



# **A Life Cycle-Based Investigation into the Potential of a Circular and Low-Carbon Plastics Economy in South Africa**

*by*

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## DECLARATION

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May our education be utilised for the benefit of society, and may we be granted the ability to practice the knowledge that we have gained.

### Prior Publication

Some sections of this thesis have already appeared in print, in two articles lead-authored by myself, but they are included in the thesis, in the interests of a comprehensive treatment of the subject matter. In particular, the methods presented in these papers have since been improved and rewritten where necessary, with attendant improvements in the precision of the results which also are presented afresh. The thesis thus supersedes the papers.

Goga, T., Harding, K., Russo, V., von Blottnitz, H., 2022. What material flow analysis and life cycle assessment reveal about plastic polymer production and recycling in South Africa. *S. Afr. J. Sci.* 118. <https://doi.org/10.17159/SAJS.2022/12522>

Goga, T., Harding, K., Russo, V., von Blottnitz, H., 2023. A lifecycle-based evaluation of greenhouse gas emissions from the plastics industry in South Africa. *S. Afr. J. Sci.* 119. <https://doi.org/10.17159/SAJS.2023/13842>

## ABSTRACT

Plastics are multi-functional materials that, while associated with numerous applications, are becoming strongly linked with the drawbacks of a primarily fossil fuel-based linear economy model. This results in the release of greenhouse gas emissions, low material recovery rates, and the environmental impacts associated with disposal and leakage. The circular economy approach is viewed as an alternative model that aims to improve environmental and economic performance, in the case of plastic systems by replacing conventional feedstock, reducing plastic litter, and creating value from waste through reuse and recovery. However, a transition from a linear to a circular model for the plastics sector remains poorly understood. Studies are generally restricted to the analysis of waste management systems with limited information available on the connection between material circularity and environmental impacts. Although several global studies have sought to explore this link using life cycle assessment methods, they do not consider national scale factors, such as the effect of a country's waste management landscape and its energy mix.

This research study investigates potential future versions of a low-carbon and circular plastics economy in South Africa. The scenarios evaluated are based on local voluntary and regulatory objectives and include increased mechanical recycling, the shift from single-use consumption to reuse, and decarbonisation of the sector by integrating renewable energy into the electricity mix as well as replacement of the fossil fuel feedstock for monomer production. Furthermore, the combination of scenarios is modelled to demonstrate the potential benefit of implementing these strategies in concert. The industrial ecology tools Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) are utilised to determine the degree of circularity and assess the impacts of these strategies along the plastics life cycle. The results are presented in terms of circularity and environmental indicators including but not limited to recycling rates, quantity of leakage, Global Warming Potential (GWP), and ecosystem quality.

The results for the reference year (2018) demonstrate that South Africa had a per capita plastic consumption of 36 kg/capita/year, with a plastic sector input recycling rate of 40.3%, employment opportunities totalling 77 348, and a carbon footprint equivalent to 3.9% of the country's total annual emissions. Based on current practices and with no policy interventions or measures, the short-term forecast indicates that plastic production will increase by a rate of 1.7% annually between 2018 and 2025 (Baseline scenario). This will lead to a projected

increase in plastic use of 1 kg/capita and a subsequent rise in leakage of 11%. Furthermore, it is expected that the degree of environmental impact will increase between 10 and 18% with a further increase of 21% in the subsequent decade. In terms of normalised results, significant impacts across all scenarios were identified as human toxicity and ecotoxicity, fossil resource scarcity, and freshwater eutrophication. Additionally, the contribution analysis revealed that the major quantifiable environmental impacts are associated with upstream processes such as monomer and polymer production and product manufacturing with a combined share of 55-85% of the total impacts at the endpoint level (Areas of Protection). This is primarily due to coal-based pathways for feedstock and energy production.

Although all the mitigation strategies, particularly elevating recycled rates, and decarbonisation of the system, display a benefit relative to the Baseline scenario, the findings demonstrate that the greatest gain amongst materiality, circularity, and environmental indicators can be achieved under the Combination scenario in 2025 with an 11.2% increase in recycled content, 1 kg/capita reduction in leakage, and an average decrease of 16% in midpoint impacts. This benefit is further extended to an additional 40.1% increase in recycled content and a 55% average improvement in environmental effects in 2035 under the medium-term forecast with levels projected to decline below historical findings for 2018. A comparison of results with global targets shows the potential of combining scenarios beyond short-term local ambitions. Notwithstanding these significant benefits in circularity and environmental impacts, leakage to the environment would still be prevalent with an estimated 256 kt of plastic debris in 2035.

Despite the identification of significant potential improvements from a material and environmental perspective through the combined application of the three modelled strategies, it is concluded that these would not transform the South African plastics sector to the extent that it could be classified as fully or even largely circular nor low-carbon in the short- to medium-term. Recommendations on the material aspects include designing for recyclability, investigating the potential for chemical recycling to complement mechanical recycling, and promoting reuse business models. From an emissions perspective, the transition to renewable energy needs to be accelerated, and the introduction of lower-carbon routes for the local polymer production process should be investigated. The findings also illustrate the need for increased coordination between upstream strategies centred around design and material innovation together with downstream processes focusing on end-of-life recycling and recovery to improve the environmental profile of the South African plastics system.

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## LIST OF ACRONYMS

BBC	Buy-Back Centres
CC	Closed Cycle
CtL	Coal-to-Liquid
EoL	End-of-life
EPR	Extended Producer Responsibility
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HD-PE	High-density Polyethylene
IPCC	Intergovernmental Panel on Climate Change
IRP	Integrated Resource Plan
IUCN	International Union for Conservation of Nature and Natural Resources
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSA	Life Cycle Sustainability Assessment
LCT	Life Cycle Thinking
LD-PE	Low-density Polyethylene
LNG	Liquefied Natural Gas
MAUT	Multi Attribute Utility Theory
MFA	Material Flow Analysis
MRF	Material Recovery Facility
NEMWA	National Environmental Management: Waste Act
OECD	Organisation for Economic Cooperation and Development
PET	Polyethylene Terephthalate
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl Chloride
RoW	Rest of World
SDG	Sustainable Development Goals
S-LCA	Social Life Cycle Assessment
USA	United States of America

## CHAPTER 1: INTRODUCTION

The varied application of plastics has caused global production to increase from two million tons in 1950 to 380 million tons in 2015 (Geyer et al., 2017). However, current levels of consumption and disposal have generated several environmental concerns. The traditional plastics production process, which involves the transformation of fossil fuels into their constituent monomers, is highly energy-intensive and is estimated to account for 400 million tons of greenhouse gas (GHG) emissions in 2012 (Organisation for Economic Cooperation and Development, 2022a). Additionally, a major percentage of annual plastic production is reserved for packaging. Due to its lightweight nature, 95% of plastic packaging material value is lost to the economy after a short single-use cycle with 32% escaping collection systems and leaking into the natural environment (Ellen MacArthur Foundation, 2017). The circular economy offers an alternative vision to achieve improved environmental and economic outcomes while harnessing the benefits of plastic packaging.

The opening chapter sets the scene by describing the local plastic sector and the advent of life cycle thinking for plastics. This is followed by a description of the problem along with the intended aim and objectives of the thesis. The chapter concludes with an outline of the structure of the thesis.

### **1.1. The South African Plastics Industry**

The South African plastics industry is well-developed with the sector's contribution representing 2.7% of the country's GDP and approximately 21.8% of the manufacturing sector's economic output (Department of Trade and Industry, 2020). Ranked 32<sup>nd</sup> by annual tonnage amongst plastics producing countries, South Africa produces over 1.8 million tons of plastic products annually (Europe Plastics and Rubber Machinery Association, 2016). Although the industry declares a high input recycling rate of 46.3%, there are a few associated challenges (Plastics SA, 2019). Amongst these are the fact that the local waste recycling economy is largely driven by the informal waste sector with 395 thousand tons of plastic material collected by informal recyclers in 2017 (Godfrey, 2021a). Other aspects of concern include the lack of effective waste disposal for 30% of the population, inefficient sorting and collection facilities, and saturated traditional end markets for recycled products (Pretorius, 2019; Rodseth et al., 2020). This leads to a notable amount of material that is not or is unable

to be recycled which is partially disposed of in sanitary landfill sites compliant with environmental regulations but also leads to activities such as illegal dumping and littering.

The focus of recent legislation has shifted from waste diversion and management to embrace a circular economy approach (Department of Environmental Affairs, 2019). The circular economy model is underpinned by three main principles namely minimisation of waste and pollution, circulation of products and materials at their highest value, and regeneration of nature (Ellen MacArthur Foundation, 2013). Applied to the plastics industry, this translates to decoupling plastics from fossil feedstocks, reducing the leakage of plastics into natural systems, and creating an effective after-use plastics economy (Ellen MacArthur Foundation, 2017). To align with this vision, the South African Plastics Pact, with GreenCape as the secretariat and various resin producers, packaging manufacturers, retailers, and recyclers as business members, aims to transform the country's plastic packaging sector by 2025, setting ambitious targets related to material recycling, reuse, and recovery (The South African Plastics Pact, 2020). Additionally, the Extended Producer Responsibility (EPR) regulations, promulgated in terms of section 69 of the National Environmental Management Waste Act (NEMWA), set yearly targets for collection and recycling as well as a mandatory percentage of recycled content for several plastic packaging products (Department of Environment Forestry and Fisheries, 2021).

The path to a circular future would necessitate a reduction in virgin fossil feedstocks - both from local and imported sources. The South African chemical industry is indirectly based on the gasification of coal followed by Fischer Tropsch process with the unique coal-to-liquid (CTL) plant situated at Sasol Secunda (Sasol, 2022). Thus, Sasol's processes are highly complex and integrated with coal feedstock being used to produce both synthetic fuels and chemicals. With a global shift towards electric vehicles, it needs to be recognised that despite Sasol setting a 30% reduction in scope 1 and 2 emissions by 2030 (Sasol, 2021a), the economic future of local liquid fuel (and associated chemicals) production is uncertain. Together with Secunda's aging infrastructure and the fact that Sasol's GHG emission profile is dominated by their CTL operations (Sasol, 2019), the cumulative effect on the chemicals industry particularly the plastics sector could prove deeply disruptive. Conversely, the reduction in demand for valuable monomers due to increased circular plastics use could adversely affect the feasibility of synthetic fuel production in South Africa. On a global scale, it has been recognised that these transition uncertainties necessitate an urgent investigation into exploring various decarbonisation options related to the combination of low-carbon energy sources for the

transportation sector as well as partial replacement of the current fossil-based feedstock utilised in primary plastic production (Energy Transitions Commission, 2018). The same applies to South Africa, but with unique differences due to the local setting.

## **1.2. Life Cycle Thinking for the Plastics Sector**

Life Cycle Assessments (LCA) have been progressively used as an assessment tool to quantify and compare the environmental impacts of various plastic products. A recent review by Chitaka and Goga (Chitaka and Goga, 2023) for LCAs conducted for single-use beverage and food products shows the steady progression of studies from 2017. Numerous LCA studies of individual plastic products and processes have also been conducted by the industry in response to a growing need to understand supply chains and their life cycle impacts (United Nations Environment Programme, 2022a, 2022b). To fulfil the Medellin declaration, recent research has been undertaken to develop metrics to quantify the environmental impacts due to marine debris such as plastics and microplastics leaking into the environment. However, these have not been incorporated into standard impact assessment methods.

To date, LCA literature for plastics has centered mainly around environmental indicators such as global warming potential, energy demand, and water use with less attention being directed towards other environmental impacts (Organisation for Economic Cooperation and Development, 2018). Furthermore, studies have generally been restricted to certain geographical locations and addressed various waste management systems rather than an assessment of the entire value chain. The study by Zheng and Suh (2019) attempted to correct this by estimating the global carbon footprint for projected plastic flows together with an assessment of several GHG mitigation strategies. In Africa, research is still in its infancy with limited emerging studies such as Stafford et al. (2022), which focused on the flow patterns of plastic as well as the quantification of environmental impacts arising from plastic production, use, and disposal activities. However, there is still a significant knowledge gap with insufficient data available to quantitatively describe key environmental impacts of current and future variants of the South African plastic industry.

## **1.3. Problem Statement**

Globally, plastics are integral to the modern economy with demand rising for this versatile material. Despite its beneficial properties and large-scale production and application, the plastic industry has recently come under increased scrutiny due to its environmental footprint. The

focus of research has been limited to assessing waste management systems and increasing the effectiveness of recycling and waste recovery processes, with only a few studies considering the environmental impacts on a national and global scale. Although the question of plastic leakage is increasingly being investigated, a life cycle-based approach has never been utilised to assess the inevitable consequences of circular materials use in a fossil carbon-intensive chemicals industry predicated on a mostly linear materials economy i.e. looking at the national plastics sector and taking the entire value chain into account. In South Africa, additional points of complexity arise due to the socio-economic impact of the existing intricate plastic waste management system, which needs to be addressed. No quantified models exist that demonstrate how the benefits of local plastics production and use could be achieved in a manner that is consistent with the requirements of a circular plastics economy and low to net-zero greenhouse gas emissions.

#### **1.4. Aim and Objectives**

This PhD thesis aims to quantitatively develop and analyse future options for a circular and low-carbon plastics economy in South Africa. To improve the circularity of the system and meet the targets set by the SA Plastics Pact and the EPR regulations, a range of future mitigation scenarios were developed. These include increasing the rate of the current practice of mechanical recycling as well as managing plastic demand by shifting from single-use to reuse. Other strategies under evaluation are the decarbonisation of both the energy mix and feedstock into the local polymer production process. Such an analysis requires the use of Material Flow Analysis (MFA) as a tool to provide an overview of the future structure of the industry culminating in the generation of mass-based indicators. Life cycle-based methods can then be utilised to obtain indicators of environmental damage such as global warming potential and water scarcity. To broaden and deepen the scope of the research to extend beyond a traditional LCA, other environmental and socio-economic performance markers were calculated. These include assessing the quantity and impact of plastic leakage into the natural environment as well as considering the impacts on employment along the plastics value chain.

#### **1.5. Outline of Structure**

The introductory chapter of the thesis begins by framing the context of the research, the motivation for the study as well as the aims and objectives. Chapter 2 goes on to critically review relevant academic literature and methods used for similar studies, relative to domestic initiatives, to support the stated aims and objectives and identification of past and present

knowledge gaps. The research design and methods used, including research questions, are thereafter presented in Chapter 3.

The research findings are discussed in Chapters 4-5. Specifically, Chapter 4 is devoted to presenting the short-term results as well as a contribution analysis for the reference and base cases together with the three mitigation scenarios. The results of a final scenario, combining the individual mitigation pathways, are also presented. This is followed by a synthesis of results which precedes a consolidative discussion, integrating part of the results presented in Chapter 4 and extending the timeline. The chapter concludes by comparing the findings against global and international targets.

The final chapter, Chapter 6, presents the contributions and implications of the research by summarising the key findings. Recommendations for future learning and research possibilities are also included.

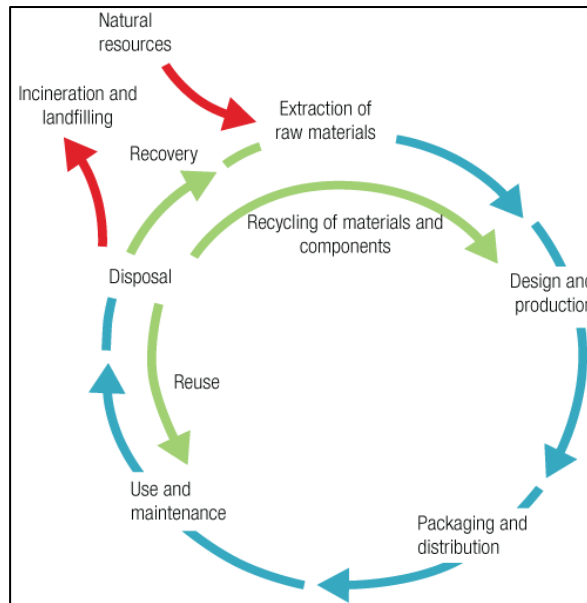
## CHAPTER 2: LITERATURE REVIEW

This chapter is presented in several sections and aims to provide an overview of key findings by summarising current literature on the themes and links between life cycle analysis and material balances, plastics, and the circular economy. The review opens with a synopsis of elementary tools and concepts related to sustainability such as Life Cycle Thinking (LCT), Material Flow Analysis (MFA), and the circular economy. The analysis continues with an overview of plastics-related research in relation to the circular economy with a complementary discussion of circular economy indicators associated with the plastics industry. The role of LCA within a circular economy setting is thereafter unpacked along with the state of research to estimate the environmental impacts of plastic leakage. This is followed by an analysis of the specific application of systems thinking to the plastics sector to transition to a circular economy. This covers studies mapping the plastic value chain including levels of plastic in the marine environment as well as plastics-related LCA studies. The review closes by examining mitigation strategies in the plastics sector from a local perspective.

### 2.1. Basic Concepts and Tools

#### 2.1.1. *Life Cycle Thinking and Management*

The concept of Life Cycle Thinking (LCT) arose as an approach to extend the traditional focus from an organization's production facility to encompass the product's entire value chain. As a sustainability management approach, the main aim of LCT is to improve the environmental performance of a product by reducing its resource use and emissions as well as decreasing the socio-economic impacts throughout its life cycle (Life Cycle Initiative, 2020). The figure below (Figure 1) illustrates that a product's life cycle includes all stages from the extraction of raw materials through materials processing, manufacture, distribution, use, repair, and maintenance to recovery, recycling, and reuse or final disposal.



**Figure 1: A Typical Product Life Cycle Diagram (Life Cycle Initiative, 2020)**

The most popular method of applying LCT is environmental Life Cycle Assessment (LCA), which was initiated in the 1960s as a response to the increased awareness of environmental protection (International Reference Centre for the Life Cycle of Products, 2015). LCA is an analytical tool that is used to determine the potential environmental impact of a product or a service process by characterising and quantifying the inputs and outputs of a specific system. In particular, the procedure provides an evaluation of the product’s life cycle from ‘cradle to grave’ i.e. from raw material procurement to production, use, treatment and recycling, and concluding with disposal (International Organisation for Standardisation, 2006). By including all the impacts at each life cycle stage, the LCA provides an extensive reflection of the potential environmental impacts and trade-offs in the selection of products and processes.

The concept of Life Cycle Management (LCM) appeared in the early 2000s as a business management approach to improve companies’ sustainability performance. LCM embraces a variety of related tools such as Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA). They are viewed as complementary techniques to an environmental LCA as they adhere to the triple-bottom-line perspective of sustainability by assessing the economic, social, and socio-economic impacts of a product system over its life cycle (United Nations Environment Programme, 2009). Shifting to a more comprehensive assessment of sustainability, the Life Cycle Sustainability Assessment (LCSA) is a more modern life cycle-based approach. By combining all three tools of LCM to create an overarching assessment, the analysis aims to

broaden and deepen the scope of a traditional LCA. Common challenges cited with the methodology include the development of quantitative and practical indicators for S-LCA and comprehensive uncertainty assessment (Guinée, 2016).

### **2.1.2. *Material Flow Analysis***

Material Flow Analysis (MFA), which is a tool used in the study of industrial ecology and resource and waste management, is defined as a systematic assessment of the flows and stocks of material within a system defined in space and time (Brunner and Rechberger, 2004). It is a material accounting tool based on the conservation of mass, which compares all inputs, accumulation of stock, and outputs of a process. Generally, MFA can be applied at three levels namely the micro, meso, and macro level which corresponds to a product, sector, and economy-wide scale assessment.

Although the MFA tool is recognized for its simplicity and flexibility, challenges inherent to studies include data uncertainty and the availability of critical information (Corona et al., 2019). Other limitations related to the use of MFA are the failure of the tool to provide information associated with the quality of materials as well as restricted environmental accounting as certain impacts (e.g. the scarcity of resources) are excluded (Elia, Gnoni and Tornese, 2017). Nevertheless, Sankey diagrams generated from MFA calculations are effective for public communication of results to a wide range of stakeholders, which is crucial for the analysis of complex systems.

### **2.1.3. *Circular Economy***

The concept of a circular economy has been gaining prominence as it is viewed as an operational model for legislators, regulators, and businesses to implement some key aspects of sustainable development. Circular economy definitions have been comprehensively reviewed in the literature with Kirchherr et al. (2017) comparing 114 descriptions and compiling the following comprehensive definition of CE as an “economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro-level (products, companies, consumers), meso-level (eco-industrial parks) and macro-level (city, region, nation and beyond), with the aim of accomplishing sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations.” Thus, the circular economy concept

aims to challenge the traditional, linear ‘take-make-dispose’ model of production and consumption, in which resources are extracted, mined, grown, manufactured, transported, and then used before being disposed of at the end of the value chain. Whilst the terminology may be used non-uniformly, a common goal is to seek opportunities to improve resource efficiency and include circularity in a product’s life cycle.

Initially, circular economy design philosophies focused on selecting recyclable materials for product development. This has now evolved to include ‘upstream and downstream circularity’ by managing resources efficiently, improving productivity in operation and consumption processes, and maximizing the value of waste materials (World Economic Forum, 2018). The Ellen McArthur Foundation, which is a prominent organization involved in developing the CE model, has highlighted three principles characterising the circular economy, namely value preservation, resource optimization, and system effectiveness (Ellen MacArthur Foundation, 2013). Although the earlier models were based on the “Three R principle” which incorporates activities such as “reduce, reuse, recycle” in order of circularity, more recent models include steps such as refurbishment and repair, repurposing, and energy recovery (Voukkali et al., 2023).

The shift towards a circular economy amongst developing countries began with the action plan ‘Closing the loop’ published in 2015 by the European Union (European Commission, 2015). The new circular economy action plan was thereafter adopted in 2020 and is one of the significant components of the European Green Deal, considered Europe’s new agenda for sustainability (European Commission, 2023). In China, the Circular Economy Promotion Law was formulated in 2008 to improve resource efficiency, realise sustainable advances, and promote the development of the circular economy (National People’s Congress Standing Committee, 2008). While the concept of the circular economy may not yet be formally well-established in Africa, a number of countries such as Kenya, Namibia, and South Africa have developed detailed national waste management strategies that focus on the promotion of the circular economy (Attafuah-Wadee and Tilkanen, 2020). Amongst the sectors identified as having significant potential for circular economic development are mining, agriculture, and manufacturing, the latter including material efficiency and product design for circularity (Godfrey, 2021b).

## **2.2. Plastics and the Circular Economy**

### ***2.2.1. Status of Plastics in the Circular Economy***

The transition from a linear to a circular economy for plastics is acknowledged as being critical for addressing the concerns around plastic leakage while potentially providing additional environmental and socio-economic benefits. General guidelines to address plastics within a circular economy include the introduction of renewably sourced feedstock, recapturing material value from waste and reducing plastic leakage into natural systems (Ellen MacArthur Foundation, 2017). In line with this, global measures and environmental policies have been established to promote the reduction and recycling of plastic and, more recently, the transition to a circular economy for plastics.

As part of the EU's circular economy action plan, the European Union launched The European Strategy for Plastics in a Circular Economy (European Commission, 2018). The strategy builds on existing measures to reduce plastic waste and is a key feature of the region's transition towards a circular and carbon-neutral economy. The European Green Deal follows up on the EU's Plastics Strategy and proposes measures including tackling microplastic release, regulation of single-use plastics, and introducing a requirement for recycled content in various products to boost the secondary raw material market (European Commission, 2023). Within Asia, the Act on the Promotion of Resource Circulation for Plastics was enacted in Japan to improve the circulation of plastics (Tamaki and Wada, 2023) while a new policy by China to introduce a phased ban on various types of single-use products follows the country's decision to ban imports of plastic waste (Myers, 2020). While other countries including Kenya and Thailand have introduced bans to reduce single-use plastic production and consumption together with an introduction of EPR policies in 16 African countries, a more holistic circular approach considering design and upstream elements is required to fully transition to a circular economy (Attafuah-Wadee and Tilkanen, 2020).

Despite recent policy initiatives to close the plastics loop, it was found that the plastics life cycle is only 8% circular (Organisation for Economic Cooperation and Development, 2022b). An estimated 139 Mt of leaked plastics has accumulated in rivers and the oceans as of 2019. Although the onset of the COVID-19 pandemic temporarily disrupted trends in plastic use and waste generation, production regained its upward trajectory in 2021 as economic activity resumed (Organisation for Economic Cooperation and Development, 2022b).

Most of the research surrounding plastics within the context of advancing towards a circular economy addresses a specific technology, product, or intervention strategy that applies to a subsection of the plastics supply chain e.g. solutions for food packaging (Guillard et al., 2018) or specialist waste treatment technologies such as chemical recycling (Meys et al., 2020) and pyrolysis (Sakthipriya, 2022). Additionally, the evidence suggests that there is a preference for studies to focus on end-of-life strategies to reduce the environmental impacts of plastics when a truly circular approach should also consider activities further up the supply chain (King and Locock, 2022). Furthermore, an evaluation of waste metrics in the framework of a circular economy shows that a shift from the linear production model frequently leads to the development of internal capabilities along the value chain and higher efficiency that leads to a reduction in costs and an increase in productivity (Voukkali et al., 2023).

### ***2.2.2. Circular Economy Indicators for Plastics***

The concept of the circular economy is systematic by design and conceives of a closed-loop production and consumption system that produces minimal material loss (Ellen MacArthur Foundation, 2013). To measure the effectiveness of a circular economy strategy, it is necessary to use monitoring and evaluation tools that generate suitable indicators. Although this has resulted in the development of numerous circularity indicators, there is inconsistency regarding their purposes, scope, and potential applications (Saidani et al., 2019).

Various studies have been conducted to develop, review, and evaluate existing circular indicators for the plastics industry (Moraga et al., 2019; Saidani et al., 2019). Van Eygen, Laner and Fellner (2018) used three indicators to describe the extent to which recirculation of plastic packaging materials occurs within the Austrian economy namely the collection rate, the sorting rate, and the recycling rate. In other studies focused on the packaging and waste sector, Pauer et al. (2019) provided a list of input-related, output-related and energy indicators relevant to food packaging while Di Maio and Rem (2015) developed a new indicator termed the Circular Economy Index (CEI) which claims to be more robust and complex compared to the commonly used 'recycling rate' indicator. Other new indicators include the Circular Economy Performance Indicator (CPI) proposed by Huysman et al. (2017) to assess the circularity of different waste treatment options as a ratio of actual environmental benefit to ideal benefit according to quality.

A more recent development saw the provision of the Plastics Circularity Index (PCI), which comprises 21 indicators for general, social, and business categories, to assess the circular usage of plastics for various European Union countries (Bagaria et al., 2020). On a broader scale, the Organisation for Economic Cooperation and Development (OECD) compiled an inventory of 474 circular economy-related indicators, with just under 40% of the indicators related to the environment as they have a direct impact on the ecosystem (e.g. emissions, production and consumption, waste generation) (Organisation for Economic Cooperation and Development, 2021). In general, the most commonly used indicators are at the macro level and are derived from a MFA (Bracquené et al., 2020).

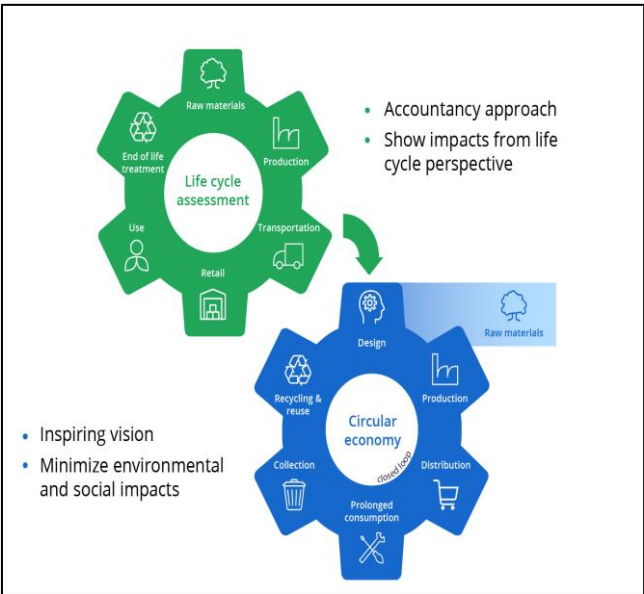
Circularity indicators also fill the gap in LCA studies by measuring circularity and material flows. Niero and Kalbar (2019) looked at the combination of life cycle analysis and circularity indicators by using the Material Circularity Indicator (MCI), which is an indicator proposed by the Ellen MacArthur Foundation, and a selection of life cycle-based indicators as inputs into a decision analysis tool for an alcohol packaging case study. Results show that various sets of indicators can be integrated, and conflicts can be resolved. Brändström and Saidani (2022) also evaluated a circular strategy by comparing four circularity metrics with three complimentary LCA indicators. The findings showed that although the circularity metrics generate accurate results when evaluating resource scarcity, they were unable to capture the benefits of reduced energy. Thus, material-based circularity indicators can be valuable for circular economy practitioners as they can align with specific results from LCAs. However, more comparisons are required to establish circularity metrics for certain situations, especially energy-based indicators. As circularity metrics measure progress according to a few defined circular economy goals, burden-shifting is possible as none of the material-based common indicators, with the exception of the LCA-derived assessment indicators, measure aspects related to the level of emissions, employment, and socio-economic improvements (Rigamonti and Mancini, 2021). Thus, a study focused purely on circularity indicators should be supplemented by an LCA study to confirm that increasing circularity also results in a corresponding benefit in environmental performance within the system.

## **2.3. Role of LCA in a Circular Plastics Economy**

### ***2.3.1. LCA and the Circular Economy***

Several reviews on circular economy show the necessity of employing a systematic view of the life cycle of resources (Ghisellini et al., 2016; Reike et al., 2018). As LCA is a holistic, science-

based technique, it has been promoted to provide technical support to CE stakeholders by assessing the trade-off of impacts related to resources such as water, energy, and raw materials (Peña et al., 2020). By combining circular economy principles with LCA methodologies, designers and developers alike can measure the environmental performance of various product and supply chain options, compare circular strategies, and ensure an environmental benefit from new circular products or services (Ingemarsdotter and Dumont, 2022). Additionally, the LCA perspective can be used to define targets and indicators to measure and promote circularity. Figure 2 shows the complementary relationship between Life Cycle Assessment and the circular economy.



**Figure 2: Simplified Model Showing the Application of LCA to the Circular Economy (Ingemarsdotter and Dumont, 2022)**

Although LCA is a mature tool for analysing the environmental impacts of anthropogenic processes, there are several challenges associated with applying LCA to assess circular economy strategies. Critics highlight the fact that LCA favours short-term gain over long-term performance as it provides a snapshot of a specific metric at a certain moment in time (Ingemarsdotter and Dumont, 2022). Furthermore, traditional LCA methods ignore impacts that are more difficult to measure such as the effect of landfill overflow or plastic accumulating in the environment (Ellen MacArthur Foundation, 2020). Other shortcomings of the current LCA methodology that need to be resolved for better application include achieving consistency in both accounting for stock changes as well as in the modelling process of open recycling loops (Peña et al., 2020). The latter pertains to the loss of quality after recycling due to downcycling activities as the usual end-of-life approaches may not provide the ideal solution based on

circular economy principles (Vargas-Gonzalez, 2017). In a systematic literature review of LCA studies applied to the beverage packaging industry, it was concluded that analysed studies do not contribute equally to circular economy principles (Sazdovski et al., 2021). Methodological choices and detailed modelling of the supply chain including company context are also critical when comparing the sustainability position of bio-based versus fossil-based products in the circular economy as they affect the validity of LCA results (Abbate et al., 2022; Dahiya et al., 2020).

### ***2.3.2. LCA Methodology and Plastic Pollution***

Due to their high stability and durability, plastics generally do not degrade to a large degree when released into the environment. Despite this, sustainability research that analyses the interaction between marine plastic litter and the environment is still young (Boulay et al., 2021). In 2017, the Medellin Declaration on Marine Litter in Life Cycle Assessment and Management was drafted, identifying that although Life Cycle Assessment (LCA) is one of the most popular sustainability assessment tools, it fails to adequately address environmental impacts due to marine debris such as plastics and microplastics (Sonnemann and Valdivia, 2017). Specifically, the declaration emphasizes the need to develop environmental management metrics to quantify the impact of plastic debris on ecosystem quality and, eventually, human health as it accumulates, fragments, and ultimately degrades in the marine environment.

Thus far, studies have considered marine plastic pollution as a research focus area. On the life cycle aspect, life cycle studies have neglected to consider the effect of leakage of plastic to the biosphere in the inventory phase with major databases failing to include these emissions in their datasets (Boulay et al., 2021). However, several studies have demonstrated the use of leakage rates as a proxy for potential marine environmental impacts with a focus on single-use packaging (Chitaka et al., 2020; Zanghelini et al., 2020). The Plastic Leak project has also focused on plastic leakage assessment by using a life cycle approach to estimate microplastic leakage at product and product and corporate level (Peano et al., 2020).

Apart from leakage assessments, fate and effects models related to marine plastic pollution are still being developed. Various studies have introduced a litter indicator for microplastic emissions that takes parameters such as dispersion, degradation rate and incentive to return post-use into account (Civancik-Uslu et al., 2019; Stefanini et al., 2021). A midpoint indicator was also developed to reflect the quantity of material leaked into the environment as well as its

average lifetime to estimate persistence (Stafford et al., 2022). In an attempt to develop a more mechanistic concept, Saling et al. (2020) proposed the creation of a toxicity factor and suggested that marine litter effects can be assessed based on the kinetics of the material. As part of the MarILCA project, Woods et al. (2021) presented a framework that links inventory data (in terms of kilograms of plastic leaked) in a specified environmental compartment to six areas of protection that include ecosystem quality, natural heritage, and socio-economic assets. A recently published output from the project presents characterisation factors for marine and freshwater emissions as well as an update of exposure and effect factors for aquatic microplastic emissions (Corella-Puertas et al., 2023). Although progress has been made, further impacts related to emissions such as transport effects and ecotoxicity of additives still need to be explored for a more comprehensive analysis.

## **2.4. Application of Systems Analysis for a Circular Plastics Economy**

### **2.4.1. Material Flow Analysis (MFA) Studies For Plastics**

To date, there have been numerous MFA studies conducted to quantify the flow and stock of plastics on a national scale. Studies have been undertaken in Europe and Asia for countries such as India, Thailand, Austria, and Poland (Bogucka et al., 2008; Bureecam et al., 2018; Mutha et al., 2006). In Austria, consumption increased by 15% within a ten-year period while the growth in India was projected to increase by a factor of six between 2000 and 2030. For the plastics economy in the United States of America (USA), a plastics material flow diagram by resin type was presented which incorporated production and sales, use markets and end-of-life management for 2017 (Heller et al., 2020). It was found that most plastic reaching end-of-life was disposed of in landfills with less than 8% of material being recycled. Although the packaging was the largest defined use market, two-thirds of plastics produced were utilised in other sectors including electronics, consumer goods, and buildings. A notable result from an MFA used to characterise plastic flows in Trinidad and Tobago is that 48% of the landfilled plastic originates from plastic packaging for imported products instead of intentional domestic use (Millette et al., 2019). This highlights a typical challenge for island nations namely the management of imported materials with limited domestic demand at the end-of-life stage.

On a global scale, stocks and flows of municipal solid waste as well as four sources of macroplastics were modelled for various scenarios between 2016 and 2040 (Lau et al., 2020). The study demonstrated that implementation of feasible interventions such as reducing and substituting plastics with alternative materials and implementing design for recycling reduced

plastic pollution by 40% from 2016 rates, with the greatest change due to a combination of pre- and post-consumption solutions. Taking a continental approach, Babayemi et al. (2019) presented the first continental analysis of the mass importation and consumption of polymers and plastics products in Africa. The assessment showed that the per capita plastic consumption in Africa for 2015 was 16 kg with GDP having a strong link to plastic consumption.

In South Africa, mass balance models of the plastic sector became more prevalent as material flow information was used to highlight the issues facing the industry and provide recommendations on interventions to support sound end-of-life management. Plastic flows were populated using available industry and trade data with unknown flows calculated via mass balances (Department of Environmental Affairs, 2017). Details regarding the year for which the study was conducted, the scope of the research including points of difference compared to other studies, and major results emanating from each study are summarised in Table 1.

**Table 1: Material Flow Analysis Models for Plastics in South Africa**

<b>Base Year</b>	<b>Scope</b>	<b>Significant Findings</b>	<b>Source</b>
2015	<ul style="list-style-type: none"> <li>• Total plastics flow including direct and indirect imports.</li> <li>• Unrecovered informal waste stream is shown as part of EoL</li> </ul>	<ul style="list-style-type: none"> <li>• 15-25% of unrecovered plastics estimated to be in informally managed waste streams</li> <li>• Plastic consumption estimated to lie between 34-52 kg/capita/year</li> </ul>	(Department of Environmental Affairs, 2017)
2017	<ul style="list-style-type: none"> <li>• Circularity in the system included</li> <li>• Flow of durable goods reaching disposal stage estimated</li> </ul>	<ul style="list-style-type: none"> <li>• 2.4 times plastic not recycled to quantity recycled.</li> <li>• Litter relatively small flow at 11kt</li> </ul>	(Blottnitz et al., 2018)
2017	<ul style="list-style-type: none"> <li>• Quantification of flows and stocks</li> <li>• Includes uncertainty evaluation</li> </ul>	<ul style="list-style-type: none"> <li>• 24 kg/capita of primary plastic and 49 kg/capita of plastic product were produced.</li> <li>• Estimated a national plastic recycling rate of 13%</li> </ul>	(Kunle Ibukun Olatayo et al., 2021)
2018	<ul style="list-style-type: none"> <li>• Mass balance by polymer and sector</li> <li>• Synthetic rubber included in the analysis</li> </ul>	<ul style="list-style-type: none"> <li>• Per capita plastic waste generation is around 41 kg/cap/year</li> <li>• Approximately 40% of waste is mismanaged.</li> </ul>	(IUCN-EA-QUANTIS, 2020)
2018	<ul style="list-style-type: none"> <li>• Update of 2017 MFA including revised % of self-help disposal.</li> <li>• Mass-based indicators calculated.</li> </ul>	<ul style="list-style-type: none"> <li>• 20% less local polymer compared to imported polymer used in South Africa</li> <li>• Increasing recycling will reduce waste disposal by 28% relative to baseline growth</li> </ul>	(Goga et al., 2022)

- |      |  |  |
|------|--|--|
| 2020 | <ul style="list-style-type: none"><li>• Macro-plastic component of municipal solid waste (MSW)</li><li>• Distinguishment between formal and informal recycling and mechanical and chemical recycling</li></ul> | <ul style="list-style-type: none"><li>• Informal waste sector responsible for collecting/sorting 76% of waste plastic that enters recycling (Stafford et al., 2022)</li><li>• Plastic pollution is dominated by the burning of waste and terrestrial pollution</li></ul> |
|------|--|--|

Generally, the majority of case studies advise that policy formulation and legislation are needed to improve waste management by reducing uncollected waste and improper disposal through the development and enforcement of environmentally sound treatment technologies. In a review article characterising existing studies and data sources on plastic flows and stock accounting, information gaps that were identified included consistent data collection and reporting, standardised methods for data reconciliation, and the need to create a common platform for data sharing (Wang et al., 2021). Locally, limitations include poor reporting on solid waste management by municipalities and a lack of data surrounding open-loop recycling, uncollected waste and plastics recovered from landfills (Stafford et al., 2022).

#### ***2.4.2. Quantification of Leakage of Plastics into the Oceans***

As one of the defining principles of a circular plastics economy is the reduction of plastic leakage into ecosystems, particularly the ocean, it is imperative to estimate the level of plastics in the environment. Thus far, efforts at quantifying the level of plastic pollution in marine environments have focussed on the deposition of debris on beaches while relatively few studies have attempted to estimate the flow of plastics into the environment. It has been established that marine litter and plastic pollution originate mainly from land-based sources (United Nations Environment Programme, 2021a; van Truong and Beiping, 2019). According to the body of research, the volume of ocean plastics is estimated to lie between 75-199 million tons (United Nations Environment Programme, 2021a). Furthermore, it is estimated that 61% of microplastic leakage stems from uncollected waste, a percentage that could increase to 70% in 2040 under a business-as-usual case (The Pew Charitable Trusts and SYSTEMIQ, 2020). Based on per capita plastics use and country-specific waste generation rates, mismanaged plastic waste totalled 32 million tons in 2010 with the proportion of this waste reaching the oceans estimated to amount to between 4.8 and 12.7 million tons (Jambeck et al., 2018, 2015; Lebreton and Andrady, 2019). This highlights the fact that although countries may claim low plastic use per capita, waste can accumulate due to inadequate waste management infrastructure.

In an initial evaluation of land-based sources of marine plastics, it was estimated that South Africa contributed 90 000-250 000 tons to the accumulation of marine plastics in 2010 thereby ranking the country as the 11<sup>th</sup> worst contributor to marine plastic pollution (Jambeck et al., 2015). Using a similar assumption regarding mismanaged waste from coastal populations that will enter the ocean, a more recent study has revised this range to lie between 15 000 and 40 000 tons of plastic carried to the oceans on an annual basis, which is considerably lower than

the previous estimate (Verster and Bouwman, 2020). By extending the analysis to encompass mismanaged waste from inland populations, it was estimated that 79 000 tons of plastic was leaked to the ocean and main rivers annually (IUCN-EA-QUANTIS, 2020). It is thus likely that leakage to the oceans is less than 5% of the plastics annually used, demonstrating that even a highly circular plastics economy (at approximately 80-90% circularity) could still contribute significantly to this environmental concern. These two concerns thus need complementary but differentiated approaches.

#### ***2.4.3. Life Cycle Assessment (LCA) Studies of Plastic Processes and Products***

Globally, solutions have been proposed to mitigate the impacts of a mostly linear plastics economy including replacing single-use items with reusable alternatives, substituting petroleum-based products with bio-based plastics, and improving waste management systems. As the environmental impacts of plastics are not restricted to greenhouse gas emissions and plastic leakage but instead extend to other impacts such as resource scarcity, eutrophication, and land use (Organisation for Economic Cooperation and Development, 2022b), LCAs have been used as a tool to quantify and compare multiple impacts across a range of scenarios. With the rising popularity of circularity and recovery of waste products, studies have also transitioned to include the benefits of reuse and recycling (Chitaka and Goga, 2023).

To develop an understanding of societal plastic flows, LCA studies have been conducted to evaluate national waste management systems. Austria and Spain have been used as case studies where the aim was to identify and minimize environmental impacts caused by plastic waste (Seigné-Itoiz et al., 2015; Van Eygen et al., 2018). The results from the Austrian LCA indicate that the greatest benefit across most impact categories was due to mechanical recycling. Although the increase in overall net benefits corresponded to the amount of material recycled, it was noted that the optimal recycling rate might lie below 100%. The results from the Spain study echoed the Austrian findings with mechanical recycling found to be the most favourable plastic waste management option. However, the results were highly dependent on the quality of recovered plastic with contamination identified as one of the factors limiting recycling. A similar environmental analysis was carried out to assess recycling and recovery options in Singapore. Taking a range of waste treatment plant capacities into account due to the country's land scarcity, it was found that the selection of technologies along with their associated available capacities played a significant role in assessing the benefits and drawbacks of different plastic waste treatment options (Khoo, 2019). MFA and LCA have also been combined with

Multi Attribute Utility Theory (MAUT) to assess waste management scenarios for Polyethylene Terephthalate (PET) in Colombia (Rochat et al., 2013). The results of this study were comparable to other studies as they demonstrated great benefits for recycling scenarios. More recently, a study combining MFA and LCA established that carbon neutrality renewable energy pathways play an important role due to major impacts generated in the coal-based plastic production and manufacturing stages (Liang et al., 2023).

On a global level, Zheng and Suh (2019) compiled a dataset of all major conventional and bio-based plastics, which was then used to evaluate projected life-cycle GHG emissions for various mitigation scenarios. Emission data was compiled for three feedstock types (fossil fuel, sugarcane, and corn) for the reference year of 2015 with impacts modelled up to 2050. Results indicated that GHG emissions will grow from 1.7 Gt CO<sub>2</sub>eq in 2015 to 6.5 Gt CO<sub>2</sub>eq in 2050 under the current trajectory. However, a combination of renewable energy, increasing recycling, and curbing demand could reduce future emissions, with decarbonisation of the energy system showing the greatest potential. Additionally, large-scale replacement of fossil fuels with biomass can further reduce emissions. The PEW Charitable Trusts and SYSTEMIQ also modelled future GHG emissions for the global plastic system. Their analysis suggests that an integrated system change scenario, which comprises upstream and downstream interventions, results in a 25% decrease in plastics-related emissions in 2040 relative to the business-as-usual case (The Pew Charitable Trusts and SYSTEMIQ, 2020). In agreement with Zheng and Suh (2019), this study also found that GHG savings could be further maximised by decarbonising energy sources. Achieving the direct industry emission reduction outcomes would necessitate significant changes to the business models of plastic production companies as well as modifying the recycling and waste disposal industries. From a planetary boundaries perspective, a GHG emissions-based assessment of the production and end-of-life treatment of 90% of global plastics revealed that improving recycling rates up to at least 75% in conjunction with biomass and CO<sub>2</sub> utilization can lead to a scenario in which plastics comply with their assigned safe operating space in 2030 (Bachmann et al., 2023).

Numerous LCA studies of individual plastic products and processes have also been conducted by the industry in response to a growing need to understand supply chains and their life cycle impacts. Findings indicate that there has been a steady increase in LCA research since 2017 with most studies following the conventional structure of LCA and others incorporating aspects such as life cycle costs, design elements, and mass-based indicators (Chitaka and Goga, 2023).

As with studies conducted on a national scale, the majority of studies focus on the evaluation and comparison of plastic waste management options where the system under scrutiny starts from the collection of post-consumer waste (Lazarevic et al., 2010; Perugini et al., 2005). Several meta-analyses of these studies conclude that plastic recycling has a significantly lower GHG footprint than incineration or landfilling (Organisation for Economic Cooperation and Development, 2018). Recently, there have also been a series of reports published comparing LCAs conducted for single-use plastic products and their alternatives such as supermarket food packaging, face masks, and PET bottles (United Nations Environment Programme, 2022b, 2022a, 2020a). Amongst the conclusions drawn is the recognition that there are trade-offs between impact categories with bio-based products displaying benefits in some impact categories but disadvantages in others. Additionally, production was found to be a significant contributor to the environmental footprint with end-of-life (EoL) management options also having a substantial influence on results (United Nations Environment Programme, 2021b). Substantial research has also been undertaken on grocery carrier bags and their alternatives with a few studies attempting to introduce littering indicators and degradation factors (United Nations Environment Programme, 2020b). A common conclusion includes the fact that reusable bags have a lower environmental impact than single-use plastic bags with usage rates being a significant parameter. In terms of littering potential, single-use bags perform poorly with weight being a significant factor.

In Africa, LCA-based research is limited with few studies focusing on the quantification of plastics-related impacts. As GHG emission factors for waste management are scarce for developing countries, Friedrich and Trois (2011) developed such factors for the recycling of glass, plastics and paper from municipal solid waste in South Africa. Results show that there is variability for the different recyclables with energy-intensive materials having higher GHG savings in South Africa compared to other countries. In terms of LCA studies for single-use food and beverage plastic products, it was found that 50% of the studies conducted for the continent were for Mauritius while the balance was carried out in the southern parts of Africa namely South Africa and Zimbabwe (Chitaka and Goga, 2023). The progression of plastics-related LCA studies conducted in South Africa is detailed in the table below with specifics regarding the scope of the study as well as noteworthy results emanating from each research project.

**Table 2: LCA Studies for Plastic Products and Systems in South Africa**

<b>No.</b>	<b>Scope</b>	<b>Significant findings</b>	<b>Source</b>
1	Comparative study for paper and plastic carrier bags	Plastic bags have a lower impact for use ratios of up to 2.5 plastic bags per paper bag	(Sevitz et al., 2003)
2	LCA on straw options in SA incorporated marine pollution impacts	Material production was the major contributor to emissions with disposable straws demonstrating a leakage rate of 38%.	(Chitaka et al., 2020)
3	Comparative analysis for PET bottle and reusable alternative	The reusable bottle generally had lower impacts than the single-use bottle with dominant factors being the mass of the bottle, transportation distances, and vehicular emissions	(Kunle I. Olatayo et al., 2021)
4	LCSA of various grocery shopping bags	Reusable, fossil fuel-based plastic bags perform better than single-use bags (conventional or bioplastic) with the assumption of maximum reuse and recycled content found to be directly proportional to overall performance	(Stafford et al., 2022)
5	Life cycle-based evaluation of GHG emissions for the SA plastics industry	Carbon footprint was estimated at 15.8 Mt CO <sub>2</sub> eq and 17.9 Mt CO <sub>2</sub> eq in 2015 and 2018 respectively with emissions strongly linked to the local coal-based monomer production process.	(Goga et al., 2023, 2022)

- |   |  |   |                         |
|---|--|---|-------------------------|
| 6 | Accounting for GHG emissions in the SA plastics life cycle using historical data and projections | Emissions under the business-as-usual case will increase 63% by 2040 while the optimal system change scenario (increasing collection & recycling, improved disposal to sanitary landfill, and reducing demand) causes a 37% decrease. | (Stafford et al., 2022) |
| 7 | Comparative assessment of plastic waste management scenarios in Johannesburg                     | A reduction in landfilling and combining recycling, incineration, gasification, and use of waste as solid refuse fuel in a cement kiln is the least environmentally impactful scenario.   | (Mazhandu et al., 2023) |
-

The summary above shows the progression of LCA-related studies for plastics in the local context. Research was initially conducted on a product-level basis by analysing single-use products such as straws, bottles, straws, and plastic bags. As the theme of circularity and the model of the circular economy became a focus, bio-based alternatives to plastics as well as reuse options were analysed. In the case of Chitaka et al. (2020) and Stafford et al. (2022), an attempt at quantifying plastic pollution impacts via leakage rates and an estimate for persistence were executed. Studies then evolved to analyse the plastics system on a city and country-wide basis. Despite the evolution, studies were restricted to analysing the end-of-life stages only or accounting for single impacts by way of carbon footprints.

## **2.5. Policies and Interventions to Support the Transition to a Circular and Low-Carbon South African Plastics Sector**

### ***2.5.1. Towards a Circular Plastics Economy in South Africa***

The shift to a circular economy is well aligned with South Africa's priorities as stated in the National Development Plan (National Planning Commission, 2012) and the Sustainable Development Goals (SDGs) (United Nations, 2023). While the South African policy landscape in relation to the circular economy is currently disjointed, encompassing different departments, significant documents which identify the need for a circular economy as a new source of growth include:

- the White Paper on Science, Technology and Innovation (Department of Science and Innovation, 2019);
- the National Waste Management Strategy (NWMS) 2020 (Department of Environment, 2020); and
- the Extended Producer Responsibility (EPR) Regulations (Department of Environment Forestry and Fisheries, 2021)

Research suggests that moving towards a circular plastics economy in South Africa will result in increased economic activity and an escalation in demand for both unskilled and skilled labour (Benn et al., 2022). In addition to the general principles of the New Plastics Economy, as stated by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2017), the vision for a circular plastics economy in South Africa requires collaboration across the value chain and for the health, safety and livelihood of all role-players to be respected in facilitating a just transition (The World Bank, 2022). To fulfil this vision, system-wide interventions are needed through a concerted effort from all stakeholders along the plastics supply chain. Chitaka et al. (2022)

demonstrated how this shift is occurring as key value chain actors' perspectives and actions are directly influenced by the increasing concern surrounding plastics-related impacts.

To achieve the ambitions set for a circular plastics economy, complexities specific to the South African context that need to be addressed include poor design of plastic packaging which hinders downstream recycling as well as a low value attached to these items (The South African Plastics Pact, 2023). Thus, various targets and indicators have been set along the plastic life cycle to tackle these difficulties. A summary of the published plastics-related targets for South Africa is presented in Table 3.

**Table 3: Summary of Plastics-Related Targets for South Africa**

Source	Targets	Reference
The South African Plastics Pact	<p>Four targets by 2025</p> <ul style="list-style-type: none"> <li>• Taking action on problematic or unnecessary plastic packaging through elimination, redesign, innovation or alternative delivery models</li> <li>• 100% of plastic packaging to be reusable, recyclable or compostable</li> <li>• 70% of plastic packaging effectively recycled</li> <li>• 30% average recycled content across all plastic packaging</li> </ul>	(The South African Plastics Pact, 2020)
The South African Plastics Industry Master Plan	<p>Three targets by 2025</p> <ul style="list-style-type: none"> <li>• Reducing the trade deficit to less than 10% of the total value of the industry</li> <li>• Maintaining or improving the tons per employee which equates to 30 tons per formal job in 2018.</li> <li>• To reduce the visible amount of plastic litter in the environment and to increase recycling rates to 60%.</li> </ul>	(Department of Trade and Industry, 2020)
EPR regulations	<p>Targets for each identified waste stream are tabled for 5 years from the date of implementation of the EPR scheme - 2021</p> <ul style="list-style-type: none"> <li>• Collection, recycling and recycle content targets for various classes of products</li> <li>• Types of plastics-related goods covered include plastic packaging, biodegradable and compostable plastic packaging, single-use plastic products, single-use biodegradable and compostable plastic products</li> <li>• No reuse targets set for these products</li> </ul>	(Department of Environment, Forestry and Fisheries, 2021)

A comparison of targets emphasises the variety between targets with different sources stating their own goals for indicators such as recycling rate. Furthermore, differences lie between key objectives and what is significant in the drive for a circular plastics economy in South Africa. It should also be noted that most of the targets focus on single-use and short-lived plastic products and packaging with no explicit targets set for products with a lengthier lifetime. On the employment front, the stated target excludes jobs in the informal sector (Department of Trade and Industry, 2020).

In addition to the targets established in the EPR document, the regulations also state that a Life Cycle Assessment should be conducted within five years of the implementation of the scheme (Department of Environment Forestry and Fisheries, 2021). This is in relation to stated products and should be in accordance with the applicable standards. According to the regulations, the LCA should, at a minimum, focus on the following aspects: “minimisation of material used in the identified product; design of the product to facilitate reuse, recycling or recovery, without compromising the functionality of the product; and reduction of environmental toxicity of the resulting post-consumer waste stream”. Although an overview document was published by the Department of Environmental Affairs and Tourism in relation to Life Cycle Assessment and integrated environmental management (Department of Environmental Affairs and and Tourism, 2004), there was no legal requirement to conduct LCA studies prior to the promulgation of the EPR regulations.

Various circular strategies have been described in policy and literature to achieve sustainability and a less extractive resource economy. Amongst these are key mitigation measures that are relevant to the local (South African) context. These include mechanical recycling, reduction in plastics demand, and the introduction of bioplastics. Although South Africa is considered one of the leaders internationally in mechanical recycling with a recycling rate of 45.7% in 2019 (Plastics SA, 2020), certain types of plastics are not economically viable to recycle in addition to other factors such as degradation and incompatibility between different polymers also inhibiting mechanical recycling rates (Chomba, 2018). It was found that increasing collection and recycling to meet five-year targets as set out in the Extended Producer Responsibility Guidelines (EPR) could cause a 33% reduction in plastic pollution and a 14% decrease in projected GHG emissions between 2023 and 2040 compared to the business-as-usual case (Stafford et al., 2022). Even though increasing recycling outputs would lower waste directed to landfills, it comes at the expense of local polymer production and imports which would

potentially result in a reduction of economic activity by four to six billion rands annually for virgin polymers; presumably this economic activity would shift to resource recovery and processing of recovered materials into secondary polymer products (Goga et al., 2022).

One of the strategies analysed by Zheng and Suh (2019) for the global plastics industry was a reduction in plastics demand growth by 2%, which was found to reduce plastics-related GHG emissions by 56% by 2050. Locally, a strategy centred around demand reduction of 1.2% per annum via reuse, elimination, and new delivery models was found to be more cost-effective than the increased recycling scenario as it reduces both the need for plastic production as well as disposal and waste treatment services (Stafford et al., 2022). Historically, year-on-year growth in domestic consumption was only below the GDP growth in 2011 and 2017 with a positive correlation existing between GDP growth rate and plastic consumption (Department of Trade and Industry, 2020). Although Africa has a relatively low global share of plastic use at under 4% (Statista, 2022), consumption rates are projected to increase rapidly, particularly in developing economies (Mutha et al., 2006).

While the introduction of bioplastics has obvious environmental advantages, the production process includes the use of limited resources such as land and freshwater (Johannes Endler and Wolf, 2019). The local sugar industry is one of the identified agri-industries that is currently under distress and could be restructured with the utilisation of over six million tons of bagasse as feedstock for downstream products such as bio-based plastics (Department of Trade, 2020; Muniyasamy, 2019). Sugarcane-derived ethanol is a suitable feedstock for the production of ethylene of which South Africa is a significant net importer (Braude and Montmasson-Clair, 2019). Despite favourable climatic conditions, issues pertaining to arable land availability and water scarcity are some of the challenges facing the development of biomaterials in South Africa (The Moss Group, 2020) with land-use change impacts mostly unaccounted for in bio-based plastics LCAs (Bishop et al., 2021). In terms of life cycle results, findings from Zheng and Suh's (2019) study shows that emissions from bio-based plastics are highly dependent on the EoL management method used. In South Africa, there is limited separation, collection and processing infrastructure to manage biodegradable plastics, which leads to a lack of economic incentives for waste collectors. These items remain in the environment or are collected with traditional plastics and sent to a landfill (The Moss Group, 2020). Additionally, sugarcane-derived supply would need to be constant to allow for uninterrupted and cost-effective production of bio-plastics (Braude and Montmasson-Clair, 2019).

### ***2.5.2. Decarbonisation of South Africa's Plastics Sector***

Since 1990, the country's average temperature has increased at a rate of more than twice that of global temperature increases, resulting in more frequent incidents of droughts and extreme weather patterns (Wolski, 2019). With South Africa's energy sector being the most coal-dependent of the G20 countries and the country producing the highest CO<sub>2</sub> emissions per unit of power produced in the G20, the local electricity landscape needs urgent rehabilitation (Climate Transparency, 2020). South Africa's climate commitments as outlined in the update of the country's first Nationally Determined Contribution (NDC) under the Paris Agreement centers around the long-term decarbonisation of the South African economy (Department of Environmental Affairs, 2021). This includes a primary focus on the electricity sector in the 2020s, a transition in the transport sector towards low-emission vehicles in the 2030s, and decarbonisation of the hard-to-mitigate sector in the 2040s. The crucial challenge during the immediate implementation period up to 2030 will be the shift in the electricity sector and attending to the associated economic and social consequences resulting from this transition in coal-producing regions within the country (Department of Environmental Affairs, 2021).

Potential solutions are available to minimise emissions related to electricity generation from fossil fuels. These include reducing the contribution of coal-fired power while simultaneously increasing the proportion of renewables in the energy mix. Although South Africa does not have a detailed coal phase-out policy, the Integrated Resource Plan (IRP)2019 proposes an expansion of renewable energy capacity from approximately 6,600 MW in 2019 (excluding large hydro) to 26,700 MW (plus 6,000 MW in distributed solar photovoltaics) in 2030 (Climate Transparency, 2022). Even though half of the country's greenhouse gas emissions are from electricity generation and liquid fuel production (Department of Mineral Resources and Energy, 2019), the role of Sasol as a key value chain actor is not discussed in the IRP.

Sasol is a significant emitter of GHGs and is listed as the largest private emitter in the country with its Secunda facility identified as the world's largest single point source of GHGs (Sasol Limited, 2020). The company's targets include a reduction in scope one and two emissions by 30% by 2030 for the Sasol Energy and Sasol Chemicals Businesses with an ambition to reach net zero by 2050 (Sasol Limited, 2022). The target supports South Africa in potentially achieving the lower end of its NDC target of 350 Mt CO<sub>2</sub> by 2030. As part of their decarbonisation approach for a Just Transition, they aim to achieve these reductions by switching to low-carbon energy sources and integrating cleaner alternative feedstocks including

green hydrogen and gas. In 2021, the company has achieved a ~7% reduction off the 2017 scope one and two baseline which is primarily attributable to reduced production rates at Sasol Energy and Secunda (Sasol Limited, 2022). Despite achievements such as concluding negotiations for over 600 MW of solar and wind renewable power as well as advanced discussions for 40 – 60 PJ/a of additional natural gas as a substitute for 10 Mtpa of coal by 2030, challenges in the medium to long-term include constrained renewable energy supply chains and sourcing affordable sustainable carbon feedstocks.

A model focused on exploring the impact of decarbonisation options for the period 2010 to 2050 in South Africa shows that the integration of low-carbon energy supply options can reduce total energy GHG emissions by 39% together with a 13% decrease in the unemployment rate (Altieri et al., 2016). When applied to the plastics industry, Zheng and Suh (2019) note that decarbonisation of the energy system shows the greatest potential among all the strategies analysed with a 100%-renewable-energy scenario capable of reducing the average life cycle emissions by half from the baseline emissions. Although the introduction of low-carbon energy is increasingly being researched as a strategy to reduce the life cycle GHG emissions of plastics, the impacts of this decarbonisation strategy on other environmental indicators remain unknown.

## **2.6. Summary**

This chapter aims to review the current state of knowledge on the status of plastics in the circular economy. This included policies focusing on the creation of a circular economy particularly for the plastics industry as well as the development of indicators to gauge the measure the circularity of plastic systems. The analysis was extended to include plastics-related comparative environmental assessment studies undertaken on various levels. The chapter concluded by touching on potential mitigation options available to the South African plastics industry in the context of a circular and low-carbon transition.

Environmental policies and regulations focusing on the transition to a circular economy have been adopted as impacts such as plastic pollution and climate change have become a focal point. Despite this, it has been found that the global plastics life cycle is only 8% circular and is responsible for 3.8% of the total emissions in 2015. Research indicates that improving recycling rates can have a beneficial impact on plastic pollution and other environmental impacts. Additionally, by increasing the proportion of renewable energy, the decarbonisation of the

energy sector has been found to have a significant impact on life cycle GHG emissions related to the plastics value chain at a global scale.

Although material flow analyses of plastics have been conducted on a national and international scale, plastic flows for all life cycle stages have not been determined with the focus generally restricted to the end-of-life stage and waste management processes. Over time, environmental assessments have evolved by expanding their scope to consider societal plastic flows and assessing future alternative scenarios. Despite these developments, the analysis is often limited to assessing the impact of plastic pollution and the release of GHG emissions. Furthermore, the relationship between circularity metrics and environmental performance has not been explicitly evaluated despite regulations setting these indicators as targets. Despite local studies having recently investigated the impact of circular strategies such as increasing recycling rates and reducing demand, there is, to date, a lack of local research which quantifies the impact of future decarbonisation targets on the local plastics industry despite global studies emphasising its potential impact.

## CHAPTER 3: METHODS

The literature assessed in the preceding chapter highlighted the various nuances when considering the individual themes of sustainability, environmental assessment, and the circular economy. Specifically, it was established that MFA and LCA both provide metrics for assessing plastic systems with measures such as increasing recycling rate and reuse having a positive environmental impact. Although assessments have expanded to include plastic systems, studies have been restricted to certain geographical locations with a focus limited to GHG emissions and the reduction of plastic litter. The relationship between plastics production and energy input has also not been evaluated on a national scale. This chapter begins with an introduction of the questions developed and goes on to present the methods utilised. This is followed by details of the scenarios that were constructed to answer the stated research questions.

### 3.1. Research Questions

This thesis aims to answer five primary research questions. The questions read as follows:

1. What would the future South African plastics sector look like if it is based on current activities without the implementation of any plastic pollution or energy-related mitigation measures?
2. How much of an improvement would achieving the voluntary or regulatory objectives be, in terms of indicators of circularity and whole life cycle environmental impacts?
3. How much of an effect could curbing domestic demand, by simulating reuse, have on circularity and indicators of environmental concern?
4. What impact reductions, beyond a reduced carbon footprint, would decarbonisation measures imply for the South African plastics value chain?
5. To what extent could the future South African plastics sector be classified as low-carbon and circular if all the mitigation strategies were implemented in concert?

The first question requires creating a baseline scenario that depicts how the local industry would appear subject to a lack of policy measures centred around end-of-life plastics management and reduction in single-use consumption. The scenario also assumes that local practices on a national level will be powered by the current energy mix with no decarbonisation interventions in place. The second question pertains to the targets set by government and voluntary organisations revolving around recycling rates in a bid to improve the circularity of the system. The question is informed by outcomes from the literature review that state that although

increased recycling could substantially decrease plastic pollution and GHG emissions, other metrics need to be investigated. The next question applies to assessing the impact of reducing plastic production via demand moderation. This is undertaken by introducing local reuse of products as one of the principles of the circular economy. The penultimate question seeks to investigate the impact of decarbonising the national energy and polymer system beyond a reduction of GHGs. This is based on South Africa's position as a carbon-intensive economy and on findings from global studies that state that reducing the carbon intensity of energy had the greatest potential to lower plastics-related GHG emissions. The final question seeks to investigate the impact of implementing individual measures in combination in relation to the end goal of a circular and low-carbon sector.

### **3.2. Research Design**

The research questions that are presented above were used as a foundation for the design of an appropriate research framework. The framework is based on a combined MFA-LCA approach on two different levels: a macro-level analysis using MFA followed by a micro-level assessment using LCA. Systems analysis and quantitative assessment were used to investigate the research questions and achieve the aims of the study. A schematic depicting the research stages and links between both assessments is shown in Figure 3.

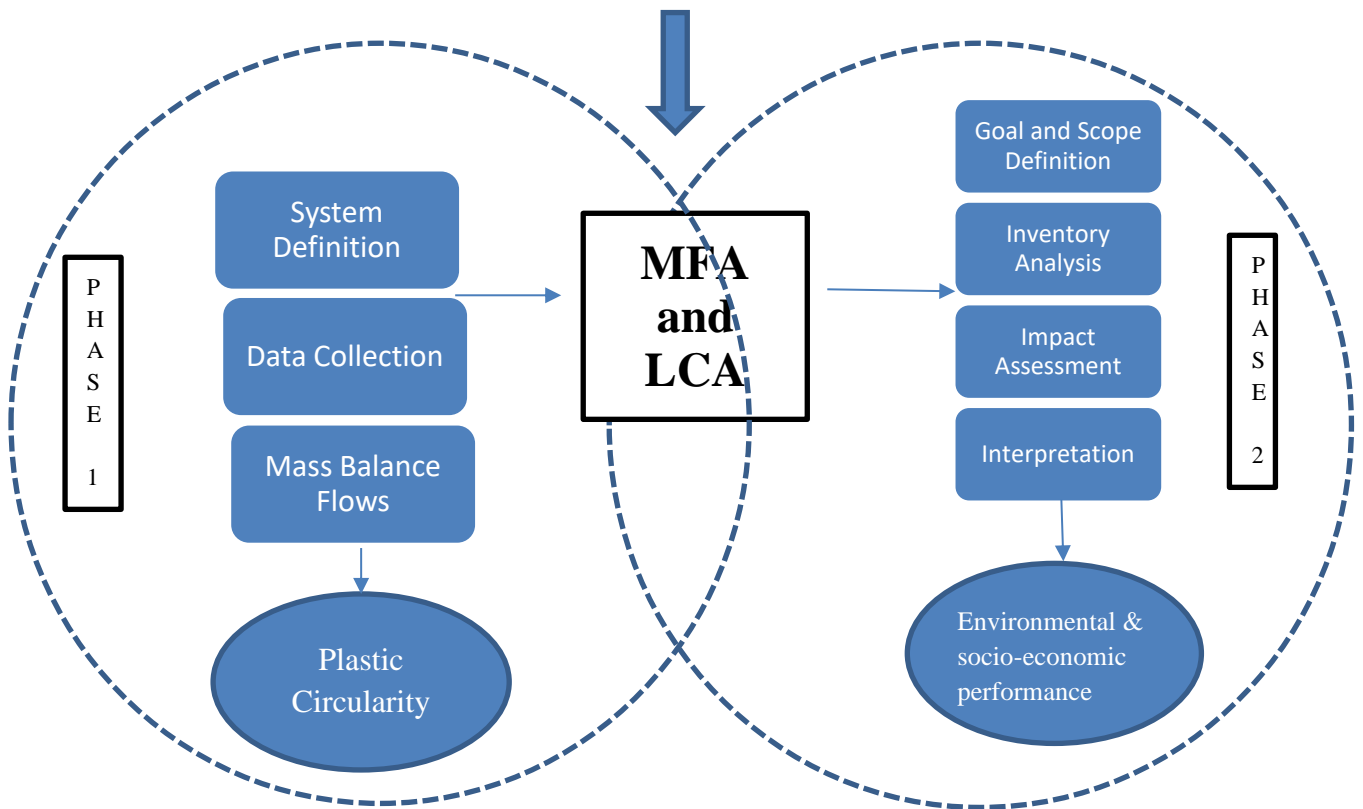
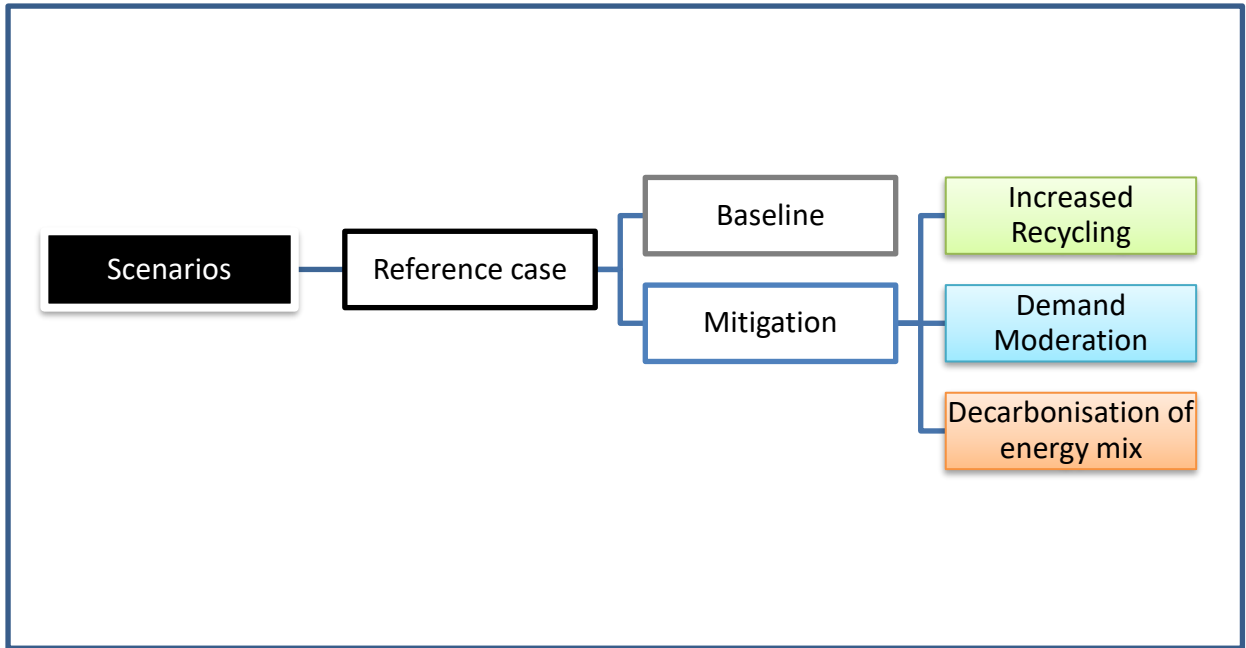


Figure 3: Research Design Framework

To estimate the mitigation potential of different intervention pathways, the combined MFA-LCA model was developed. In addition to the Baseline scenario, three mitigation scenarios were created to estimate the reductions in environmental impacts and improvements in the circularity of plastics. Using historical data gathered for 2018 which serves as the Reference case, flows were projected to 2025 followed by an extension of scenarios up to 2035. The strategies can be broadly classified as upstream (such as reducing demand) or downstream (such as increased recycling) interventions. Additionally, the energy supply to the plastics system was varied to reduce the overall environmental footprint of the system.

In phase 1, the system boundary is defined for the MFA along with the sub-processes and scope of study. The following stage incorporates the collection of data used in the calculation of material input and output flows. The resulting numbers are then utilised to calculate relevant mass-based circularity indicators.

The second phase of the analysis illustrates the LCA methodology which comprises four stages as presented in the ISO 14044 (International Organisation for Standardisation, 2006) documents. The first component, namely goal and scope definition, seeks to firstly identify the objective of the study by establishing the intended application while the scope goes on to determine the product system, functional unit, and system boundary. The next stage of the LCA process consists of the collection and calculation of data for the quantification of input and output flows. The inventory data obtained from the MFA is utilised for this stage. Stage three of the LCA transforms these elementary flows to a list of environmental impact scores via various characterisation factors. The final stage of the assessment involves an analysis of the results acquired from the previous stages to draw conclusions and present recommendations.

For this study, the MFA is used to describe plastic flows from the polymer production stage (including the production of monomers) to the flows that encompass the end-of-life stage. These direct mass measurements are a result of the quantification of the material cycle of the South African plastics system and provide necessary input for the calculation of resource use and environmental impacts via a life cycle approach. In this manner, the analysis is extended by not only creating an inventory of the local system's inputs and outputs but also their potential environmental impacts across the value chain. By integrating MFA with LCA, the comprehensive assessment of resources and environmental effects of material flows can be analysed.

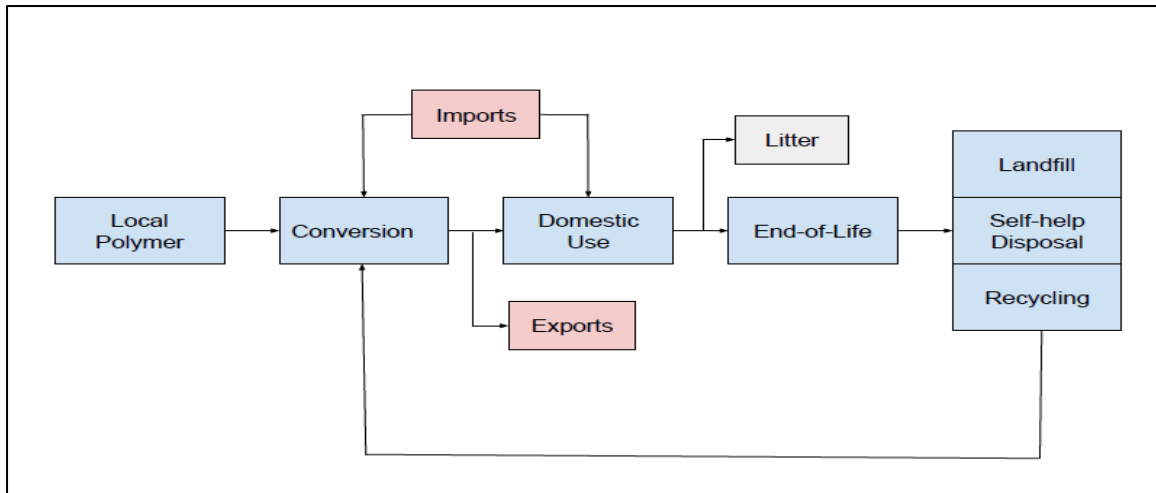
### **3.3. Methodological Choices and Reference Case**

The research design dictates the selection and details of the appropriate study methodology. This research uses an expanded sustainability framework synthesising both material indicators emerging from the MFA and resulting critical environmental impacts from the LCA. In this way, direct mass flows as well as environmental exchanges are accounted for within the system. The individual methodologies for the use of the MFA and LCA tools are expanded upon in the following sub-sections.

#### **3.3.1. *Material Flow Analysis (MFA)***

Material Flow Analysis or MFA is a commonly used tool used to trace the source, path, and destination of materials along their life cycle within a specific geographical location. The OECD recommends the application of MFA to analyse the flows of natural resources and materials into, through and out of a specified system employing the principles of conservation of matter (Organisation for Economic Cooperation and Development, 2008). As MFA is an accounting tool used to describe the metabolism of a system, it can be integrated into static or dynamic models.

For the purposes of this study, plastic flows for the South African economy were modelled via the use of the MFA tool. The resulting system map produced a graphic illustration showing input and output flows between the various life cycle stages – from production of polymer and conversion into plastic products, to importing products and packaging for local consumption and exporting locally manufactured products, through to collection for recycling, disposal and waste treatment. A simplified depiction of the MFA model is shown in the figure below.



**Figure 4: Simplified MFA model for the South African Plastics Sector**

As a basis, an initial Excel-based mass balance compilation for 2017 was used (Blottnitz et al., 2018). Following this, the first MFA was developed for 2018 (Goga et al., 2022), which provided a sound basis for the construction of the Reference case as well as all the future scenarios. This study provided an update of these figures accounting for current plastic production, use, and disposal activities. The software package e!Sankey was thereafter utilised to generate the resulting Sankey diagram of material flows. Thereafter, a series of MFA models were produced to depict the resulting process systems arising from a business-as-usual case as well as from a series of future mitigation strategies. This data was thereafter utilised to compile a sequence of LCAs.

To provide an overview of the current plastics sector, the MFA framework requires data for key input and output flows. The MFA model uses available industry and trade data to populate the plastic flows, with unknown flows calculated via mass balances or estimated using expert input either from industry or academic sources. A list of resources used are presented in Table 4.

**Table 4: Data Sources Used for the MFA Model**

<b>Flow</b>	<b>Source</b>	<b>Notes</b>	<b>Reference</b>
Imports	South African Revenue Services (SARS)	Trade data under tariff code 39	(South African Revenue Services, 2023)
Domestic product	Plastics SA recycling survey	Quantity of polymer locally converted into product	(Plastics SA, 2019)
Collected for recycling	Plastics SA recycling survey	Material collected contains 9% non-plastic items	(Plastics SA, 2019)
Recyclate	Plastics SA recycling survey	Total quantity of recyclate obtained post-separation and sorting	(Plastics SA, 2019)
Self-help disposal	Peer-reviewed journal article	Percentage of domestic waste disposed informally	(Rodseth et al., 2020)
Litter	Domestic Waste Characterisation study	Litter composition	(Nelson Mandela Bay Municipality, 2016)
Exports	South African Revenue Services (SARS)	Trade data under tariff code 39	(South African Revenue Services, 2023)

In the South African context, plastic products are produced from virgin and recycled polymers to meet the market demand. The incoming flow of plastics is modelled as a composite of six major polymer types consumed in South Africa viz. Low-density Polyethylene, High-density Polyethylene, Polypropylene, Polyethylene Terephthalate, Polyvinyl Chloride and Polystyrene (LD-PE, HD-PE, PP, PET, PVC and PS) with the addition of an ‘other’ plastics category. This category comprises plastics polymers that are locally consumed to a smaller degree such as polyurethane and acrylics (Department of Trade and Industry, 2020). Products that are locally manufactured are supplemented by imported products and packaging for domestic use. These imports refer to direct plastic imports and exclude products that partially contain plastic or are

packaged in plastic and fall under a code other than HS 39, which is the numerical code used to specify “Plastics and articles thereof” (South African Revenue Services, 2023). Domestic consumption was divided into short-lived use as well as the use of durable goods. The definitions for the different types of use (and thus waste) were partially based on those utilised in the MFA developed for the USA by Heller et al. (2020). Using this as a basis, short-lived use was defined as products that are used and disposed within a single year with this specific waste stream described as short-lived waste. Waste streams include formal disposal to landfills (both compliant and non-compliant) as well as informal disposal as open dumping, burning or leaked into the environment as litter. The informal disposal or self-help disposal stream, as is labelled in the model, describes the portion of waste that remains uncollected and untreated via formal management practices. This percentage is estimated to be 29% of the waste that remains post-collection for recycling and is based on Rodseth et al. (2020) study on the quantity of domestic waste disposed informally in South Africa. The material collected for recycling is sourced from both the formal and informal supply chains in the form of baled materials from the formal sector, collectors and waste management companies as well as unbaled material provided by waste reclaimers (Plastics SA, 2018).

The selection of circularity indicators for this thesis was based on the various indicators and associated targets prescribed in the regulatory and voluntary landscape as described in Section 2.5.1. The indicators along with their definitions as used throughout this thesis is presented in Table 5.

**Table 5: Definition of Circularity Indicators**

<b>Indicator</b>	<b>Definition</b>
Collection rate	Collections/ Total waste
Input recycling rate	Collections/ Short-lived waste
Output recycling rate	Recyclate (local & exported)/ Short-lived waste
Recycled content	Used recyclate/ Total production

For the purposes of this research, a distinction is made between input and output recycling rates as well as between collection and input recycling rates. Although the definition of collection rate aligns with the formula presented by Plastics South Africa in their annual recycling survey (Plastics SA, 2020), the definitions for both types of recycling rate differ as the denominator for these indicators in this document considers total short-lived waste, inclusive of consumption from virgin and recycled sources of material.

### ***3.3.2. Life Cycle Assessment (LCA)***

The second environmental assessment tool utilised is commonly referred to as a Life Cycle Assessment (LCA). An environmental LCA is defined as a “compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle.” (International Organisation for Standardisation, 2006). Thus, the tool aims to track the impact of product and service value chains and assess them from a systems perspective, identifying strategies for improvement without burden shifting. The focus is usually on a single product system and its alternative(s), but as shown in Section 2.4.3 of the literature review, LCA has also been applied to whole industrial sectors or value chains at various levels.

For the LCA component, this study follows the guidelines laid out in the ISO 14000 series. As per the standards, the research steps were divided according to the four stages listed in the ISO 14040 document namely goal and scope definition, inventory, impact assessment, and interpretation (International Organisation for Standardisation, 2006). To model these stages and perform the mathematical calculations, a simulation software package known as SimaPro was used. The software contains, amongst others, the ecoinvent database which features new and updated South African data for a range of industrial processes including electricity generation, coal liquefaction, water supply and freight, road, and rail transport (ecoinvent, 2020). Additionally, the waste treatment and recycling datasets have been enhanced with new data collected for formal and informal recycling practices. These datasets, together with the figures obtained from the MFA models, were used to inform the inventory data. The results included a baseline LCA showing a projected version of the current national plastics industry with current policies and measures in place. Additionally, alternative models were constructed to predict the impacts arising from potential mitigation scenarios based on circular economy and low-carbon guidelines.

To extend the analysis beyond an environmental assessment, a socio-economic indicator describing the employment impact across the life cycle was explored. As not all aspects of sustainability are covered by the concept of circular economy and not all the principles of circular economy can be assessed via the individual application of MFA and LCA, the combination of MFA and LCA-based indicators formed an integral part of a holistic sustainability assessment. The circularity and profile of each scenario are tested by incorporating these indicators into a comparative dashboard. Using the LCA approach

described above, the main phases of the LCA study are expanded upon in detail in the following sections.

### 3.3.2.1. Goal and Scope Definition

#### Goal Definition

The first phase of a LCA study includes the goal definition, which describes the reason behind conducting the study as well as provides insight into the intended target audience and application of the study (International Organisation for Standardisation, 2006). For this study, the goal was to identify, model, measure and compare future pathways of the South African plastics value chain in terms of environmental performance. Thus, this study considered several scenarios to assess these pathways. The study was divided into two parts; firstly the impacts of interventions over a short-term were assessed i.e. from 2018 up to 2025 which was followed by an extended projection and trend analysis up to 2035. The intention was thus to evaluate a range of circular and low-carbon mitigation strategies that are relevant to the South African context to provide recommendations regarding which combination of interventions would yield the greatest benefit. Such evidence-based research should aid current and future policy discussions centred around the future of the local monomer operations, the release of GHG emissions from waste management practices and the reduction of plastic pollution.

This study is intended to inform a range of stakeholders who are involved in various stages of the plastics value chain. Specifically, role-players such as polymer producers, converters, recyclers, and waste management practitioners will gain knowledge regarding the key environmental and socio-economic impacts associated with each life cycle stage. As the EPR guidelines (Department of Environment Forestry and Fisheries, 2021) have mandated the use of LCAs for certain plastic products, the results will also provide insight to brand owners. Furthermore, the results will inform consumers and the general public regarding the broad implications of mitigation strategies. As the entities responsible for drafting public policy, government departments will benefit from information on key environmental and social aspects on a national and provincial level. Other interested parties include scientists and researchers, relevant industry groups, producer responsibility organisations, academic institutions, NGOs and civil society.

As this study will be available in the public domain, the ISO documents recommend a critical review of the research. This thesis will be examined and reviewed by three external examiners

prior to publication. In this manner, the robustness of the study is supported by improving the quality of the research.

### Scope

The LCA scope aims to provide details about the product system under study. Aspects that are usually defined in the scope include the function and functional unit, system boundary which denotes which processes are included and excluded, assumptions and limitations, type of system model to be used, data quality requirements, and approach to impact assessment.

To fulfil the goal of this study, this research considered several scenarios, which are comprised of a combination of processes that encompass each product system. Thus, each scenario is a representation of the product system. Some of these scenarios are an extension of existing activities while others are recommended strategies that are gradually being put into practice. Other strategies using advanced recycling technologies (e.g. pyrolysis and gasification) are still in the development stages with a limited number of operating plants and were thus not considered in the scope of the study (The South African Plastics Pact, 2022). Additionally, introduction of bioplastics was not evaluated as the penetration of bio-based plastics production in South Africa is low due to market demand and financial support for large scale applications (Patel and Montmasson-Clair, 2021). A brief description of the considered scenarios is given in Table 6.

**Table 6: Considered Mitigation Scenarios and Strategies**

<b>Scenario</b>	<b>Strategy</b>	<b>Description</b>
Baseline	Reference case	Maintaining current plastic and energy flows at each life cycle stage
Increased Recycling	Increase in mechanical recycling	Using the targets set by the SA Plastics Pact as a guide
Demand Moderation	Introduction of reuse	Decrease in domestic single-use consumption
Decarbonisation of the energy system	Decarbonisation of the energy system (Integration of low-carbon energy sources)	National energy mix decarbonises gradually as per IRP 2019 document
	Decarbonisation of the polymer system	Decarbonisation of Sasol's unit operations as per targets in Climate Change report

The system's function characterises the purpose of the product system and for this study is taken as the national value-addition from plastic goods for local use. The functional unit is defined as a quantified description of the function or performance of the product systems in such a manner that it serves as a reference basis for the impact assessment phase (Arzoumanidis et al., 2020). In this manner, functional units are integral to LCAs as they enable objective comparison across systems that serve the same function. For this study, the functional unit is defined as the annual consumption of plastic products to satisfy local market demand. As such, the key reference flows will be kilotons of plastics consumed from both local and imported sources in one calendar year.

Each product system was modelled over its entire life cycle i.e. from cradle to grave. This is the most comprehensive type of analysis as it covers all life cycle stages from abstraction of raw materials to end-of-life and waste treatment. For this study, the following life cycle stages were included in the analysis:

- Extraction of raw materials
- Monomer and polymer production
- Conversion into plastic products
- End-of-life

Additionally, transport between the various stages as well as energy use for the various unit operations within the system were considered. Although the use stage per se as defined in the MFA scope was excluded from the analysis due to difficulty in sourcing data for a wide range of applications for different plastic products and packaging, transport of finished goods (from local manufacturers as well as importers) was included. The imported and exported recyclate streams were also not considered as they fell below the selected cut-off limit. The system under study is depicted in Figure 5 with the biophysical environmental boundary represented by a dashed line and an additional distinction made between the unit operations included in the assessment.

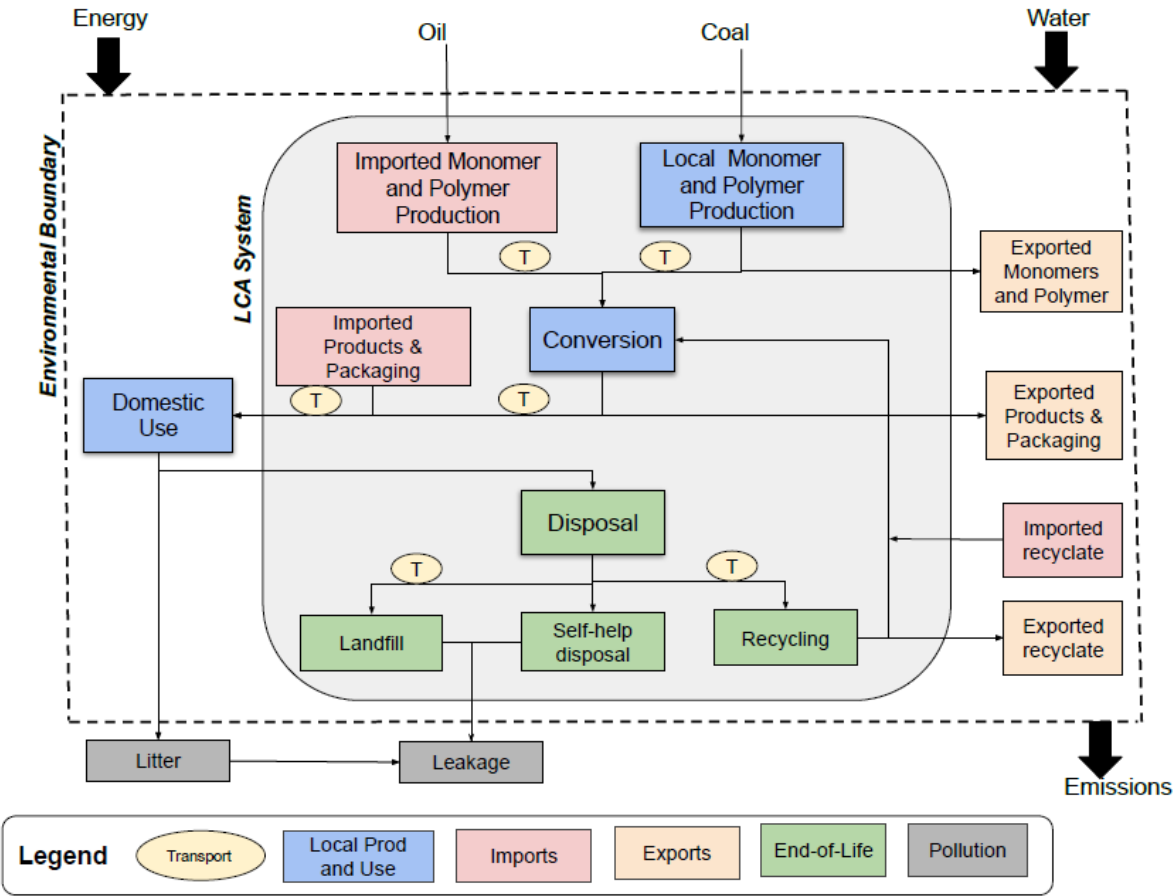


Figure 5: Depiction of System Boundary

The system boundary for the LCA model differs slightly from the MFA boundary due to constraints in the modelling of specific stages (e.g. domestic use). In terms of geographical boundaries, it is assumed that the polymers used in the local production of plastic products are from imported and local sources. To remain consistent with the goal, locally produced monomers and polymers for export purposes are excluded from the system under study. For domestic consumption, goods manufactured in South Africa are supplemented by imported

products and packaging. To satisfy the functional unit, the quantity of polymer produced and locally converted to plastic products and packaging for export purposes is excluded as well as the end-of-life stage for these exported goods. Water and energy are illustrated as inputs and emissions as outputs into all the unit operations within the defined product system.

Regarding the LCA approach to follow, a choice needs to be made between attributional and consequential. An attributional approach estimates the share of global environmental burdens related to a particular product while the consequential approach approximates the effect of the product on the global environment (Ekvall, 2019). Based on the stated goal and scope of the study, the attributional approach was chosen thereby average data was used to divide the environmental burdens of the studied product system throughout its life cycle stages. This choice also affects the system model and the modelling of the EoL stage, particularly the recycling process, as avoided processes are not utilised in open-loop recycling models within attributional LCAs.

Within the attributional approach, the cut-off system model was selected. This method was chosen because it is easily understood and has a high degree of transparency which makes the findings easier to reproduce (Ekvall et al., 2020). It is also recommended by the International Environment Product Declaration (EPD) system, PAS 2050, and the Greenhouse Gas Protocol. As no process is included beyond the product life cycle, the product is assigned only the environmental impacts of the processes in the life cycle of that product. This satisfies the definition of the attributional LCA and is compatible with the ISO 14044 standard (International Organisation for Standardisation, 2006) where the approach is referred to as 'process subdivision'. The method, also referred to as the recycled content approach, represents the strong sustainability concept and accounts for environmental impacts at the time that they occur (Frischknecht, 2010). An assessment of various methods indicates that the cut-off method is the easiest approach to model and does not require any environmental data on processes beyond the scope of the product life cycle (Ekvall et al., 2020).

In LCA studies, limitations to the assessment may be experienced which lead to making assumptions and using estimates. The sourcing of data is typically a challenging step of the LCA process. For this study, accurate data was difficult to obtain particularly for unmanaged and uncontrolled waste management processes with leakage to different environments also proving to be difficult to gauge. Furthermore, the trade data used to populate import and export

flows makes it difficult to precisely differentiate between the various polymer types. Although secondary data used in the construction of datasets was adapted to the local context, data may not completely represent the reality of the system under study. Limitations with respect to the chosen allocation method are that the cut-off system model does not provide incentives for recycling after use when the disposal has a small or positive impact.

### 3.3.2.2. Inventory Analysis – MFA Results

The inventory analysis stage is the data collection phase of an LCA study. Data is collected in terms of the various inputs and outputs for a product system or process i.e. extraction of raw materials and resources, energy and heat, water, and emissions to air, soil, or water. As the LCA process is iterative, challenges experienced in the data collection stage can lead to refining the initial goal and scope.

The different life cycle stages as well as the individual sub-processes were informed by a literature analysis supplemented by data sourcing via industry reports and other life cycle inventory assessments. The inventory data was compiled using a combination of foreground and background data. Foreground data for flows in the plastic value chain was obtained via the MFA analysis while secondary data was sourced from literature reviews; background datasets were sourced from the ecoinvent 3.6 database available on the SimaPro LCA software. The ecoinvent database contains local datasets for the unique Coal-to-Liquid (CTL) process used in the manufacture of synthetic fuels as well as plastic polymers as a by-product. Additionally, electricity, coal, transport, and water datasets representing the South African context are also included in the database and were utilised in the modelling process. In the event that local datasets were unavailable, international datasets which included the location-specific code RoW and GLO (denoting ‘Global’ and ‘Rest of World’ data) were the preferred datasets to use as a basis. As RoW datasets represent global data minus local geographies for which database processes exist, they were initially selected and thereafter modified with the substitution of local energy mix and water sources.

The sub-sections below expand upon the data collection and construction process for each of the major life cycle stages in the product system. Specifically, details regarding modelling choices and assumptions are elaborated upon together with an explanation of the development of processes and corresponding product stages. The selected datasets used together with information regarding how they were adapted are detailed in Appendix A.

## Raw Material Extraction, Polymer Production and Conversion

Datasets were constructed for the production of polymers to mimic the flow of plastics into the system. The local production of monomers, specifically ethylene and propylene, were represented by theecoinvent datasets “*Ethylene, average {ZA}| synthetic fuel production, from coal, high temperature Fisher-Tropsch operations | Cut-off, U*” and “*Propylene {ZA}| synthetic fuel production, from coal, high temperature Fisher-Tropsch operations | Cut-off, U*”. Activities included within these datasets are the receipt of coal from the mining sites in the Secunda complex as well as the electricity generated by both steam and gas that is used to gasify the coal (Russo and von Blottnitz, 2018). The resulting syngas is then converted to synthetic fuel via Sasol’s proprietary Fischer–Tropsch synthesis process. Downstream chemicals such as solvents and polymers are also produced. The average South African production mix was modelled using a combination of these datasets and supplemented with imported feedstock produced from oil (represented by the datasets “*Propylene {RoW}| production | Cut-off, U*” and “*Ethylene, average {RoW}| production | Cut-off, U*”). This monomer mix was thereafter used in the modelling of the Polyethylene (both low and high density) as well as for Polypropylene local flows. To supplement the local production, polymers produced from conventional oil production processes were used to depict the imported Polyethylene and Polypropylene flow. In the case of PET, the polymer was modelled using the stated ethylene mix mentioned above together with imported terephthalic acid. Similarly, PVC was modelled using vinyl chloride with the modelled ethylene as an input. The construction of the Polystyrene polymer dataset included an equal division of polymer to fulfil both general-purpose and high-impact applications.

To accurately construct the ‘other’ polymer stream, domestic virgin polymer consumption statistics from the Plastics Master Plan (Department of Trade and Industry, 2020) were utilised to determine the most commonly utilised polymers in South Africa apart from the six detailed above. These were established to be Polyurethane, Acrylics, and Unsaturated Polyester. Polyurethane was modelled in a similar manner to polystyrene by equally encompassing flexible and rigid foams. To represent acrylic polymers, a dataset representing the production of Polymethyl methacrylate (PMMA) was selected. This is because they encompass the largest applications of Acrylics in terms of tonnages used and are utilised in moulded and fabricated plastic articles (Joseph and Ebdon, 2001). In the case of Unsaturated Polyester, the dataset describing the production of maleic Unsaturated Polyester resin was chosen as they are amongst

the most commonly used thermoset resin. The distribution of locally produced polymers in 2017 is presented in Table 7.

**Table 7: Distribution of Local Production of Polymers in 2018**

<b>Polymer</b>	<b>Quantity (kt)</b>
LDPE	129
HDPE	86
PP	288
PS	0
PVC	92
PET	83
Other	10

After the initial stage of resin production, the polymers are converted into final products for specific purposes. According to a country survey, the most common processing methods in South Africa were found to be injection moulding, extrusion, and stretch blow moulding (Europe Plastics and Rubber Machinery Association, 2016). Injection moulding and extrusion are amongst the primary fabrication techniques for rapidly creating large quantities of plastic products ranging from disposable food containers to high-precision engineering components while stretch blow moulding is generally used to form bottles and containers from a preform (Feraldi, R., Sauer, B. Cashman, 2011). The percentages representing the local use of these transformation processes for 2018 were extracted from the survey document (Europe Plastics and Rubber Machinery Association, 2016) and thereafter adapted to the Reference case. The distribution of processes along with the corresponding SimaPro datasets is listed in Table 8 with the adaptations to the general datasets stated in Appendix A.

**Table 8: Distribution of Plastic Conversion Processes for South Africa in 2018**

<b>Conversion Process</b>	<b>Dataset in SimaPro</b>	<b>Percentage</b>
Extrusion	<i>Extrusion of plastic sheets and thermoforming, inline {RoW}  processing  </i>	56.9
Injection Moulding	<i>Injection moulding {RoW}  processing  </i>	22.6
Stretch Blow Moulding	<i>Stretch blow moulding {RoW}  stretch blow moulding  </i>	12.5
Blow Moulding	<i>Blow moulding {RoW}  blow moulding  </i>	6.7
Polymer Foaming	<i>Polymer foaming {RoW}  processing  </i>	1.3

### End-of-Life

The waste scenario and thereafter disposal scenarios considered the various waste treatment practices occurring in South Africa. These include waste collected for recycling, disposal of waste into compliant and deficient landfills, disposal through open dumping and burning, and leakage of plastic into the environment.

The end-of-life flows for the inventory analysis stage were determined as an extension of the MFA model. The self-help disposal stream mapped in the Sankey diagram can be further expanded to show the portion of waste dumped and burnt. Based on an IPCC report (Intergovernmental Panel on Climate Change, 2006), it is estimated that 60% of the waste discarded in open dumps burns. Furthermore, 56.4% of landfill sites treating waste in South Africa are unlicensed (Department of Environmental Affairs, 2018) and were thus considered non-compliant or deficient with the balance of landfilled waste assumed to be treated in compliant landfills. Estimated leakage rates from the various treatment options were taken from a previous mass balance model compiled for South Africa (Russo et al., 2020). On this basis, it was modelled that 1% from compliant landfills, 30% from non-compliant landfills, and 80% of the flow to an open dump was leaked into the environment. The additional stream of direct litter is also presumed to be added to this plastic leakage stream. The conversion of the respective percentages is therefore applied to the product system resulting in mass flows for 2018 which are displayed in Figure 6.

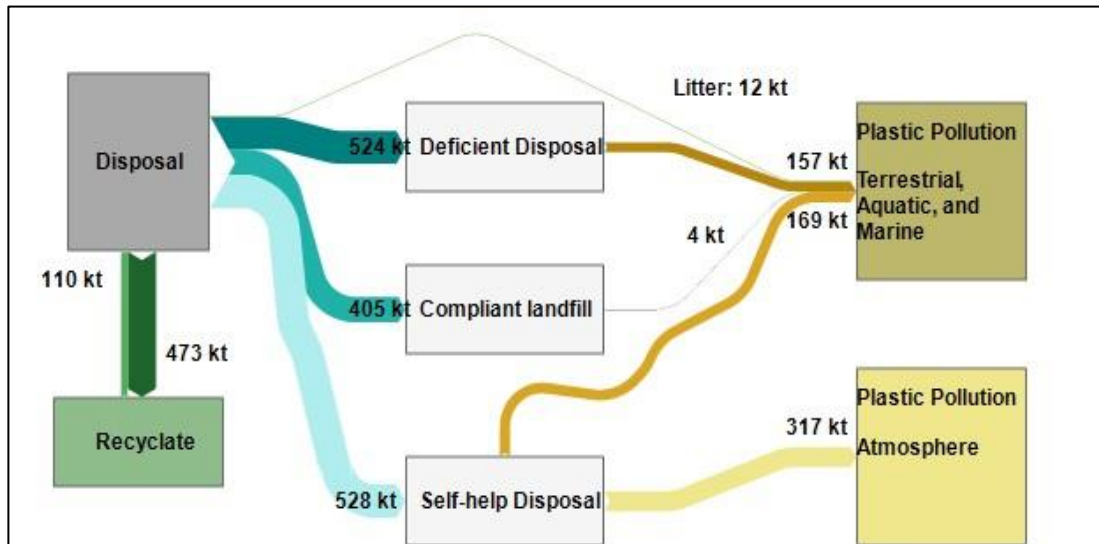


Figure 6: End-of-Life Flows for the South African Plastics Sector in 2018

One of the selected databases, namely ecoinvent, displayed an expanded waste-specific inventory database to include additional low-tech disposal processes such as open burning and open dumping (Doka, 2018). Unsanitary landfill datasets were also created to describe managed landfills where waste is compacted and a daily cover is applied (Doka, 2017). Additional environmental effects are mitigated via sanitary landfills which capture some landfill gas and treat the leachate. These dump and landfill disposal datasets were constructed for different climate classes based on annual water infiltration. South Africa was thus assigned as being part of the dry infiltration class due to factors such as population density, annual precipitation and evapotranspiration rates (Doka, 2018). For this study, these open burning and open dumping datasets for South African climate conditions were used for the expansion of the self-help disposal stream into plastic waste dumped and burnt. Additionally, the disposal to compliant and deficient landfills was modelled as the treatment of waste plastic via South African sanitary and unsanitary landfills respectively. As current inventory databases do not contain a dataset describing plastic leakage, disposal to an open dump was used as a proxy. Similarly, the litter stream was also modelled as waste disposed in an open dump. Care was taken to keep waste types constant throughout the modelling process of each of the life cycle stages i.e. from polymer production through to the waste scenarios.

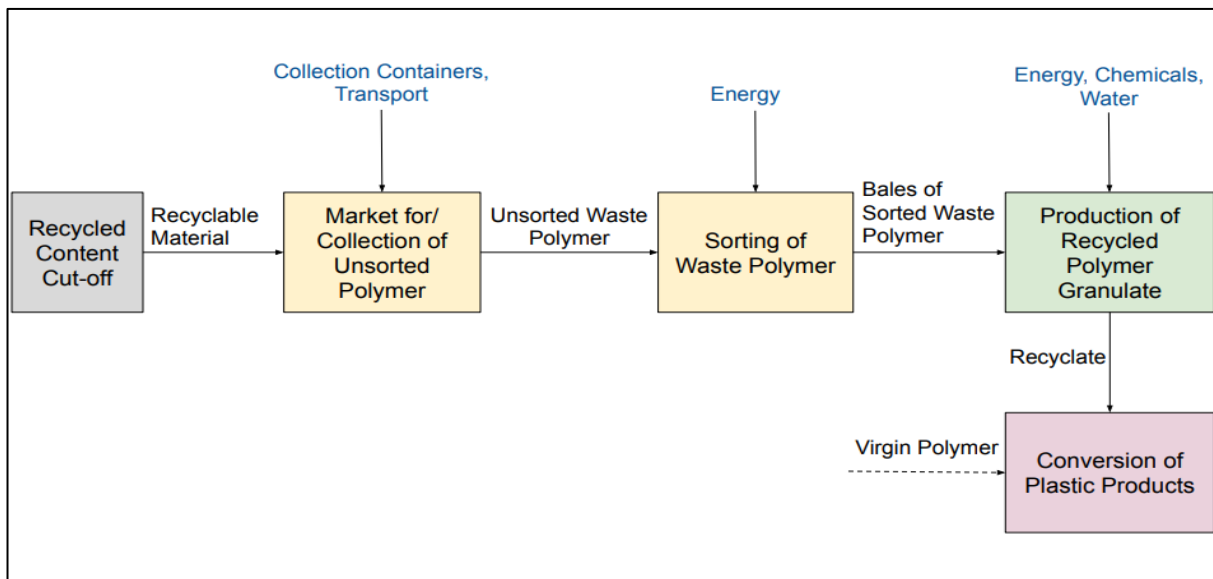
Waste scenarios were constructed to represent each of the EoL streams i.e. self-help disposal, compliant and deficient landfill, recycling, and direct litter. The compilation of each waste scenario consists of a section detailing materials separated from waste as well as a section expanding upon waste streams remaining after separation. In terms of compliant and deficient

landfill waste scenarios, the materials separated from waste are the waste treatment processes of individual polymers either via sanitary or unsanitary landfills. These are in the format “*Waste polymer {RoW-ZA} | treatment of waste polymer, sanitary/unsanitary landfill*” where the word ‘*polymer*’ can be replaced by the specific polymer. The corresponding percentages are calculated based on the leakage rates and are a proportion of the quantity treated by each EoL option divided by the total flow into that particular sub-stream. It was assumed that post-separation, the waste plastic remaining would be discarded in open dumps. For the self-help disposal scenario, the waste remaining is divided according to the above-mentioned ratio of waste remaining in the open dump to waste being burnt. In the case of the direct litter scenario, it is assumed that there is no waste separated but instead, all the waste is discarded in an open dump (to mimic the receiving environment). The various waste treatment processes as well as the adaptations made are stated in Appendix A.

### Recycling

As recycling can be viewed as a multi-functional process, end-of-life allocation is required to distribute the benefits and burdens of the recycling process to the respective life cycles. As the cut-off system model was selected, burdens are allocated at a point where a product is sold and applies a cut-off at a point that the recyclable material leaves the product system (Williams and Eikenaar, 2022). Thus, recyclable materials are cut-off from the producing system viz. they are displaced from the producing activity with a lack of burdens or benefits allocated to them. Thus, secondary materials only bear the burden of the recycling process and are free from the burdens linked to the primary production of the material (Wernet et al., 2016).

To introduce the cut-off, the system model introduces specific datasets which have the phrase “*recycled content cut-off*” and which contain no other flows besides the reference product itself (Wernet et al., 2016). This dataset was used to show that cut-off is occurring as well as to maintain mass balances. The end-of-life modelling followed the cut-off approach presented in Nordelöf et al. (2019). The approach is depicted graphically in the figure below (Figure 7).



**Figure 7: Diagram Showing Cut-Off Process for Recycling**

Output recycling rates per polymer were calculated and used in the modelling of the recycling waste scenario. As the cut-off model was used, the waste treatment datasets are empty datasets. It was assumed that the waste remaining after separation would be disposed of in a sanitary landfill. The recyclate i.e. secondary material, is charged with the burdens associated with the recovery and upgrading processes only.

### Transport

The study considered the role of transport as a link between various life cycle stages. For the pre-consumer use stages, the importing of polymer and products was considered as well as the movement between polymer producers and converters. The local trade data indicates that polymers are imported from Asia, America, and Europe. In the Asia-Pacific region, the two major polymer producers by volume were China and India (Statista, 2023a). The average distance between the two major ports within each country (Port of Shanghai and Jawaharlal Nehru Port) and South Africa was calculated and utilised (iContainers, 2021). Similarly, the largest ports in the major polymer-producing countries in Europe (Port of Hamburg in Germany and Trieste in Italy) were used as reference points. North America accounted for roughly 20 percent of global plastics materials production (Statista, 2023b) with the largest ports situated in Los Angeles and New York. As the port of Durban is the largest port facility in South Africa (Sinha, 2021), it was used as the local destination for imports. The distance between polymer producers and converters was calculated on the basis that converters would be based in the three major cities in South Africa i.e. Johannesburg, Durban, and Cape Town. For use, it was assumed

that converted products would be distributed in the same or neighbouring province. Imported products were assumed to originate from China, the world's largest plastic producer (Statista, 2023b).

For the end-of-life stage, distance to buy-back centres (BBCs) and material recovery facilities (MRFs) were considered. The distance was based on the population distribution between urban and rural areas according to a census report (Statistics South Africa, 2003). It was assumed that transport from landfill sites would be in close proximity to disposal locations. Furthermore, there was no transport allocation for self-help disposal due to the nature of the informal disposal method.

In terms of modelling choices, a mixed transport dataset for local transport via lorry was selected due to uncertainty regarding the size of vehicles used and compliance with EURO emission regulations. Similarly, for transport by ship, a general dataset was utilised. As distance is denoted in SimaPro as the product of mass and distance, the mass of material transported was also considered. For the local and imported stages, the transport datasets were added to the respective assembly product stages for ease of modelling. However, the transport of local and imported products was added to the life cycle product stage to signify the major impacts within the use stage. Details regarding the distances and mode of transport used are stated in Table 9.

Table 9: Details regarding Transportation between Stages

Stage	Product	Origin and Destination	Dataset in SimaPro	Distance (km)
Polymer Production	Imported polymer	From Asia/America/Europe to Durban	<i>Transport, freight, sea, container ship {GLO}/ transport, freight, sea, container ship  </i>	11 500
	Local polymer	From Secunda to Johannesburg, Durban or Cape Town	<i>Transport, freight, lorry, unspecified {ZA}  market</i>	730
Conversion	Imported polymer	From Durban to Johannesburg or Cape Town	<i>for transport, freight, lorry, unspecified  </i>	680
	Imported products	From China to Durban/Cape Town	<i>Transport, freight, sea, container ship {GLO}/ transport, freight, sea, container ship  </i>	13 600
Use	Imported products	Within the same/neighbouring province as the ports	<i>Transport, freight, lorry, unspecified {ZA}  market for transport, freight, lorry, unspecified  </i>	500
	Local products	Within the same/neighbouring province as the converters		300
End-of-life - recycling	Collection of unsorted plastics for sorting	From curbside /households/collection sites to BBCs and MRF		Urban - 50 Rural – 200
	Sorted plastics to be baled and granulated	From MRF to recycling facility	<i>Transport, freight, lorry, unspecified {ZA}  market for transport, freight, lorry, unspecified  </i>	40
	Recyclate	From recycling facility to converters		50
End-of-life - Landfill	Landfilled waste	From disposal site to landfill	<i>Transport, freight, lorry, unspecified {ZA}  market for transport, freight, lorry, unspecified  </i>	20

### 3.3.2.3. Impact Assessment

The third stage of the study focuses on the calculation of potential environmental impacts due to the product system. This evaluation is conducted via category indicators and characterisation models to translate the inventory analysis data into potential consequences on human health and the environment. For this study, a range of midpoint and endpoint indicators were considered to incorporate a wide spectrum of environmental impacts and avoid burden-shifting. The persistence of plastic in the environment, not represented in this method, was modelled separately. One socio-economic indicator, employment along the value chain, was investigated. Midpoint and endpoint indicators are complimentary as midpoint characterisation has a stronger link to the environmental flows and results in lower parameter uncertainty whereas the endpoint characterisation comes with greater confidence in the degree of damage but with a higher uncertainty in the characterisation (Hauschild and Huijbregts, 2015).

The ISO standards do not recommend any methods but require the chosen method to be a globally accepted one for comparative intentions. ReCiPe 2016 is considered a harmonised life cycle impact assessment method at both midpoint and endpoint level (Huijbregts et al., 2017). Furthermore, it provides characterisation factors that are representative of the global scale rather than just the European context. The hierarchist perspective, which is the default standpoint for scientific modelling, was selected for this study. The link between the eighteen midpoint and three endpoint indicators in ReCiPe is presented in Figure 8 below.

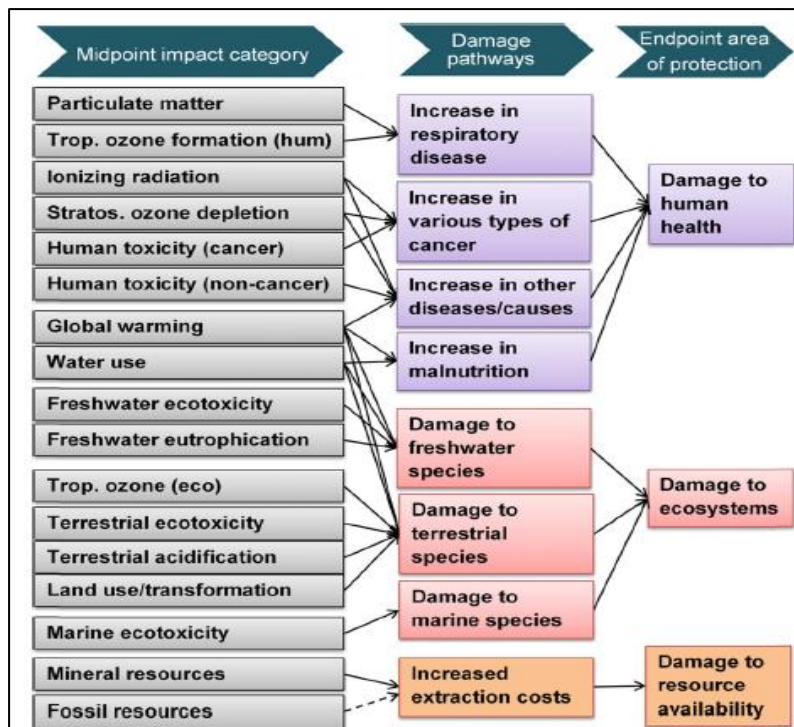


Figure 8: Overview of the Impact Categories that are in the ReCiPe 2016 Method (Huijbregts et al., 2017)

### Plastic Leakage and Persistence

As per the literature reviewed in Section 2.3.2, research pertaining to plastic pollution impacts is ongoing. An example is the MarILCA project which recently published characterisation factors assessing the impacts of aquatic microplastic emissions via the ecosystem quality damage category (Corella-Puertas et al., 2023). However, it has been acknowledged that additional impact categories related to plastic emissions are required for a more detailed assessment for future incorporation into current impact assessment methods.

For the purposes of this study, the significance of plastic leakage was assessed using a mid-point indicator developed by Stafford et al. (2022) based on the persistence of plastics leaked to the environment. This indicator reflects the specific local context of the waste management options by way of flow data as well as the biodegradability of the material. As it is constructed on the assumption that the longer a material persists in the environment, the more likely it is to cause damage, it can serve as a valuable proxy for damage caused by plastics and other materials. The persistence of leaked material indicator,  $P_{LM}$ , is defined as the product of the quantity of material disposed into a particular environment and the average lifetime of the material in that environment (Stafford et al., 2022). Accordingly, this persistence is expressed in kiloton-years (kton.yr) as it considers both mass and time as per the equation below.

$$P_{LM} = \sum_{T=1}^n \sum_{w=1}^m m_T \tau_w \quad \text{Equation 1}$$

Where  $m_T$ : Total amount of material disposed disposed of into the receiving environment(s) (kton)

$\tau_w$ : Weighted mean lifetime of a given amount/mass of product material degrading in different receiving environments (year)

As there are no major life cycle impact models that evaluate the impact of plastic leakage, spreadsheet-based modelling was used. The end-of-life flows that were developed in the inventory analysis phase were used as a basis to estimate the quantity of total material leakage from the product system. This overall leakage flow was sub-divided according to leakage in different natural environments i.e. terrestrial and aquatic environments. For each of these environments, flows were distributed according to whether the plastic is buried or subject to sunlight and air. The flow of pollution into the marine environment was based on the upper-level estimate calculated by Verster and Bouman (2020) which was then assumed to be equally split between the marine environment and accelerated degradation in the marine environment i.e. subject to sunlight and air. Thereafter, the amount of plastic buried on land was estimated as half the leakage from the open dumping stream. The remainder of the leakage flow, which was calculated via a mass balance, was assumed to thus leak into the terrestrial environment and is subjected to accelerated degradation via the mechanisms of light and air. To further sub-divide these flows to specify individual polymer leakage flows to the different environments, results from a waste characterisation study (Nelson Mandela Bay Municipality, 2016) were used in the absence of specific polymer leakage data.

To evaluate the second part of the indicator, the mean average lifetimes of the various polymers were necessary. Estimated half-lives of the polymers were converted to mean average lifetimes using the following two equations:

$$T_{\frac{1}{2}} = \frac{\ln 2}{k'} \quad \text{Equation 2}$$

$$\tau = \frac{1}{k'} \quad \text{Equation 3}$$

Where  $T_{\frac{1}{2}}$ : Time taken for material to biodegrade to half its original value and  $k'$  is a biodegradation rate constant

Data for the estimated half-lives of polymers were obtained from a research paper that used linear extrapolation from mean specific surface degradation rates (SSDR) (Chamas et al., 2020). The resulting data for the mean lifetime per polymer in the different receiving environments was calculated as per Table 10.

**Table 10: Average Lifetime of Polymer in Different Receiving Compartments**

Polymer	Mean Lifetime (year)			
	Land (buried)	Land (Accelerated by UV/heat)	Marine (Buried)	Marine (Accelerated by UV/heat)
PET	3607	1224	48	3
HDPE	3787	2951	908	402
PVC	3607	1224	197	-
LDPE	7	3	5	7
PP	3316	1125	76	126
PS	3607	649	104	-
Other	3102	1447	321	-

Data from Chamas et al. (2020) were supplemented by studies analysing the environmental fate of Polystyrene due to exposure to sunlight and the degradation potential of PET bottles in the marine environment (Ioakeimidis et al., 2016; Ward et al., 2019). For the polymers where degradation rates were unknown for the specific environment, a proxy was used by averaging the ratio of the sourced mean lifetime of the polymers.

## Employment

To incorporate a socio-economic aspect that is particularly significant to South Africa, employment was added as a supplementary indicator for analysis. Employment opportunities were grouped according to the main life cycle stages: local virgin polymer production, conversion, and recycling. As the model was based on scaling the employment figures per stage to a kiloton of product, figures for total material produced were required at each phase, loosely following the methodology employed in the LCSA of grocery carrier bags (Russo et al., 2020). Data was obtained from various sources such as company and industry reports as per Table 11.

**Table 11: Breakdown of Employment Calculation per Life Cycle Stage**

<b>Life Cycle Stage</b>	<b>Jobs/kt</b>	<b>Sources</b>
Local virgin polymer production	2.8	(Sasol, 2021b, 2021c)
Conversion	17.5	(Trade and Industrial Policy Strategies, 2021)
Recycling	121	(Plastics SA, 2020)

For the first stage, mass allocation was used to ratio employee numbers obtained from the annual Sasol Integrated report and production volumes from the summary of production and sales metrics. For the conversion process, the total sum of employees of South African companies producing various plastic products was used. To quantify employment opportunities in the recycling stage, jobs in both the informal and formal sectors were considered. The informal income opportunities were converted to full-time equivalents using a full-time equivalence concept (Parliamentary Monitoring Group, 2012). The amount of material converted and recycle obtained was sourced from the annual Plastics SA recycling survey.

#### 3.3.2.4. Interpretation

The final phase of the study involves the interpretation of the results obtained during the assessment. This is performed to evaluate the results based on the goal and scope of the study. As per the ISO 14040 document (International Organisation for Standardisation, 2006), this concluding stage should identify the environmental hotspots based on the inventory analysis and impact assessment phases and develop corresponding conclusions, as well as highlight the limitations and challenges of the study. Recommendations originating from the research are also included.

### **3.4. Baseline Scenario**

The Baseline scenario represents the reference model for comparison with the investigated alternative scenarios. In this scenario, the plastics sector grows but remains structurally unchanged. As such, it is a projection of the 2018 model with no circular or decarbonisation interventions modelled.

#### **3.4.1. Material Flow Analysis (MFA)**

This scenario was constructed using local gross domestic product (GDP) data. As the global plastics industry grew at an average rate of 4% between 2010 and 2015 (Geyer et al., 2017), the

initial projection for the annual local production rate was based on this historical average. However, a more refined calculation made use of the local gross domestic product (GDP) growth rate. The GDP, which represents the total final value of domestic goods and services produced annually, was sourced from Statista for the period 2017 to 2027 (Statista, 2023c). For the MFA model in 2025, the average GDP growth rate from 2017-2025 was used. The GDP growth rate for 2020 was excluded as the COVID-19 pandemic was viewed as an anomaly that can dramatically change the results thus obscuring true representation. Thus, the average growth rate was calculated as 1.72%. For the mass balance models post-2025, a 1.4% production rate was applied based on the projected GDP rate from 2025-2027. The application of these production rates provided the total quantity of plastics produced locally on an annual basis.

To populate the mass balance model, data was required for the streams depicted in the flow model. For the import and export flows (viz. imported virgin and recycled polymer, imported products, and exported products and packaging), the quantity of polymer domestically converted into plastic products was utilised as a reference point. Thereafter, the average ratio of these flows to the amount of plastic products produced for 2017 and 2018 was calculated. This ratio was applied to the quantity of plastics produced locally that was calculated according to the GDP rate as detailed above. The same methodology was applied to calculate plastic material collected for recycling. For the quantity of recyclate obtained, the reference point was selected as the amount of material collected.

In terms of distribution of use into short-term and long-term applications, the same ratio used in the Plastics SA recycling survey (Plastics SA, 2019) was utilised i.e. 40% of the total amount converted will be used for durable applications. As the model takes the accumulation of plastics for long-term applications (e.g. in buildings etc) into account, data was required. As a first pass, it was assumed that 50% of durable use would be retained in the system as stock while the remainder becomes waste. An updated estimate was obtained using a material lifetime analysis as per Berge and von Blottnitz (Berge et al., 2022). An exponential growth formula in the form of Equation 4 is used to calculate the amount of material one lifetime ago.

$$Q_0 = \frac{Q}{e^{rt}} \quad \text{Equation 4}$$

where  $Q_0$  is the plastic material used one lifetime ago,  $Q$  is the new material used,  $r$  is the plastic industry growth rate, and  $t$  is the material service life.

Using the above formula together with 1.4% as a value for  $r$  (Plastics SA, 2014) and a 25-year service material service lifetime yields a result that is equivalent to 70% of plastic material for durable purposes remaining in stock. Thus, 30% exits the long-term use system as waste.

### **3.4.2. *Life Cycle Assessment (LCA)***

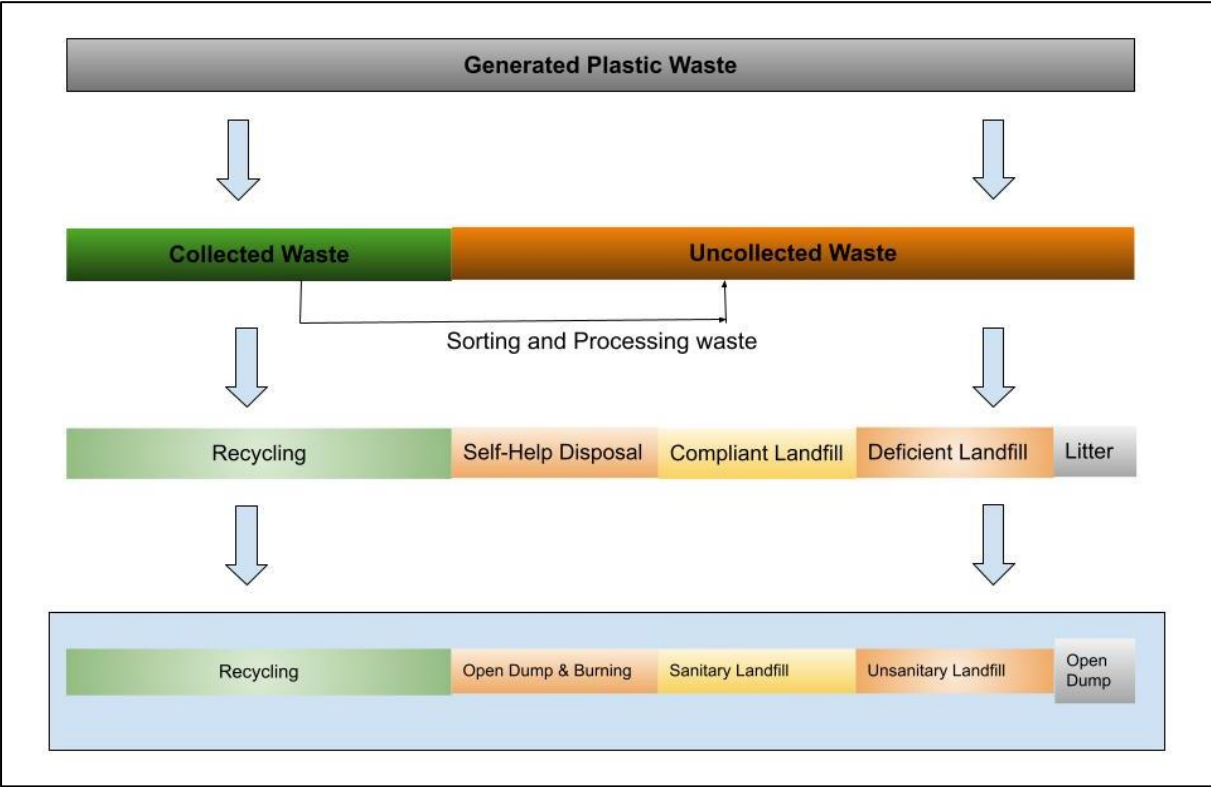
The LCA model was changed according to flows calculated in the preceding MFA model. This affected the inventory analysis stage of the assessment process.

For the production of local polymers, RoW unit datasets were adapted by substituting international water and energy datasets with the local alternatives. Another significant amendment was the utilisation of the organic chemical production datasets for South Africa. These are compiled to represent the Fischer-Tropsch technology developed by Sasol to produce synthetic fuels and chemicals. For the production of PET granulate, the allocation of amorphous to bottle grade was obtained from a document published by the Producer Responsibility Organisation (PRO) which stated the ratio as 30:70 (PET Recycling Company NPC, 2019). For imported polymers, RoW datasets were primarily utilised.

To accurately reflect the mix of conversion methods for plastic production in South Africa, country-specific percentages from a report providing an overview of the global plastic market including plastics processing information was applied as per Section 3.3.2.2. Over and above integrating local energy and water data, these data sets were adapted by including locally produced LDPE and PP granulate to represent the bags utilised for collection purposes as well as for transportation to manufacturing sites. Furthermore, the organic chemical data set used, which describes the usage of solvents, was substituted with the South African coal-based chemical production process. For products and packaging that were imported into the country, the manufacturing process was represented in the modelling procedure by polymer production followed by conversion. The RoW datasets were selected to mimic these processes. As the use phase was not explicitly modelled except for the addition of transport, there was no differentiation made between short-lived and durable plastics. Similarly, imported products and packaging were represented as a single flow irrespective of their differing lifetimes.

For each of the local production and conversion datasets, outputs to technosphere by way of waste and emissions to treatment is included. The original end-of-life plastic waste scenario for South Africa, which models the disposal mix of 1kg of waste plastic mixture, comprises 3% of

open burning, 3% of open dumping, and 93% of unsanitary landfill (Global LCA Data Access, 2019a). According to GLAD, which is the largest global directory of LCA datasets from independent database providers, this is also the distribution of other municipal solid waste materials such as packaging paper and glass (Global LCA Data Access, 2019b, 2019c). As the MFA diagrams for this study portray a different reality from the existing datasets, these were then utilised to form the basis of a new South African plastic waste end-of-life model. As the recycling process (from sorting to baling to conversion into granulate) was modelled and this complete recycling process was only documented in SimaPro for PET, the process was duplicated and used as a basis for other polymers. The general distribution of waste post-use along with the inventory waste treatment processes are depicted in Figure 9 below.



**Figure 9: Schematic to show the Distribution of Waste Treatment Processes**

To compile the life cycle model, each sub-stage, with a combination of the different polymers, was modelled as an assembly. These include polymer production (from virgin and recycled sources) as well as the overall conversion process. Thereafter, the disposal scenario was constructed to depict the split between the various treatment options. Finally, the life cycle

model was constructed by linking the relevant assembly model to the corresponding disposal scenario.

### **3.5. Increased Recycling Scenario**

The Increased Recycling scenario focuses on the primary waste treatment option in South Africa. Specifically, the strategy is based on an increase in the mechanical recycling rate and therefore recycled content within the converted plastic product. Amongst the regulatory and voluntary targets set, the South African Plastics Pact targets were selected. The targets state that the recycling rate in 2025 should reach 70% for plastic packaging with an average recycled content of 30% across all packaging (The South African Plastics Pact, 2020).

#### **3.5.1. Material Flow Analysis (MFA)**

An initial mass balance was undertaken to confirm the link between both indicators cited in the South African Plastics Pact targets i.e. if an input recycling rate of 70% is equivalent to a 30% recycled content. Once this was established and verified, the input recycling rate for 2025 was set to 70% in the MFA model. This entailed that the collection of plastic material for recycling was set at 70% of short-lived waste which corresponds to the stated definition of input recycling rate (Table 5). The MFA model was also adjusted to include the increase in recycled content. The final recyclate that is being fed into the conversion operation was set at 30% of the total plastics converted. This signified an increase in recyclate which denoted a subsequent decrease in virgin material input. It was assumed that this decrease in virgin material was shared equally between local and imported polymer sources. It is acknowledged that fulfilling both targets related to recycling rate and recycled content would imply high efficiencies in the recycling process. As recycling rates increase, it was assumed that other end-of-life options are also impacted with the amount of plastic waste treated by landfills showing a reduction proportionate to the increase in collection and the amount of waste disposed via self-help disposal will remain the same. This is due to the assumption that an increase in recycling will initially impact urban areas thereby resulting in decreased waste managed via deficient and compliant landfills. The ratio of waste treated by compliant to deficient landfills follows the method used for the Reference Case and Baseline scenario.

As the year 2025 is fast-approaching, an extension of the timeline was necessary to gauge the impact of alternative scenarios beyond a short-term horizon. To extend the assessment past the year 2025, the percentage difference in collections between the 2018-2025 period was

calculated and applied to the amount of material collected in 2025 to obtain an estimate for collections in 2030. A similar method was applied for the calculation of recyclate. As per the modelling on a short-term basis, it was assumed that this increased collection rate would also result in a decrease in the amount of waste treated by compliant and deficient landfills.

For the year 2035, a maximum collection rate of 85% was set to account for material losses and contamination in the collected material. Using this target value, the forecasting tool Goal Seek was used to calculate a yearly increase in collections of 3.6% over a five-year period from 2030 to 2035. This annual increase was also applied to the amount of recyclate obtained post-recycling.

**3.5.2. Life Cycle Assessment (LCA)**

As the MFA model states, the polymer input into the manufacturing process is amended by increasing the ratio of recycled polymer to virgin polymer. Thus, the four streams that are primarily affected are the local polymer, imported polymer, material that is uncollected and disposed of in landfills and self-help disposal, and the overall material that is collected for recycling. These flows for the Increased Recycling scenario, which are used as inputs into the LCA model, are presented in Table 12.

**Table 12: Output Data Post-Conversion for Baseline and Increased Recycling Scenario**

	<b>Baseline (kt)</b>	<b>Increased Recycling (kt)</b>
	<b>2025</b>	<b>2025</b>
<b>Polymer Production</b>		
Local polymer	848	730
Imported polymer	868	750
<b>Disposal</b>		
Collected for recycling	531	910
Waste to landfill and self-help disposal	1 619	1375

Conversion datasets remain the same as the quantity of polymer converted does not change. Thus, the same quantity of waste originates from the domestic consumption phase. However, the distribution of waste into the various waste disposal options differs in accordance with the mass balance model.

In terms of the end-of-life stage and waste treatment flows, the increase in material collected for recycling has a quantifiable impact on all the streams post-use. In particular, the compliant and deficient landfill flows are lower than the Baseline scenario due to the assumptions made in the MFA modelling process. Furthermore, the recycling streams and all the associated flows (sorting, baling, and processing into granulate) all increased.

Other than adjusting the flowrates of plastics at these identified points in the inventory model, no changes were made to the LCA when calculating the impacts of this altered system configuration.

### 3.6. Demand Moderation Scenario

This scenario is centred around introducing a new stream that mimics the reuse of products. The strategy is based on policy documents and legislation that call for action on single-use packaging by developing alternative (reuse) models (Department of Environment Forestry and Fisheries, 2021; Department of Trade and Industry, 2020; The South African Plastics Pact, 2021).

#### 3.6.1. Material Flow Analysis (MFA)

This scenario was constructed by building the mass balance model by diverting a percentage of single-use consumption towards the reuse of products. To achieve this, a substitution ratio was required to convert the mass of single-use products to a reusable alternative. This was obtained from the Life Cycle Sustainability Assessment (LCSA) conducted by the Council for Scientific and Industrial Research (CSIR) focusing on the evaluation of single-use plastic shopping bags and various alternatives available in South Africa (Russo et al., 2020). From the calculation of the reference flow for the various types of bags, the following source data was extracted:

**Table 13: Excerpt of Grocery Bag Data (Russo et al., 2020)**

<b>Type of Bag</b>		<b>Reference flow</b>
		(g per person per annum)
Single-use bag	HDPE_24_100	572
Reusable bag	HDPE_70	34.89
Substitution ratio		16.39

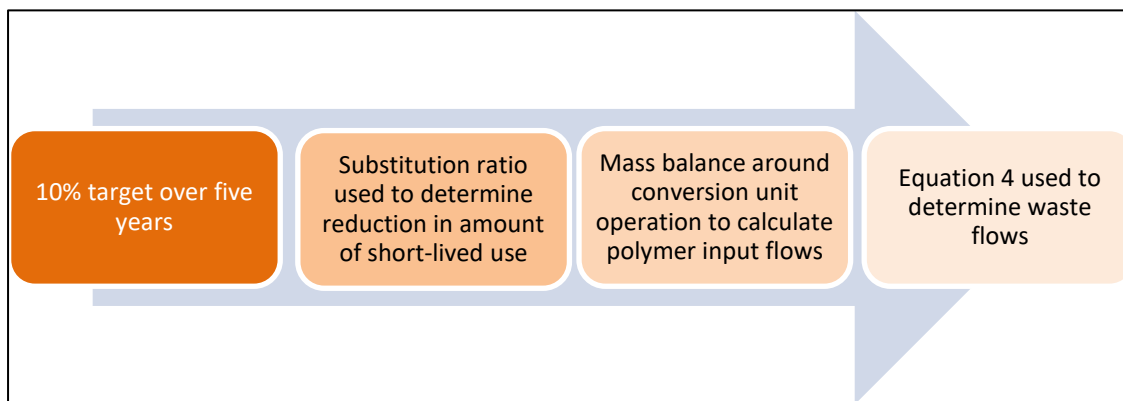
Therefore, a shift from single-use to reusable would decrease the mass flow by a factor of 16. The World Economic Forum released a report evaluating the future of reusable consumption models (World Economic Forum, 2021). Within the report, potential reuse scenarios were outlined. One of the scenarios, which is based on proposals from France and the EU Parliament, states that 10-20% of all packaging is reusable. The lower limit of this target was selected and used as a basis for this study's Demand Management scenario. Therefore, if 10% of short-lived use was transformed to reuse in 2025, the resulting flows would change as per Table 14.

**Table 14: Input Data Post-Conversion for Baseline and Demand Moderation Scenarios**

	<b>Baseline (kt)</b>	<b>Demand Moderation (kt)</b>
	<b>2025</b>	<b>2025</b>
<b>Use</b>		
Short/lived (1 yr)	1 079	971
Non-durable goods (<3 yrs - Reuse)	-	6.6
Durable goods (>3 yrs)	846	846
Exports	190	190
	<b>2 114</b>	<b>2014</b>

The reuse stream has an impact on processes upstream. According to Table 14, polymer input decreases by 100 kt when comparing the Baseline to the Demand Moderation scenario. It was assumed that this would be at the expense of virgin material which would be divided equally between imported and local polymer streams. In terms of downstream activities, Equation 4 was utilised to calculate the waste generated from the reuse and durable streams.

For future projections, the above-mentioned process was repeated. The calculation procedure is depicted in Figure 10 below.



**Figure 10: Flow Chart showing Calculation Steps for Demand Management in 2030 and 2035**

To populate flows for the MFA model in 2030 and 2035, the 10% target was used as a basis to estimate the shift in consumption over a five-year period from short-lived products to reusable goods. Once the target was applied, output flows from the conversion unit operations were calculated. This was then considered in the computation of polymer feedstock flows. Similarly, the use flows were utilised to calculate downstream waste flows via Equation 4.

### **3.6.2. Life Cycle Assessment (LCA)**

The Demand Moderation scenario is primarily focused on the use phase i.e. decreasing the production and use of plastics by introducing the reuse of plastic items. As the LCA model does not explicitly model the use stage (with the exception of transport of finished goods), the changes to the baseline model are not directly reflected in the LCA. However, as indicated in Section 3.6.1, upstream and downstream flows in terms of polymer inputs and waste flows respectively were affected. The reduction in these flows was reflected in the inventory stage of the LCA model.

### **3.7. Decarbonisation Scenario**

The focus of this scenario is the decarbonisation of the national energy and polymer system. In particular, this includes an analysis of the proposed low-carbon national energy system, reduction of emissions at Sasol, and substitution of the coal-based monomer production process with a conventional oil-based process. As per the outline in the scope definition, this scenario is split into two strategies:

- A. Decarbonisation of the national energy mix for all processes excluding the unit operations in the synthetic fuels and chemical production at Sasol’s Secunda site.
- B. Decarbonisation of the Sasol energy mix and monomer production process.

### **3.7.1. Material Flow Analysis (MFA)**

As the scenario is centred around changes to the energy mix, the mass flows remain constant. Thus, the MFA model for this strategy is the same model generated for the Baseline scenario which is detailed in Section 3.4.1.

### **3.7.2. Life Cycle Assessment (LCA)**

#### **3.7.2.1. Strategy A**

The aim of this scenario is to model the impacts of the forecasted national power sector energy mix on the local plastics value chain. The Integrated Resource Plan (IRP) 2019 was used as a primary resource as it represents the most recent iteration of the IRPs as published by the Department of Mineral Resources and Energy (DMRE). It also signifies the newly established policy position on the national energy mix to 2030 (Department of Mineral Resources and Energy, 2019). The time horizon was thereafter expanded beyond 2030 to 2050 by the CSIR using the same input assumptions listed in the IRP 2019 publication (Wright and Calitz, 2020).

The IRP 2019 demand scenario is based on median demand and was developed using statistical methods (Koen et al., 2017). The forecast is based on an average annual GDP of 4.4% to 2030 and thereafter 3.7% to 2050 taking into account changes in the electrical intensity of the country's manufacturing and commercial sector. This results in an average annual electricity demand growth of 1.8% to 2030 decreasing to 1.1% up to 2050 (Wright and Calitz, 2020). This forecast encompasses the entire electrical demand for the country inclusive of the majority share met by Eskom-owned generators and Independent Power Producers (IPPs).

This scenario considered all input assumptions as defined in the IRP 2019 document including Eskom generation fleet decommissioning dates and new-build dates. The scenario shows that the initial new build capacity occurs in 2022 and consists of 1.0 GW of solar PV, 1.6 GW of wind (repeated annually in most years until 2030), and 0.5 GW of stationary storage (Department of Mineral Resources and Energy, 2019). This is followed by 1.0 GW of new gas capacity in 2024 and 2.5 GW of imported hydro-based electricity in 2030. To meet ambitious power sector carbon dioxide mitigation targets, wind and solar play an increasingly significant role.

The IRP document specifies electricity demand in terms of terawatt hours (TWh). A plot digitiser was used to extract data from the source bar chart. Individual energy sources were

ratioed according to the total annual energy demand and were thereafter applied to the South African high voltage production mix (dataset name: “*Electricity, high voltage {ZA}| market for*”). The resulting energy mix along with the respective SimaPro datasets are reflected in Table 15 below.

Table 15: Projected Energy Mix for 1 kWh for the Period 2025-2035

Energy Source	SimaPro Dataset	2025	2030	2035
<b>Existing</b>				
Coal, conventional	<i>High voltage {ZA}  hard coal, conventional  </i>	$6.35 \times 10^{-1}$	$3.67 \times 10^{-1}$	$3.21 \times 10^{-1}$
Coal, supercritical	<i>High voltage {ZA}  hard coal, supercritical  </i>	$1.70 \times 10^{-2}$	$1.57 \times 10^{-1}$	$1.38 \times 10^{-1}$
Hydro, pumped storage	<i>High voltage {ZA}  hydro, pumped storage  </i>	-	$9.27 \times 10^{-4}$	$4.44 \times 10^{-3}$
Hydro, reservoir	<i>High voltage {ZA}  hydro, reservoir, non-alpine region  </i>	$3.40 \times 10^{-2}$	$8.81 \times 10^{-2}$	$7.95 \times 10^{-2}$
Nuclear	<i>High voltage {ZA}  nuclear, pressure water reactor  </i>	$5.1 \times 10^{-2}$	$4.7 \times 10^{-2}$	$4.9 \times 10^{-2}$
Oil	<i>High voltage {ZA}  oil  </i>	$7.44 \times 10^{-4}$	$7.44 \times 10^{-4}$	$7.44 \times 10^{-4}$
Solar thermal/Concentrated Solar Power (CSP)	<i>High voltage {ZA}  solar thermal parabolic trough, 50 MW  </i>	$8.49 \times 10^{-3}$	$8.96 \times 10^{-3}$	$4.38 \times 10^{-3}$
Wind	<i>High voltage {ZA}  wind, 1-3MW turbine, onshore  </i>	$1.11 \times 10^{-1}$	$1.72 \times 10^{-1}$	$2.21 \times 10^{-1}$
Imports	<i>High voltage {ZA}  import from MZ</i>	$4.6 \times 10^{-2}$	$4.6 \times 10^{-2}$	$4.6 \times 10^{-2}$
<b>Additional</b>				
Gas	<i>High voltage {ZA}  natural gas, combined cycle power plant  </i>	$8.49 \times 10^{-3}$	$6.80 \times 10^{-3}$	$8.82 \times 10^{-3}$
Photovoltaic	<i>Low voltage {RoW}  photovoltaic, 570kWp open ground installation, multi-Si  </i>	$3.40 \times 10^{-2}$	$4.91 \times 10^{-2}$	$6.62 \times 10^{-2}$
Distributed generation	<i>Low voltage {ZA}  photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted  </i>	$3.40 \times 10^{-2}$	$4.38 \times 10^{-2}$	$5.30 \times 10^{-2}$
Biomass	<i>High voltage {ZA}  heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014  </i>	$8.46 \times 10^{-3}$	$5.87 \times 10^{-3}$	$4.41 \times 10^{-3}$
Other storage	Same as hydro, pumped storage	$8.52 \times 10^{-3}$	$4.64 \times 10^{-3}$	$4.56 \times 10^{-3}$

Processes have been divided into what was already in the existing energy mix as well as new processes that had to be added to fulfil the projected energy mixes. It is expected that the supercritical power stations (namely Medupi and Kusile) will be operating at full capacity and therefore contributing 30% of the coal-based electricity in 2030 and 2035 (Department of Mineral Resources and Energy, 2019). To accurately represent the forecast model, representative datasets from the ecoinvent database were required. Distributed generation was represented by grid-connected rooftop solar panels. Additionally, energy from gas is assumed to be generated via a natural gas combined cycle (CC) plant. As the local dataset to represent energy from photovoltaics is limited to 3 kWp, a RoW dataset containing a 570kWp energy source was used.

As small-scale industries require medium voltage (defined as 1-24 kV according to the respective ecoinvent dataset documentation), a transformation dataset was required to step down the electricity voltage from high to medium. Similarly, the voltage was also transformed from medium to low voltage due to the electricity requirements of the recycling process. These datasets included losses incurred during voltage transformation. Once the medium and low voltage datasets were configured, they represented the dataset format “*Electricity, low/medium voltage {ZA}| market for*”. These were then utilised as the energy input from technosphere. The energy inputs were thereafter used for foreground processes such as polymerisation and conversion as well as utilised for background datasets including the production of ethylene glycol and vinyl chloride.

As mentioned in the section 3.7.1, the plastic flows for this scenario remain unchanged. Thus, the LCA model constructed for the baseline scenario was used as a foundation together with changes to the energy mix as described. As this scenario focussed on the projected local energy mix, the production of imported polymers and products was not affected. The modelled energy datasets were added to local unit operations other than the production of synthetic fuel (organic chemical production from the Fischer-Tropsch process) as this was the focus of the next section of the decarbonisation scenario.

#### 3.7.2.2. Strategy B

The second part of the decarbonisation scenario revolves around the emission-reduction plan proposed by Sasol. As a part of the Sasol Chemicals division, local plastics production is intrinsically linked to Sasol’s climate change policy. Sasol’s CTL-based facility, which

produces organic chemicals used for monomer production, is estimated to account for 85% of their global scope 1 and 2 emissions (Sasol, 2019).

According to the analysis undertaken, it is expected that fossil fuel feedstock acceptability will become increasingly constrained due to the transition from their ‘Current Pathway’ to the proposed ‘Net Zero’ case (Sasol Limited, 2022). Thus, Sasol has committed to gradually reducing its exposure to coal, thereby contributing to a lower emissions profile for its South African operations. In terms of targets, Sasol has pledged to reduce scope 1 and 2 emissions by 30% by 2030 off a 2017 baseline. This is applicable to their Energy and Chemicals entity. Additionally, renewable energy is in the process of being procured with the intention of providing 100% purchased renewable electricity for Sasol Chemicals by 2030.

To create a representative LCA model, Sasol’s decarbonisation targets were used. As the targets speak to both direct and indirect emissions, a multi-tiered approach was used. The method used is outlined in Table 16.

**Table 16: Approach to Convert Sasol’s Decarbonisation Targets**

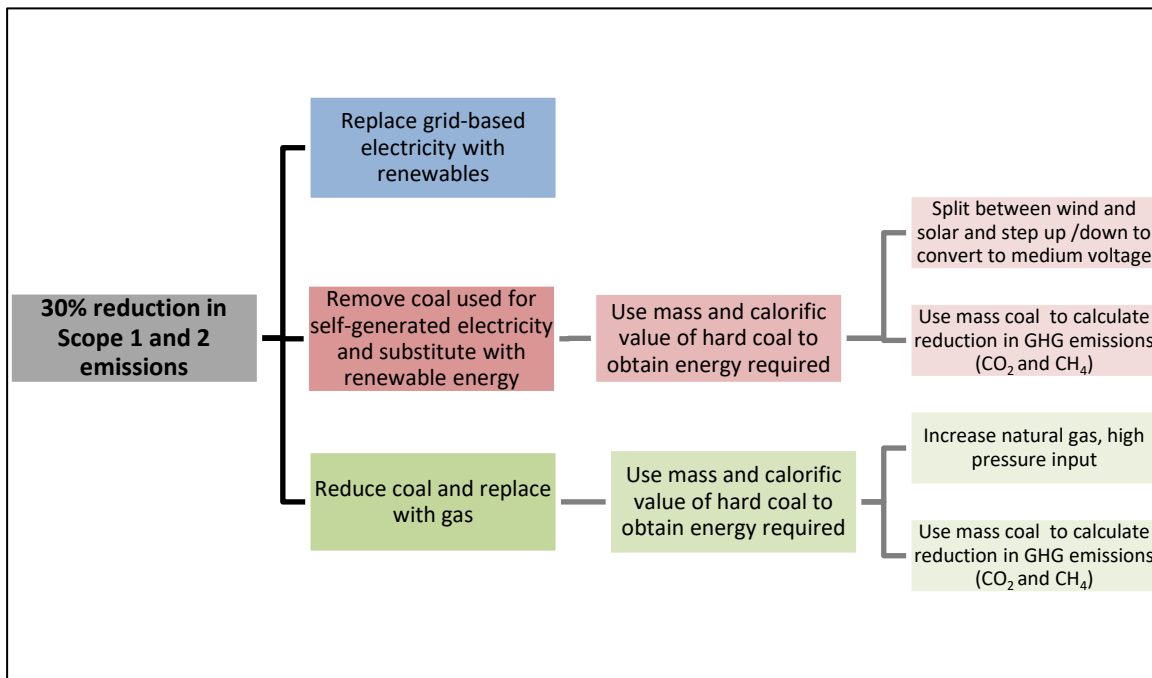
2025	2030	2035
<ul style="list-style-type: none"> <li>• Grid mix as per IRP</li> </ul>	<ul style="list-style-type: none"> <li>• Replace grid-based electricity with renewables</li> <li>• Decrease in coal used for energy. Increase in renewable energy (solar and wind) and gas.</li> <li>• GHG emissions decrease due to decrease in coal according to pre-modelled ratio of coal to emissions</li> </ul>	<ul style="list-style-type: none"> <li>• Replace local monomers with imports.</li> </ul>
<p><i>Dataset name: Chemical, organic {ZA}  synthetic fuel production, from coal, high temperature Fisher-Tropsch operations  </i></p>		

In the climate change report, it is stated that Sasol is concluding agreements to secure more than 600 MW of renewable energy before end-2025 via three short-listed IPPs (Sasol, 2022).

Therefore, there is no change in self-generated electricity on-site in the year 2025. Electricity consumption from purchased electricity i.e. from the grid, comprises 48% of the total electricity requirements to power this chemical production process (Sasol Limited, 2017).

In the medium-term, Sasol has set several ambitious targets related to its decarbonisation pathway. Amongst these is a 30% reduction in emissions by 2030 which represents a tripling of Sasol's initial target which aimed to reduce emissions to just under 58 million CO<sub>2</sub>eq by the end of the decade (Sasol Limited, 2021). In their report, Sasol acknowledges that for the power sector, a renewables-dominated energy mix with gas as a peaking fuel has been analysed to be the least-cost pathway for South Africa (Sasol, 2022). For the Secunda plant in particular, large-scale renewables and sustainable carbon sources were cited as being central to achieving Sasol's fossil fuel-free future.

To this end, Sasol Energy has endeavoured to sizeably increase its portfolio of wind and solar projects in South Africa by procuring 1 200 MW of renewable energy by 2030. This will reduce their scope 2 emissions by replacing grid-based electricity and assist with the mitigation of scope 1 emissions by decreasing the self-generation of electricity from coal. An additional 25% reduction in coal usage is expected to be achieved by securing 40-60 PJ/a of liquified natural gas (LNG) to supplement the current requirements of 160 PJ/a (Sasol, 2022). This is expected to be delivered via Matola, Mozambique in 2026. Gas is seen as a transition feedstock towards the end goal of green hydrogen and sustainable carbon feedstocks as it possesses a significantly lower GHG footprint compared to coal. Therefore, gas is viewed as a key substitute feedstock in the CTL sector for the short-medium term period. The calculation steps as well as associated datasets that have been amended to obtain the reduced emission load are summarised in Figure 11.



**Figure 11: Flowchart Depicting Steps to Satisfy Emission Reduction Targets for 2030**

Between the period 2030 and 2050, Sasol has committed to creating new value propositions via feedstock transformation through gas, green hydrogen, and more renewable energy. As liquid fuels demand and the corresponding supply declines, it is projected that South African crude refineries and the CTL process could cease production by 2035 (Marquard et al., 2022). This would result in an end to the local production of ethylene and propylene which would entail the fulfilment of local demand for monomers by the international market as imported feedstock. In the LCA model, this translates to a substitution of the coal-based production process with the conventional oil-based process.

### 3.8. Combination Scenario

The Combination scenario comprises modelling the individual measures in concert. Although there are various ways to model this scenario, the order in which strategies were modelled were as follows:

1. Shrinking of the system and enabling it to be more materially efficient by applying the Demand Moderation scenario.
2. This was followed by the application of the Increased Recycling scenario to improve the circularity of the system.
3. Finally, the Decarbonisation scenario, including Strategy A and B were applied.

A slight variation in the modelling arose upon modelling of the Increased Recycling scenario. The three different approaches were:

- a) Application of the Increased Recycling scenario targets to the Demand Moderation model
- b) Application of the difference between the Increased Recycling and Baseline scenario results to the Demand Moderation model
- c) Application of the Increased Recycling flows to the Demand Moderation model

The first approach consisted of applying the targets (input recycling rate and recycled content) directly to the stated indicators and thereafter calculating the mass flows whereas a direct change in the collection and recycle flows was made for the other two approaches. The last approach was selected as it maximised results across indicators and described the combination of strategies with the greatest potential. In this manner, the Combination scenario considered both material and energy aspects.

### **3.9. Conclusion and Results Outlook**

The methods described the approach that was followed to construct the various scenarios by detailing the joint utilisation of MFA and LCA. The application of the methods led to a series of results. The results and discussion section are divided into two complementary chapters. The first section provides a snapshot of results that can be generated per scenario while the second part produces a medium-term forecast comparing scenarios for selected indicators. The structure of the two chapters is shown graphically in Figure 12.

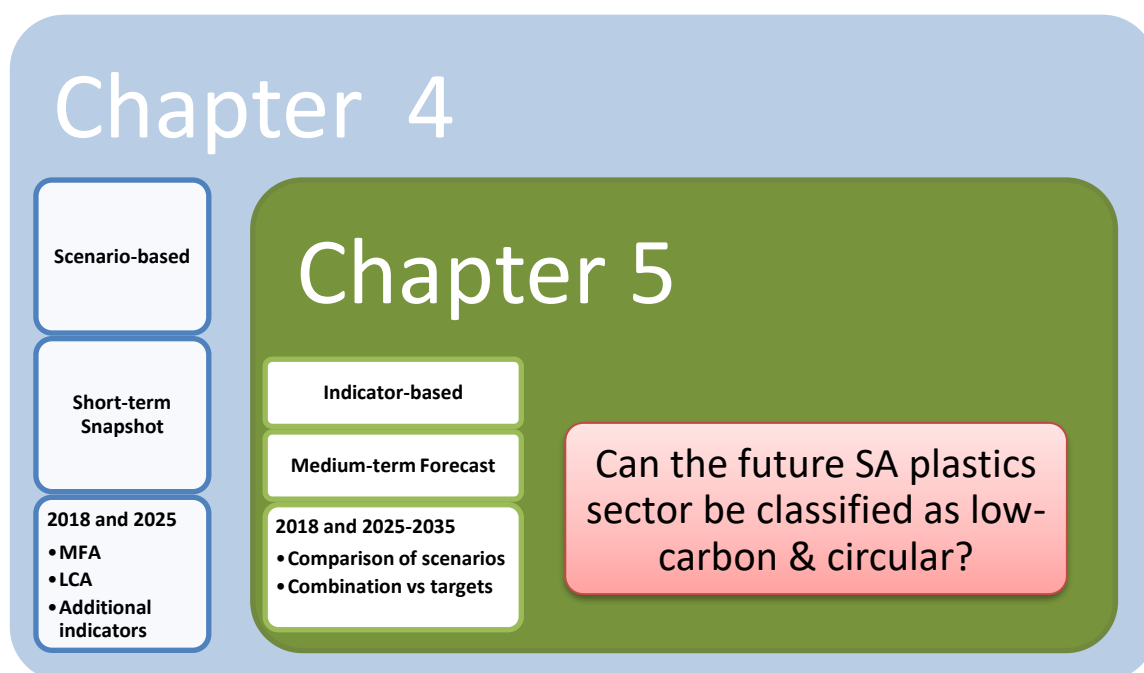


Figure 12: Summary of Results Presentation

The structure of Chapter 4 mimics the layout of the preceding chapter with results segregated per scenario. Each scenario is described in terms of the results of the MFA followed by findings from the respective LCAs. The Reference case was modelled to present the state of the sector in 2018 while the scenarios show future projections of the local plastics system in 2025. This short-term snapshot of results was undertaken to analyse how the performance of the system would measure up against stipulated targets set for the local context. This chapter aims to highlight the potential type and format of results that the joint application of environmental assessment tools can generate. Thus, the results of the various MFAs are presented in the form of a system map, circularity, and mass-based indicators, while the findings of the LCA are represented by normalised results and a contribution analysis showing hotspots to differing degrees of granularity. The impact of implementing a combination of strategies is also presented along with an exploration of additional indicators in the form of plastic persistence and employment. The chapter concludes by summarising the key findings from the short-term analysis.

Following up from the previous chapter, Chapter 5 aims to firstly show the comparison of the individual scenarios in the medium-term per selected indicator. This is to gauge the best scenario for each indicator, as well as show the combined effect of implementing scenarios in concert. The chapter closes by referencing the title of the study and seeks to investigate what

the combination of strategies can achieve from a circular and low-carbon perspective when compared to relevant medium and long-term global ambitions and targets.

## CHAPTER 4: RESULTS AND DISCUSSION (SNAPSHOT)

This chapter starts by presenting results according to the various scenarios outlined in Chapter 3. The findings are segregated into MFA and LCA results with the discussion extending to a benchmarking the results against relevant international and local studies. These findings are supplemented with the exploration of additional indicators across the outlined scenarios. To conclude, the impact of combining scenarios is presented as well as a summary of the key take-aways from this chapter.

### 4.1. Reference Case

#### 4.1.1. *Material Flow Analysis (MFA)*

##### 4.1.1.1. System Map

The flow diagram showing the state of the South African plastics economy in 2018 is depicted in Figure 13. Results are shown in the form of a Sankey diagram where the width of the line is related to the actual material flow. The Reference case provides the basis for modelling the national plastics system as it is the first iteration of a mass balance that encompasses all stages of the plastics life cycle in the local context – from polymer production and conversion into products to consumption, and thereafter disposal via various waste treatment options and collection for recycling. Leakage from the waste management streams is also displayed.

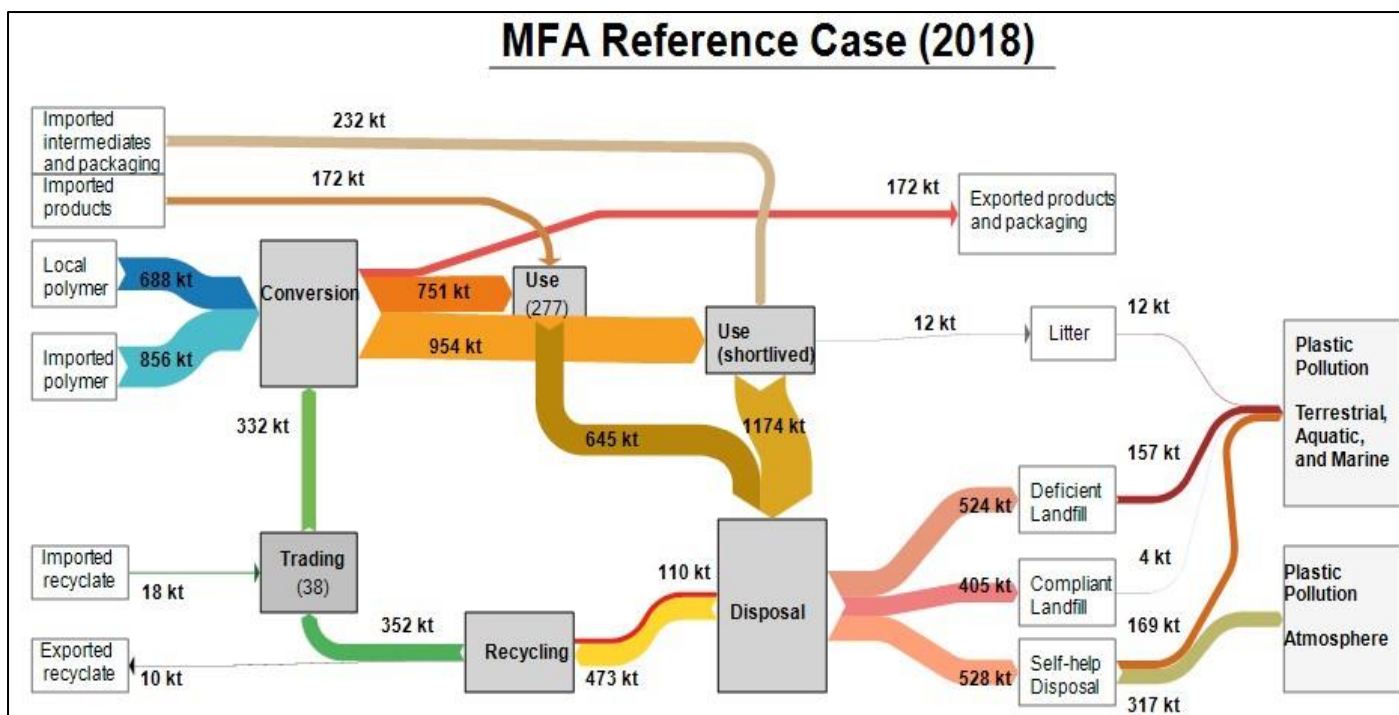


Figure 13: MFA Results for Reference Case for 2018

The diagram indicates that the quantity of polymer locally produced in 2018 was approximately 20% less compared to polymer imported into the country. On a polymer basis, the polymers that were imported in significant quantities include Polyethylene and Polyethylene Terephthalate based on results from the SARS trade data. Post-conversion, 51% of plastics produced were utilised in single-use or short-term applications where the product is expected to be used and disposed of within the same year of manufacture. The balance of products locally produced is split between durable or long-term applications (40%) and products and packaging for exported purposes (9%). The total quantity of products and packaging that were imported to supplement goods produced in South Africa was estimated at 404 kt which was equivalent to 22% of local manufacture.

Based on the assumptions made and described, all the short-lived products are disposed of whereas the discarded durable plastic goods equated to only 30% by weight of new durable goods. Post-consumption, 12 kt of short-lived products were disposed as direct litter which represents 0.7% of the total local plastic waste. Most of the waste was disposed of and treated via either a formal or informal waste management system. The data suggests that of the plastic entering the end-of-life stage, 22% was treated via compliant landfills and 29% via non-compliant or deficient landfills with the balance through self-help disposal or collected for recycling. In 2018, a net quantity of 363 kt of plastic waste was collected, sorted, and sent to

recycling. This excludes the flow of sorting and processing waste that emerged from the recycling process and was returned for disposal (depicted on the diagram as 110 kt).

#### 4.1.1.2. Circularity Metrics and Selected Mass-Based Indicators

Circularity indicators are necessary to assess the current status as well as monitor the progress of strategies. Furthermore, they also aid in the identification of measurement gaps. As the scope of this study was set at a macro (national) level, a set of circularity indices representative of the resources and waste sector was developed. These were calculated according to the definitions presented in Table 5. Additionally, significant production and consumption flows were included to assess the performance of scenarios from a material perspective. The results for the Reference case are presented in Table 17 .

**Table 17: Flow and Circularity Indicators based on MFA for Reference Case (2018)**

<b>Mass-based Indicators (kt)</b>	
Virgin Polymer	1 544
Recyclate	332
Domestic Production	1 876
Plastic Use	2 108
Total Local Waste	1 831
Leakage	342
<b>Circularity Indicators (%)</b>	
Collection Rate	26.0
Input Recycling Rate	40.3
Output Recycling Rate	30.9
Recycled Content	17.7

The results from the MFA indicate that just over 1 800 kt of plastic products were locally manufactured in 2018. They were made from feedstocks including 82.3% virgin polymer (local and imported resin) as well as 17.7% recyclate, mostly obtained from local recycling activities. In terms of local consumption, just over two thousand kilotons of plastic products were consumed. This is equivalent to a per capita plastic consumption of 36 kg/capita/year which is significantly lower than the plastic footprint of citizens in the European Union at 84-129 kg per capita per year (Amadei et al., 2022).

The total annual plastic waste generated for 2018 was 1 831 kt or 32 kg/capita/year; of which 1 174 kt was short-lived waste and 645 kt from durable applications. From the generated waste, 363 kt per annum of plastic was collected for recycling – this represents an ‘input recycling rate’ of 40.3 %. This is comparable to the EU 28 + 2’s (European Union countries plus Norway and Switzerland) packaging recycling rate of 42% (Plastics Europe, 2019).

Plastic pollution arises primarily due to waste that is littered, uncollected and disposed of in open dumps, or collected and disposed of in non-compliant landfills. On the other hand, disposal in sanitary landfills partially prevents plastic leakage. In 2018, there was an estimated total of 342 kt of plastic leaked into the environment. This represents 18.7% of the plastic that reached the end-of-life stage with a leakage rate per capita of 6 kg/year. This is in the same order of magnitude as other developing countries such as Vietnam and Thailand with leakage rates of 4.7 and 4.8 kg/capita/year respectively, although these figures pertain to marine plastic leakage only (International Union for Conservation of Nature and Natural Resources, 2021).

#### 4.1.1.3. Comparison with Related Local Studies

Due to the complex nature of the local plastics system, there are several mass balance models that have been constructed for the period 2015-2020. The key results of these studies have been extracted and compared to the findings from this study.

The initial MFA model for 2015 published by the Department of Environmental Affairs highlighted high uncertainty pertaining to the indirect plastic imports flow as well as the quantity of unrecovered plastics (Department of Environmental Affairs, 2017). From the calculated three scenarios, the median scenario was proposed to be the most accurate. This yielded a plastic recovery rate (calculated as recovered plastic divided by total plastic consumption, with plastic consumption calculated as virgin polymer conversion plus imports less exports) of 15% and plastic consumption of 34 kg/capita/year. The plastic recovery rate appears to be similar to this study’s findings for recycled content (18.8%) although the denominator of total plastic consumption excludes conversion of recyclate. Furthermore, the figures for annual domestic consumption per capita is comparable (36 vs 34 kg/capita/year).

Another mass balance model was developed illustrating material flows for plastics in 2017 (Blottnitz et al., 2018). The difference in key flows was that 50% of the plastics annually produced for long-lived purposes was assumed to remain in the economy as stock, whereas this study used a calculated value of 30%. This results in a higher value of total plastic waste that is

not recycled and is disposed of via landfill, self-help disposal, and littering i.e. 1 469 vs 1 201 kt. The expansion of this methodology for 2018 (Goga et al., 2022) indicated that most of the waste that is locally generated is discarded via self-help disposal as well as via the landfill system which correlates with the findings of this study. A second version of a material flow diagram for 2017 was published recently. Although it was acknowledged that total input does not tally with total output, the modelling showed that 32 kg/capita of primary plastic was consumed, and 40 kg/capita of plastic waste was generated (Kunle Ibukun Olatayo et al., 2021). This is comparable to the findings noted in Section 4.1.1.2 although the numbers for per capita plastics use is higher than plastics waste due to accumulation of durable plastics within the system.

The study conducted by the International Union for Conservation of Nature and Natural Resources (IUCN), which modelled the country's plastic material flows for 2018, used an expanded definition of plastics, including synthetic textiles. It was estimated that South Africa generates approximately 2 371 kt or 41 kg/cap/year of waste which is above the global average of 29 kg/cap/year (IUCN-EA-QUANTIS, 2020). This is substantially higher than the 32 kg/cap/year calculated from this study. The results for collection rate also vary significantly (70% vs 26%) as the stated definition for material collected includes everything that is collected for recycling, 'properly' and 'improperly' disposed whereas this study only considered the former. The leakage rate of 1.4 kg/capita was substantially lower than this study's findings of 6 kg/capita which can be attributed to the limited scope of marine plastic leakage.

The focus of the system model generated for 2020 by the CSIR was on post-use and waste management. Due to the COVID-19 lockdown and associated changes in consumption, the model generated for 2020 showed a low total of 1 546 kt for plastic waste generated (Stafford et al., 2022). The resulting collection rate of 22% is comparable although the recycling rate of 19% is based on total plastic waste rather than short-lived waste. At 488 kt, the study's leakage rate is 43% higher due to differences in the modelling of managed and mismanaged waste.

#### **4.1.2. Life Cycle Assessment (LCA)**

According to Section 3.3.2.3, the impact assessment method selected was the ReCiPe 2016 method. As the selection of a method should be consistent with the goal and scope of the study, this method was chosen due to the global nature of the imported polymer and products supply chain which was included in the scope of the research. The selected method has been developed

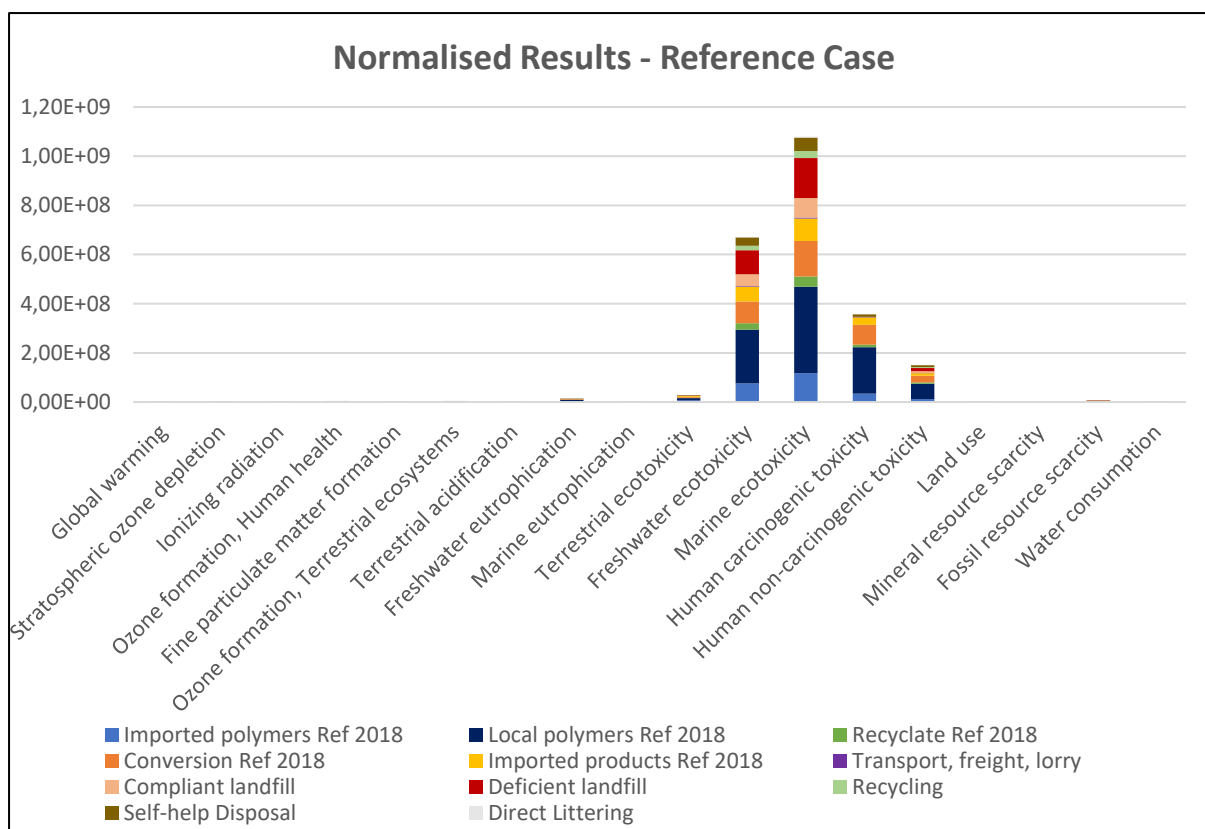
to the midpoint and endpoint level and contains 18 mid-point indicators and three end-point indicators of damage.

The value of an LCA lies in the ability of the tool to highlight areas of significant potential impact (known as hotspots) as well as identify trade-offs between various categories. According to a report published by UNEP/SETAC, the benefits of a hotspot analysis include ensuring that the focus is on the most significant contributors so that the relevant stakeholders can effectively dedicate resources to evaluate and implement solutions (UNEP and SETAC, 2017). A hotspot can be identified at several levels of granularity viz. impact category, life cycle stage, process or at the level of elementary flow.

Early results derived from the MFA constructed for 2015 (Goga et al., 2023) as well as the MFA developed for 2018 (Goga et al., 2022) were published on a single-indicator basis by focusing on the release of greenhouse gas emissions. The LCA results derived and presented in this thesis expand on the full range of indicators from both a midpoint and endpoint perspective.

#### 4.1.2.1. Analysis of Normalised Results

To aid interpretation, the optional step of normalisation was applied to characterised results to support the identification of the most significant impact categories. This also ensures that the focus is maintained on priority issues such as water, waste, or certain materials of concern. The impact assessment methods available in SimaPro, specifically ReCiPe, provide normalised scores for mid-point impact categories with the possibility to calculate endpoint damage categories by aggregating normalised midpoint scores. The results of the life cycle after application of normalisation factors are presented in Figure 14.

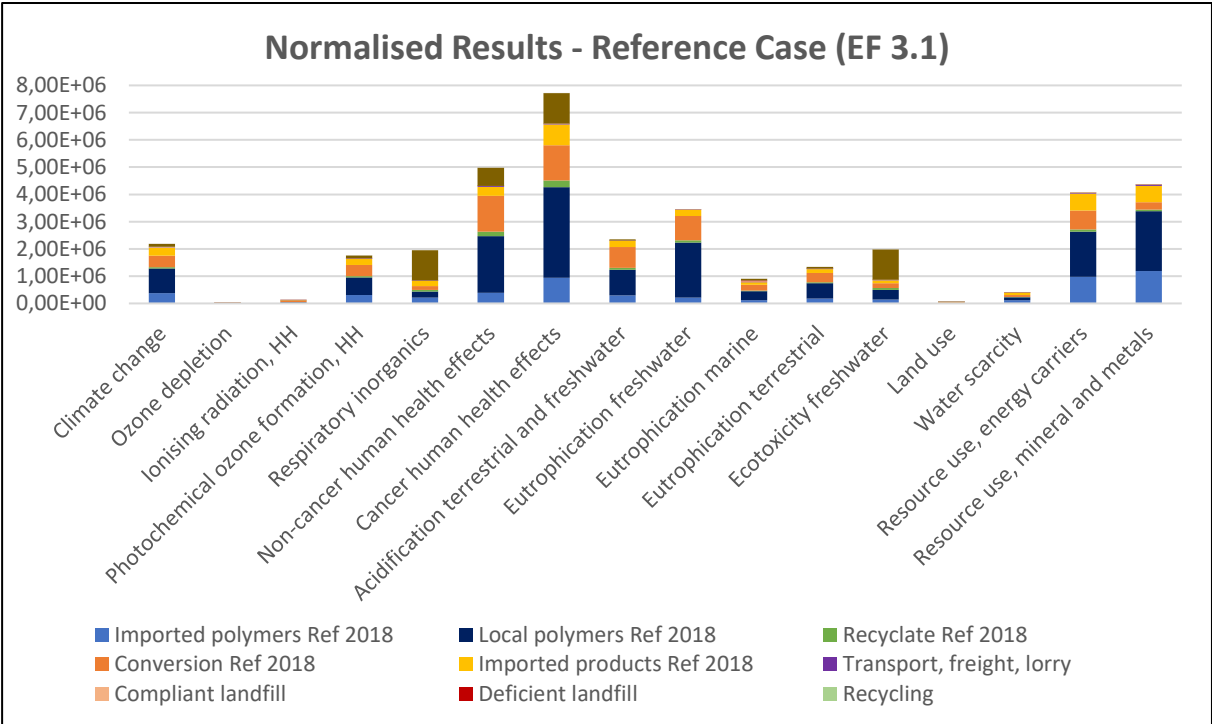


**Figure 14: LCA Normalised Results for Reference Case for 2018**

The normalised scores for ReCiPe represent the environmental impact per category for the product system divided by the relative units emitted per global citizen in 2010 (Dutch National Institute for Public Health and the Environment, 2020). The results presented in Figure 14 show that the most significant impact categories in descending order are ecotoxicity (marine and freshwater) followed by human toxicity (carcinogenic and non-carcinogenic). The least significant categories are identified as mineral resource scarcity and land use. In terms of contribution per life cycle stage, the polymer production stage has the largest influence across all categories. This is due to the CtL method of monomer production employed locally. For the end-of-life stage, the waste treatment method of landfill via a non-compliant site has a visible contribution towards both categories of ecotoxicity.

Studies have indicated that after conversion to a common scale of measurement, discrepancies in impact scores between different impact assessment methods can be large for impacts related to toxicity (Dong et al., 2021; Owsianiak et al., 2014). Furthermore, it can be observed that LCA results in certain cases with a shorter time horizon are dominated by toxicity-related

impacts (Zampori et al., 2016). Therefore, as an additional layer of analysis, a sensitivity analysis was performed by using an alternative method. The Environmental Footprint 3.1 method was utilised to test the robustness and correlation between results. It is acknowledged that although the normalisation factors for some categories are similar (e.g. global warming/climate change), each method contains its own normalisation factors. The findings of the additional analysis are presented in Figure 15.



**Figure 15: LCA Normalised Results Using EF 3.1 for Reference Case for 2018**

The normalised results based on the EF 3.1 method indicate that the most significant categories are human toxicity, resource use, freshwater eutrophication, and climate change. The contribution analysis shows that although polymer production has the highest contribution, self-help disposal rather than deficient landfill dominates the end-of-life stage. Based on these results, the initial normalisation results were unpacked further to pinpoint which categories are overshadowed by the significantly high toxicity categories. Therefore, a supplementary graph was produced using the ReCiPe method with the same vertical axis as Figure 15. The additional plot is mapped in Figure 16.

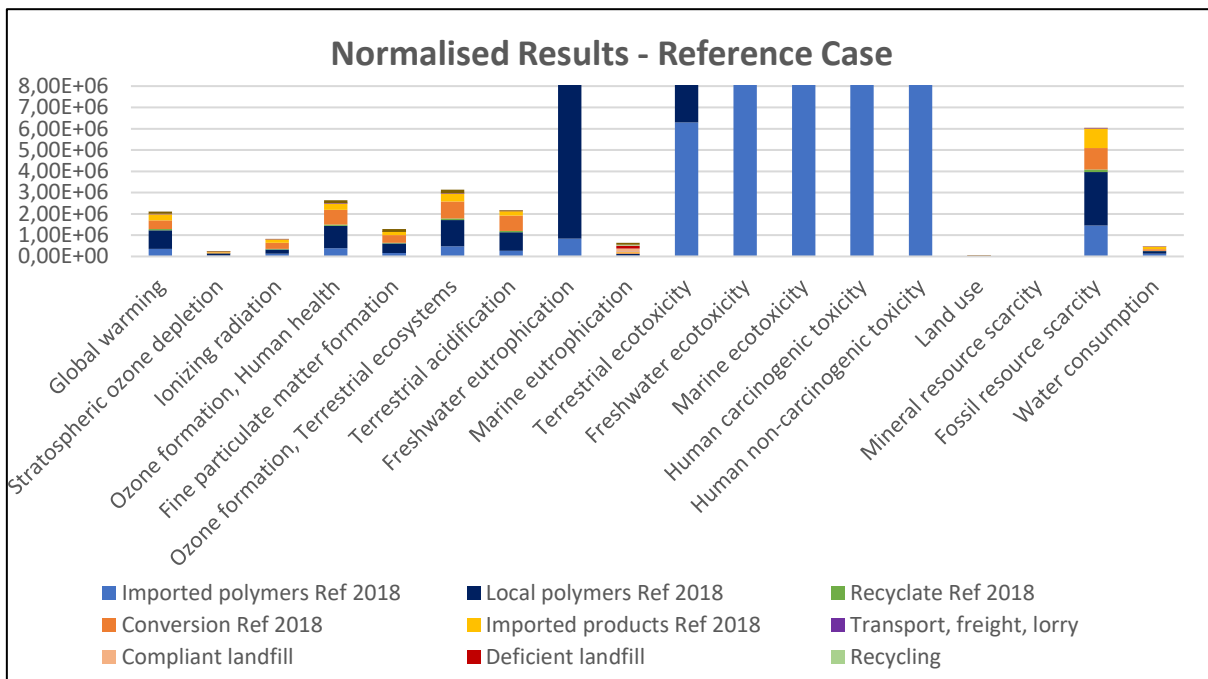


Figure 16: LCA Normalised Results for Reference Case (Alternative Axis)

The graph above shows that other than the dominant toxicity results, other categories that have a significant impact and are in a similar range to the results in Figure 15 include freshwater eutrophication, fossil resource scarcity, and climate change. This confirms that other than for the toxicity indicators, the initial results produced using ReCiPe are in a comparable range to results produced by the EF impact assessment method. Therefore, the key normalised results for all other scenarios are presented in terms of the ReCiPe method.

#### 4.1.2.2. Contribution Analysis

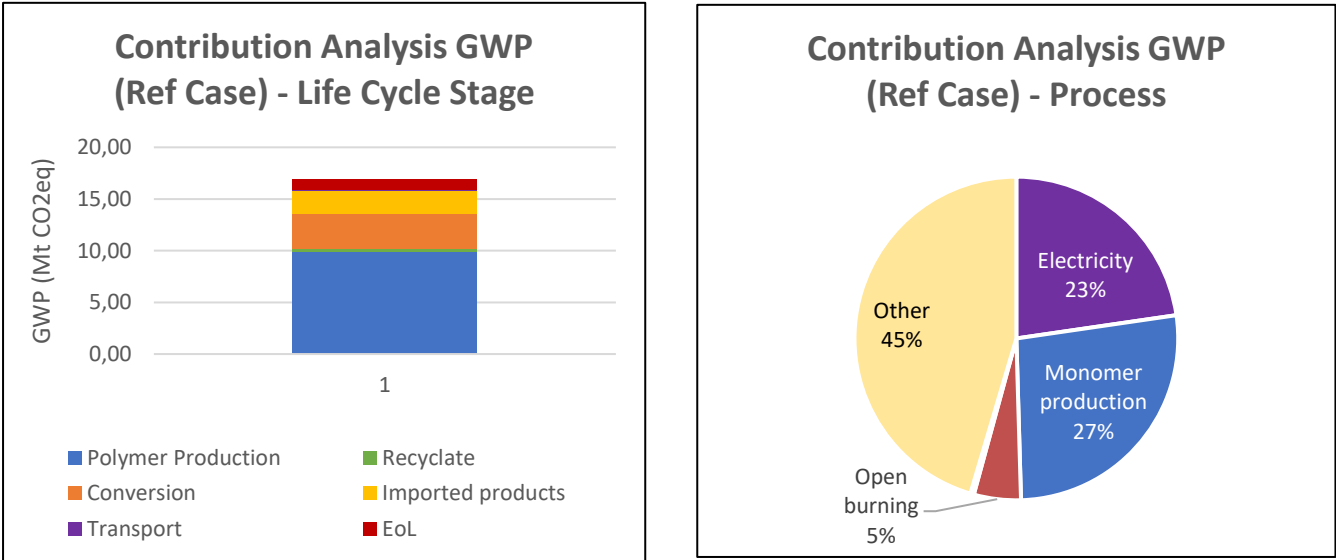
In addition to the normalised results presented above, a contribution analysis is performed at the level of indicators. To assist in improved interpretation of results and aid transparency, a combination of midpoint and endpoint indicators were analysed. This is due to the acknowledgement that although mid-point indicators remain useful in the identification of reduction targets for specific environmental concerns, end-point assessment is required for effective and sound decision-making support (Kägi et al., 2016).

For the analysis of results from the two perspectives, it was decided to analyse results further along the environmental mechanism by looking at the three Areas of Protection. These endpoint indicators also incorporate all midpoint indicators including those that were highlighted as

impacts of concern in the normalised results. These range from terrestrial, freshwater, and marine ecotoxicity to global warming and freshwater eutrophication. As the normalisation results indicated that the most significant impact categories revolved around toxicity and ecotoxicity, the ecosystem damage category was expanded.

**Global Warming Potential**

The results for climate change are presented in Figure 17 (a and b) below.



**Figure 17: Contribution Analysis of Global Warming Potential (Reference) at the Level of a. Life Cycle Stage and b. Process**

The figures above show two different levels of analysis. The figure on the left refers to a breakdown of total climate change impact per life cycle stage while the figure on the right shows a further characterisation per major contributors at the level of processes. Only the highest three individual contributors are shown as the ‘other’ category encompasses inventory-level processes with a contribution of less than 5% each.

From Figure 17a, the results indicate that the polymer production stage is responsible for 58% of the total impacts. This is primarily due to the production of local polymers which are derived as a result of the CTL process. Other than CTL generating a significant quantity of emissions, it has been found that it is seven times more energy-intensive compared to a traditional crude refining process (Majozi and Veldhuizen, 2015). In addition to local polymer production, conversion also has a significant contribution (20%). The source of these emissions can be traced to the coal-dominated energy mix in South Africa. The EoL stage comprises the least

impacts from a climate change lens at 0.98 MtCO<sub>2</sub>eq. In total, the local life cycle GHG emissions for the local plastics sector in 2018 amounted to 16.7 MtCO<sub>2</sub>eq or 3.9% of the country’s overall carbon footprint for that year. This is 6.7% lower than the results presented in Goga et al. (2022), which can be attributed to the differences in perspectives specifically consumption versus production that led to the exclusion of the exported products stream for this thesis.

An analysis of the carbon footprint from a process perspective as per Figure 17b reveals that the production of monomers namely propylene and ethylene is responsible for just under a third of the total emissions. The process that has the second highest contribution is the use of electricity (23%) due its associated burdens stemming from the local energy mix. The waste treatment process that has the highest impact is self-help disposal which is primarily attributed to the incidence of open burning.

A comparison of a global analysis indicates that conventional plastics emitted 1.8 Gt CO<sub>2</sub>eq or 3.8% of the world's annual emissions for 2015 (Zheng and Suh, 2019). This is comparable to the results cited above. It was found that the resin contribution stage also generated the majority of emissions with the percentage contribution in the same order of magnitude (58% versus 61%). Furthermore, at 9% of the total emissions, the EoL stage also had the smallest contribution although incineration was listed as the most dominant waste treatment process.

### Endpoint Analysis

The endpoint category results are presented in the form of a heat map depicted in Table 18.

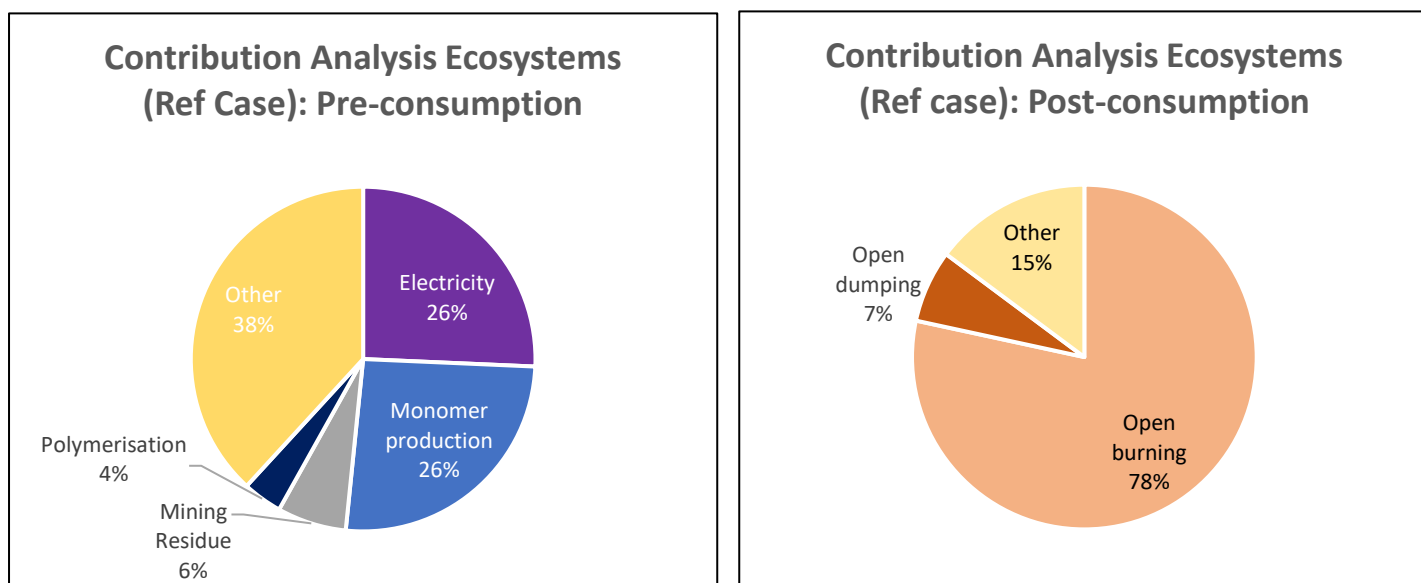
**Table 18: LCA Endpoint Results for Reference Case for 2018**

Damage Category	Unit	Virgin Polymer	Recyclate	Conversion	Imported Product	Transport	End-of-Life
		Production					
Human health	DALY	2.4 x 10 <sup>4</sup>	1.2 x 10 <sup>3</sup>	1.1 x 10 <sup>4</sup>	5.2 x 10 <sup>3</sup>	2.3 x 10 <sup>2</sup>	4.2 x 10 <sup>3</sup>
Ecosystems	species.yr	4.8 x 10 <sup>1</sup>	2.1 x 10 <sup>0</sup>	2.0 x 10 <sup>1</sup>	1.0 x 10 <sup>1</sup>	5.4 x 10 <sup>-1</sup>	3.6 x 10 <sup>0</sup>
Resources	USD2013	9.0 x 10 <sup>8</sup>	1.9 x 10 <sup>7</sup>	1.1 x 10 <sup>8</sup>	3.0 x 10 <sup>8</sup>	1.1 x 10 <sup>7</sup>	1.6 x 10 <sup>6</sup>

The table above shows the breakdown of the three categories per main life cycle stage. The degrees of impact are reflected in the differing shades of colour where the darker shade indicates a more intense impact. This means that the dark red and green have the highest and lowest contribution respectively with the lighter shades indicating the next highest and lowest contribution.

The contribution analysis results are relatively consistent across the first two damage categories i.e. human health and ecosystems. For both indicators, the life cycle stages that had the highest impacts were the local virgin polymer production followed by conversion of polymer into plastic goods. The least dominant stages were transport and the production of recyclate. Although the significant life cycle stages were the same, the contribution of each life cycle stage to the total damage differed. For the human health impact, virgin polymer production contributed 52% to the overall impact whereas the contribution for ecosystems is 5% higher at 57%. For the resource depletion category, the findings differed slightly compared to the first two categories. Although the production of local polymer still has the highest contribution, the importing of products was responsible for the second highest share at 23% of the impact on resources. The stage with the lowest impact was the end-of life stage with a marginal contribution of 0.1%.

As the normalisation results indicated that the most significant impact categories revolved around toxicity and ecotoxicity, the ecosystem damage category was expanded. The results of the additional analysis around ecosystem impacts are presented in Figure 18a and b below.



**Figure 18: Contribution Analysis of Ecosystem Health (Reference Case) for a. Pre-Consumption and b. Post-Consumption**

The distribution of impacts per process level are depicted in the figures above. In the production phase, monomer production and electricity use, which are both coal-based, have the same contribution at 26%. These processes have also been highlighted in Figure 17b as the highest contributors to climate change. Spoils from hard coal mining which include waste-specific emissions from lignite spoils leachate as well as the polymerisation process have the next highest contributions at 6- and 4% respectively. Post-consumption, the specific waste treatment process with an overwhelming burden is open burning which has a contribution of over 75%. Together with open dumping, 85% of the impacts on the ecosystem for the end-of-life stage can be attributed to the self-help disposal waste management process.

A similar assessment was undertaken for the Chinese plastic sector in 2016 where ten indicators were selected to reflect four types of environmental damages using the CML-IA method (Liang et al., 2023). It was found that plastic production and plastic product manufacturing were the significant life cycle stages which correlated with the above-mentioned analysis. Similarly, coal-based processes were also found to have a substantial contribution with feedstock for polymer formation and electricity contributing to over 30% of the environmental impacts with 60% on GHG emissions and marine ecotoxicity.

### 4.1.2.3. Comparison with Related Local Studies

For the business-as-usual scenario investigated within the CSIR report (Stafford et al., 2022), it was estimated that the total GHG emissions for the local plastics sector in 2020 was estimated at 9.96 MtCO<sub>2</sub>eq. This is 40% lower compared to the results from this study which can be attributed to decreased production during that year. However, the contribution analysis produces similar results with the top three contributors to plastics-related GHG emissions listed as virgin plastic production (40%), conversion (19%), and open burning (6%). There is no other life cycle-based studies that measure impacts other than climate change across the entire plastics value chain on a national scale.

## 4.2. Baseline Scenario

### 4.2.1. Material Flow Analysis (MFA)

#### 4.2.1.1. System Map

The material balance for the baseline scenario for the local plastics sector in 2025 is illustrated in the Sankey diagram below. The MFA constructed for the Reference case was used as a basis for the Baseline scenario as it depicts a business-as-usual scenario with no interventions or mitigation measures. Furthermore, the scenario assumes that there are no changes in the country's energy mix.

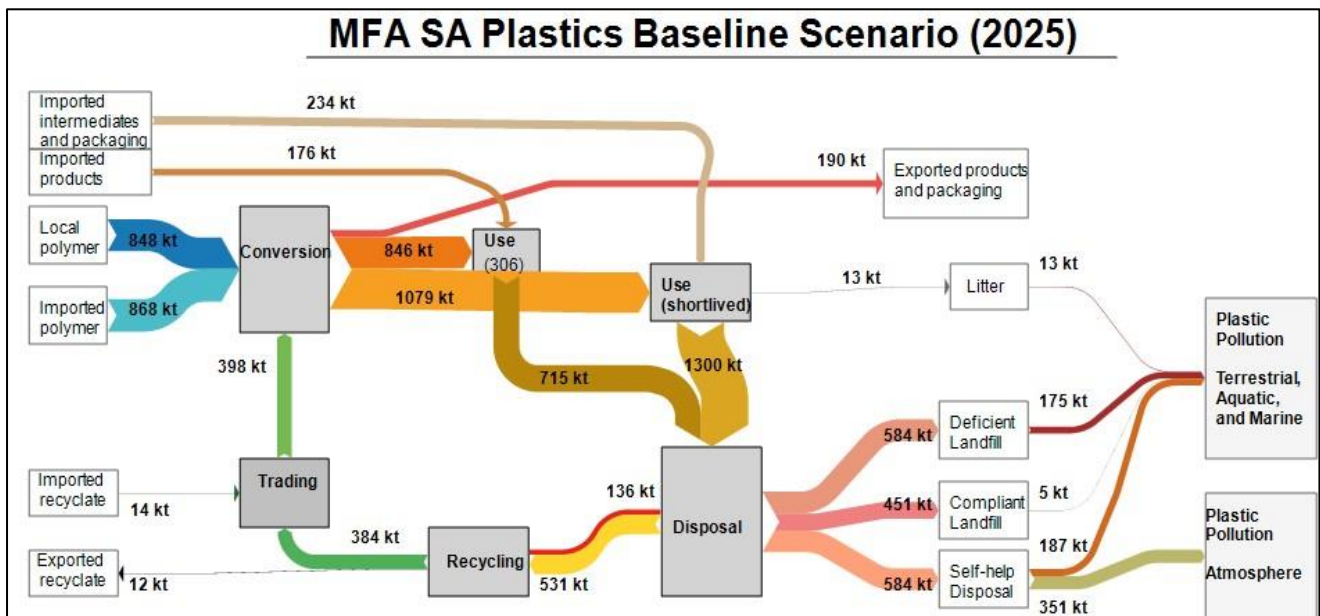


Figure 19: MFA Results for Baseline Scenario for 2025

Under this scenario, there is a projected growth in production of 1.7% annually between 2018 and 2025 due to projected population growth and increasing per capita plastics use, based on the assumptions stated in Section 3.4.1. This results in the quantity of converted goods increasing to 2 114 kt. The ratio of imported products to locally produced products changes by a minimal percentage of 2% to 0.19:0.81. On the consumption side, it is estimated that a total of 2 334 kt of plastic products will be consumed in 2025. In terms of the disposal stage, self-help disposal and deficient landfills receive equal quantities of waste with approximately 23% less plastic waste directed to compliant landfills.

4.2.1.2. Circularity Metrics and Selected Mass-Based Indicators

The results for key circularity and mass-based indicators are presented in Table 19.

**Table 19: Flow and Circularity Indicators based on MFA for Baseline Scenario**

<b>Mass-based Indicators (kt)</b>	
Virgin Polymer	1 716
Recyclate	398
Domestic Production	2 114
Plastic Use	2 334
Total Local Waste	2 028
Leakage	379
<b>Circularity Indicators (%)</b>	
Collection Rate	26.4
Input Recycling Rate	40.9
Output Recycling Rate	30.4
Recycled Content	18.8

By 2025, it is estimated that plastic use will have increased by 1 kg/capita from the 2018 values, with a total of 2 334 kt of plastic used annually. This will lead to 2 028 kt of waste being generated domestically – an increase of 11% from 2018. The amount of plastic waste collected for recycling is 531 kt or 26.4%. For the Baseline scenario, the percentage of recyclate in the converted product will increase marginally from 17.7% in 2018 to 18.8% in 2025. Furthermore, an increase of 11% in leakage is projected from 2018 to 2025 if there are no effective policy

interventions or measures. The quantity of plastic leaked is also expected to be in the range of the amount of recyclate available as feedstock for new products.

4.2.1.3. Comparison with Related Local Studies

As this a short-term projected outlook for comparison with the alternative scenarios, there are no comparative studies available for the local context. This also reinforces the novelty of the research.

4.2.2. *Life Cycle Assessment (LCA)*

4.2.2.1. Analysis of Normalised Results

The results of applying the material flow to the life cycle model for the Baseline scenario and running the assessment with the addition of normalisation are presented in Figure 20.

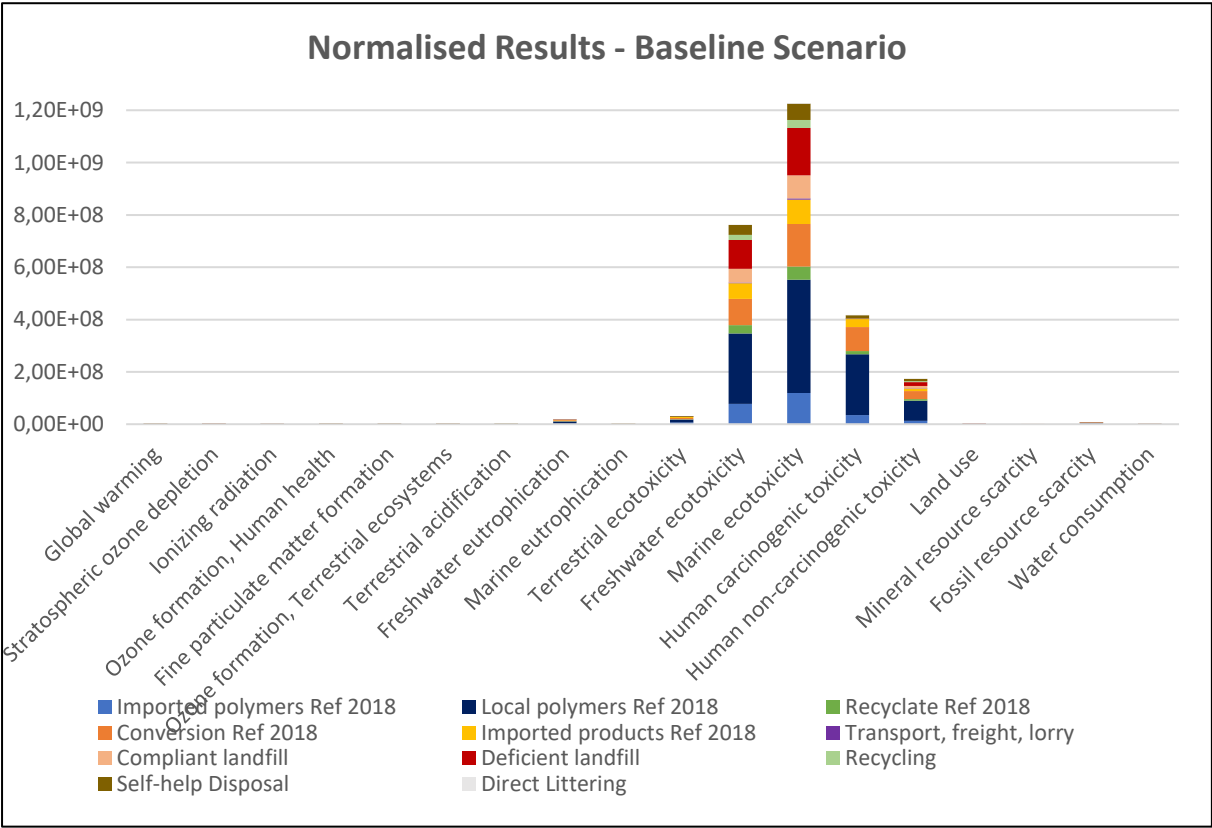


Figure 20: LCA Normalised Results for Baseline Scenario for 2025

According to the plot, the major impacts of the projected scenario center around human toxicity and ecotoxicity. The other significant categories that are in the range of  $3 \times 10^6 - 3 \times 10^7$  include ozone formation, fossil resource scarcity, and freshwater eutrophication. The degree of impact has increased between 10- and 18% from 2018 to 2025 and illustrates the outcome if no

alternative strategies are implemented. As per the assessment for the Reference case, the polymer production process, which is depicted in shades of blue, has a substantial proportion of the total impact at just over 50%. Post-consumption, the waste treatment option that features conspicuously for marine eutrophication and ecotoxicity is disposal via deficient landfill which has an average contribution of 16% over these categories while self-help disposal has a share of approximately 11% of fine particulate matter formation and marine eutrophication.

4.2.2.2. Contribution Analysis

Global Warming Potential

In terms of individual midpoints, the findings for climate change are presented in the form of a bar and pie graph as in Figure 21 (a and b).

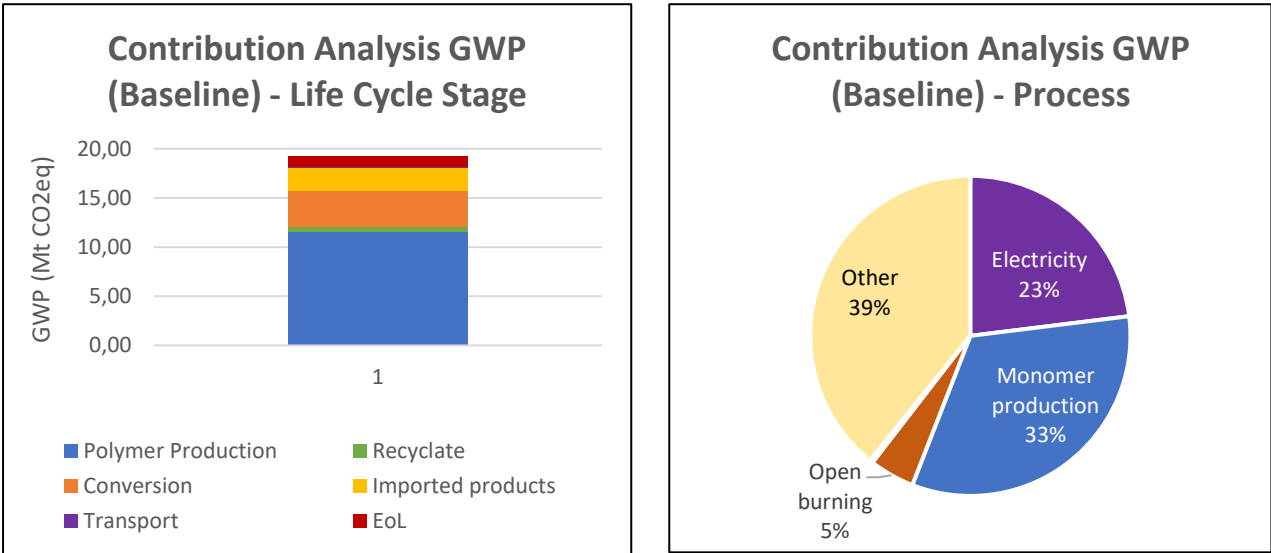


Figure 21: Contribution Analysis of Global Warming Potential (Baseline) at the Level of a. Life Cycle Stage and b. Process

The analysis reveals that total GHG emissions would increase by 14% from 2018 to 2025. The breakdown of the LCA results per stage shows that the majority of emissions are concentrated in the upstream processes prior to consumption. The hotspot analysis also highlights the specific impact of the local polymer production process as well as the coal-dominated national energy mix. Although self-help disposal via the occurrence of open burning contributes only 5%, it is responsible for the highest GHG emissions amongst the formal and informal management options.

## Endpoint Analysis

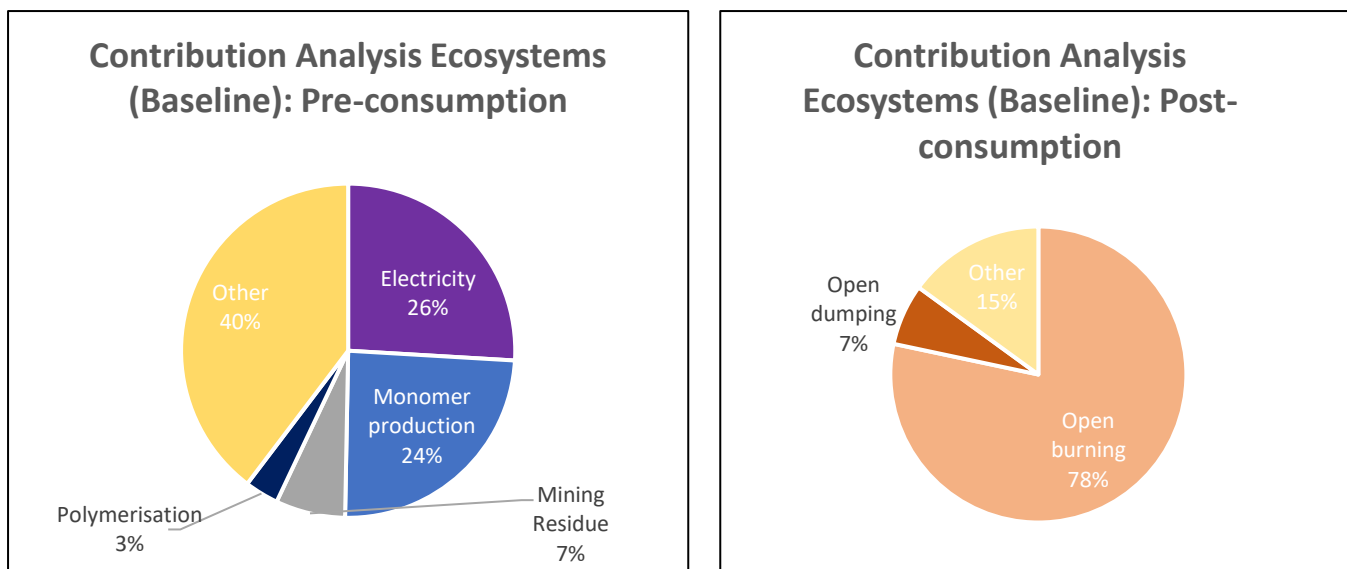
The results for the endpoint analysis for the Baseline scenario are presented in Table 20.

**Table 20: LCA Endpoint Results for Baseline Scenario for 2025**

<b>Damage Category</b>	<b>Unit</b>	<b>Virgin Polymer Production</b>	<b>Recyclate</b>	<b>Conversion</b>	<b>Imported Product</b>	<b>Transport</b>	<b>End-of-Life</b>
Human health	DALY	2,8 x 10 <sup>4</sup>	1,5 x 10 <sup>3</sup>	1,2 x 10 <sup>4</sup>	5,2 x 10 <sup>3</sup>	2,5 x 10 <sup>2</sup>	4,7 x 10 <sup>3</sup>
Ecosystems	species.yr	5.6 x 10 <sup>1</sup>	2,5 x 10 <sup>0</sup>	2.3 x 10 <sup>1</sup>	1.0 x 10 <sup>1</sup>	5.9 x 10 <sup>-1</sup>	4.0 x 10 <sup>0</sup>
Resources	USD2013	9,9 x 10 <sup>8</sup>	2,3 x 10 <sup>7</sup>	1,3 x 10 <sup>8</sup>	3,1 x 10 <sup>8</sup>	1,2 x 10 <sup>7</sup>	1,8 x 10 <sup>6</sup>

The tabulated results show that the damage indicators increase by an average of 12% compared to the results for 2018, with impacts on human and ecosystem health increasing by 14% each and the effect of resource depletion rising by 9%. The contribution analysis remains the same as for the Reference case for all damage indicators. Additionally, results using both midpoint and endpoint analysis reveal that the virgin polymer production process is the dominant stage. Transport between stages as well as the production processes associated with the manufacturing of recyclate have the lowest burdens for the ecosystem and human health impacts while the end-of-life stage has the smallest contribution (0.1%) to the impact on resources.

As per the rationale provided in Section 4.1.2.2, a contribution analysis is applied to the ecosystem damage indicator as shown in Figure 22 a and b.



**Figure 22: Contribution Analysis of Ecosystem Health (Baseline) a. Pre-Consumption and b. Post-Consumption**

In terms of process-level impact on ecosystem health, significant contributors remain the same as for 2018. Electricity production for use is still the highest individual contributor at 26% with the contribution from monomer production dropped by 2%. The significant contributors from sub-processes at midpoint and endpoint level (specifically for GWP and ecosystem health) are similar. For the EoL stage, the breakdown still shows self-help disposal as the waste management process with the highest impact with open burning having the greatest individual contribution.

#### 4.2.2.3. Comparison with Related Local Studies

As stated in Section 4.2.1.3, this a short-term forecast for comparison with the alternative scenarios. Thus, there are no comparative studies available for the local context at this timeline.

### 4.3. Increased Recycling Scenario

#### 4.3.1. *Material Flow Analysis (MFA)*

##### 4.3.1.1. System Map

The results of the MFA constructed for the Increased Recycling scenario are depicted in Figure 23. This model incorporates the recycling targets for plastic packaging set by the South African Plastics Pact for implementation by 2025.

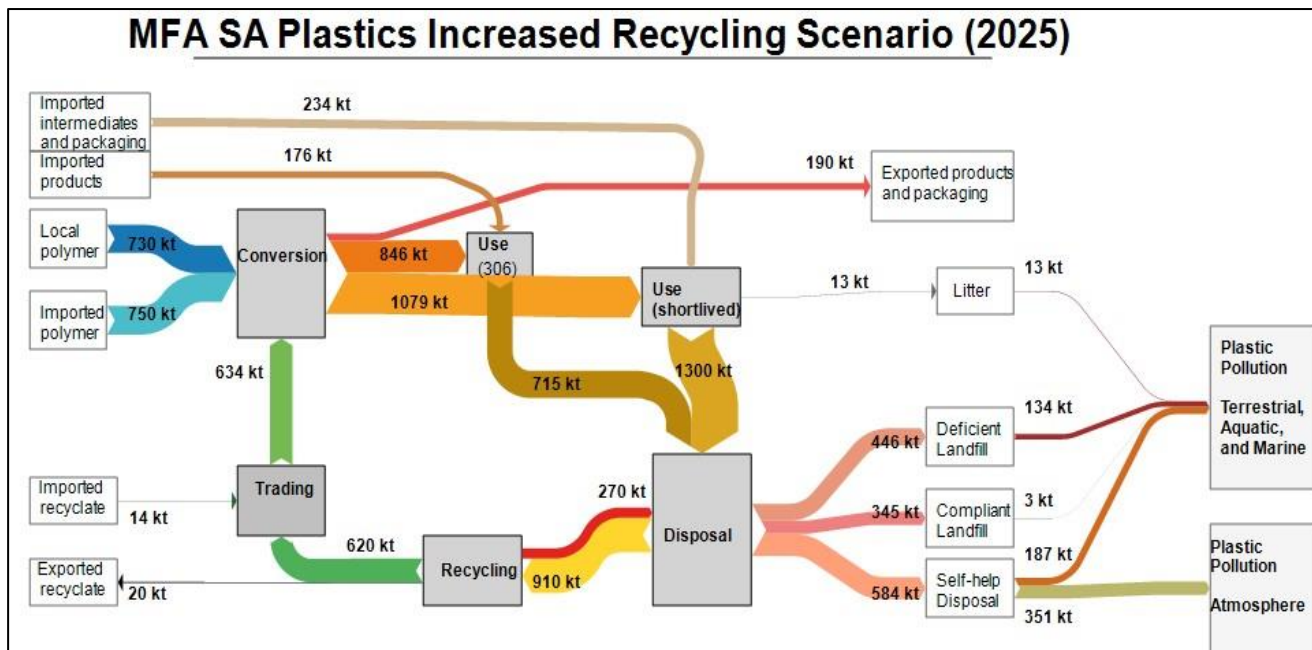


Figure 23: MFA Results for Increased Recycling Scenario for 2025

The Sankey diagram shows that the quantity of plastics produced locally as well as the imports of finished goods are consistent with the Baseline scenario. Due to the incorporation of the recycling targets, plastics collected for recycling would increase by 71%. The quantity of plastics that are not recycled decreased by 15% compared to the Baseline scenario with 791 kt being landfilled and 584 kt being improperly disposed and subjected to open burning and dumping.

#### 4.3.1.2. Circularity Metrics and Selected Mass-Based Indicators

A summary of key results in terms of inventory flows and circularity indicators for the Increased Recycling scenario is presented in Table 21.

**Table 21: Flow and Circularity Indicators based on MFA for Increased Recycling Scenario**

<b>Mass-based Indicators (kt)</b>	
Virgin Polymer	1 480
Recyclate	634
Domestic Production	2 114
Plastic Use	2 334
Total Local Waste	2 028
Leakage	337
<b>Circularity Indicators (%)</b>	
Collection Rate	45.2
Input Recycling Rate	70.0
Output Recycling Rate	49.2
Recycled Content	30.0

The table above indicates that for the Increased Recycling scenario, there is no change in the amount of plastics used or waste generated. However, the increase in the amount of material being collected for recycling, and consequently, the recycling rate, has an impact on the ratio of recycled plastics to virgin material. This impact is emphasised by a 59% increase in the quantity of recyclate compared to the Baseline scenario which is equivalent to a year-on-year increase of 8.4%. This would lead to the subsequent decrease in virgin polymer, with both imported and local polymer decreasing by 14% over the seven-year period. As there is more waste being recycled rather than disposed of, the amount of plastic leaked has decreased by 11% in contrast to the Baseline scenario.

A study with a similar scope was undertaken for Thailand where an alternative scenario mapping increased waste collection and sanitary landfill according to targets set by the country's national waste management plan for 2020 (Bureecam et al., 2018). It was predicted that by increasing the waste collection rate by 40% and sanitary landfill rate by 40% compared to 2011 rates, the ratio of waste directed to sanitary landfill to total plastic consumption would be 31.9%. Upon reworking the numbers presented in Table 21, it was found that the percentage of waste sent to sanitary landfills as a function of overall use was 17% lower than the Thailand MFA. This can be attributed to the fact that there are no published targets for disposal to

compliant landfills in the South African waste sector. However, the ratio of material leaked in the open environment to plastic use was in the same range (14% vs 9.5%).

4.3.1.3. Comparison with Related Local Studies

One of the scenarios that was modelled in the local MFA-related study was the implementation of five-year EPR targets for plastic packaging (Stafford et al., 2022). It was found that the targets increased what was termed “the plastics recycling rate” from 19- to 35% during the period 2023-2028. In terms of recycled content, the numbers are comparable (35% in 2028 vs 30% in 2025). Furthermore, there was no basis for comparison of leakage as a short-term calculation for leakage was not undertaken.

4.3.2. *Life Cycle Assessment (LCA)*

4.3.2.1. Analysis of Normalised Results

The results of analysing the LCA model after the application of normalisation factors are presented in Figure 24.

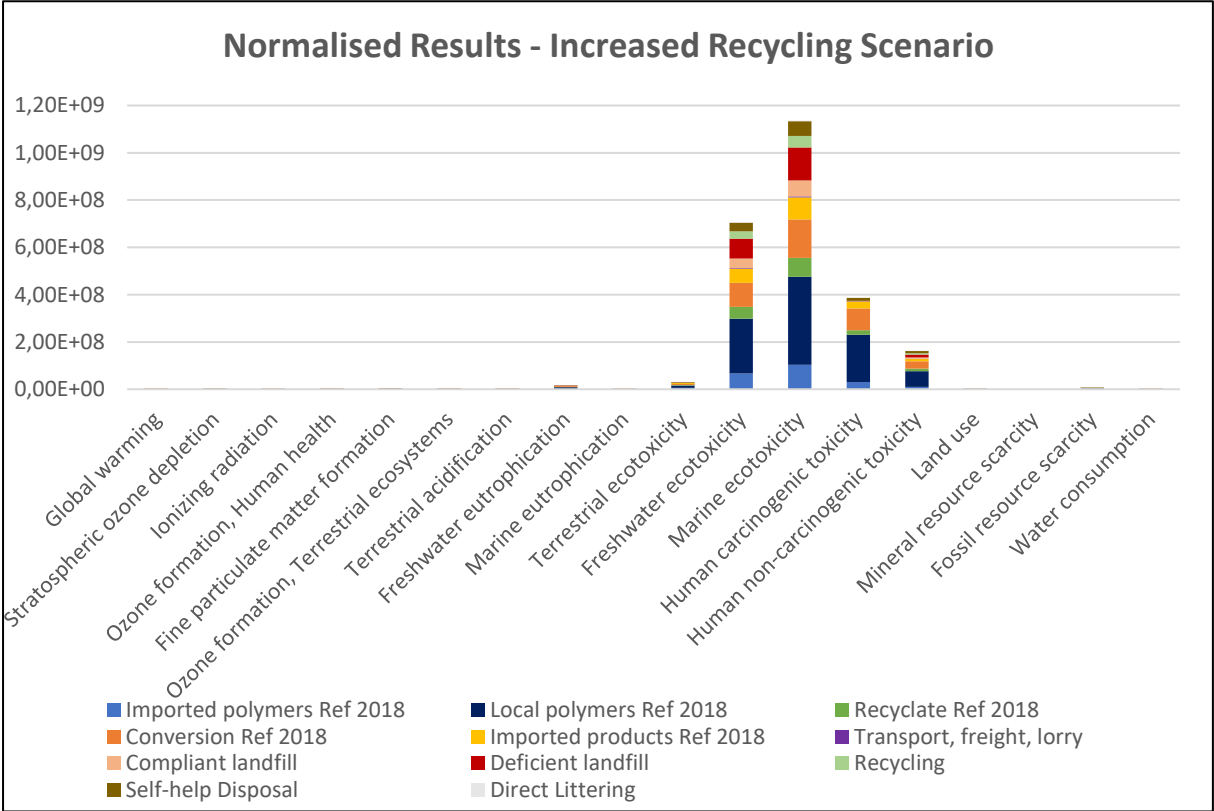


Figure 24: LCA Normalised Results for Increased Recycling Scenario for 2025

The normalisation results indicate that the degree of environmental impact has decreased by 4-10% across all impacts compared to the Baseline scenario. This correlates well with the LCA conducted for the Austrian plastic waste management system where for ten of the sixteen impact categories, the overall benefit increases as more material is mechanically recycled (Van Eygen et al., 2018). Besides the ecotoxicity and human toxicity impacts that are significant by their visibility in the plot, other categories that have a totalised normalised score in the range of  $6 \times 10^6 - 3 \times 10^7$  are fossil resource depletion and freshwater eutrophication. Although the polymer production stage is still a significant contributor, its percentage of the total impact has decreased by 7-28%. Furthermore, conversion has a non-trivial average contribution of 22% across all categories. Amongst the waste treatment options modelled, the deficient landfill and self-help disposal processes have the most substantial contributions, particularly for impacts such as marine eutrophication and ecotoxicity.

4.3.2.2. Contribution Analysis

Global Warming Potential

The findings for climate change at the level of life cycle stage and process are graphically depicted in Figure 25 a and b respectively.

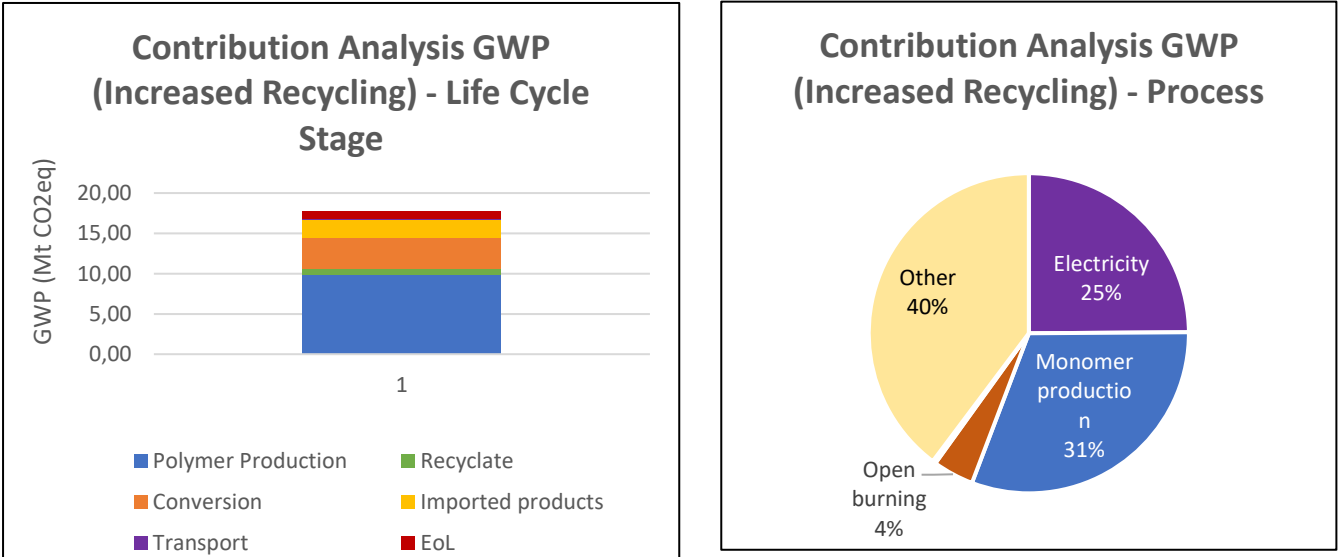


Figure 25: Contribution Analysis of Global Warming Potential (Increased Recycling) at the Level of a. Life Cycle Stage and b. Process

Overall, total GHG emissions from the entire life cycle decreased by 7% relative to the Baseline case. This can be partially attributed to the reduction in emissions for the monomer and polymer

production stage from 11.5 to 9.9 kt compared to the original scenario depicting the projected status quo. Although the increased recycling offers the benefit of directing waste away from landfills and non-compliant disposal methods, the processing of recycling material (via sorting, shredding, washing, and cleaning etc) requires energy. Thus, as the amount of recycle increases, the associated impacts increase by 60% relative to the Baseline scenario. The contribution analysis at the process level (Figure 25b) mimics the analysis at the point of the life cycle with a 2% reduction in the contribution of the monomer production stage. As there is less waste treated by self-help disposal methods, the share of emissions due to open burning decreases by 1% compared to the Baseline analysis.

### Endpoint Analysis

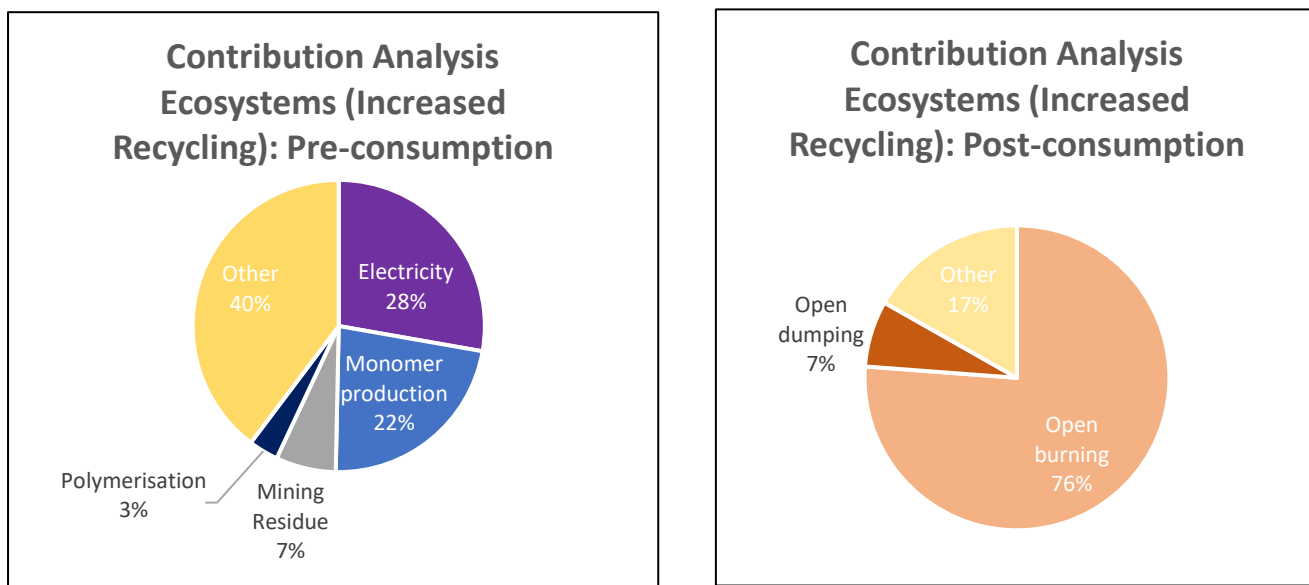
The results of the analysis in terms of the three damage categories are presented in Table 22 below.

Table 22: LCA Endpoint Results for Increased Recycling Scenario for 2025

Damage Category	Unit	Virgin Polymer Production	Recyclate	Conversion	Imported Product	Transport	End-of-Life
Human health	DALY	$2.4 \times 10^4$	$2.3 \times 10^3$	$1.2 \times 10^4$	$5.2 \times 10^3$	$2.5 \times 10^2$	$4.5 \times 10^3$
Ecosystems	species.yr	$4.8 \times 10^1$	$4.0 \times 10^0$	$2.3 \times 10^1$	$1.0 \times 10^1$	$5.9 \times 10^{-1}$	$3.9 \times 10^0$
Resources	USD2013	$8.5 \times 10^8$	$3.7 \times 10^7$	$1.3 \times 10^8$	$3.1 \times 10^8$	$1.2 \times 10^7$	$1.7 \times 10^6$

The Increased Recycling scenario can reduce the impact on all three areas of protection by an average of 7.5% relative to the Baseline scenario, which is, in part, a result of recyclate replacing virgin plastic feedstock. In terms of a contribution analysis at the level of life cycle stage, the endpoint results mimic the normalisation findings by showing the dominance of the upstream processes i.e. the polymer production and conversion stages. The combined impact of these two stages totals 73-80% for all three damage categories. The least influential stages are transportation (1%), the production of recycled material and the end-of-life stage (~4-5% each).

An expansion of the ecosystem category leads to the pie charts as per Figure 26 (a and b).



**Figure 26: Contribution Analysis of Ecosystem Health (Increased Recycling) a. Pre-Consumption and b. Post-Consumption**

A disaggregation of results describing the impacts of the plastic product system on ecosystem health shows that significant impacts arise from electricity, monomer production, and self-help disposal by way of open burning and dumping. As per the contribution analysis for climate change, the share of impacts attributed to monomer production decreased by 2% due to increased production of recyclate. However, this increase in recycling activities also causes a 2% increase in the percentage of total ecosystem damage attributed to energy production and use.

#### 4.3.2.3. Comparison with Related Local Studies

A study for the city of Johannesburg seeking to determine the least environmentally impactful scenario of managing plastic waste in South Africa found that incorporation of mechanical recycling had a considerable benefit for impacts such as global warming, human health, and terrestrial ecosystems when compared to other treatment processes (Mazhandu et al., 2023). On a national level, although it was found that the EPR scenario discussed in Section 4.3.1.3 could avoid GHG emissions in the medium-term, no short-term forecast was formulated.

## 4.4. Demand Moderation Scenario

### 4.4.1. Material Flow Analysis (MFA)

#### 4.4.1.1. System Map

The flows of the national plastics sector upon modelling the Demand Moderation scenario are illustrated in the form of a Sankey diagram in Figure 27.

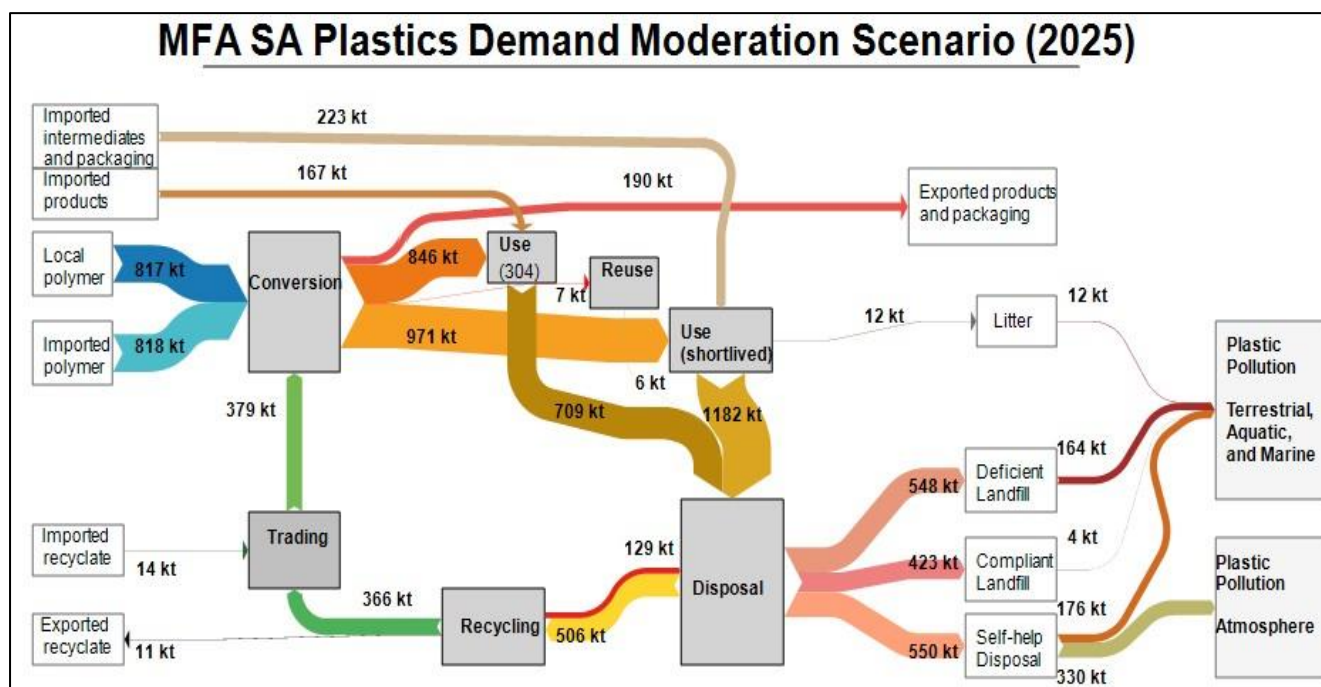


Figure 27: MFA Results for Demand Moderation Scenario for 2025

The graphical model of the Demand Moderation scenario depicts the additional consumption flow that represents the reuse of products with a service lifetime of 1-3 years. Due to this stream, the quantity of both upstream and downstream flows is impacted. As the reuse of products partially substitutes single-use or short-lived consumption, the annual production rate decreases by 100 kt from 2 114 kt to 2 014 kt. Downstream, the waste streams are also affected with 6% less reaching the disposal stage, which can be primarily attributed to the reduction in short-lived waste.

#### 4.4.1.2. Circularity Metrics and Selected Mass-Based Indicators

Based on the MFA flows, the results for selected mass and circularity indicators are presented in Table 23.

**Table 23: Flow and Circularity Indicators based on MFA for Demand Moderation Scenario**

<b>Mass-based Indicators (kt)</b>	
Virgin Polymer	1 635
Recyclate	379
Domestic Production	2 014
Plastic Use	2 214
Total Local Waste	1 910
Leakage	356
<b>Circularity Indicators (%)</b>	
Collection Rate	26.7
Input Recycling Rate	42.6
Output Recycling Rate	31.7
Recycled Content	18.8

As the total production decreases, the quantity of virgin polymer subsequently decreases by 5% when compared to the projected Baseline case. Additionally, as a portion of the short-lived use is replaced by the reuse of products, total use decreases by 2 kg/capita. The quantity of recyclate also decreases as less waste is generated and therefore less plastic material is available for collection. In terms of the circular economy indicators, specifically the recycling rates, it is assumed that reuse waste will be recycled and collected. Thus, it forms part of the denominator along with short-lived waste. The reduction in short-lived waste explains the average increase of 1.5% in recycling rates relative to the Baseline scenario. Furthermore, the generation of less waste leads to a 6% reduction in leakage to the environment.

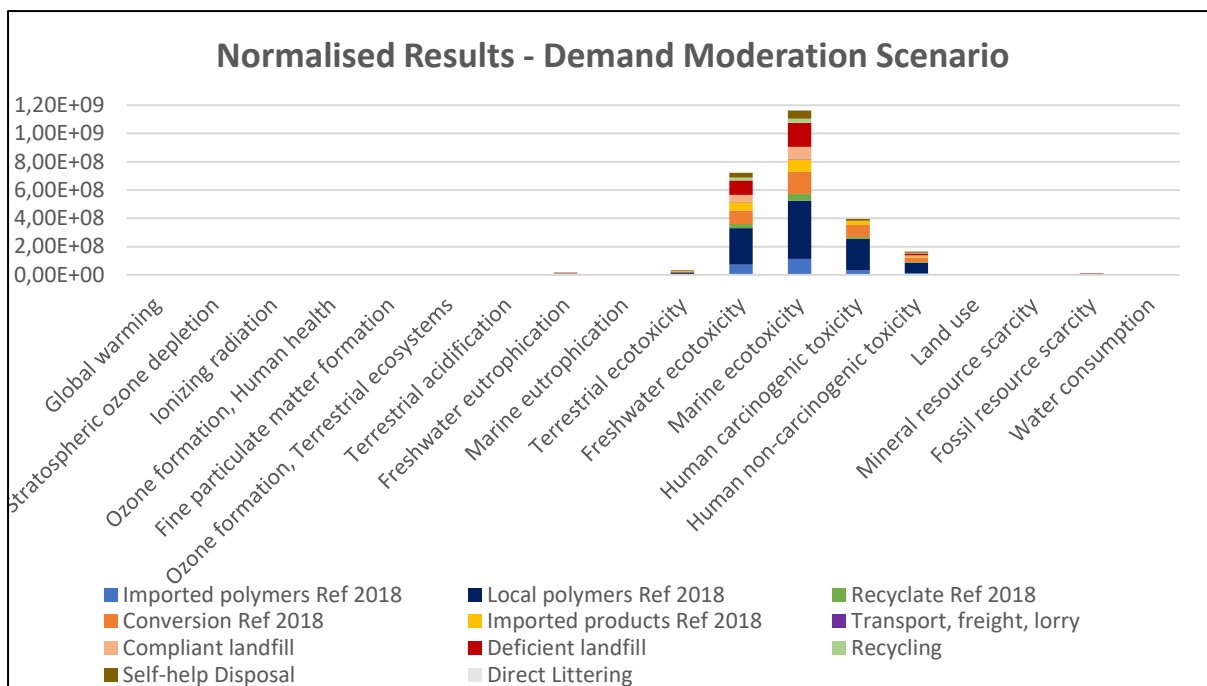
#### 4.4.1.3. Comparison with Related Local Studies

Although the reuse of plastics is considered a sub-strategy of a larger demand reduction scenario (Stafford et al., 2022), the net benefits in terms of material-based indicators have not been evaluated in the short-term. The quantitative modelling of reuse as an intervention has rarely been attempted in MFA studies to date.

### **4.4.2. *Life Cycle Assessment (LCA)***

#### 4.4.2.1. Analysis of Normalised Results

The normalised LCA results of this scenario are presented in Figure 28 below.



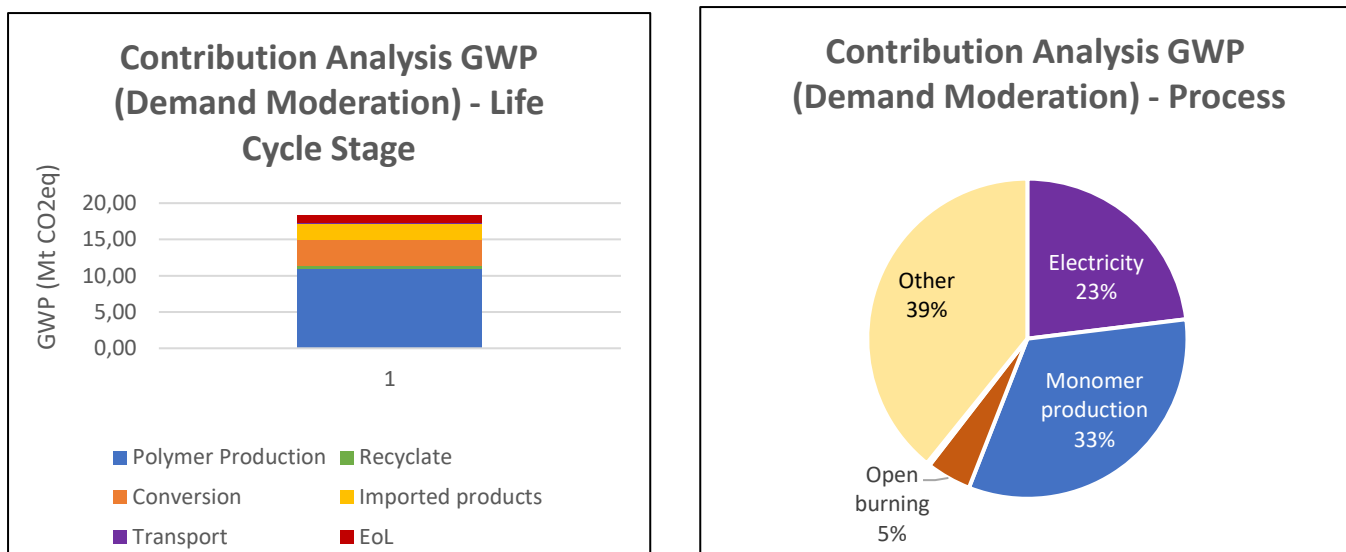
**Figure 28: LCA Normalised Results for Demand Moderation Scenario for 2025**

For the Demand Moderation scenario, the results once normalisation factors are applied show a similar picture to the graph produced for the Baseline scenario. The impact of toxicity on both ecosystems and human beings has the highest overall score. However, the mitigating impact of this scenario can be seen in the decline of comparative scores with a 5% reduction in toxicity impacts relative to the Baseline case. As the reuse stream entails the reduction of feedstock, the polymer production stage also has a lower contribution. Although waste disposed in deficient landfills still has the highest impact from an end-of-life standpoint, there is a relative decrease of 6% which can be attributed to reduced plastics demand and consequently, a decrease in generated waste.

#### 4.4.2.2. Contribution Analysis

##### Global Warming Potential

The results for the midpoint analysis of the system specifically in terms of Global Warming Potential is reflected in Figure 29.



**Figure 29: Contribution Analysis of Global Warming Potential (Demand Moderation) at the Level of a. Life Cycle Stage and b. Process**

Similar to the findings for normalised results, overall emissions due to climate change decrease by 5% relative to the Baseline scenario. This reduction in projected emissions can be directly attributed to the decrease in 0.5 Mt CO<sub>2</sub>eq or 4% in emissions related to the production of local polymer. The partial substitution of single-use plastics for reusable alternatives also lead to a decrease in waste which is evidenced in the 6% reduction in emissions for the end-of-life stage. In terms of the contribution analysis per process, the defining contributors remain the same with monomer production, electricity, and open burning amounting to 61% of the total system emissions.

### Endpoint Analysis

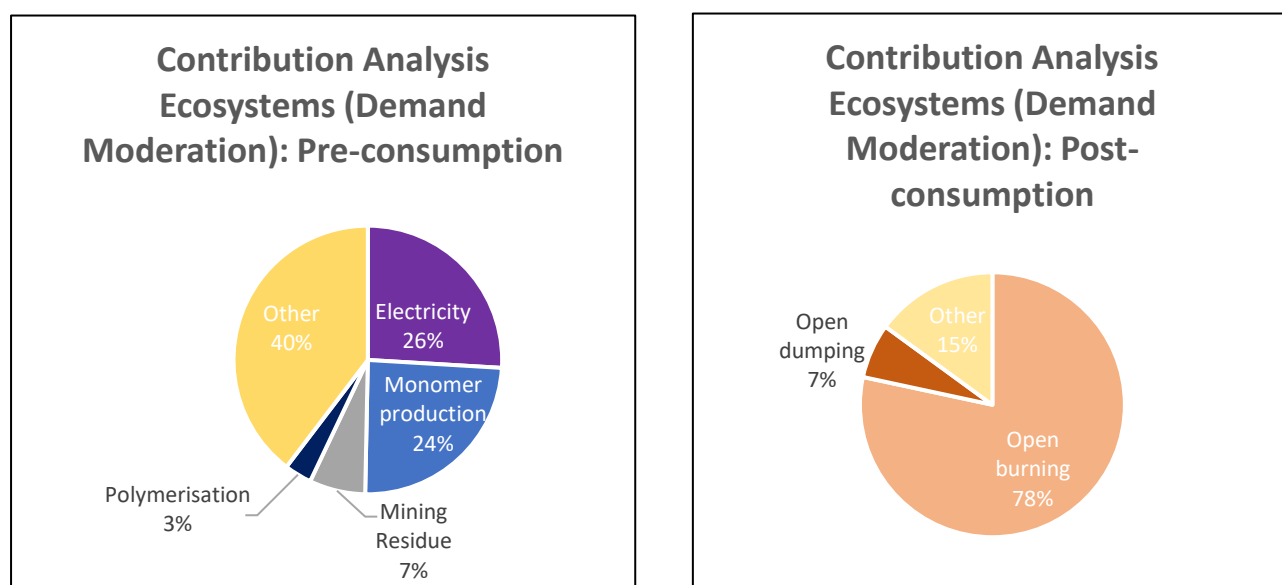
Moving further along the environmental mechanism, the results of the endpoint analysis are displayed in Table 24.

**Table 24: LCA Endpoint Results for Demand Moderation Scenario for 2025**

Damage Category	Unit	Virgin Polymer Production	Recyclate	Conversion	Imported Product	Transport	End-of-Life
Human health	DALY	$2.6 \times 10^4$	$1.4 \times 10^3$	$1.1 \times 10^4$	$5.0 \times 10^3$	$2.3 \times 10^2$	$4.4 \times 10^3$
Ecosystems	species.yr	$5.4 \times 10^1$	$2.4 \times 10^0$	$2.2 \times 10^1$	$9.8 \times 10^0$	$5.6 \times 10^{-1}$	$3.8 \times 10^0$
Resources	USD2013	$9.4 \times 10^8$	$2.2 \times 10^7$	$1.2 \times 10^8$	$2.9 \times 10^8$	$1.1 \times 10^7$	$1.7 \times 10^6$

The reduction in impacts at the endpoint level for this scenario is highlighted by an average reduction of 5% in total impacts compared to the Baseline scenario. This correlates well with the midpoint and endpoint analysis. The ranking of life cycle stages is also consistent for both normalised midpoint and characterised endpoint results i.e. polymer production and manufacturing are the significant contributors at 60 and 18% respectively. The comparative contribution of other phases such as the processing of recycled granulate and the disposal stage relative to the total also tallies with both the midpoint results as well as the distribution of impacts in the Baseline case.

A contribution analysis expanding upon the impact of the life cycle on ecosystems is presented in the form of two pie charts in Figure 30 (a and b) below.



**Figure 30: Contribution Analysis of Ecosystem Health (Demand Moderation) a. Pre-Consumption and b. Post-Consumption**

A process-level analysis of the damage on ecosystems reveals that the two coal-based processes i.e. hydrocarbon virgin feedstock for monomer synthesis and electricity production, contribute to half of the total upstream impacts. Conversely, the downstream impacts are dominated by the self-help disposal waste management process with open burning contributing close to 80% of the end-of-life emissions. This corresponds well with the climate change analysis of this scenario as these three processes were also highlighted due to their relative significance.

#### 4.4.2.3. Comparison with Related Local Studies

As per Section 4.4.1.3, the projected individual impacts associated with a demand moderation scenario has not been analysed in the local context via a life cycle lens.

### **4.5. Decarbonisation Scenario**

#### ***4.5.1. Material Flow Analysis (MFA)***

As detailed in Section 3.7.1, this strategy is centred around future forecasts to the energy mix. Thus, the plastic material flows remain constant as are there no changes to the plastic system mass flows calculated for the Baseline scenario. Thus, the model generated from this scenario as well as the resulting circular and inventory indicators are the same as those presented in Section 4.2.1.

#### ***4.5.2. Life Cycle Assessment***

##### 4.5.2.1. Analysis of Normalised Results

The Decarbonisation scenario for 2025 encompasses changes to the grid mix only as there are no targets set for 2025 in terms of the local monomer production process. The normalised midpoint results for the Decarbonisation scenario are presented in Figure 31.

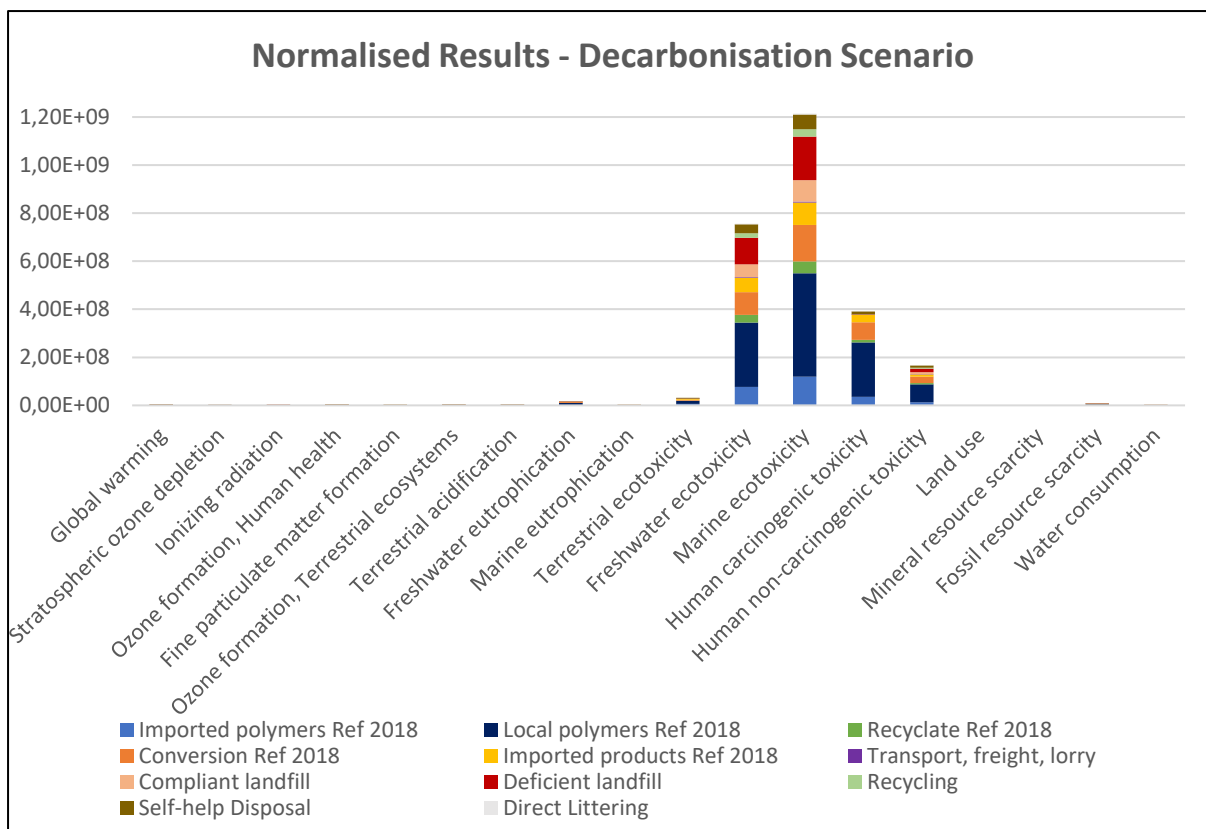


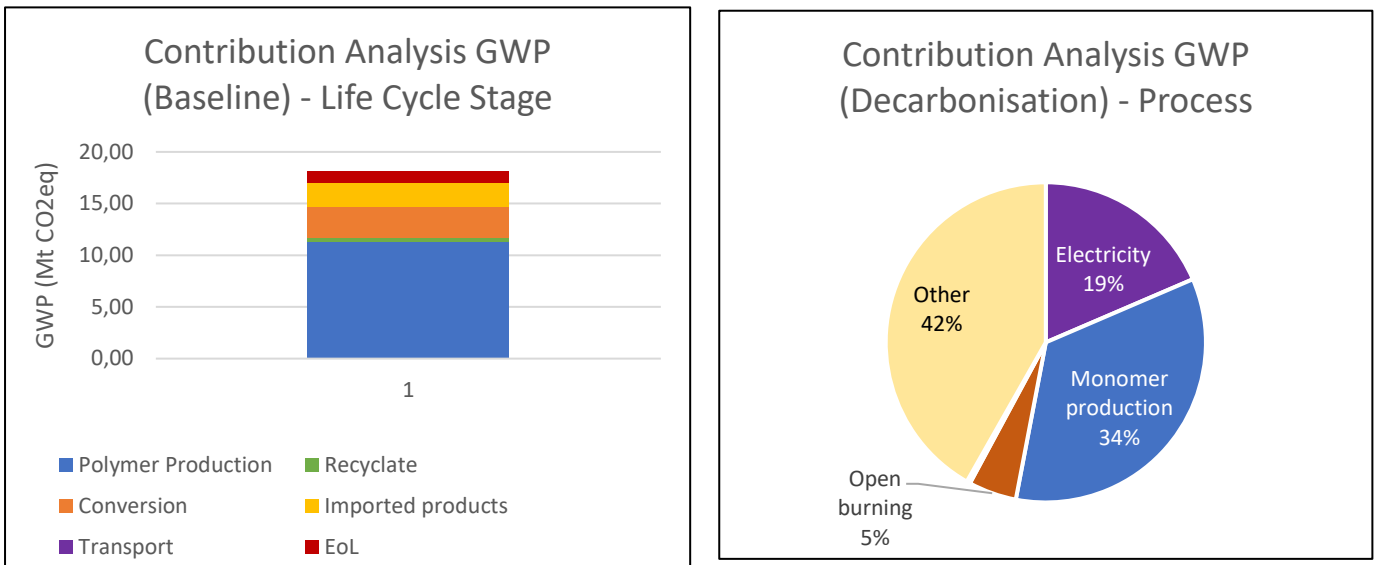
Figure 31: LCA Normalised Results for Decarbonisation Scenario for 2025

On a category level, the most significant impacts of this scenario are still ecotoxicity, toxicity, and freshwater eutrophication. However, compared to the Baseline scenario, the quantity of impact after applying normalisation factors has decreased by an average of 5%. The impact categories that have the greatest relative average reduction of 10% and contribute to damage to human health and ecosystems include ionising radiation, ozone formation, acidification, and eutrophication. In contrast, the specific categories where this scenario performs slightly worse (average of 2%) relative to the Baseline model are land use, water consumption, and mineral resource scarcity which is directly related to the integration of renewable energy sources.

#### 4.5.2.2. Contribution Analysis

##### Global Warming Potential

The characterised results for the Global Warming Potential impact are reflected in Figure 32 a and b.



**Figure 32: Contribution Analysis of Global Warming Potential (Decarbonisation) at the Level of a. Life Cycle Stage and b. Process**

The figure showcasing emissions per life cycle stage (Figure 32a) shows that the emissions for this scenario totals 18 Mt CO<sub>2</sub>eq. This represents a 6% reduction in emissions relative to the Baseline model. Although virgin local polymer production has the largest share of emissions, the greatest reduction in terms of life cycle stages is for conversion (20%) due to the coal-based nature of the processing step. Due to the declining role of coal, electricity has a smaller contribution for climate change compared to the Baseline analysis.

### Endpoint Analysis

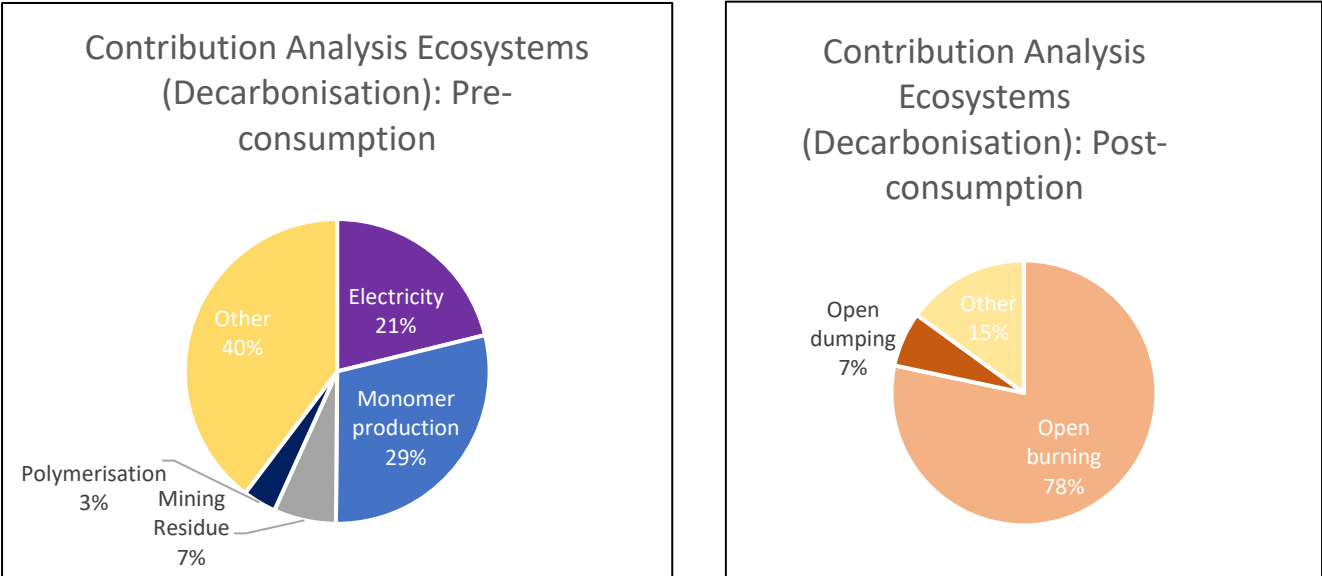
The results for the endpoint analysis in terms of the three endpoint areas of protection are presented in Table 25.

**Table 25: LCA Endpoint Results for Decarbonisation Scenario for 2025**

Damage Category	Unit	Virgin Polymer Production	Recyclate	Conversion	Imported Product	Transport	End-of-Life
Human health	DALY	2.7 x 10 <sup>4</sup>	1.3 x 10 <sup>3</sup>	9.4 x 10 <sup>3</sup>	5.2 x 10 <sup>3</sup>	2.5 x 10 <sup>2</sup>	4.7 x 10 <sup>3</sup>
Ecosystems	species.yr	5.5 x 10 <sup>1</sup>	2.2 x 10 <sup>0</sup>	1.8 x 10 <sup>1</sup>	1.0 x 10 <sup>1</sup>	5.9 x 10 <sup>-1</sup>	4.0 x 10 <sup>0</sup>
Resources	USD2013	9.9 x 10 <sup>8</sup>	2.2 x 10 <sup>7</sup>	1.1 x 10 <sup>8</sup>	3.1 x 10 <sup>8</sup>	1.2 x 10 <sup>7</sup>	1.8 x 10 <sup>6</sup>

There is a reduction in the range of 3-7% for the analysed damage indicators compared to the initial Baseline model. This benefit is solely attributed to the forecasted change in the energy mix and the decrease in the percentage of coal-fired power. The production of local polymer and the conversion from granulate to products still have the greatest contribution at 62- and 16% respectively. However, the respective share of these stages is 2% smaller compared to the Baseline case. The stages that have the lowest contribution remain the same and are the transport, manufacturing of recycled material and the disposal phase post-consumption.

An additional analysis of the damage to ecosystems leads to Figure 33 (a and b).



**Figure 33: Contribution Analysis of Ecosystem Health (Decarbonisation) a. Pre-Consumption and b. Post-Consumption**

As per the contribution analysis of climate change, the role of electricity has declined by 5% relative to the Baseline scenario. Conversely, the share of impacts attributed to local production of ethylene and propylene has increased by 5%. This correlates with the normalisation findings that show that this scenario has the potential to increase damage to freshwater and terrestrial species via land transformation and water consumption. The distribution of impacts for the end-of-life stage remains the same as there is no energy consumption in the disposal phase.

4.5.2.3. Comparison with Related Local Studies

To date, there is a lack of comparative studies that consider how decreasing the carbon intensity of the local energy supply can impact the South African plastics sector in terms of life cycle impacts.

## 4.6. Combination Scenario

### 4.6.1. Material Flow Analysis (MFA)

#### 4.6.1.1. System Map

The material flows that arise upon combining all the mitigation strategies are graphically presented in Figure 34.

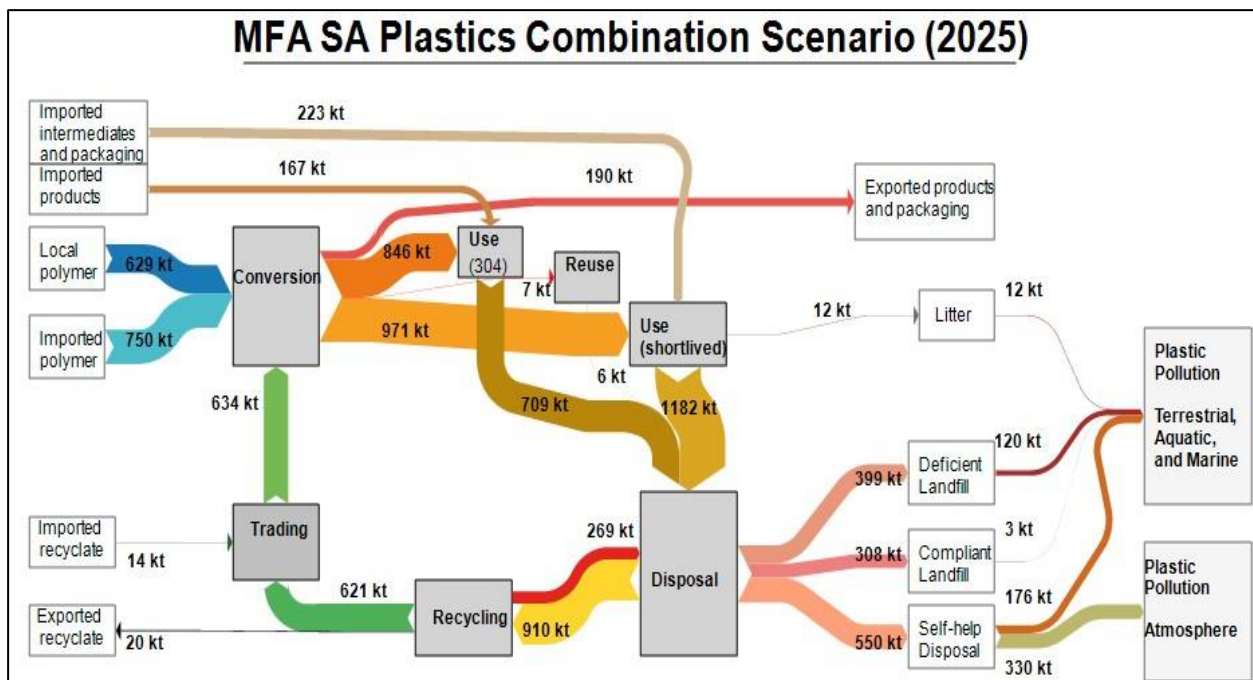


Figure 34: MFA Results for Combination Scenario for 2025

The Sankey diagram for this scenario differs substantially from the system map presented for the Baseline scenario. Notable differences include the addition of the reuse flow which reduces demand by 5% relative to the Baseline scenario and therefore, influences the polymer input into the system. This also influences the quantity of short-lived plastic waste which decreases by 329 kt. Furthermore, the modelling of the increased recycling rate has positively impacted the distribution of waste with a 33% reduction in waste that is uncollected and disposed in primarily landfills but also via self-help disposal. Despite the reduction in demand and uncollected waste, it is evident from Figure 34 that plastic flows would still be largely linear in 2025.

#### 4.6.1.2. Circularity Metrics and Selected Mass-Based Indicators

The results for the calculation of key mass-based and circularity indicators are reflected in Table 26.

**Table 26: Flow and Circularity and Indicators based on MFA for Combination Scenario**

<b>Mass-based Indicators (kt)</b>	
Virgin Polymer	1 379
Recyclate	634
Domestic Production	2014
Plastic Use	2 214
Total Local Waste	1 910
Leakage	310
<b>Circularity Indicators (%)</b>	
Collection Rate	43.8
Input Recycling Rate	76.6
Output Recycling Rate	53.9
Recycled Content	31.5

Due to the projected moderation in demand which results in the partial replacement of short-lived consumption with reuse of products, plastic use will be reduced by 2 kg/capita relative to the Baseline scenario. This translates to a decrease in waste of 118 kt. Additionally, implementation of the increased recycling strategy results in the recycled content of plastic products increasing by 12.7%. The combination of the above two strategies has a net effect on virgin polymer feedstock with a 20% reduction compared to the Baseline case. The quantity of plastic leaked is also impacted with leakage decreasing by 1 kg/capita, thus representing 17% of the end-of-life of plastics.

#### 4.6.1.3. Comparison with Related Local Studies

Although it is acknowledged that combining material strategies such as increased collection and recycling and reduced plastics demand results in a long-term improvement for the South African plastics sector (Stafford et al., 2022), there are no projections for impacts prior to 2040.

## 4.6.2. Life Cycle Assessment (LCA)

### 4.6.2.1. Analysis of Normalised Results

Once the life cycle for the Combination scenario had been modelled, the characterisation results with the application of global normalisation factors is displayed in graphical format via Figure 35.

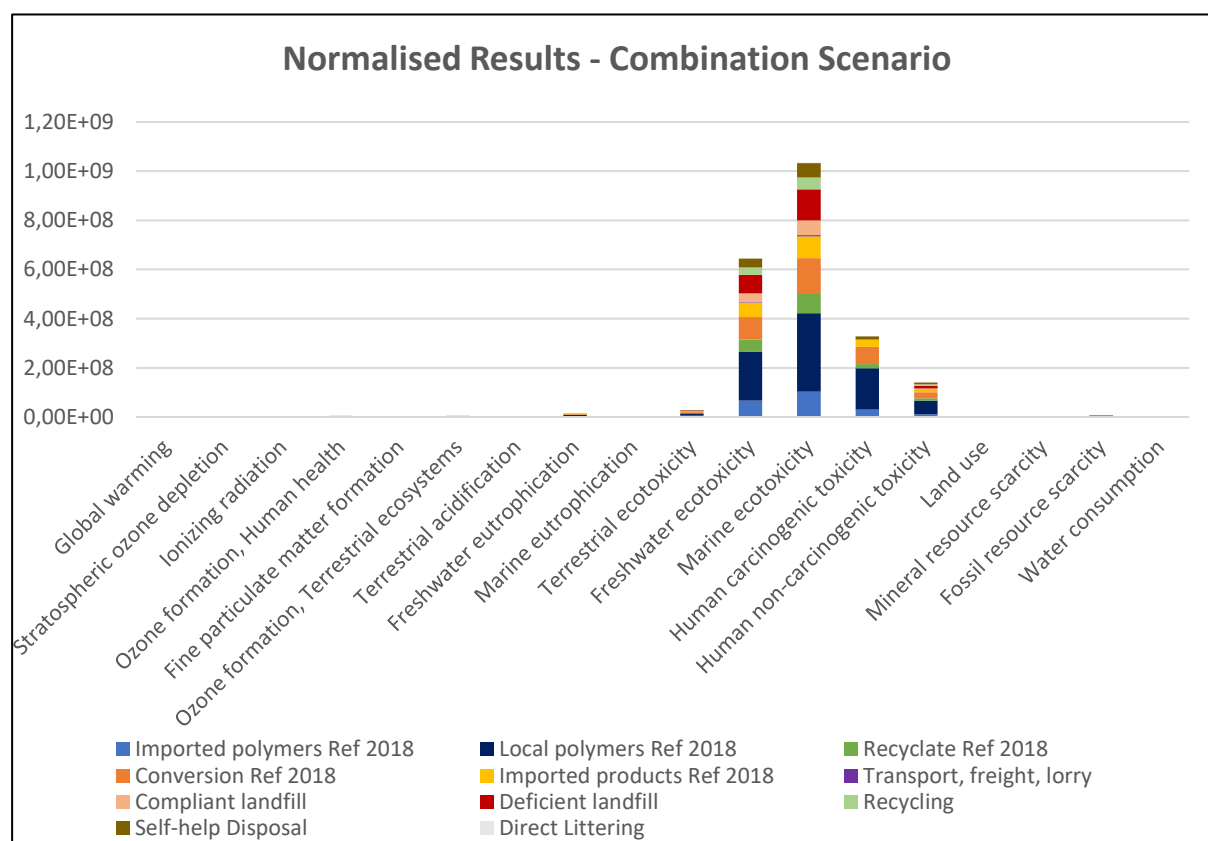


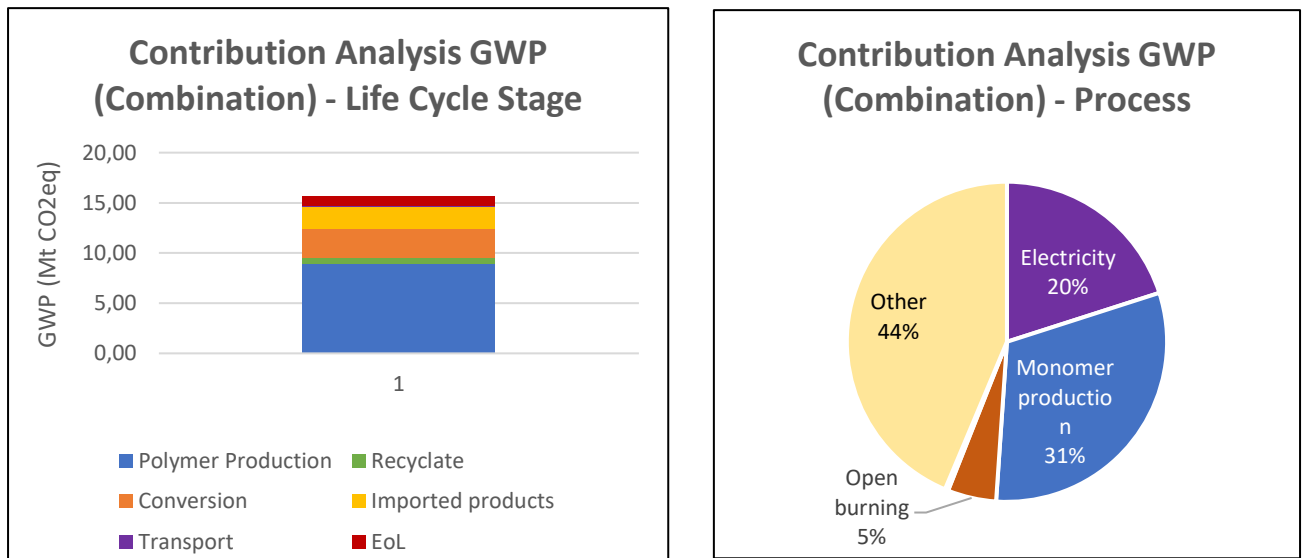
Figure 35: LCA Normalised Results for Combination Scenario for 2025

There is an average decrease of 17% in impacts across all midpoint categories upon comparison to the findings from the Baseline LCA. This is attributed to both the material and energy strategies i.e. the reduction in plastic demand and increasing mechanical recycling coupled with the reduction in coal-based electricity. The greatest improvements at an average of 20% are seen for impacts such as human toxicity, acidification, ozone and fine particulate matter formation, and global warming. Although monomer and polymer production are still the greatest contributors, their share has decreased from 54% to 37%. In terms of the downstream processes, disposal to deficient landfills has a significant burden (average of 14%) for impacts related to the damage of marine and freshwater species.

#### 4.6.2.2. Contribution Analysis

##### Global Warming Potential

The results in terms of the contribution analysis for climate change is presented in the form of the two graphs shown in Figure 36 a and b.



**Figure 36: Contribution Analysis of Global Warming Potential (Combination) at the level of a. Life Cycle Stage and b. Process**

As with the analysis of overall normalised results, total GHG emissions declined significantly by 19% compared to the Baseline scenario in 2025 and to below emissions recorded for the Reference case in 2018. This is partially due to the reduction in emissions from monomer and polymer production which are now under 9 Mt CO<sub>2</sub>eq. Although a substantial reduction is noted for other stages such as conversion (23%), the production of recyclate is projected to have a rising share in total emissions with a 33% increase (from 2.4 to 4.2%). An analysis of the results through a process lens shows a 2-3% decrease in contributions from monomer production and electricity consumption.

#### Endpoint Analysis

The summary of results per areas of protection are listed in Table 27.

Table 27: LCA Endpoint Results for Combination Scenario for 2025

Damage Category	Unit	Virgin Polymer Production	Recyclate	Conversion	Imported Product	Transport	End-of-Life
Human health	DALY	$2.1 \times 10^4$	$2.0 \times 10^3$	$9.0 \times 10^3$	$5.0 \times 10^3$	$2.4 \times 10^2$	$4.3 \times 10^3$
Ecosystems	species.yr	$4.2 \times 10^1$	$3.4 \times 10^0$	$1.8 \times 10^1$	$9.8 \times 10^0$	$5.6 \times 10^{-1}$	$3.7 \times 10^0$
Resources	USD2013	$8.0 \times 10^8$	$3.4 \times 10^7$	$1.0 \times 10^8$	$2.9 \times 10^8$	$1.1 \times 10^7$	$1.6 \times 10^6$

The results of the damage assessment correlate with the analysis of the midpoint results with an average 18% reduction in impacts across the three endpoint categories relative to the findings for the Baseline scenario. Additionally, impacts have reduced to the extent of falling below results for 2018. Polymer production and manufacturing of plastic products are still the greatest contributors at a combined sum of 74% of the total although their individual contribution has decreased by an average of 2%. Despite recyclate production having a relatively small contribution, its share increased by 1.5% to an average of 4%.

Following the pattern of the individual scenarios, the damage to ecosystems is disaggregated in Figure 37 (a and b).

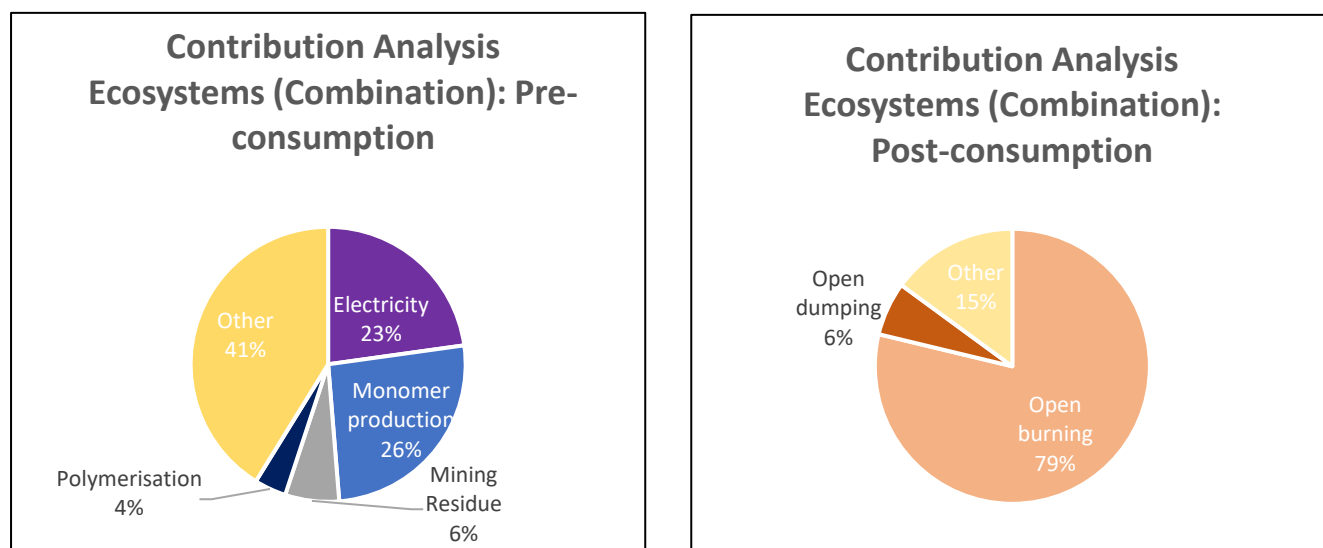


Figure 37: Contribution Analysis of Ecosystem Health (Combination) a. Pre-Consumption and b. Post-Consumption

The contribution analysis shows minimal changes at a process level compared to the Baseline model. There is a slight decrease of 3% in the contribution of energy which is offset by a 2% increase in the share of impacts due to the local production of ethylene and propylene. Furthermore, the combined total impacts associated with self-help disposal remain the same at 75% of the damage to ecosystems at the EoL stage.

4.6.2.3. Comparison with Related Local Studies

There are currently no other studies that consider the modelled strategies (including decarbonisation of the energy system) into a life cycle-based short-term forecast for the local plastics system.

**4.7. Exploration of Additional Indicators**

This section is an investigation into additional indicators such as plastic persistence and employment opportunities across scenarios.

**4.7.1. Persistence**

As an exploration into the potential impact of plastic leakage, an analysis was undertaken to estimate the effect of persistence. Using the calculation sequence laid out in the Section 3.3.2.3, the plastic persistence for the various scenarios per receiving compartment is presented graphically in a clustered bar graph in Figure 38 below.

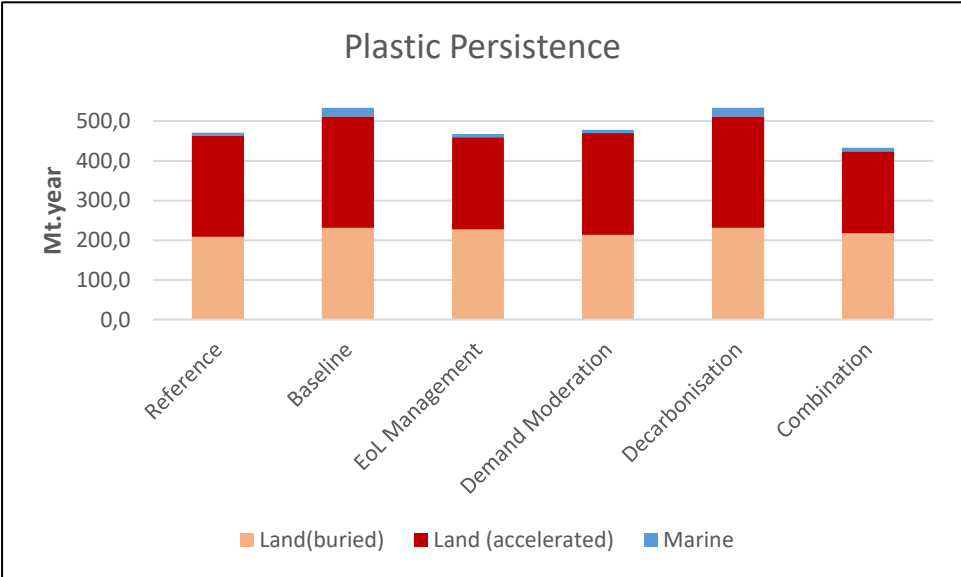


Figure 38: Plastic Persistence across Scenarios for Different Environments

The figure above shows that if the current situation continues, plastic persistence will increase by 13% from 2018-2025 or at an annual increase of 1.9%. Other than the decarbonisation strategy which has no effect on material flows, all the mitigation strategies result in a decrease in plastic persistence. However, the scenario that yields the greatest reduction is the Combination scenario with a 19% reduction relative to the projected status quo (Baseline scenario). According to the modelling, both the Increased Recycling and the Combination scenarios are capable of yielding persistence figures below that estimated for the Reference case in 2018.

In terms of the distribution between different environments, plastic remaining in the marine environment has a lower impact compared to those buried in land or material that resides on the surface of the ground. This is in line with the conclusion of a local study that states that plastic pollution in the country is dominated by terrestrial pollution with aquatic pollution (freshwater and marine) having a relatively small effect (Stafford et al., 2022). These findings are contrary to the current research landscape where most studies are focused on marine plastic pollution (Section 2.4.2).

#### 4.7.2. Employment

The scope of the study was extended to include employment as a key socio-economic aspect to investigate. The impacts on employment were analysed based on the number of jobs associated with the main life cycle stages as well as the total material produced at each stage. The results of the analysis are presented in Table 28.

**Table 28: Employment Opportunities per Life Cycle for All Scenarios**

Scenario	Jobs per Life Cycle Stage			Total	
	Local Polymer Production	Virgin	Conversion Recycling		
Reference Case		1926	32 830	42 592	77 348
Baseline		2 374	36 995	46 464	85 833
Increased Recycling		2 044	36 995	75 020	114 059
Demand Moderation		2 288	35 245	44 286	81 819
Decarbonisation		2 374	36 995	46 464	85 833
Combination		1 761	35 245	75 020	112 026

The findings indicate that the majority of employment opportunities are in the conversion and recycling stages of the value chain. The increase in employment between the Baseline and Reference case of 11% is due to the increase in material being processed. Similar to the analysis of plastic persistence, the two best-performing strategies are the Increased Recycling and the Combination scenario. The Combination scenario yields a slightly lower total due to reduced quantities of virgin polymer production and conversion. Overall, there is a projected increase in employment prospects of between 31-33% for these two scenarios relative to the Baseline scenario with a major increase of 61% observed in recycling. The distribution of jobs as well as the overall results correspond with the findings from the comparative local study (Stafford et al., 2022).

#### **4.8. Summary**

This chapter focused on presenting results per strategy with an expansion of MFA and LCA results and concluded by showing what the combination of strategies can achieve. Furthermore, an exploratory assessment of additional indicators was undertaken. A summary of the key indicators is presented in Table 29.

Table 29: Summary of Key MFA and LCA Results (Snapshot)

Indicators	Unit	Scenarios					
		Reference Case	Baseline	Increased Recycling	Demand Moderation	Decarbonisation	Combination
<b>Mass-based Indicators</b>							
Virgin Polymer	kt	1 544	1 716	1 480	1 635	1 716	1 410
Domestic Production	kt	1 876	2 114	2 114	2 014	2 114	2014
Plastic Use	kt	2 108	2 334	2 334	2 214	2 334	2 214
Leakage	kt	342	379	337	356	379	310
<b>Circularity Indicators</b>							
Collection Rate	%	26.0	26.4	45.2	26.7	26.4	48.0
Input Recycling Rate	%	40.3	40.9	70.0	42.6	40.9	76.6
Output Recycling Rate	%	30.9	30.4	49.2	31.7	30.4	53.9
Recycled Content	%	17.7	18.8	30.0	18.8	18.8	31.5
<b>Environmental and Socio-Economic Indicators</b>							
Climate Change	Mt CO <sub>2</sub> eq	16.9	19.2	17.9	18.4	18.2	15.5
Human Health	DALY	4.5 x 10 <sup>4</sup>	5.1 x 10 <sup>4</sup>	4.8 x 10 <sup>4</sup>	4.9 x 10 <sup>4</sup>	4.8 x 10 <sup>4</sup>	4.1 x 10 <sup>4</sup>
Ecosystem Health	species.yr	8.4 x 10 <sup>1</sup>	9.6 x 10 <sup>1</sup>	9.0 x 10 <sup>1</sup>	9.2 x 10 <sup>1</sup>	9.0 x 10 <sup>1</sup>	7.7 x 10 <sup>1</sup>
Resource Depletion	USD2013	1.3 x 10 <sup>9</sup>	1.5 x 10 <sup>9</sup>	1.3 x 10 <sup>9</sup>	1.4 x 10 <sup>9</sup>	1.4 x 10 <sup>9</sup>	1.2 x 10 <sup>9</sup>
Persistence	Mt.year	470	534	467	478	534	433
Employment	Jobs	77 348	85 833	114 059	81 819	85 833	112 026

The findings indicate that although all the mitigation scenarios have a positive impact relative to the Baseline scenario, the best overall strategy in the short-term from a material and environmental perspective is applying the individual strategies in concert. This excludes the results for employment opportunities, where the strategy of increasing end-of-life mechanical recycling looks to achieve the highest benefits. However, further method development is required for a more holistic assessment of the additional indicators.

The contribution analysis revealed that across all the scenarios, most of the impacts occur upstream prior to use and disposal. The most dominant contributors per life cycle stage pre-consumption is local polymer production while monomer production and electricity have substantial shares on a process level. For the end-of-life stage, the deficient landfill and self-help disposal treatment processes had the greatest impacts on a normalised scale whereas open burning and dumping had the highest contribution from a process perspective.

Despite improvements in the system and the potential to keep 2025 emissions comparable to 2018 levels when combining strategies, circularity and mass-based indicators show that the local plastics system is still relatively linear in the short-term. Furthermore, notwithstanding the reduction in environmental impacts, the local plastics sector is still responsible for environmental burdens, particularly the emission of GHGs which slows the progression to a low-carbon sector.

## CHAPTER 5: SYNTHESIS RESULTS AND DISCUSSION (MEDIUM-TERM FORECAST)

This chapter extends the timeline of the short-term analysis presented in the previous chapter by demonstrating the potential of each scenario over the period 2025 – 2035. Additionally, results are displayed per selected circularity and environmental indicators for direct comparison between strategies. The chapter goes on to assess if the modelled future local plastics sector could be considered as fully low-carbon and circular, by assessing the impact of the combined strategies against international ambitions and targets. Finally, the strengths and limitations of the study are detailed.

### 5.1. Medium-Term Outlook

#### 5.1.1. *Plastic Waste per Capita*

In terms of waste metrics within the framework of a circular economy, plastic waste generation is a widely cited indicator to assess the level of circularity in waste management systems between countries (Bagaria et al., 2020). The per capita waste generation for South Africa was projected for the period 2025-2035 and is stated in Table 30.

Table 30: Results for Plastic Waste Generation per Scenario for 2025-2035

Scenario	Plastic Waste (kg/capita)		
	2025	2030	2035
Baseline	32	34	36
Increased Recycling	32	34	36
Demand Moderation	30	32	34
Decarbonisation	32	34	36
Combination	30	32	34

The findings for the medium-term Baseline scenario display a steady increase of 2 kg/capita every five years up to 2035. Both the Increased Recycling and the Decarbonisation scenarios will have no effect on waste generation as the former has no impact on the quantity of waste generated while the latter affects energy-related inputs only. Conversely, the implementation of the Demand Moderation scenario will result in a benefit equivalent to a reduction of 2 kg/capita in 2030 and 2035 relative to the Baseline scenarios. The Combination scenario reflects

the same benefits of the Demand Moderation, the latter being the one having an impact on the plastic waste generated per capita indicator.

A comparison of the results with a global study reveals that waste generation in 2040 would increase by 70% compared to 2020 with a global ambitious scenario modelling early, stringent, and combined policy action showing a reduction of waste generation by a quarter below baseline in 2040 (Organisation for Economic Cooperation and Development, 2023). Although the results presented in Table 30 show a more conservative benefit of 6% under the Combination scenario relative to the Baseline model in 2035, the projected increase of 13% from 2018-2035 under the Baseline scenario is also significantly lower than the global estimated increase due to lower plastics demand projected for the local context. This correlates with the study modelling global plastic flows up to 2060 which shows that although plastic waste in Africa will quadruple between 2019-2060 due to rising living standards and increasing population growth, non-OECD countries will still produce less waste per capita compared to OECD countries (77 kg vs 238 kg) in 2060 (Organisation for Economic Cooperation and Development, 2022c).

**5.1.2. Recycled Content**

As the rate of recycling is an indication of the country’s approach towards resource management, the percentage of recyclate within plastic products manufactured in South Africa was analysed over the medium-term. This choice is due to the fact that few studies specify whether an input or output recycling rate is considered with a lack of a standardised definition for these indicators, which hampers comparability in different local and international contexts (Hotta et al., 2016). The results for recycled content for the period 2025-2035 are displayed in Table 31 below.

**Table 31: Results for Recycled Content per Scenario for 2025-2035**

Scenario	Recycled Content (%)		
	2025	2030	2035
Baseline	18.8	18.8	18.8
Increased Recycling	30.0	52.4	56.0
Demand Moderation	18.8	18.8	18.8
Decarbonisation	18.8	18.8	18.8
Combination	31.5	55.1	58.9

The outcome indicates that the recycled content will continue to remain stagnant during the ten-year period without any curbing strategies in place. Despite demand being moderated for the second mitigation strategy, there is no significant impact on the results in the medium-term. However, implementing either the Increased Recycling or the Combination scenario will yield an increase in recycled content of 37.2% and 40.1% respectively compared to the Baseline scenario in 2035 with the net result inferring that plastic products manufactured in South Africa from 2030 will contain just over 50% of recycled content under these scenarios. The Combination scenario reflects the same benefits as the Increased Recycling scenario, with the latter being the one having an impact on the recycled content indicator.

As related studies use recycling rate with differing definitions as a policy intervention rather than as a metric, it is difficult to directly compare results. It would be necessary for each study to repeat the exercise described in Section 3.5.1 to establish the correlation between recycling rates and recycled content to undertake an accurate comparison. Although a study of interest that is based on a dynamic MFA of plastics in China reports that secondary plastics could supply 49.1% of demand by 2050 (Luan et al., 2021), the scenario analysis is founded on a stock-driven model rather than mitigation pathways which increases the complexity of a direct comparison.

**5.1.3. Leakage**

As one of the aims of achieving a plastic circular economy is to eliminate stages associated with waste such as leakage, an indication of plastic pollution is required. In place of ongoing development related to methodology and supporting data, a plastic leakage inventory indicator is utilised. The results for leakage for all the modelled scenarios are presented in Table 32.

**Table 32: Results for Leakage per Scenario for 2025-2035**

Scenario	Leakage (kt)		
	2025	2030	2035
Baseline	379	415	458
Increased Recycling	337	275	288
Demand Moderation	356	389	430
Decarbonisation	379	415	458
Combination	310	246	256

The Baseline Scenario predicts that the quantity of plastic leaked will continue unabated and increase by 2% annually over the upcoming decade if left unabated. Although the implementation of the Increased Recycling scenario would result in a minor reduction of 42 kt in 2025 relative to the Baseline, this increases to 140 kt and a final reduction of 170 kt is projected in 2035. This is equivalent to a 37% reduction in 2035 compared to the Baseline scenario, with both scenarios presenting the same plastic waste per capita trends over time Table 30. Despite the Demand Moderation scenario performing well in the short-term, the benefits are minimal as time progresses (most likely eroded by the consumption trend). The modelling suggests that implementing the interventions in concert (Combination scenario) yields a 44% reduction compared to the baseline in 2035 with the levels also falling below those for the projected baseline in 2025.

The assessment of pathways towards reducing ocean plastic pollution shows that an ambitious recycling strategy can reduce ocean leakage in 2040 by 38% relative to the modelled business-as-usual case (The Pew Charitable Trusts and SYSTEMIQ, 2020). Although this corresponds with the percentage reduction calculated above for the Increased Recycling scenario, the reduction due to implementing multiple interventions is much higher at approximately 80%. The results differ slightly for the local iteration with the research showing a more moderate reduction of 33% and 63% over the period 2023-2040 for the increased recycling and combination scenarios respectively (Stafford et al., 2022).

#### ***5.1.4. Global Warming Potential***

A projected rise in plastic production will result in an increase in life cycle GHG emissions of plastics if no measures are taken to reduce carbon intensities. However, meeting international climate targets will require a commitment to net-zero carbon emissions by the latter half of the century (Rogelj et al., 2018). Thus, the reduction potential of mitigation strategies is significant. The results for Global Warming Potential in the medium-term are displayed in Table 33.

**Table 33: Results for Global Warming Potential per Scenario for 2025-2035**

Scenario	Global Warming Potential (Mt CO <sub>2</sub> eq)		
	2025	2030	2035
Baseline	19.2	21.0	23.2
Increased Recycling	17.9	16.6	18.3
Demand Moderation	18.3	20.1	22.1
Decarbonisation	18.2	16.3	13.0
Combination	15.5	11.9	10.4

An extension of the short-term Baseline analysis reveals that GHG emissions would increase by 4 Mt CO<sub>2</sub>eq or a percentage increase of 21% between 2025 and 2035. The implementation of the Demand Moderation scenario could produce a projected benefit equivalent to a 5% reduction by 2035 compared to the Baseline scenario. Despite increased recycling in 2035 for the Increased Recycling scenario, the rate of production and plateau in collection rate (detailed in Section 3.5.1) ensures that the projected carbon footprint of the system in 2035 does not follow the steep gains exhibited during the period 2025-2030, with higher recycling rates translating into higher GHG emissions. However, there is still a projected decrease in impacts of just over 20% in 2030 with a final reduction of 21% projected for 2035 compared to the respective Baseline scenarios. Furthermore, the declining role of coal for power generation combined with the fulfilment of decarbonisation targets by Sasol in 2030 should lead to emissions decreasing by 22% relative to the Baseline scenario in 2030. Additionally, the use of imported feedstock as a substitute for local monomer production due to the CTL process ceasing production by 2035 would lead to a total reduction of 44% compared to the Baseline scenario in 2035 - the greatest reduction amongst the individual strategies. However, the combination of measures would yield the greatest benefit with a 12.8 Mt CO<sub>2</sub>eq reduction in emissions compared to the 2035 Baseline scenario. This translates to a potential relative reduction of 55% in the medium-term.

In terms of comparative studies, the modelling of the Chinese plastic system yields comparable, although slightly more moderate benefits for the various mitigation scenarios. Under the renewable energy transition scenario, value chain environmental impacts will be reduced by 1-8% in 2030 while increasing plastic recycling will reduce impacts by a maximum of 6% in 2030 and 16% in 2060 with projected recycling rates of 35 and 60% respectively (Liang et al., 2023). Similar to the results presented in Table 33, the combined scenario presents the greatest

reduction potential particularly for climate change with a 50% decrease albeit only achieved in 2060. Zheng and Suh’s study (2019) presents an analogous trend with an aggressive decarbonisation scenario comprising of switching to 100% renewable energy capable of reducing life cycle emissions by 62% in 2050 relative to 2015 levels. If combined with demand management or extensive recycling, these scenarios have the potential to maintain current levels of emissions up to 2050. A corresponding local study displays results comparable to Table 33 for the increasing recycling scenario with a 14% reduction in GHG emissions between 2023-2040 (Stafford et al., 2022). However, the combination scenario yields relatively modest gains (37% reduction) due to decarbonisation not being considered as a mitigation scenario.

### 5.1.5. Human and Ecosystem Health

In addition to the medium-term analysis of Global Warming Potential, a corresponding analysis is necessary to gauge the environmental footprint and human health implications of the local plastic chain. Instead of projecting the environmental performance for all the significant midpoint categories identified in the hotspot analysis in Chapter 5, results are instead estimated for the relevant endpoint indicators. The findings for both human and ecosystem health are presented in Table 34.

**Table 34: Results for Human and Ecosystem Health per Scenario for 2025-2035**

Scenario	Human Health (DALY)			Ecosystem Health (species.yr)		
	2025	2030	2035	2025	2030	2035
Baseline	5.1 x 10 <sup>4</sup>	5.6 x 10 <sup>4</sup>	6.2 x 10 <sup>4</sup>	96	105	116
Increased Recycling	4.8 x 10 <sup>4</sup>	4.6 x 10 <sup>4</sup>	5.1 x 10 <sup>4</sup>	90	84	93
Demand Moderation	4.9 x 10 <sup>4</sup>	5.3 x 10 <sup>4</sup>	5.9 x 10 <sup>4</sup>	92	101	111
Decarbonisation	4.8 x 10 <sup>4</sup>	4.5 x 10 <sup>4</sup>	3.4 x 10 <sup>4</sup>	90	83	62
Combination	4.1 x 10 <sup>4</sup>	3.4 x 10 <sup>4</sup>	2.9 x 10 <sup>4</sup>	77	61	51

The medium-term forecast follows the short-term trajectory with an average increase of 21% in human and ecosystem health impacts during the ten-year period spanning 2025 to 2035. The implementation of measures focused on moderating demand would produce a projected benefit equivalent to a 5% reduction by 2035 relative to the Baseline scenario. Although the Increased Recycling and Decarbonisation scenarios display the same impacts on a short-term basis (2018-2025), the greatest impact for the former scenario is seen during the period 2025-2030 with an 18-20% reduction in impacts affecting ecosystems and human health relative to the 2030

Baseline scenario. The diminished increase in impacts between 2030 and 2035 for this scenario correlates with the climate change impact findings presented in Section 5.1.4. An analysis of the results for the Decarbonisation scenario reveals a similar pattern as noted for the Global Warming Potential findings viz. an approximate reduction in impacts of 20% in 2030 which extends to a final reduction of 46% in 2035 relative to the projected Baseline scenarios. Despite the Decarbonisation scenario displaying the greatest benefit amongst the individual scenarios, the potential of implementing strategies in concert is highlighted by the Combination scenario achieving the same impact of the Decarbonisation scenario albeit within a shorter timeframe (2030 as opposed to 2035). Thus, the Combination scenario displays the greatest potential benefit with a 55% reduction in 2035 relative to the 2035 Baseline with impacts to potentially fall below the 2025 Baseline results.

Unlike the comparative analysis for Global Warming Potential, there are fewer studies analysing the potential impact of mitigation strategies on indicators at the end of the environmental mechanism such as ecosystem and human health. The study performed by Liang et al (2023) partially echoes the analysis above by stating that although relatively high reductions can be observed from increasing plastic recycling in the Chinese context, particularly for impacts related to human toxicity and marine ecotoxicity, the decarbonisation scenario will lead to the highest emission reduction potential amongst seven of the ten studied midpoint indicators when comparing individual measures. Furthermore, combining strategies will produce a reduction of 14-57% in 2060 for nine indicators. This is in the range of expected reduction (~55%) for the Combination scenario albeit within a shorter period (2035 vs 2060).

## **5.2.Can the Future SA Plastics Sector be Low-Carbon and Circular?**

The analysis thus far reveals the potential benefit that can be achieved by adopting the investigated mitigation strategies in both the short- and medium-term. To demonstrate the benefit of combining significant strategies on several circularity and environmental indicators over the entire modelled timeline relative to implementing the strategies in isolation, a graphical representation is displayed in Figure 39 below. Each line represents an individual scenario modelled with the dashed line referring to the Reference case and Baseline scenario, the solid colour-coded lines representing the individual mitigation pathways, and the solid black line reflecting the results for the Combination scenario.

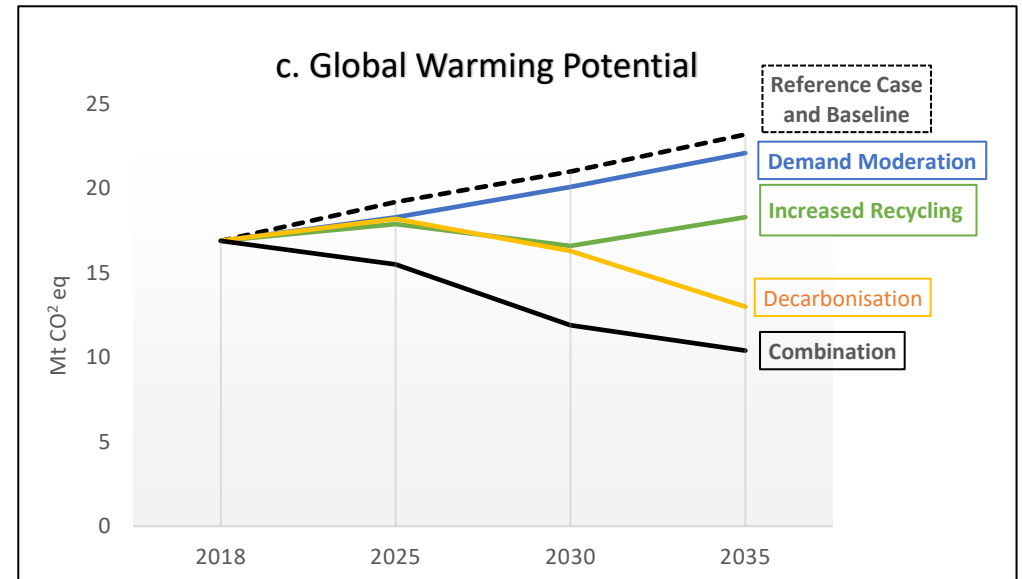
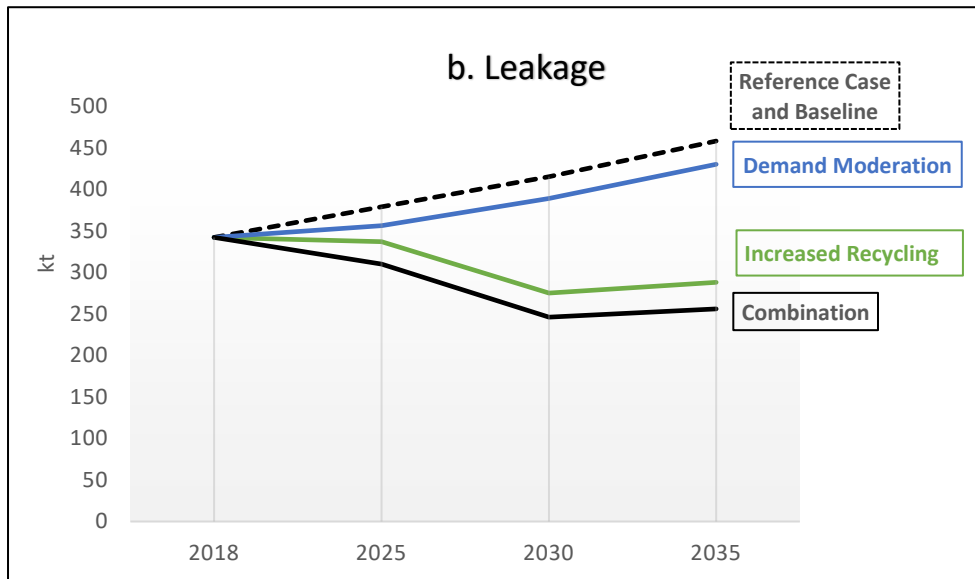
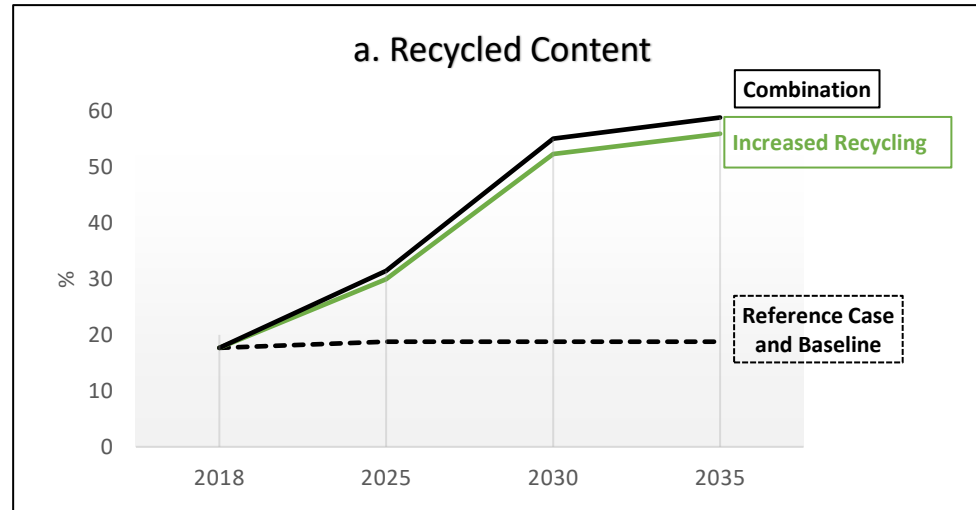


Figure 39: Benefit of Combining Strategies at Indicator-Level for the Period 2018-2035 (a. Recycled Content, b. Leakage, c. Global Warming Potential)

Despite the projected annual growth in production from 1 876 kt in 2018 to 2 551 kt in 2035, Figure 39a demonstrates that measures to enhance recycling and, to a lesser extent, curb demand, are pivotal in ensuring that the secondary demand for plastics increases by almost three-fold from 2018 to 2035. The figure also highlights the instrumental role that these combined strategies play in reducing the volume of plastic waste that is mismanaged (i.e. not collected for recycling or disposed of in sanitary landfills) and therefore leaked to the environment (Figure 39b). Policies that moderate demand and improve recycling would not just deliver substantial decreases in leakage relative to baseline levels in 2025-2035 but would also lead to a reduction by a quarter below levels in 2018. Together with the decarbonisation of the country's energy mix and monomer supply, these measures jointly facilitate the transition to a lower carbon plastics system by reducing the impact of Global Warming potential by 38% when comparing projected emissions in 2035 to historical emissions in 2018 (Figure 39c).

The plots reveal that while the combination of policies to increase recycling and to foster reuse in 2035 would contribute to the 25% reduction in plastic leakage from 2018 levels, this would only result in a minor change in GHG emissions for the period 2018-2035. The decarbonisation strategy is crucial to accelerate the shift and prevent significant increases compared to the 2018 impacts. Whereas some strategies such as increasing recycling rates play a significant role in increasing secondary material usage, others are instrumental in reducing plastic leakage to ecosystems or decreasing the associated carbon footprint of the local plastics value chain. The combination of measures delivers an almost immediate improvement in indicators in 2025 and a 25-41% reduction by 2035 relative to the findings in 2018. Thus, the comprehensive mix of upstream and downstream strategies modelled in the Combination scenario holds the promise of significant local benefits for both human and ecosystem health.

As the analysis above concluded that combining individual circular and decarbonisation strategies has the potential to effect the greatest change across multiple indicators, the Combination scenario is presented at different points along the modelled timeline. To benchmark results, international targets are included and presented in Table 35.

**Table 35: Comparison of Results for Combination Scenario against Global Targets**

<b>Indicators</b>	<b>Unit</b>	<b>2018</b>	<b>Combo 2025</b>	<b>Combo 2030</b>	<b>Combo 2035</b>	<b>Global International Target</b>	<b>and/or</b>
Recycled Content	%	17.7	31.5	55.1	58.9	40% by 2060	
Leakage	kt	342	310	246	256	50% reduction in plastic litter at sea from 2005-2030	
Global Warming Potential	Mt CO <sub>2</sub> eq	16.8	15.5	11.9	10.4	43% reduction from 2019-2030	

In terms of recycled content targets, a global ambition of 40% by 2060 is set by the Organisation for Economic Co-operation and Development (OECD) in their Global Plastics Outlook report (Organisation for Economic Cooperation and Development, 2022b). The target is based on coordinated policy measures such as a tax on primary plastics together with a subsidy on secondary plastics. The results in the table indicate that combining measures could result in the target for 2060 being achieved much earlier in South Africa i.e. already in the period 2025-2030.

As a global target for plastic leakage has not yet been agreed upon, a target adopted by the European Commission was utilised. The target, which is aimed at speeding up reducing pollution at source, is based on the zero-pollution vision for 2050 (European Commission, 2022). As one of the deliverables of the European Green Deal, the ambition aims to reduce pollution to levels no longer considered harmful to natural ecosystems and human health. As the target is for a period prior to this study’s timeline and for plastic litter to the sea, a limited comparison with the findings is possible. However, this research shows a projected 25% decrease in impacts is possible when combining strategies over a 17-year period (i.e. between 2018-2035). In the South African context, it must be noted that the majority of plastic leakage is associated with a lack of waste collection services for approximately 30% of the population, and without this deficiency being addressed, plastic leakage would remain unacceptably high.

For Global Warming Potential, the Sixth Assessment report published by the Intergovernmental Panel on Climate Change (IPCC) states that global GHG emissions should be reduced by 43%

by 2030 from 2019 levels in global modelled pathways that limit warming to 1.5°C (Pathak et al., 2022). The results for the Combination scenario state that emissions can be reduced by 29% by 2030 and 38% by 2035 off a 2018 result. Although this does not wholly fulfil the overall, nationally undifferentiated IPCC target, the modelled reductions might qualify for a ‘fair share contribution’ by South Africa, thereby indicating the policy relevance of the modelled mitigation scenarios and emphasises the potential of integrating circularity and decarbonisation measures.

### **5.3. Strengths and Limitations**

This research aimed to develop material flow and life cycle models of the South African plastics sector at various points in time by utilising historical data to construct future scenarios. Unlike global studies, the study is nationally grounded and used local knowledge and data to integrate factors as well as considered targets unique to the South African context into the analysis. These include but are not restricted to the local production of monomers, disposal, and recycling routes, and import and export patterns. Furthermore, the bottom-up construction of the system lends itself to improved granularity into key material flows throughout the entire life cycle without limiting the analysis to the end-of-life stage. Due to the above aspects, the research is both labour and expertise intensive which limits its application to a long-term analysis. The comparative analysis reveals that studies generally tend to focus on singular aspects pertaining to either material or environmental indicators with only a few studies attempting to link these aspects. Although these models may be of similar product systems, a direct comparison of existing results with this study is challenging due to the variation in the year of study, scope of research, and definition of key indicators.

The uncertainties and limitations associated with the study’s findings are predominantly restricted to data collection and analysis. Although data on certain aspects such as domestic recycling rates were easily accessible, quantitative information for other circular strategies such as the local reuse of products was difficult to obtain. Similarly, plastic-specific data was lacking for waste disposed in compliant and deficient landfills. The disaggregation of plastic material flows per polymer type was also unavailable for several disposal flows. As a proxy, the results of the cited waste characterisation study were utilised. It has also been noted that there are limitations due to the methodological approach, specifically due to the selection of pathways under assessment. As measures were assessed on the basis of available data, relevant targets, and potential for implementation in the local context, several strategies such as the introduction

of bioplastics and CCU, which were evaluated in other regions, were excluded from the scope of this research.

Due to data and method availability for the LCA component, international data and LCIA methods (including normalisation factors) were utilised where the local equivalents were unavailable. The lack of detailed information also played a role in the analysis of the additional indicators where figures for employment opportunities in countries which import polymers and finished goods to South Africa could not be retrieved. Similarly, degradation rates for certain receiving compartments were unavailable for several polymers for the persistence calculation with available rates based on typical plastic products. Nevertheless, the study still fulfilled the aim of estimating leakage in both terrestrial and marine environments without the focus being limited to ocean leakage as per the scope of other studies.

## CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

This thesis aims to develop and analyse potential future circular and low-carbon scenarios of the South African plastics sector. This involved the creation of several models depicting variations of the local plastics system, utilising two industrial ecology tools in tandem as detailed in Chapter 3. The results, which sought to assess the benefit of these measures based on their degree of circularity as well as the intensity of environmental impacts, were presented by considering the short-term impacts of fulfilling various voluntary and regulatory targets (Chapter 4) as well as extending the analysis by demonstrating the reduction potential of these scenarios in the medium-term and comparing to global targets (Chapter 5). This chapter seeks to firstly review the thesis contents by revisiting the research questions and the resulting research methodology. The conclusions are thereafter presented in relation to the research questions. The chapter concludes by stating policy recommendations as well as outlining future research needs.

### 6.1. Thesis Review

This thesis was centred around five primary research questions:

1. What would the future South African plastics sector look like if it is based on current activities without the implementation of any plastic pollution or energy-related mitigation measures?
2. How much of an improvement would achieving current voluntary and regulatory objectives be, in terms of indicators of circularity and whole life cycle environmental impacts?
3. How much of an effect could curbing domestic demand, by stimulating more reuse, have on circularity and indicators of environmental concern?
4. What impact reductions, beyond a reduced carbon footprint, would decarbonisation measures imply for the South African plastics value chain?
5. To what extent could the future South African plastics sector be classified as low-carbon and circular if all the mitigation strategies were implemented in concert?

To attend to these questions, four scenarios were constructed as detailed in Chapter 3. The Reference case, which maps the local plastics sector in 2018, formed the basis of the creation of a future system without any interventions in place, namely the Baseline scenario. Based on the local context as well as the literature review, the mitigation scenarios that were modelled

included improving the mechanical recycling rate (Increased Recycling scenario), managing plastic demand by introducing the reuse of products (Demand Moderation scenario), and decarbonisation of the energy mix and the local polymer supply (Decarbonisation scenario). To test the potential of integrating both material and energy-based strategies, a final scenario was created (Combination scenario). A mass flow accounting tool together with an environmental analysis tool (namely MFA and LCA) was used to model these scenarios. The results and discussion were presented in two stages: the first stage analysed the implications if short-term targets were met (up to 2025) followed by an additional analysis showing the potential if scenarios were extended from 2025 to 2035. The findings were presented in terms of circularity indicators and inventory-level plastic flows as well as environmental impacts with an exploratory short-term analysis performed on non-conventional indicators such as persistence and employment. As a final layer of assessment, selected indicators were compared to several international targets to demonstrate the potential of combining upstream and downstream measures within the local plastics value chain.

## **6.2. Conclusions**

### ***6.2.1. Reference Level and Baseline State***

The Reference case scenario suggests that in 2018, the South African plastics sector had an input recycling rate of 40.3%, emitted 16.8 Mt CO<sub>2</sub>eq, and was responsible for human health and ecosystem damage to the extent of 4.5 x 10<sup>4</sup> DALY and 84 species.yr respectively. Additionally, 342 kt of plastic debris was leaked into the environment, while employment opportunities across the local value chain totalled just over 77 000 in 2018. In the absence of policies and alternative measures, plastic production will continue to grow by an expected 675 kt over the period 2018-2035. This would lead to a projected increase of 4 kg/capita in waste generation, 38% increase in GHG emissions, and a 36-39% increase in other environmental impacts in 2035 relative to the results calculated for 2018. This is coupled with a minimal increase in recycled content of 1.1% as well as a projected rise in leakage of 34% over the studied timeline.

A hotspot analysis at the level of impacts identified human toxicity and ecotoxicity, fossil resource scarcity, and freshwater eutrophication as significant environmental categories of concern. Furthermore, the contribution analysis revealed that the majority of the quantifiable environmental impacts occur upstream as virgin monomer and polymer production and conversion constitute 55-85% of total impacts at the end of the environmental chain i.e. in terms

of Areas of Protection. It is noted that there are still no readily accepted scientific methods available to quantify the ultimate impacts of plastic leakage into the environment in these terms.

### ***6.2.2. Influence of Mitigation Strategies***

The results indicate that the Increased Recycling scenario is crucial to achieving a more circular and low-carbon local plastics system. By building upon the 2025 short-term voluntary and regulatory targets of the SA Plastics Pact and the National Waste Management Strategy, the recycled content of locally produced plastic products could increase to 56% by 2035 with a corresponding decline of 37% in leakage compared to the Baseline scenario. Additionally, using the voluntary recycling targets as a foundation could reduce other environmental impacts by 18-20% in 2035 relative to the Baseline scenario and on par with historical levels in 2018.

Despite the Demand Moderation scenario performing well in the short-term, its benefits in the medium-term are modest with a 2 kg/capita reduction in plastic waste and a 5% improvement in environmental performance in 2035 relative to the Baseline scenario. Whilst there is no tangible impact on the recycled content fraction, the decline in plastic demand results in a 6% decline in leakage in 2035 relative to the Baseline results. It is noted that the Demand Moderation scenario constructed and modelled is a rather modest one, shifting a small fraction of single- and short-term plastic use to reusable options. More aggressive demand moderation options could be envisaged, that reduce not only demand for plastic, but for the services it delivers.

The findings emanating from modelling the Decarbonisation scenario suggests that this measure could have a significant impact on the projected medium-term environmental performance of the system. The reduction potential of the scenario is emphasised particularly in 2035 when decarbonisation of both the energy supply and the local polymer production process is expected to result in a 44% decrease in Global Warming Potential as well as a 46% decline in ecosystem and human health impacts relative to the Baseline scenario. These results represent the greatest reduction from an environmental perspective amongst the individual strategies.

The contribution analysis for all the alternative scenarios reveals that the significant life cycle stages and individual processes remain the same as those identified for the Reference case and Baseline scenario.

### ***6.2.3. Impact of Combining Strategies***

As the final pathway, the Combination scenario integrated the previous mitigation options that were modelled independently. The findings indicate that the concurrent implementation of multiple system interventions results in the greatest environmental benefit amongst all the measured circularity and environmental impact indicators. In particular, the short-term gains achieved in 2025 increased to a projected 44% reduction in leakage and 55% in endpoint environmental damage in 2035 compared to the Baseline scenario. The degree of impact is highlighted by a threefold increase in recycled content together with a 38% reduction in estimated GHG emissions when comparing projected results in 2035 to historical figures in 2018. Despite these significant gains in circularity and environmental impacts, the combination of strategies is not enough to prevent leakage to the environment with an estimated 256 kt of plastic leaked to the environment in 2035.

The graphical presentation of the Combination scenario highlights the fact that although individual strategies such as moderating demand may have a moderate impact on indicators when modelled in isolation, the greatest gains are only materialised via modelling strategies in concert. Furthermore, the benchmarking exercise indicates that while the South African plastics sector would not reach absolute circularity nor a low to net-zero carbon state in the medium term, the coordination of upstream and downstream interventions facilitates the transition to a lower emitting and more circular future.

### **6.3. Recommendations**

The modelling results indicate that a more circular local plastics sector with a lower environmental footprint can be attained by utilising processes and technologies that are already available. Thus, policies that foster the implementation of these tools need to be encouraged and promulgated. These include policies that promote reuse as a business model and discourage the use of unnecessary single-use packaging. Additionally, improved design can increase the useful lifespan of products, thereby reducing plastics demand. Advancement in design is also essential to enable the execution of circular solutions throughout the value chain including safe reuse and recycling together with appropriate collection and sorting policies. These will also aid in the reduction and prevention of plastic leakage. On the decarbonisation aspect, the renewable energy transition needs to be enforced as a low-carbon energy mix is necessary for reduced environmental impacts, Furthermore, a lower carbon route is necessary to improve the environmental profile of the major monomer and polymer producer, Sasol.

The fulfilment of current ambitions requires alignment between technology and policy as well as economic incentives and market drivers. To harmonise research and policy-making, including the setting of targets, definitions of indicators and goals at a local, regional, and global level need to be standardised. Moreover, increased coordination between material and energy-related targets and recovery and recycling goals are necessary in the South African context.

#### **6.4. Future Research Needs**

This research identified several existing data gaps, which should be addressed by future research. Amongst these is the development of recycling datasets for plastic polymers as well as an update of country-specific waste mixes within the databases used for LCA modelling. The compilation of additional local datasets and regional normalisation factors are also necessary to improve the accuracy of results. Data are also needed within the South African recycling industry to estimate recycling rates of durable and long-lived products.

To accurately account for the effect of plastic pollution, a complete representation of all impacts attributed to debris within the LCA scope is required. Although characterisation factors assessing the impacts of aquatic microplastic emissions via the ecosystem quality damage category have been recently published, they are yet to be incorporated into current impact assessment methods. Furthermore, additional impacts related to plastic emissions also need to be considered. The impacts associated with employment also need to be fully investigated including the incorporation of opportunities within the import plastic market supplying the local sector with polymer and manufactured products.

The development of an updated global LCIA method will provide an opportunity to utilise revised factors in the calculation of human health, ecosystem, and natural resources as well as combine impacts into an aggregated score. Furthermore, the modelling of additional circular interventions such as chemical recycling to go beyond conventional mechanical recycling processes as well as CCU technologies should also be explored in the local context to enhance the mitigation potential of the modelled strategies.

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## APPENDIX A: Datasets

Table A 1: Datasets to Represent Polymer Production Processes including Adaptations

Polymer	Sub-type and Distribution	Unit process	Adaptations for SA process
HDPE		<i>Polyethylene, high density, granulate production {RoW}</i>	Average ethylene and propylene (local monomer) production mix {ZA} Chemical, organic, synthetic fuel from coal {ZA} Electricity mix, medium voltage {ZA} Water, unspecified natural origin {ZA} Waste plastic, mixture {ZA}
LDPE		<i>Polyethylene, low density, granulate production {RoW}</i>	Same as HDPE
PP		<i>Polypropylene, granulate production {RoW}</i>	Same as HDPE and LDPE
PET	30% amorphous	<i>Polyethylene terephthalate, granulate production, amorphous {RoW}</i>	Chemical, organic, synthetic fuel from coal {ZA} Ethylene glycol {GLO-ZA} Electricity mix, medium voltage {ZA} Water, unspecified natural origin {ZA} Waste plastic, mixture {ZA}
	70% bottle grade	<i>Polyethylene terephthalate, granulate production, bottle grade {RoW}</i>	Same as Amorphous PET
PVC		<i>Polyvinylchloride, production, bulk polymerisation {RoW}</i>	Combination of emulsion and suspension polymerised PVC Chemical, organic, synthetic fuel from coal {ZA} Vinyl chloride production, {RoW-ZA} electricity mix, medium voltage {ZA}

				Water, cooling, unspecified natural origin {ZA}
				Water, lake, river, and well {ZA}
				Waste plastic, mixture {ZA}
PS	50% purpose	general	<i>Polystyrene, production, general-purpose {RoW}</i>	Hard coal {ZA}
				Water, cooling, unspecified natural origin {ZA}
				Water, lake, river, and well {ZA}
				Waste plastic, mixture {ZA}
	50% impact	high	<i>Polystyrene, production, high impact {RoW}</i>	Same as general-purpose PS

**Table A 2: Datasets to Represent Conversion Processes including Adaptations**

<b>Technology</b>	<b>Unit process</b>	<b>Adaptations for SA process</b>
Stretch moulding (SBM)	blow <i>Stretch blow moulding {RoW}</i>	Electricity mix, medium voltage {ZA}
		Water, unspecified natural origin {ZA}
		Water{ZA} (Emissions to water)
		Waste plastic, mixture {ZA}
Injection (IM)	moulding <i>Injection moulding, processing {RoW}</i>	Chemical, organic, synthetic fuel from coal {ZA}
		Electricity mix, medium voltage {ZA}
		Polyethylene, low density, granulate production {RoW-ZA}
		Polypropylene, granulate production {RoW-ZA}
		Water, unspecified natural origin {ZA}

		Water{ZA} (Emissions to water)
		Waste plastic, mixture {ZA}
Extrusion (E & T)	<i>Extrusion of plastic sheets and thermoforming, processing, inline {RoW}</i>	Chemical, organic, synthetic fuel from coal {ZA}
		Electricity mix, medium voltage {ZA}
		Polypropylene, granulate production {RoW-ZA}
		Tap water {ZA}
		Water{ZA} (Emissions to water)
		Waste plastic, mixture {ZA}
Blow moulding (BM)	<i>Blow moulding {RoW}</i>	Electricity mix, medium voltage {ZA}
		Polyethylene, low density, granulate production {RoW-ZA}
		Water, unspecified natural origin {ZA}
		Water{ZA} (Emissions to water)
		Waste plastic, mixture {ZA}
Polymer Foaming	<i>Polymer foaming, processing {RoW}</i>	Electricity mix, medium voltage {ZA}

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Water, unspecified natural origin  
{ZA}

Water{ZA} (Emissions to water)

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**Table A 3: Datasets to Represent End-of-Life Processes including Adaptations**

<b>Process</b>	<b>Unit process</b>	<b>Adaptations for SA process</b>
Sanitary landfill	<i>Waste plastic, mixture, treatment of waste plastic, sanitary landfill {RoW}</i>	Electricity mix, low and high voltage {ZA} Cement, unspecified {ZA}
Unsanitary landfill	<i>Waste plastic, mixture, treatment of waste plastic, unsanitary landfill, dry infiltration class (100mm) {GLO}</i>	N/A
Open dump	<i>Waste plastic, mixture, treatment of waste plastic, open dump, dry infiltration class (100mm) {GLO}</i>	N/A
Open burning	<i>Waste plastic, mixture treatment of waste plastic, open burning {GLO}</i>	N/A