential regulatory implications of selecting specific locations. Similarly, waste transport and logistics are not considered in the model due to the decentralized approach.
- This study did not look at technology development for small-scale application, as done by projects like DECISIVE [86]. Further work is required to adapt and improve certain technologies as well as process control philosophies for small-scale application. This falls outside the focus of this study.

Despite these limitations, the WUDSS provides valuable support for SMMEs in the early stages of waste management project development. Further research and development can address these limitations, broadening the scope and enhancing the accuracy of the system.

In addition to the items mentioned above, potential future research from this thesis is proposed as follows:

- Further expansion of the risk-based approach can be conducted to include additional risk considerations. At present, inclusions for the risk-based approach are limited to basic considerations to prove the value and working of this function. The risk-based approach to waste utilisation decision support can be expanded into a separate study if required. Simple additions with regards to the risk-based approach could include, for example, an indicative schedule output that can be provided by the system based on risk scenarios, e.g., for the planning of the overall project timeline while considering environmental and regulatory permitting timelines.
- To add to the value chain approach for end-product selection, future market growth expectations can also be considered. At present, only the current market situation is considered per end-product, which might provide a limited view of the real opportunities. It should be noted that it is expected of the decision support system user to undertake a market study in addition to using the system to test the viability of a specific configuration. As part of future work, the value chain approach can be provided as a guidance function as part of the decision support system to assist the user in selecting the correct end-product for business development purposes.

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Appendix A

A market analysis was done to calculate the estimated market potential of various products in South Africa to test the viability of starting new businesses around the selected end-products. The information used to calculate the estimated market potential is shown in Table A.1.

The data below is based on general and widespread market research as well as various assumptions in order to attain the high-level indication of market potential. For the “Complexity of Market Penetration” item, the end-products are ranked from 1 to 5, where 5 is the most complex.

Table A.1: Input data for estimated market potential calculations

End-Product	Uses	Commodity Cost (ZAR)	South African Market Currently	Target Market	Existing Competitors	Number of Existing Competitors	Potential Market Share	Comments on Market Share Estimate	Average Annual Consumption	Complexity of Market Penetration
Syngas	- Direct use in combustion engines for power generation - Used as feedstock to produce: - Ammonia, urea, sulphates and ammonia nitrates (fertiliser industry) - Acetic acid - Oxo Alcohols, such as n-butanol, as well as propene. - Chemical products (largest application, high value), e.g. TDI PC, MDI, DMF, DMC, etc.	R65/GJ	Sasol gas dominates this market. Internationally: "Biomass/waste is projected to be the fastest-growing feedstock segment in the syngas & derivatives market..."	Syngas is seen as an intermediate gas. It can be used directly for energy generation; however, its value lies in its "optionality" to produce various end-products. - Industrial gas - Gas for electricity, heat, cooking, etc. - Specialist gas - Intermediate for other product generation	- Sasol - The Linde Group - Air Products and Chemicals Inc. - Air Liquide - Afrox	20	5%	- Potential customers is 1/10,000 of the SA population - Market share includes about 1% of the industrial and residential sectors	722.51	3
Electricity	- General use in households and industry.	R 1 / kWh	Energy benefits are based on savings from not requiring grid energy.	Small scale users (self-generation)	Main generation via Eskom. Renewable and off-grid power production by	584400	0.000171%	- Assumption: 1 per 10 people in SA has a generator, solar backup or other	52 027 628	3

End-Product	Uses	Commodity Cost (ZAR)	South African Market Currently	Target Market	Existing Competitors	Number of Existing Competitors	Potential Market Share	Comments on Market Share Estimate	Average Annual Consumption	Complexity of Market Penetration
					numerous players in the public and household sectors.			backup electricity sources.		
Hydrogen	Hydrogen use in SA is relatively young. Some applications include: - Electricity production via fuel cells - Use as intermediate (e.g. desulphurisation in refining) - High purity hydrogen is used for analytical and other laboratory applications - Transport: application in development in SA (e.g. Engie project with Anglo for a hydrogen-fuelled truck) - Metallurgic industry - Glass Production	46.35	Rapidly growing market in South Africa. Small players can play a role. The biggest potential competitor is Renergen (helium and hydrogen project). Internally growing market. Hydrogen is a current investment area and South Africa is strategically set to export. Green hydrogen is preferred - to be considered above blue and grey hydrogen. HYSA by DSI was tasked to create hydrogen infrastructure in South Africa.	Specific projects to be investigated. Hydrogen is a growing field in South Africa with small projects developed all over SA. Hydrogen is currently used as laboratory gas (existing market) and in industries. Used as utility gas in manufacturing processes. Small Scale Hydrogen could be sold into existing markets as: - Laboratory/specialist gas - Gas for artisan applications Due to the developing nature of hydrogen projects, H2 on small scale can be used in energy/transport projects. Project developer/partner / off-taker to be found.	International players in South Africa: - Singapore-based Horizon - US-based Element One - Powercell Sweden (hospital fuel cells) - Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH South African Players: - Bambili Group - Hydrox Holdings DSI is heavily invested. Hydrogen is in line with SA's development strategy.	10	10%	Small market with very few existing players.	200 000	3
Petrol	- Transportation - Backup power (generators)	R16.15 / litre	The market is governed by large players.	Transport industry.	The current market includes: - About 4 600 service	4646	0.02%	Large industrial market with settled players.	79800 00000	3

End-Product	Uses	Commodity Cost (ZAR)	South African Market Currently	Target Market	Existing Competitors	Number of Existing Competitors	Potential Market Share	Comments on Market Share Estimate	Average Annual Consumption	Complexity of Market Penetration
		(03/03/2021)	comparison to be based on reduction in fuel purchased (savings model).		stations - Wholesale companies, of which the main players include BP Southern Africa, Engen Petroleum, Sasol Oil, Chevron South Africa, Shell South Africa, PetroSA, and Total South Africa			penetration will require branding and partnering / intense market penetration strategy. Small players will have difficulty entering this market.		
Diesel	- Transportation - Backup power (generators)	R16.04 / litre (01/03/2021)	The market is governed by large players. Cost comparison to be based on reduction in fuel purchased (savings model).	Transport industry.	The current market includes: - About 4 600 service stations - Wholesale companies, of which the main players include BP Southern Africa, Engen Petroleum, Sasol Oil, Chevron South Africa, Shell South Africa, PetroSA, and Total South Africa	4646	0.02%	Large industrial market with settled players. Market penetration will require branding and partnering / intense market penetration strategy. Small players will have difficulty entering this market.	93800 00000	3
Jet Fuel	- Aviation fuel Two types of jet fuel are used in SA: - Hydrocarbon Aviation fuel (refined from crude), e.g. Jet A, Avtur, JP8, or Jet A-1 - Newer fuels, e.g. SASOL semi and synthetic fuels. Green fuels may fall under this category	"Avgas per Litre: R 16.19	Jet fuel is produced by SASOL and imported. Jet fuel product registration and testing requirements makes this a very difficult market to penetrate. Jet fuels are traded under 3 standards, namely: - ASTM D 1655 - DefStan 91-91 - AFQRJOS Compliance requires 3rd party testing and	Aviation Industry	- SASOL produces most of the jet fuel used in SA Suppliers of Jet Fuel include: - Total Aviation SV1 MH Aviation Services - DSL Fuels - Gulfstream Energy - Air BP - Caltex - Astron Energy - Chevron - Engine (refinery fire in December 2020 -	30	3%	Large industrial market with settled players. Market penetration will require branding and partnering / intense market penetration strategy. Small players will have difficulty entering this market. Biofuel market to be investigated - support networks (e.g. IDC, TIA,	935 799 207	5

End-Product	Uses	Commodity Cost (ZAR)	South African Market Currently	Target Market	Existing Competitors	Number of Existing Competitors	Potential Market Share	Comments on Market Share Estimate	Average Annual Consumption	Complexity of Market Penetration
			laboratory verification.		long term effect to be verified) Notes: - PetroSA considering an investment in green aviation fuel production (Mossel Bay to be repurposed) in the short term			green funding) available.		
Biofuels Only		Jet A1 per Litre: R 11.83 Diesel: Comparable with transport fuel	Developing	Transport Sector	Small companies, e.g. - Greentech Biofuels - Mabele Fuels - Bio fires	10	10%	Market penetration supported for small players: "The IDC has undertaken an economy-wide impact assessment of a 460 million Litres 1st generation biofuels programme in South Africa and concluded that the economic benefits (e.g. over 13,000 direct new jobs in rural areas, R1.8 billion corporate and individual tax contributions to the Fiscus, balance of payment savings of R1.3 billion from reduced fuel imports) far outweigh the cost of the subsidy which was estimated at R800million year	460 000 000	2

End-Product	Uses	Commodity Cost (ZAR)	South African Market Currently	Target Market	Existing Competitors	Number of Existing Competitors	Potential Market Share	Comments on Market Share Estimate	Average Annual Consumption	Complexity of Market Penetration
								(equivalent to 3,5c/Litre on fuel used in the country). "		
Methane / Natural Gas	- Power generation - Industrial heating - Transportation - Hydrogen production - Fertiliser or ammonia production - Domestic use, e.g., heating, cooking, etc.	Aeroshel I W100 (946ml): R 110	NG is seen as a "critical bridge fuel" and demand is growing (especially for the power sector). SA only produces 41% of natural gas used locally (NG is mostly imported). Domestic demand for NG is being met by imports from Mozambique (ROMPCO). Sasol (NG to syngas process) & PetroSA (GTL plant) uses 75% of the NG consumed in SA. The second biggest consumer is the electricity sector (~2% of total electricity is produced from NG). The price for NG is regulated, and local distribution infrastructure is lacking. The easiest market to penetrate is the domestic market - cooking, water and space heating. Gas bottle supply is a limiting factor	Domestic / Residential Market	All NG is SA is either: - Imported via the Mozambique pipeline (ROMPCO) - Produced by SASOL (Note 1: PetroSA's gas block is depleted Note 2: LNG imports to become the next biggest competition for large market use) Domestic Competitors - Egoli Gas - Puregas - Renergen - CNG Holdings - Shell - The Gas Company (cylinder exchange) - The GAS Company - Afrox - Air Liquide - Total - BP - FacetGas - Stargas + more	100	1%	-	22 617	4

End-Product	Uses	Commodity Cost (ZAR)	South African Market Currently	Target Market	Existing Competitors	Number of Existing Competitors	Potential Market Share	Comments on Market Share Estimate	Average Annual Consumption	Complexity of Market Penetration
CNG	Bottled natural gas is mostly used for small-scale domestic use or backup power generators		(project/market feedback). CNG is a growing market in South Africa. Industrial consumers use CNG for steam production / alternative fuel sources.	Household use: cooking and heating Electricity or heat production	- Afrox - Air Liquide	10 000	0.01%	- Number of gas bottle suppliers in South Africa is numerous due to private sector players. - Gas Bottles are the limiting factor in the market, so owning gas bottles improves the change of market penetration. - Regulations and safety risks around gas bottles to be managed.	0.12	
Methanol	- Green fuel (ICE) - industrial intermediate (acetic acid and formalin production, as well as various chemicals) - Gasoline additive - Solvent (antifreeze) - Wastewater plant - Production of chemicals	(07/03/2021)"	Methanol is used for the production of green fuels. The local methanol market is growing with the growth in biofuel demand.	Various (green fuel production).	- SASOL is the only producer of methanol in South Africa - PetroSA to build a large methanol plant (2003), which was not realised	10	10.0%	Methanol is used as a precursor for biofuels only. Domestic, pharma, laboratory uses	29 077	2
Ethanol	- Green fuel (ICE) - industrial intermediate (acetic acid and formalin production, as well as various chemicals) - Gasoline additive - Solvent (antifreeze) - Could be used for ethylene production (green plastic pathway)	Estimated at R16 / litre to match petrol & diesel costs	Ethanol is used as a fuel additive in South Africa. Fuel blending with ethanol was made mandatory in 2012 (10% ethanol blend). Ethanol is also used as a primary fuel for heaters or fireplaces.	Vehicle fuelling companies (specifically trucks since this is an easier market to penetrate). Will need a contract with a downstream partner for blending.	South Africa: - Glendale Distilling Co. - Ilovo Sugar, Merebank - NCP Alcohols - Sasol South Africa Swaziland: - Royal Swazi Sugar Corp - USA Distillers	6	8%	EPASA members in South Africa and Swaziland.	262	3
Ammonia	- Chemical intermediate used for fertiliser	R165.90 / GJ	Fertiliser business case is much	Small Scale: Small-scale	Local production: Sasol	15	7%		781 420	2

End-Product	Uses	Commodity Cost (ZAR)	South African Market Currently	Target Market	Existing Competitors	Number of Existing Competitors	Potential Market Share	Comments on Market Share Estimate	Average Annual Consumption	Complexity of Market Penetration
	production (ammonium nitrate) - Explosives - Urea production - Lab chemical - Beauty industry (e.g. hair treatments) - Ammonia-based cleaners		improved by using locally produced LAN (cheaper). '- Input for nitrogenous fertilisers (Sasol, Omnia and AECI) - Nutri-Flo and Profert	laboratory chemical/chemical market supply - Refrigeration customers - Process industries - Heat treatment (metals) Ammonia recovery - Cleaners and soap production	Importing ammonia into SA: - Omnia - Foskor - Kynoch (Yara) ~ Richards Bay ammonia import facility (shared ownership between 3 companies and 25% to Sasol) '- Puregas (supplies from Sasol) - Chemlab suppliers					
Fertiliser (LAN) (compost comparison)	28 % N, 5 % Ca, urea (46%N) and ammonium sulphate (21 % N and 24 % S). Most popular fertiliser	"R245 / 9 kg cylinder	South Africa imports > 60 % of its local fertiliser demand SA is self-sufficient in terms of LAN production (Ammonia-based) SA exports to the Americas, Europe, Oceania and Asia. Largest export to Zimbabwe, followed by Malawi	Small Scale: - Directly to farmers (small-scale farmers) - Specialist fertiliser for gardens - Focus on niche outputs, e.g. specific plants/technologies	- Kynoch - Sasol - Omnia - Profert - Triomf - Nutri-flo - Greenlands - Nitrophoska - Yara	9	11%		251 050	2
Fertiliser (MAP)	MAP (11% N, 22% P)	R380 / 14 kg	South Africa imports > 60 % of its local fertiliser demand Largely imported from Western Europe.	Small Scale: - Directly to farmers (small-scale farmers) - Specialist fertiliser for gardens - Focus on niche outputs, e.g. specific plants/technologies	- Kynoch - Sasol - Omnia - Profert - Triomf - Nutri-flo - Greenlands - Nitrophoska - Yara	9	11%		251 050	2

End-Product	Uses	Commodity Cost (ZAR)	South African Market Currently	Target Market	Existing Competitors	Number of Existing Competitors	Potential Market Share	Comments on Market Share Estimate	Average Annual Consumption	Complexity of Market Penetration
Charcoal / Briquettes	- Back yard braais (domestic use) - Fire places	R518 / 19 kg"		Focus only on Household use.	- ENPROTEC - Legacy Foundation - ABC Machinery (1 tonne/hr plant in Durban) - Ignite Products - Bakgat-briquet charcoal - Home Charcoal Briquettes - Hi-Lite - Kamado Jan - Eco Coal Namibia - Castle Lager Briquettes - Living Out Lumpwood Charcoal - Braai - Camp Master Briquettes	100	1%	Market heavily dominated by the private sector. Briquettes are easy to produce and numerous players are currently producing briquette products.	5 500	1
Bio-oil (HFO) Crude	- Low quality used for fuel blending or input to refineries.	R2 610		Target market based on HFO market in SA. "Crude oil"	- Energy Solutions - SA Oil - Econoil - Bud Chemicals - Mdubane Energy Services - Shell - BP - Sasol - Afric Oil - Energas - SADO - Glencore - AB Shipping	20	5%		23404. 47605	3
Bio-oil (HFO) High Quality (Upgraded)	- Mostly consumed on commercial sites (low-speed generators). Used as bunker / marine oil.	R18 961		Target market based on HFO market in SA.	- Energy Solutions - SA Oil - Econoil - Bud Chemicals - Mdubane Energy Services - Shell - BP	20	5%		19417. 0468	3

End-Product	Uses	Commodity Cost (ZAR)	South African Market Currently	Target Market	Existing Competitors	Number of Existing Competitors	Potential Market Share	Comments on Market Share Estimate	Average Annual Consumption	Complexity of Market Penetration
					- Sasol - Afric Oil - Energas - SADO - Glencore - AB Shipping					
Biochar (Fertiliser Grade)	Similar to LAN	R3 114		Fertiliser suppliers or open market (similar to LAN market)	- Kynoch - Sasol - Omnia - Profert - Triomf - Nutri-flo - Greenlands - Nitrophoska - Yara	9	11%		251 050	3
Biochar (Non Fertiliser Grade)	- Charcoal production - Soil application	R1 545		All charcoal producing companies.	- ENPROTEC - Legacy Foundation - ABC Machinery (1 tonne/hr plant in Durban) - Ignite Products - Bakgat-briquet charcoal - Home Charcoal Briquettes - Hi-Lite - Kamado Jan - Eco Coal Namibia - Castle Lager Briquettes - Living Out Lumpwood Charcoal - Braai - Camp Master Briquettes	100	1%		251 050	1
Biochar - Activated Carbon	- Adsorption matter	R28 393		Water treatment and emission systems	- Rotocarb - Watericon - Aquamat - Calgon Carbon - Jacobi - CP Technologies etc.	15	7%	Open sector suppliers. Fewer producers of AC in SA.	9 500	1

Appendix B

The Waste Conversion Process fatal flaw analysis information is given in Table B.1.

Table B.1: Waste Conversion Process fatal flaw analysis (long list)

Waste Conversion Processes	Size	Technology Maturity	Complexity	General Comment	Decision
<u>Physical Options</u>					
Briquetting	1	1	1		GO
Pelletizing	1	1	1		GO
<u>Sorting & Resale for Recycling</u>					
Metals	1	1	1		GO
Plastics	1	1	1		GO
Glass	1	1	1		GO
Paper	1	1	1		GO
Rubber	1	1	1	Rubber recycling is not common	NO GO
<u>Recovery</u>					
Composting	1	1	1		GO
Protein Recovery	1	1	0	Licensing of recovered protein is complex	NO GO
<u>Thermal Processing</u>					
Incineration	1	1	1		GO
Gasification	1	1	1		GO
Pyrolysis	1	1	1		GO
Gasification & Plasma Post Processing	1	1	1		GO
<u>Direct Gas Production</u>					
Supercritical Water Combustion	1	0	0	SC technology is relatively novel and complex	NO GO
Supercritical Water Gasification	1	0	0	SC technology is relatively novel and complex	NO GO
Supercritical Water Pyrolysis	1	0	0	SC technology is relatively novel and complex	NO GO
Wet Anaerobic Digestion (AD)	1	1	1		GO
Dry Anaerobic Digestion (AD)	1	1	1		GO

Waste Conversion Processes	Size	Technology Maturity	Complexity	General Comment	Decision
Methane Harvesting	1	1	1	Included in digestion options.	GO
Hydrothermal Liquefaction (HTL)	1	0	0	Complex and untested.	NO GO
<u>High-Temperature Deconstruction</u>					
Fast Pyrolysis	1	1	1		GO
Hydrolysis	1	1	1	Similar to AD. Included as "AD"	GO
<u>Low-Temperature Deconstruction</u>					
Transesterification / Alcoholysis	1	1	1	Not viable on any of the considered feedstocks	NO GO
Fermentation	1	1	1		GO
<u>Solid Fuel Production</u>					
Torrefaction	1	1	1		GO
Carbonization	1	1	1	Considered under "Torrefaction" due to similarities.	GO

Appendix C

The cost index data used in the financial escalation calculations is shown in Figure C.1.

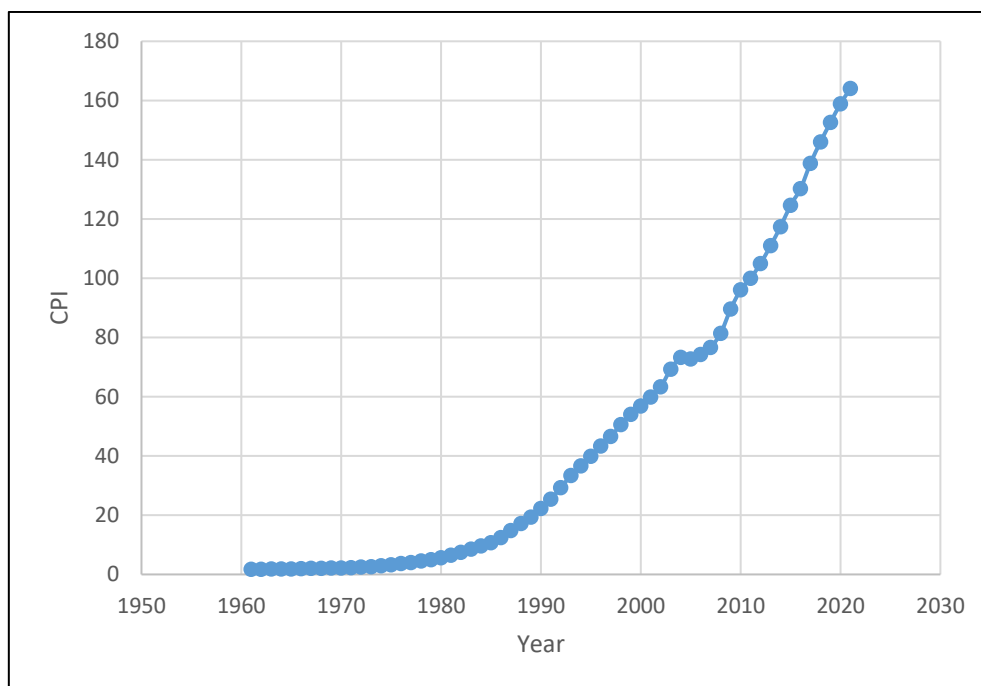


Figure C.1: South African Cost Index (CPI)

Appendix D

Important characteristics of the prototype Process Calculations include:

- Simplicity of use
- Rapid response
- Concise outputs and recommendations
- Visualisation of results

To keep the process flow as simple as possible, the spreadsheet-based decision support system (Process Calculations) works from single input cells as far as possible and keeps these input values well-sorted in a centralised location. This simplifies updates or changes to the sheet since a single cell value can be changed to update the input to all the calculations – e.g., densities of specific components, exchange rates, etc.

The data management of the decision support system is facilitated through:

1. The primary input fields in the Input Sheet
2. Various Baseline or Data Sheets act as the basis of calculations, containing assumptions, conversions, input values (e.g., exchange rates, densities, etc.), factors and other data that form the basis of the calculations. To protect the integrity of the decision support system, the user is unable to access these sheets.

The tonne/day throughput of waste is used as one of the primary inputs for the mass balance calculations. The Baseline or Data Sheets feed into the calculation sheets and are relatively independent of the user input conditions. All calculations are completed in the Main Calculation Sheets and fed into a centralised Results Summary Sheet. The result for a specific configuration is then selected from the consolidated list based on the user inputs. This approach allows the prototype WUDSS to deliver a rapid response to the user without the need for complex calculations.

Figure D-1 shows the process flow of the spreadsheet-based prototype WUDSS as well as the various dependencies between sheets.

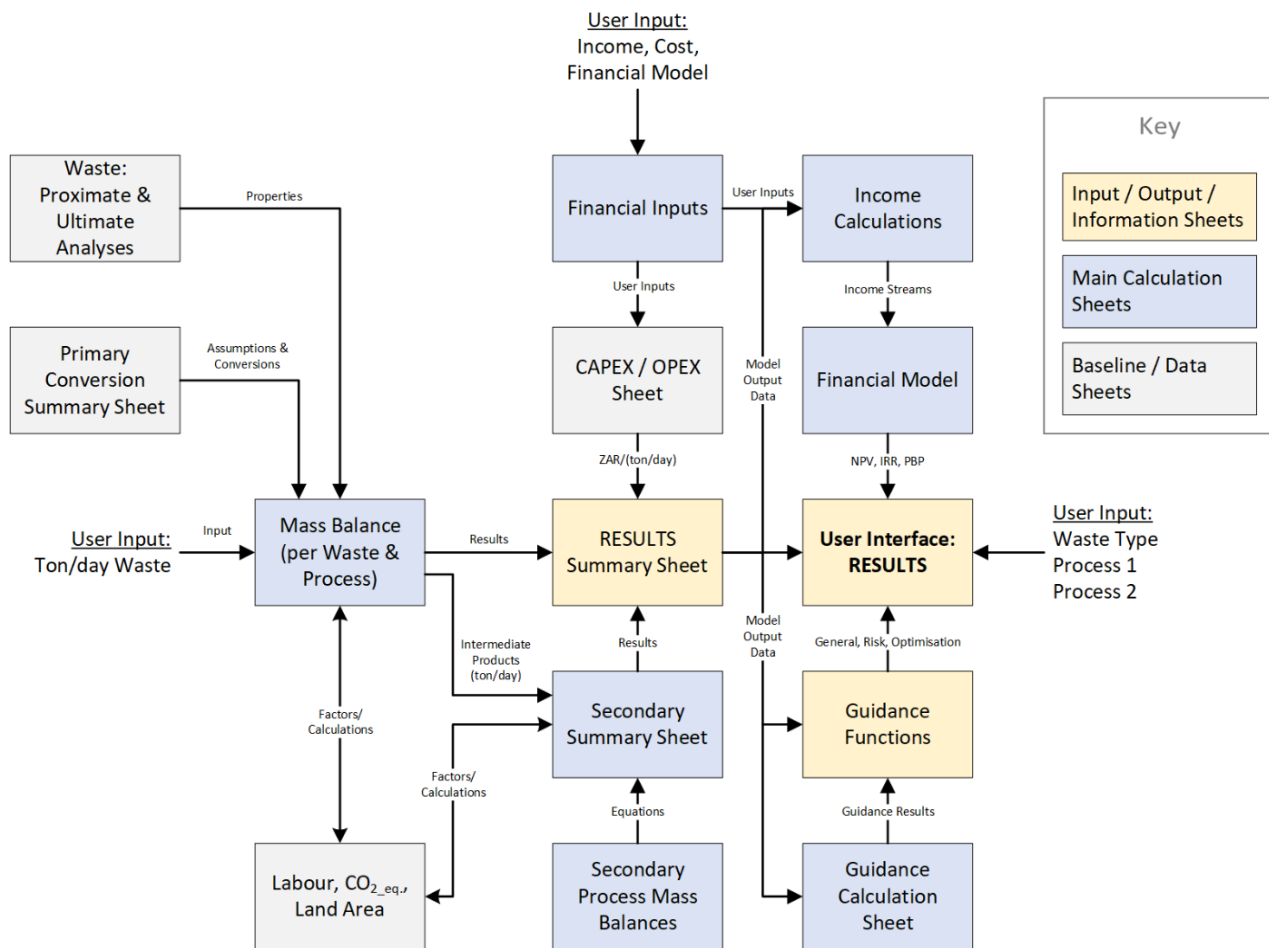


Figure D-1: Spreadsheet-based prototype system synthesis

The user interface for the spreadsheet-based prototype system is divided into four sheets, namely:

1. Introduction & FAQ (Figure D-2)

- This sheet gives the user an overview of the decision support system, its goal, output categories, level of detail to be expected from the analysis, and how to use the system.
- A FAQ section is included to answer expected questions about the use, synthesis, inclusions, and general characteristics of the decision support system.

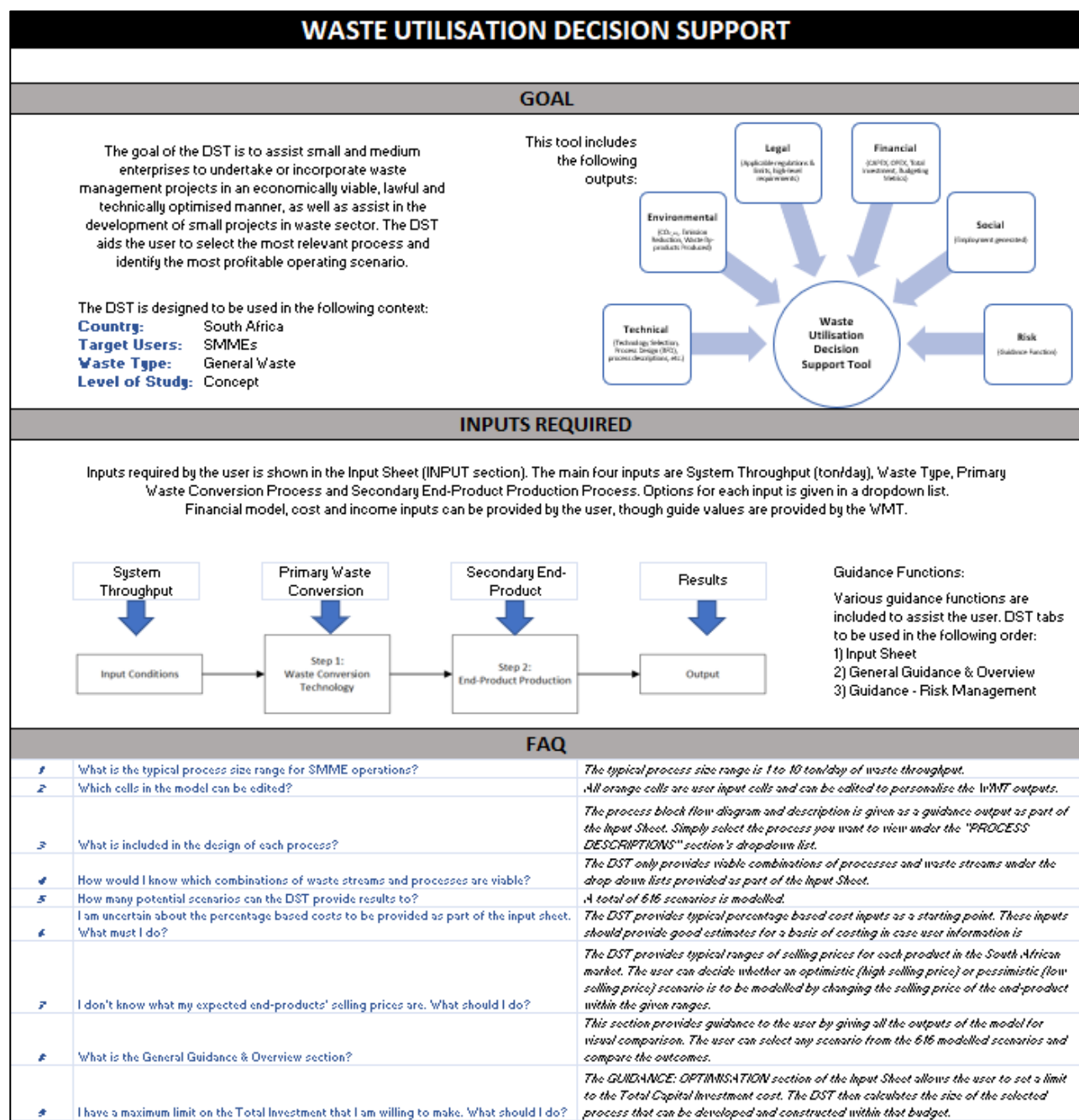


Figure D-2: Prototype introduction and FAQ section

2. Input Sheet

- The input sheet (Figure D-3) is divided into two main categories, namely the Input and Results sections. The optimisation section is included under the Input section.

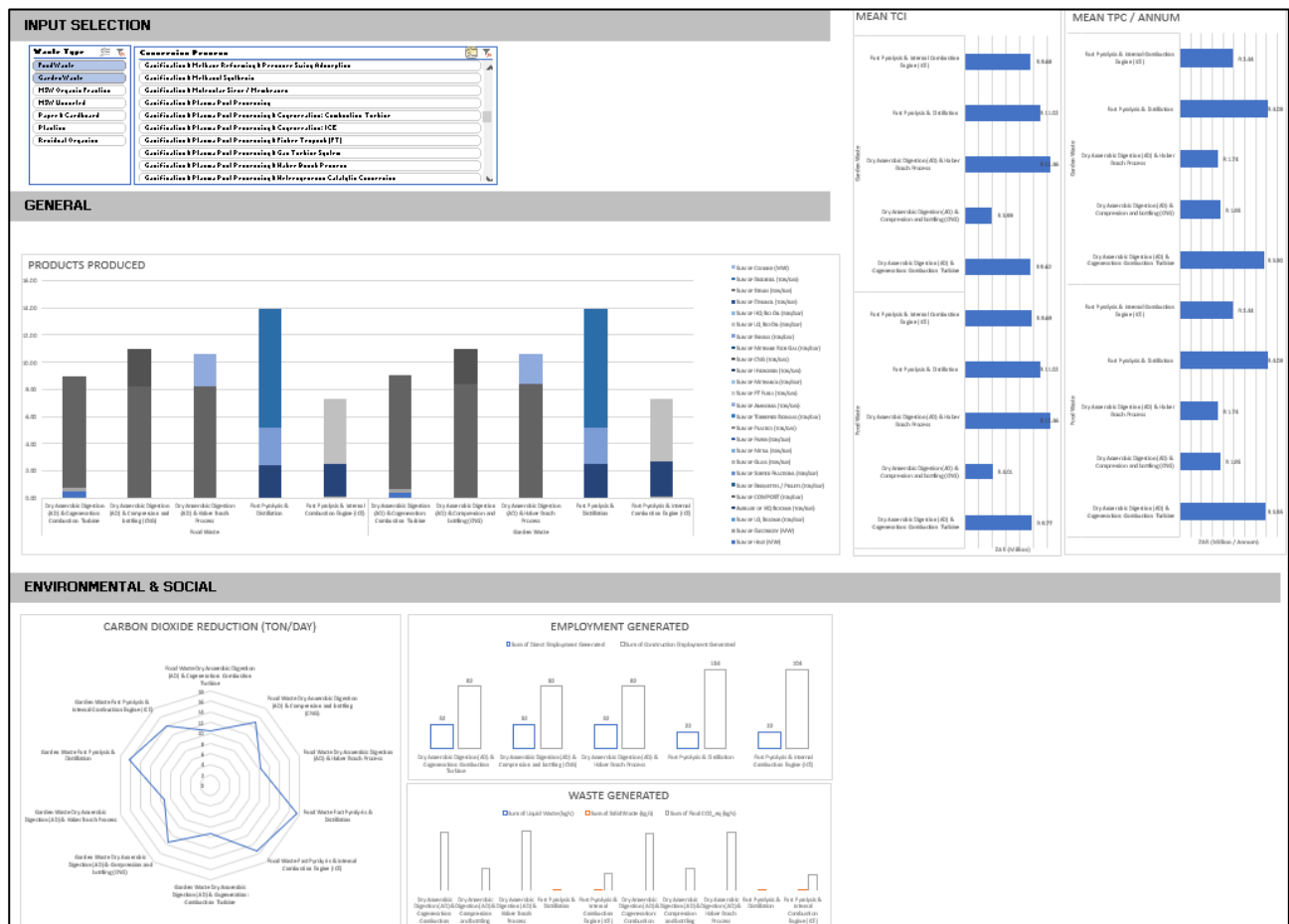


Figure D-5: General Guidance & Overview section of the prototype

4. Guidance – Risk Management (Figure D-6)

- The risk management guidance sheet includes three sections, namely Risk-based Multicriteria Analysis of Waste Processing or Post Processing Processes, Specific Risk-based Considerations and Regulatory Considerations.

Specific Risk-based Considerations:

These specific considerations should be noted early on during the project development and allowed for during allowed for by adding to the cost and schedule contingencies.

Category	Inputs:	Risks and Recommendations:
Project Location	City	1) Risk: EIA requirements are more strict in a city 4) Review listed Land Use permits
Land Type	Urban / Near Temporary Housing	Might trigger a "Land Use Rights" permit requirement.
Distance from Waste Source (Feedstock)	Transport Required	1) Onsite waste storage to be considered as design input. 2) Include transport cost in project cost model.
Product Market / Offtaker(s)	Uncertain	1) Undertake a market study 2) Initial discussions with potential offtakers should be undertaken during the early phase of the project to test the market requirements / appetite.
Grid Connection	Grid Connection not required	No risk.
Treatment Type	Thermal Treatment	Might trigger a "Atmospheric Emissions License" requirement.
Recommendation:	Include risk mitigation actions in the project contingency. Contingency percentage to be increased to:	30%

Regulatory Considerations:

Specific regulatory considerations that could affect this project is given below.

Possible Licences and Permits	Grid Connection	Commissioning Tests Customer Use of System Agreement Dry run test results Final Grid Code compliance testing Generation licence Grid Code compliance matrix Grid Code compliance simulation study Grid Connection Budget Quotation Grid Connection Cost Estimate Letter Operating Agreement Power Purchase Agreement (PPA)
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Figure D-6: Risk Management Guidance sections from the prototype

Appendix E

Data for the general verification is shown in the tables below (Table E.1 to Table E.3). This includes data from the literature as well as outputs from the decision support system for comparison purposes.

Table E.1: Specific cost values for South African scenarios (literature)

Process Type	Literature : Median	Literature : Scenario A	Literature : Scenario B	Literature: Median Source	Literature: Scenario A Source	Literature: Scenario B Source
Composting	R530	R908		Soos <i>et al.</i> , 2015. [179]	Soos <i>et al.</i> , 2015. [179]	Soos <i>et al.</i> , 2015. [179]
Wet Anaerobic Digestion	R1 135	R3 171		Soos <i>et al.</i> , 2015. [179]	Purser. 2011. [175]	
Incineration with Energy Recovery	R2 043	R3 569	R2 855	Soos <i>et al.</i> , 2015. [179]	Maisiri.2016. [180]	Maisiri.2016. [180]
Gasification	R2 119	R1 908		Soos <i>et al.</i> , 2015. [179]	Purser. 2011. [175]	Purser. 2011. [175]
Pyrolysis Fast	R2 101			Soos <i>et al.</i> , 2015. [179]		
Pyrolysis Catalytic	R2 101			Soos <i>et al.</i> , 2015. [179]		
Briquetting		R1 097			CDM EB. 2012. [181]	
Gasification & Fischer Tropsch		R6 764	R6 904		Leibbrandt. 2010. [182]	Leibbrandt. 2010. [182]
Fermentation		R3 776			Leibbrandt. 2010. [182]	
Pyrolysis Flash	R2 101			Leibbrandt. 2010. [182]		
Pyrolysis and Distillation		R7 934	R6 990		Nkosi <i>et al.</i> , 2020. [183]	Pilusa <i>et al.</i> , 2014. [184]
Pyrolysis Slow	R2 270	R1 343		Soos <i>et al.</i> , 2015. [179]	Soka and Oyekola. [185] 2020.	
Anaerobic Digestion and Cogeneration	R3 802	R3 653		Gogela <i>et al.</i> , 2017. [177]	Gogela <i>et al.</i> , 2017. [177]	

Table E.2: Decision support tool specific cost values

Process Type	DST: Minimum Specific Cost	DST: Median Specific Cost	DST: Maximum Specific Cost
Composting	R455	R754	R1 053
Wet Anaerobic Digestion	R1 791	R1 911	R2 031
Incineration with Energy Recovery	R2 837	R3 128	R3 419
Gasification	R847	R1 649	R2 451
Pyrolysis Fast	R1 619	R2 464	R3 308

Process Type	DST: Minimum Specific Cost	DST: Median Specific Cost	DST: Maximum Specific Cost
Pyrolysis Catalytic	R1 007	R2 448	R3 889
Briquetting	R45	R621	R1 197
Gasification & Fischer Tropsch	R3 926	R5 864	R7 803
Fermentation	R51	R2 405	R4 759
Pyrolysis Flash	R1 593	R4 238	R6 883
Pyrolysis and Distillation	R5 978	R8 979	R11 981
Pyrolysis Slow	R545	R3 634	R6 724
Anaerobic Digestion and Cogeneration	R1 579	R3 577	R5 576

Table E.3: Mass balance-specific product output comparison data

Source	Scenario	Product Type & Unit	Literature Product Fraction (tonne/tonne of waste)	WUDSS Product Fraction (tonne/tonne of waste)	WUDSS Waste Type
N. Rajendran <i>et al.</i> , 2021. [186]	Fermentation of Potato Peel	Ethanol (tonne/tonne waste)	0.320	0.227	Food Waste
N. Rajendran <i>et al.</i> , 2021. [186]	Fermentation of Food Waste	Ethanol (tonne/tonne waste)	0.205	0.227	Food Waste
N. Rajendran <i>et al.</i> , 2021. [186]	Fermentation of Food Waste	Ethanol (tonne/tonne waste)	0.189	0.227	Food Waste
N. Rajendran <i>et al.</i> , 2021. [186]	Fast Pyrolysis & ICE of MSW	Biofuel (tonne/tonne)	0.104	0.296	MSW unsorted
N. Rajendran <i>et al.</i> , 2021. [186]	Fast Pyrolysis & ICE of MSW	Electric (MW/tonne/day)	0.009	0.007	MSW unsorted
Torres <i>et al.</i> , 2020. [187]	Slow Pyrolysis of Organic Waste	Biochar (tonne/tonne waste)	0.417	0.423	MSW OF
Torres <i>et al.</i> , 2020. [187]	Slow Pyrolysis of Organic Waste	Biochar (tonne/tonne waste)	0.375	0.383	Garden Waste
Torres <i>et al.</i> , 2020. [187]	Slow Pyrolysis of Organic Waste	Biochar (tonne/tonne waste)	0.344	0.375	Food Waste
Torres <i>et al.</i> , 2020. [187]	Slow Pyrolysis of Organic Waste	Biochar (tonne/tonne waste)	0.323	0.383	Garden Waste
Torres <i>et al.</i> , 2020. [187]	Slow Pyrolysis of Organic Waste	Biochar (tonne/tonne waste)	0.312	0.375	Food Waste
Zhang <i>et al.</i> , 2021. [188]	Gasification & Methanol Synthesis of Organic Waste	Methanol (tonne/tonne waste)	0.298	0.252	MSW OF

Source	Scenario	Product Type & Unit	Literature Product Fraction (tonne/tonne of waste)	WUDSS Product Fraction (tonne/tonne of waste)	WUDSS Waste Type
Zhang et al., 2021. [188]	Gasification & Methanol Synthesis of Organic Waste	Methanol (tonne/tonne waste)	0.289	0.252	MSW OF
Svanberg et al., 2013. [189]	Torrefaction of Willow	Torrefied Biomass (tonne/tonne waste)	0.872	0.851	Garden Waste
Svanberg et al., 2013. [189]	Torrefaction of Willow	Torrefied Biomass (tonne/tonne waste)	0.770	0.851	Garden Waste
Svanberg et al., 2013. [189]	Torrefaction of Willow	Torrefied Biomass (tonne/tonne waste)	0.668	0.851	Garden Waste
Visser et al., 2020. [190]	Torrefaction of Pulpwood	Torrefied Biomass (tonne/tonne waste)	0.476	0.851	Garden Waste
Klinger. 2021. [191]	Torrefaction of Plastic	Torrefied Biomass (tonne/tonne waste)	0.400	0.371	Plastics
Ansah et al., 2016. [192]	Torrefaction of Plastic	Torrefied Biomass (tonne/tonne waste)	0.220	0.371	Plastics
Gilbert and Thornley. 2010. [193]	Gasification & Haber Bosch of Biomass	Ammonia (tonne/tonne waste)	0.337	0.482	MSW OF
Sara et al., 2016. [194]	Gasification & PSA of Fruit Bunch	Hydrogen (tonne/tonne waste)	0.052	0.168	Food Waste
Sara et al., 2016. [194]	Gasification & PSA of Biomass	Hydrogen (tonne/tonne waste)	0.069	0.057	RO
Sara et al., 2016. [194]	Gasification & PSA of Biomass	Hydrogen (tonne/tonne waste)	0.079	0.057	RO
Rajendran et al., 2021. [186]	Incineration & Steam Turbines of Undetermined Waste	kWh	500.000	331.828	Garden Waste
Rajendran et al., 2021. [186]	Incineration & Steam Turbines of Undetermined Waste	kWh	600.000	589.917	Paper & Cardboard
He, 2017. [136]	Membranes Separation of Syngas	Hydrogen (tonne/tonne H2 in inlet gas)	0.252	0.247	Syngas
Gilbert and Thornley. 2010. [193]	Gasification & Haber Bosch of Willow	Ammonia (tonne/tonne waste)	0.437	0.525	Garden Waste
Swanson. 2010. [141]	Gasification & Fischer Tropsch of Biomass	FT Fuels (tonne/tonne waste)	0.125	0.183	MSW OF

Source	Scenario	Product Type & Unit	Literature Product Fraction (tonne/tonne of waste)	WUDSS Product Fraction (tonne/tonne of waste)	WUDSS Waste Type
Luning <i>et al.</i>, 2003. [195]	Anaerobic Digestion of OFMSW	Biogas (tonne/tonne waste)	0.150	0.203	Dry AD MSW OF
Olivard. 2017. [126]	Anaerobic Digestion & CHP of MSW	Biogas (tonne/tonne waste)	0.168	0.146	Dry AD & ICE Cogen MSW
Olivard. 2017. [126]	Anaerobic Digestion & CHP of MSW	Fertiliser (tonne/tonne waste)	0.409	0.342	Dry AD & ICE Cogen MSW
Olivard. 2017. [126]	Anaerobic Digestion & CHP of MSW	Heat (MWh/y / tonne waste)	0.349	0.508	Dry AD & ICE Cogen MSW
Olivard. 2017. [126]	Anaerobic Digestion & CHP of MSW	Electricity (MWh/y / tonne waste)	0.246	0.378	Dry AD & ICE Cogen MSW
Olivard. 2017. [126]	Anaerobic Digestion & CHP of MSW	Biogas (tonne/tonne waste)	0.140	0.146	Dry AD & Turbine Cogen MSW
Olivard. 2017. [126]	Anaerobic Digestion & CHP of MSW	Fertiliser (tonne/tonne waste)	0.318	0.342	Dry AD & Turbine Cogen MSW
Olivard. 2017. [126]	Anaerobic Digestion & CHP of MSW	Heat (MWh/y / tonne waste)	0.104	0.508	Dry AD & Turbine Cogen MSW
Olivard. 2017. [126]	Anaerobic Digestion & CHP of MSW	Electricity (MWh/y / tonne waste)	0.111	0.338	Dry AD & Turbine Cogen MSW
Van Schalkwyk. 2019. [122]	Catalytic Pyrolysis of Forest Residues	Biochar (tonne/tonne waste)	0.873	0.919	Garden Waste
Van Schalkwyk. 2019. [122]	Catalytic Pyrolysis of Forest Residues	Biochar (tonne/tonne waste)	1.044	1.919	Garden Waste
Van Schalkwyk. 2019. [122]	Catalytic Pyrolysis of Forest Residues	Bio-Oil (tonne/tonne waste)	0.201	0.186	Garden Waste
Van Schalkwyk. 2019. [122]	Catalytic Pyrolysis of Forest Residues	Bio-Oil (tonne/tonne waste)	0.371	1.186	Garden Waste
Karaduman <i>et al.</i>, 2000.	Flash Pyrolysis of Polystyrene	Syngas (tonne/tonne waste)	0.344	0.716	Plastics
Karaduman <i>et al.</i>, 2000. [196]	Flash Pyrolysis of Polystyrene	Biochar (tonne/tonne waste)	0.168	0.151	Plastics

Source	Scenario	Product Type & Unit	Literature Product Fraction (tonne/tonne of waste)	WUDSS Product Fraction (tonne/tonne of waste)	WUDSS Waste Type
Karaduman <i>et al.</i> , 2000. [196]	Flash Pyrolysis of Polystyrene	Bio Oil (tonne/tonne waste)	0.304	0.124	Plastics
Klaimy <i>et al.</i> , 2021. [197]	Flash Pyrolysis of Plastic	Syngas (tonne/tonne waste)	0.432	0.716	Plastics
Klaimy <i>et al.</i> , 2021. [197]	Flash Pyrolysis of Plastic	Biochar (tonne/tonne waste)	0.360	0.151	Plastics
Klaimy <i>et al.</i> , 2021. [197]	Flash Pyrolysis of Plastic	Bio Oil (tonne/tonne waste)	0.108	0.124	Plastics
Gao <i>et al.</i> , 2022. [198]	Gasification & Plasma Post Processing of Biomass	Syngas (tonne/tonne waste)	0.850	0.757	Food Waste
Gao <i>et al.</i> , 2022. [198]	Gasification & Plasma Post Processing of Biomass	Syngas (tonne/tonne waste)	0.750	0.685	MSW OF
Hwang <i>et al.</i> , 2020. [199]	Composting of Kitchen waste & sawdust	Compost (tonne/tonne waste)	0.907	0.980	Food Waste
Liyanage. 2013. [135]	Gasification & IGCC of Rice Husks	Electricity (MWh / tonne waste)	0.620	1.017	Garden Waste
Liyanage. 2013. [135]	Gasification & IGCC of Rice Husks	Electricity (MWh / tonne waste)	0.520	0.349	RO
Liyanage. 2013. [135]	Gasification & IGCC of Rice Husks	Electricity (kW / tonne waste)	0.205	0.349	RO
Nina. 2017. [145]	Heterogeneous Catalytic Conversion of Syngas	Fuels (tonne/tonne syngas)	0.319	0.285	syngas
Miranda <i>et al.</i> , 2020. [200]	Heterogeneous Catalytic Conversion of Syngas	Fuels (tonne/tonne syngas)	0.212	0.285	syngas
Miranda <i>et al.</i> , 2020. [200]	Heterogeneous Catalytic Conversion of Syngas	Fuels (tonne/tonne syngas)	0.222	0.285	syngas
Miranda <i>et al.</i> , 2020. [200]	Heterogeneous Catalytic Conversion of Syngas	Fuels (tonne/tonne syngas)	0.562	0.285	syngas
GIZ. 2016. [201]	Trigeneration of Natural Gas	Total Output (MWh/y / tonne gas)	7397.847	8463.622	MRG
Khan and Adewuyi. 2019. [140]	Distillation of Bio Oil	Fuels (tonne/tonne bio-oil)	1.856	1.856	Bio-oil
Khan and Adewuyi. 2019. [140]	Distillation of Bio Oil	Fuels (tonne/tonne bio-oil)	1.665	1.856	Bio-oil

Source	Scenario	Product Type & Unit	Literature Product Fraction (tonne/tonne of waste)	WUDSS Product Fraction (tonne/tonne of waste)	WUDSS Waste Type
Liyanage. 2013. [135]	Gasification & Gas Turbine System of Rice Husks	Electricity (MWh/tonne biomass)	3.333	0.557	Food waste
Eke <i>et al.</i>, 2020. [202]	Fast Pyrolysis of MSW	Biofuel (tonne/tonne)	0.253	0.296	MSW unsorted
Eke <i>et al.</i>, 2020. [202]	Fast Pyrolysis of MSW	Biofuel (tonne/tonne)	0.326	0.296	MSW unsorted
Mavridis and Voudrias. 2021. [203]	Anaerobic Digestion & CHP of MSW	Heat (MWh/y / tonne waste)	0.363	0.508	Dry AD & ICE Cogen MSW
Mavridis and Voudrias. 2021. [203]	Anaerobic Digestion & CHP of MSW	Electricity (MWh/y / tonne waste)	0.290	0.378	Dry AD & ICE Cogen MSW
Jin <i>et al.</i>, 2021. [204]	Anaerobic Digestion & CHP of Food Waste	Heat & Electricity (MWh/y / tonne waste)	1.125	0.886	Dry AD & ICE Cogen MSW
Vera <i>et al.</i>, 2011. [205]	Gasification & Gas Turbine System of Olive Pits	Electricity (MWh/tonne biomass)	0.875	0.557	Food waste
Vera <i>et al.</i>, 2011. [205]	Gasification & Gas Turbine System of Exhausted pomace	Electricity (MWh/tonne biomass)	0.853	0.557	Food waste
Jordal <i>et al.</i>, 2015. [206]	Membranes Separation of Syngas	Hydrogen (tonne/tonne H ₂ in inlet gas)	0.232	0.247	Syngas
Swanson. 2010. [141]	Gasification & Fischer Tropsch of Biomass	FT Fuels (tonne/tonne waste)	0.190	0.183	MSW OF
Zhang. 2007. [207]	Composting of Food Waste	Compost (tonne/tonne waste)	1.107	0.980	Food Waste
Zhang. 2007. [207]	Composting of Food Waste	Compost (tonne/tonne waste)	0.786	0.980	Food Waste
Tang <i>et al.</i>, 2021. [208]	Trigeneration of MRG	Heat and electricity (MW/tonne gas)	10441.080	8463.622	MRG