Dissecting the Metabolism of South Africa's Power House: Mpumalanga

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Abstract

Combatting anthropogenic climate change, arguably the biggest threat facing humanity, necessitates the phasing out of fossil fuels. In this context, South Africa’s heavy reliance on coal for primary energy and electricity presents significant challenges, intensified by the nation's persistent issues of poverty, inequality, and unemployment. The risks inherent in the country’s inevitable shift away from coal are, however, unevenly distributed.

The province of Mpumalanga plays a pivotal role in powering the nation with its coal-fired power stations, placing it at the heart of South Africa's energy transition. This dissertation sets out to provide an empirical and theoretically grounded contribution to the extensive research being done to inform and guide Mpumalanga's transition. Employing the lens of social metabolism, this study collates and analyses the province's material, energy and water flows, which are foundational to its economic structure. The primary objective is to present a baseline metabolic assessment of Mpumalanga for the year 2017, as defined by its provincial boundaries. This involves regionalising national accounts to the province's unique context, ascertaining the need for and availability of additional data, and developing provincial metabolic indicators.

The concept of social metabolism has gained recognition for its utility in sustainability assessments, yet its application in South Africa, and specifically within Mpumalanga, remains limited. To achieve the research objectives, the dissertation adopts a quantitative approach that adheres to an established economy-wide material flow analysis framework. To make it a metabolic analysis, this approach is broadened to account for both nutritional and technical energy flows, alongside water. Data were sourced from both national and provincial statistics, as well as industry reports. Where data were lacking or insufficient, estimates were derived from national accounts using proxies. It is recognised that the study's reliance on quantitative metrics limits its scope, focusing on the province's metabolism without delving into the influence of regulatory mechanisms that shape the observed flows. The resulting metabolic profile of the province is analysed within the dual contexts of Mpumalanga’s own energy dynamics and the broader national trends towards sustainability.

The analysis reveals Mpumalanga's coal-centric socio-economic metabolism, dominated by coal exports, electricity generation, coal-to-liquid processes, and heavy industry (smelters). This is quantitatively evident in the province's significant per capita domestic extraction (65 tons), net exports (22 tons), air emissions (14 tons) and extractive waste (12 tons). All these exhibit intensities surpassing the national average seven- to thirteen-fold, on both a per capita and per area basis. Moreover, coal's dominance is reflected in the province's technical energy and water flows, with coal accounting for 97% of domestic technical energy inputs and with 17% of the water supply allocated to coal-based energy infrastructure, more than five-times the national

average. This overwhelming focus on coal has likely led to the suppression of other resource flows and their associated industries, with agriculture being the most obviously affected.

In preparation for Mpumalanga's transition to a low carbon economy, it is recommended to strategically reduce the province's coal dependency alongside actively planning for revitalising and growing supressed and alternative metabolic pathways. The coal phase-out should offer opportunities in water, renewable energy, and agriculture. However, further efforts are necessary to improve data monitoring and reporting at the sub-national level, as well as to identify and explore strategic alternative pathways for economic diversification within the province.

Acknowledgments

I would like to express my sincere gratitude to all those who have supported me throughout the journey of completing this dissertation.

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Last but not least, a special thank you to my family and friends for their constant encouragement. A heartfelt mention to Ross for his steadfast belief in me and to my father, Mark, for imparting the wisdom of a well-placed comma and for always reminding me that punctuation is no small matter – lest we eat, shoot, and leave.

Contents

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List of Acronyms

BOKU	The University of Natural Resources and Life Sciences, Vienna
CER	Centre for Environmental Rights
CSIR	Council for Scientific and Industrial Research
DARDLEA	Department of Agriculture, Rural Development, Land and Environmental Affairs
DE	Domestic Extraction
DEA	Department of Environmental Affairs
DEC	Domestic Energy Consumption
DEDT	Department of Economic Development and Tourism
DEI	Domestic Energy Input
DM	Dry Matter
DMC	Domestic Material Consumption
DMI	Domestic Material Inputs
DMRE	Department of Mineral Resources and Energy
DPO	Domestic Processed Output
DU	Dissipative use
DWS	Department of Water and Sanitation
EoL	End-of-life
Eurostat	European Union Statistical Division
eUse	Energetic use
EW-MFA	Economy-wide Material Flow Analysis
FAO	Food and Agriculture Organisation
GCV	Gross Calorific Value
GDP	Gross Domestic Product
GHG	Greenhouse Gas

GHS	General Household Survey
HANPP	Human appropriation of net primary production
IASS	Institute for Advanced Sustainability Studies
IET	International Energy Transition
IntOut	Interim Output
IPCC	Intergovernmental Panel on Climate Change
IPCC	Intergovernmental Panel for Climate Change
IRP	Integrated Resource Plan
IUCMA	Inkomati-Usuthu Catchment Management Agency
MMT	Methylcyclopentadienyl manganese tricarbonyl
mUse	Material use
NAS	Net Addition to Stock
NCV	Net Calorific Value
NRW	Non-revenue Water
PCC	Presidential Climate Commission
PM	Processed materials
SA-LEDS	South Africa’s Low Emission Development Strategy
SAMI	South Africa’s Mineral Industry
SASoW	South Africa State of Waste
SAWIC	South Africa’s Waste Information Centre
SEEAW	United Nations integrated environmental and economic accounting for water resources
SFRA	Stream Flow Reduction Activity
SLO	Solid and liquid outputs
SM	Secondary materials
StatsSA	Statistics South Africa
TDS	Total Dissolved Solids

TMR	Total Material Requirement
TWQR	Total Water Quality Ratings
UNEP	United Nations Environment Programme
USGS	United States Geological Survey
WMA	Water Management Area
WWTW	Wastewater Treatment Works

List of Symbols

%	Percentage
C	Carbon
Cap	Capita
CO_2	Carbon Dioxide
GWh	Gigawatt hours (one billion watt hours)
Ha	Hectare
km	Kilometres
kt	Kiloton (one thousand metric tons)
L	Litre
l/c/d	Litres per capita per day
m^3	Cubic metres
MJ/kg	Megajoule per kilogram
Mm^3	Million cubic metre
Mt	Megaton (one million metric tons)
MW	Megawatt
MWh	Megawatt hour (one million watt hours)
N	Nitrogen
O	Oxygen
ºC	Degrees Celsius
PJ	Petajoule (one million billion joules)
S	Sulphur
t	Metric ton
TJ	Terajoule (one trillion joules)
yr	Year

Chapter 1 : Introduction

1.1. Background

Anthropogenic climate change is arguably the biggest threat facing humanity today. Unequivocal evidence shows that in order to avert the worst impacts of climate change and maintain a liveable planet, the rise in average global temperature needs to be limited to 1.5ºC above pre-industrial levels (Intergovernmental Panel on Climate Change [IPCC], 2022). Given that the energy sector is responsible for around two thirds of global greenhouse gas (GHG) emissions, the sector is integral to achieving net-zero emissions and limiting the effects of climate change (IPCC, 2022). Humanity's extraction and combustion of fossil fuels is, however, not the only global issue that needs to be addressed. Other sustainability challenges that need to be addressed include, but are not limited to, poverty, inequality, hunger, environmental degradation and biodiversity loss.

Transitioning to a sustainable and low carbon society is thus a major task and will require large-scale, society-wide shifts across multiple socio-technical systems, involving major changes in infrastructure and the provision and consumption of services and resources (Fischer-Kowalski, 2011; Haberl *et al.*, 2011; Swilling, 2020). The level of change needed can be likened to historical socio-metabolic regime shifts where society's patterns in material and energy use altered significantly along with society's modes of production and reproduction. Considering the fact that many of these global challenges are interconnected, it is essential that systemic interdisciplinary approaches are followed to mitigate trade-offs and maximise synergies.

South Africa faces a host of sustainability challenges and is particularly vulnerable to climate change. High levels of poverty, inequality and unemployment are felt throughout the country and in recent years the country has experienced an increase in the frequency and intensity of extreme weather events (IPCC, 2022; Presidential Climate Commission [PCC], 2022). Severe droughts and floods have caused massive damage to infrastructure, ecosystems and livelihoods, displacing thousands of people and placing additional strain on the provision of water and food (PCC, 2022). As one of the top 20 global emitters of greenhouse gases, South Africa has pledged to contribute to global efforts to limit the rise in average global temperature (South Africa's Low-Emission Development Strategy [SA-LEDS], 2020). Transitioning to a low carbon economy in South Africa is likely to require the complete phase out of coal for power generation, which poses considerable risks to both economic growth and sustainable development if not managed properly (Burton, Marquard and McCall, 2019; Strambo, Burton and Atteridge, 2019; SA-LEDS, 2020; PCC, 2022). Currently in South Africa, coal makes up around 74% of the primary energy supply and about 80% of the electricity generation mix (Climate Transparency, 2022; Pierce and Le Roux, 2023). Additionally, coal is responsible for around 70% of South Africa's GHG emissions, the majority of which can be linked directly to two entities: Eskom and Sasol (Department of Agriculture, Rural Development, Land and Environmental Affairs [DARDLEA], Unpublished). The coal-based infrastructure and associated impacts, such as those on air and water quality, are not evenly distributed across the country, but are concentrated in the province of Mpumalanga (DARDLEA, Unpublished).

Mpumalanga is the second smallest of South Africa's nine provinces, the fourth largest contributor to national gross domestic product (GDP) and home to almost half of the country's high potential arable land (DARDLEA, Unpublished). The province is also home to vast coal fields and provides more than 80% of the country's coal, a fair share of which is exported and generates significant revenue (DARDLEA, Unpublished). Strategically located close to the mines are coal-fired power stations, which collectively generate around 75% of the country's electricity (Roselt and Mpofu, 2021; Montmasson-Clair *et al.*, 2022; DARDLEA, Unpublished). Another large consumer of coal in the province is Sasol's coal-to-liquids fuel plant (DARDLEA, Unpublished). Despite the crucial role the province plays in the country's economy, its dependence on coal has resulted in serious risks relating to air, water and land quality, which impacts human health and water and food security, as well as exacerbating biodiversity loss (Centre for Environmental Rights [CER], 2018; Simpson *et al.*, 2019; DARDLEA, Unpublished). This is an area of great concern given that the province is among the largest producers of the country's staple food, maize, and is considered to be important in terms of biodiversity, possessing key wetland systems and other important habitats (Simpson *et al.*, 2019).

From the nation's Integrated Resource Plan (IRP) (2019), it is clear that Mpumalanga will be strongly affected in the coming years as the country's shift away from coal accelerates. This effectively places the province at the heart of the nation's energy transition. Consequently, the province has received considerable policy attention on the energy transition. The policy interventions and strategies implemented include a Just Transition Strategy, a Green Economy Development Plan, the recent formation of the Mpumalanga Green Cluster, as well as plans to repower and repurpose decommissioned coal-fired power plants and mines (Burton, Marquard and McCall, 2019; Strambo, Burton and Atteridge, 2019; Institute for Advanced Sustainability Studies [IASS]/International Energy Transition [IET]/Council for Scientific and Industrial Research [CSIR], 2022; Montmasson-Clair *et al.*, 2022; DARDLEA, Unpublished). Additionally, recent analyses have been undertaken in strategic intervention areas including energy, water and agriculture in the hopes that they will inform economic diversification and job creation in the province (Nyamadzawo, 2021; Roselt and Mpofu, 2021; Shal, 2021). However, none of these represent an integrated systemic assessment of the province's material and energy flows.

The concept of social metabolism has emerged as a systemic approach to assesses the sustainability of nature-society interactions (Haberl *et al.*, 2019). Quantitative socio-metabolic tools can provide empirical assessments of both the physical and energetic dimensions of economies that can then be used to inform, monitor and guide strategies towards sustainable development. Performing a socio-metabolic accounting study across the province of Mpumalanga could provide insights into the current status quo of the province’s material, energy and water flows, which facilitate the province’s economy. This, in turn, could contribute to the existing empirical assessments that are currently informing the transition away from coal in the province as well as the wider sustainability orientated transition.

1.2. Problem Statement

The province of Mpumalanga faces numerous risks associated with the inevitable transition to a low carbon economy. However, there is limited research from which to systemically evaluate and inform sustainable development plans and strategies for the future of the province. The growing field of social metabolism has emerged as a useful concept, with numerous analytical tools, to monitor, inform and guide sustainability. Socio-metabolic studies have been performed to a limited extent in South Africa but never for the province of Mpumalanga. Thus, the overall objective of the proposed research is to conduct a baseline metabolic study for Mpumalanga, as defined by the provincial boundaries, encompassing material, water and energy flows.

Rather than being confirmatory, the proposed research is exploratory and sets out to explore the relationships between and within material, energy and water flows for the province. Thus, a key research question is defined below instead of a hypothesis (Colaço, 2018).

1.3. Aims and Objectives

Key Research Question:
What insights can a baseline metabolic analysis of Mpumalanga provide that could potentially be used to inform and guide strategies to increase the sustainability of the province?

Sub-Research Questions:

1. Is there adequate data to establish a comprehensive baseline of the province's flows of materials, water and energy?
2. What are the provincial metabolic indicators?
3. What does the metabolic profile indicate about Mpumalanga’s socio-metabolism and how does it compare to the results of the most recent national study?
4. Which material and energy flows are most susceptible to changes from the province's shift towards a low carbon society?
5. Does incorporating energy and water flows enhance our understanding of the nature of Mpumalanga's metabolism beyond what is revealed by standard material flow analysis?

1.4. Limitations

The main limitation of the study is that it omits the regulation mechanisms behind the material and energy flow accounts, which could provide insights into how exactly change may play out in the province.

1.5. Dissertation Structure

The structure of this dissertation is depicted in Figure 1-1. The first chapter, the Introduction, sets the stage for the study by giving background information, context, and the reason behind this study, in addition to, the main research questions. Following this, the next chapter reviews relevant literature to provide a solid base for the study. It focuses on the province of Mpumalanga, the concept of social metabolism, quantitative methods for measuring social metabolism and existing socio-metabolic research in South Africa.

Chapter 3 explains the research methodology used to carry out a baseline metabolic study for the province. It starts with describing the material flow accounting approach, followed by energy and water. The main data sources, processing techniques and adaptations from general practice are all explained. Chapter 4 presents the results of the material flow, energy and water accounts for Mpumalanga in 2017, separately and in that order. This chapter looks at the size and main features of the provincial metabolic profiles, leaving the systemic interpretation of the results for Chapter 5.

Chapter 5 interprets the data presented earlier, giving a better understanding of the findings in a broader context. Lastly, Chapter 6 concludes the research by highlighting the key findings and suggesting recommendations for future research.

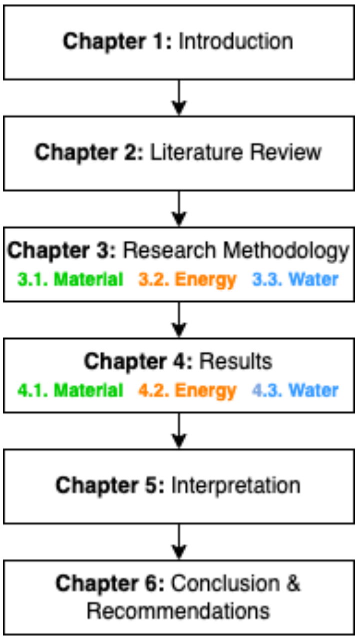


Figure 1-1: Dissertation Structure

Chapter 2 : Literature Review

This chapter reviews publications relevant to the topic of this dissertation. It starts by further unpacking the current sustainability challenges present in Mpumalanga and reviews the relevant literature that is specific to the region. Following this, the concept of social metabolism is introduced and an account of its central principles and research traditions is provided: the insights gathered thus far are highlighted. The quantitative methods to operationalise the metabolic approach are also discussed with a focus on material flow analysis and a widening of the scope thereof. Lastly, a synthesis of socio-metabolic research in South Africa is presented.

2.1. Transition Risks in Mpumalanga

The province of Mpumalanga has been identified as a priority area with respect to South Africa’s transition to a low carbon economy, for reasons outlined earlier (Department of Mineral Resources and Energy [DMRE], 2021). The majority of the recently published work on the province focusses on a just transition away from coal. While the definition of a just transition remains contested in South Africa, these reports underline the key risks and potential opportunities of phasing out coal in the region (Burton, Marquard and McCall, 2019; Strambo, Burton and Atteridge, 2019; Nyamadzawo, 2021; Roselt and Mpofu, 2021; Shal, 2021; IASS/IET/CSIR, 2022; Montmasson-Clair et al., 2022; DARDLEA, Unpublished). The risks associated with the transition include (thousands of) job losses throughout the coal value chain and other heavy industries, a reduction in coal exports and resultant revenue, as well as a massive decline in the formal and informal local economy (Burton, Marquard and McCall, 2019; DMRE, 2021b; PCC, 2022). The effects of these changes are expected to be higher in municipalities that have a higher economic dependence on coal, Figure 2-1, and they are expected to exacerbate the current levels of regional poverty, inequality and unemployment (Bohlmann et al., 2019; Montmasson-Clair et al., 2022; DARDLEA, Unpublished).

The opportunities for the province are predominantly based on economic diversification and include the development of a circular economy, sustainable agriculture, green infrastructure and transport, eco-tourism and ecosystem-based adaptation (DARDLEA, Unpublished). The Mpumalanga Green Cluster Agency has published a series of green economy market opportunity briefs for sectors that detail key investment opportunities to assist in economic diversification and job creation (Nyamadzawo, 2021; Roselt and Mpofu, 2021; Shal, 2021). However, prior to implementing these sector opportunities, the sustainability implications need to be assessed which will require updated and comprehensive empirical data from which to conduct the necessary risk assessments (DARDLEA, Unpublished).

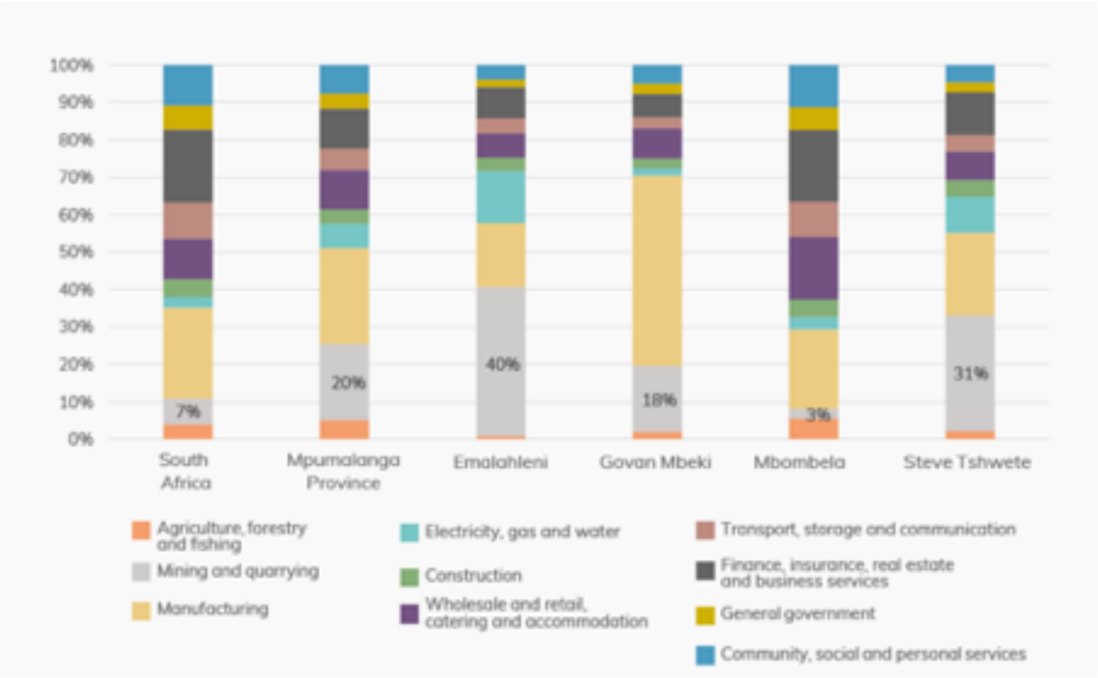


Figure 2-1: Gross value added shares in Mpumalanga and high-risk municipalities; taken from Montmasson-Clair et al. (2022).

A number of academic studies have been conducted that detail the environmental and health impacts of the province's economic activities, particularly the impacts linked to mining and coal-fired power generation. These include studies on air pollution, water quality, soil degradation and biodiversity loss (Steyn and Herselman, 2006; Holland, 2017; CER, 2018). Eskom's coal-fired power stations (80% of which are situated in the province) generate significant quantities of air pollutants, causing premature deaths and increased levels of illness (Holland, 2017). Coal and other mining practices have reduced the quality of both surface and groundwater, largely as a result of acid mine drainage (CER, 2018). The soil quality in the region has deteriorated due to poor mining practices, as well as the overapplication of fertilisers for agricultural production (Steyn and Herselman, 2006). These environmental implications are re-iterated in the province's Environmental Outlook Report 2018/19, where negative environmental trends in air quality, waste management, land, climate and climate change, water and biodiversity have been observed (DARDLEA, 2019).

Despite the above-listed studies, few have been conducted in the region that holistically investigate the interactions between sectors. One particular study stands out in this regard, that by Simpson and colleagues (2019), and it semi-quantitatively analyses the complex interactions and resultant trade-offs between water, energy and food in the province. The study illustrates that the availability and quality of water resources is at risk due to the impacts of extensive mining and agricultural activities, and it emphasises the effects too of climate change (Simpson et al., 2019), which, in turn, is expected to impact both food and energy security. This is reflected by the fact that agriculture consumes just under half of the province's surface water, while mining, heavy industries and power generation collectively consume just under 20% (Simpson et al., 2019; Roselt and Mpofu, 2021). Competition for land between the agricultural and energy sectors is also stressed, with a significant proportion of the region's (potentially abundant) arable land either being mined or subjected to prospectus mining rights as illustrated in Figure 2-2 (Simpson et al., 2019). These authors highlight the need for empirical assessments to inform integrated public policy so that resource security issues and land-use conflicts can be addressed in a way that promotes sustainability.

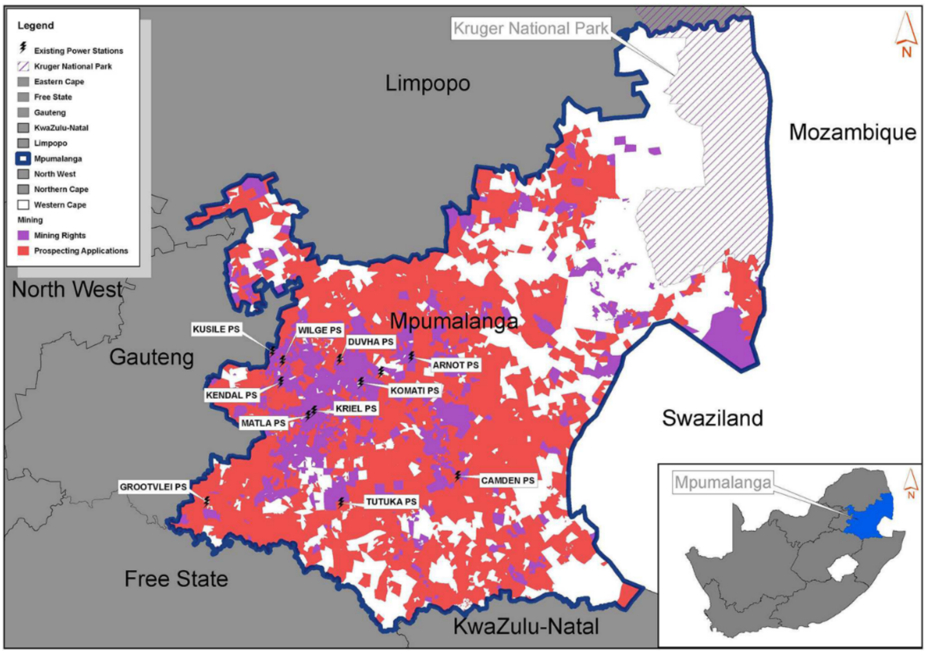


Figure 2-2: Map of The province of Mpumalanga showing the coal-fired power stations, mining rights and farms where prospecting applications have been submitted; taken from Lotter (2010).

2.2. Social Metabolism

The concept of social metabolism, also referred to as "economic", "socio-economic" or "society's" metabolism, regards human societies as organisms. The concept can be traced back to the 1860s when Marx and Engels first applied the term metabolism to social systems in an effort to describe the labour process (Fischer-Kowalski, 1998). It was not until the late 20th century, however, that the concept started to gain traction within the general field of socio-environmental studies (Fischer-Kowalski, 1998). The modern concept has emerged as a holistic approach to studying society-nature interactions and encompasses both material and energy flows exchanged between society and nature as well as flows within and between social systems (Pauliuk and Hertwich, 2015; Haberl *et al.*, 2019).

Social metabolism is regarded as a key concept to promote the sustainability agenda and it has been widely adopted within interdisciplinary fields including industrial ecology, ecological economics and integrated land-change science (Pauliuk and

Hertwich, 2015; Krausmann *et al.*, 2017; Haberl *et al.*, 2019). Pauliuk and Hertwich (2015) argue that the concept of social metabolism is “a powerful boundary object that can serve as a research paradigm for studying the biophysical basis of human society”. This, in turn, can enable comprehensive assessments of sustainable development strategies that bridge the gap between the natural and social sciences (Pauliuk and Hertwich, 2015).

Haberl *et al.* (2019) describes three key principles upon which socio-metabolic research builds. Firstly, human society relies on a continuous throughput of materials and energy to maintain its function, as illustrated in Figure 2-3. Society’s ability to organise (transform, distribute etc…) these biophysical flows, extracted from the environment, dictates the production and reproduction of human society’s population, livestock, infrastructure and other material stocks (Pauliuk and Hertwich, 2015; Haberl *et al.*, 2019). Secondly, the principles of thermodynamics are applicable to the metabolic processes of societal structures, including the economy. Rather than biophysical flows being ‘consumed’ by society, they are processed, transformed and stored, but eventually leave the system in the form of waste and emissions (Krausmann *et al.*, 2017; Haberl *et al.*, 2019). Lastly, society’s resultant impact and stress on the environment is determined by “the composition, magnitude and patterns of its social metabolism”; also referred to as society’s metabolic profile (Haberl *et al.*, 2019). It has been argued that many of the environmental sustainability challenges facing human society today can be directly linked to its metabolism (Krausmann *et al.*, 2017).

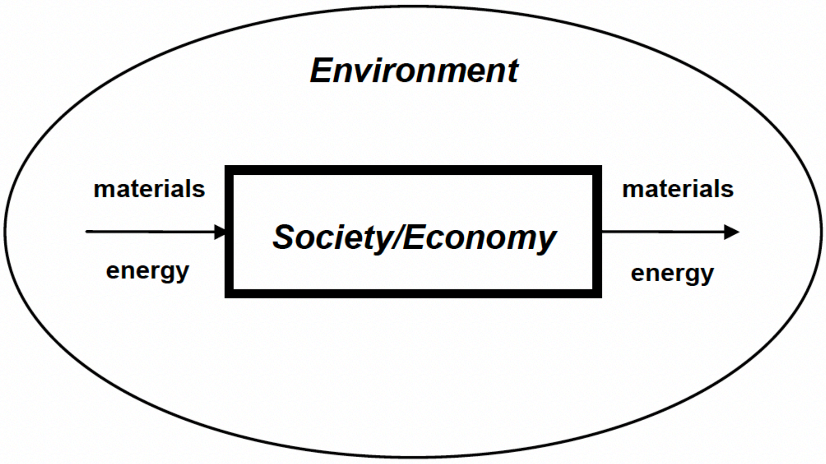


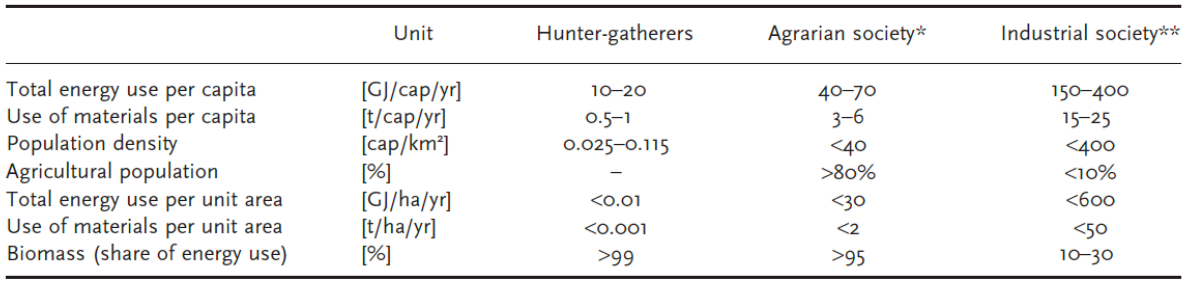
Figure 2-3: The environment and social system; taken from Eurostat (2001).

Haberl *et al.* (2019) conducted a review of a number of research traditions within the field of social metabolism that have emerged including, but not limited to, urban metabolism, multi-scale integrated analysis of societal and ecosystem metabolism, biophysical economics, material and energy flow analysis and environmentally extended input-output analysis. While these approaches are shown to overlap in many regards, they diverge in scope depending on the research purpose (Gerber and Scheidel, 2018; Haberl *et al.*, 2019). Urban metabolism and biophysical economics, for example, both investigate aspects of the biophysical basis of society, building on the three aforementioned assumptions, though urban metabolism focuses solely on urban systems while biophysical economics focuses primarily on the role energy plays in the economy (Haberl *et al.*, 2019). All socio-metabolic research traditions have their own strengths and weaknesses and are usually accompanied by quantitative methods that provide the foundations for empirical analysis (Pauliuk and Hertwich, 2015; Gerber and Scheidel, 2018; Haberl *et al.*, 2019).

To date, socio-metabolic research has provided a number of valuable insights into the patterns, drivers, feedbacks and implications of nature-society interactions for a range of different systems across multiple spatial and temporal scales (Haberl *et al.*, 2019). Long-term historical studies on social metabolism have identified three distinct socio-metabolic profiles; hunter-gatherers, agrarian and industrial society, although the latter is currently contested (Krausmann *et al.*, 2008; Fischer-Kowalski, 2011; Haberl *et al.*, 2011). These specific modes of human production and reproduction are also referred to as socio-metabolic regimes and can be characterised by their unique patterns in material and energy flows as depicted in Table 2-1 (Krausmann *et al.*, 2008; Haberl *et al.*, 2011). Other distinguishing characteristics include differences in population dynamics, institutional organisation, economic and governance structures and knowledge transfer mechanisms (Krausmann *et al.*, 2008; Haberl *et al.*, 2011).

According to the theory of socio-metabolic regimes, the most basic constraint for the differentiation of regimes is the energy system, including the dominant energy source and associated energy conversion technology (Krausmann *et al.*, 2008; Fischer-Kowalski, 2011). The energy system of the hunter-gatherers is characterised by biomass harvesting without human intervention and is based on the use of uncontrolled solar energy; the agrarian society is typified by biomass harvesting with intervention and the use of controlled solar energy, while the industrial society is characterised by the extensive use of fossil fuels (Haberl, 2001).

Table 2-1: Metabolic profiles of hunter-gatherers, agrarian and industrial society; taken from Haberl et al. (2011).



	Unit	Hunter-gatherers	Agrarian society*	Industrial society**
Total energy use per capita	[GJ/cap/yr]	10–20	40–70	150–400
Use of materials per capita	[t/cap/yr]	0.5–1	3–6	15–25
Population density	[cap/km²]	0.025–0.115	<40	<400
Agricultural population	[%]	–	>80%	<10%
Total energy use per unit area	[GJ/ha/yr]	<0.01	<30	<600
Use of materials per unit area	[t/ha/yr]	<0.001	<2	<50
Biomass (share of energy use)	[%]	>99	>95	10–30

The theory of socio-metabolic regimes also claims that, within a regime, a dynamic equilibrium exists between nature and society and should certain conditions exceed the regime's critical threshold, a transition process is started (Krausmann *et al.*, 2008). Transitions from one socio-metabolic regime to another have occurred throughout history and illustrate the evolution of mankind and human societies (Beyers and Swilling, 2016). Transitioning from one regime to the next constitutes a fundamental re-organisation of material and energy flows (Krausmann *et al.*, 2008; Fischer-Kowalski, 2011; Haberl *et al.*, 2011; Beyers and Swilling, 2016). Table 2-1 compares the patterns in material and energy use for the three socio-metabolic regimes detailed above and illustrates the differences in size, scale and composition of flows and fluxes.

Quantitative research approaches have provided empirical data on historical and current metabolic profiles, as well as their future trajectories, which have in turn corroborated the need for a transition to a more sustainable way of life; essentially a new socio-metabolic regime (Krausmann *et al.*, 2008; Haberl *et al.*, 2011).

2.3. Quantitative Analysis of Social Metabolism

Quantitative methods are a central component of socio-metabolic research because they form the basis for the empirical analysis of society's biophysical flows and stocks, which can be used to inform, guide and monitor sustainability strategies (Haberl *et al.*, 2019). A number of quantitative research methods exist ranging from descriptive physical modelling approaches and footprint-type methods to prospective methods (Pauliuk and Hertwich, 2015). Material flow analysis, often used interchangeably with "material flow accounting", is a commonly used method to quantify the material throughput of society/social systems. Other quantification methods include energy accounting, life cycle assessment and footprint-type methods. All the latter can be used in conjunction with material flow analysis to widen the scope of any analysis for application to different systems and address different research objectives (Krausmann *et al.*, 2017).

2.3.1. Material Flow Analysis

Material flow analysis applies a mass balance approach to comprehensively assess the flow and stock of materials through a defined social system: total input = total output + net accumulation (Huang *et al.*, 2012; Krausmann *et al.*, 2017). The results of this provide a systemic account, in tons (t), that can then be used to analyse the interactions between material flows, human activities and environmental pressures (Huang *et al.*, 2012; Krausmann *et al.*, 2017). Material flow analysis can be applied to different spatial and temporal scales for a range of different systems and materials (Huang *et al.*, 2012; Krausmann *et al.*, 2017). Substance flow analysis, for example, traces groups of related substances or individual chemical elements through supply chains typically linked to a product or service, while economy-wide material flow analysis (EW-MFA) traces the entire material throughput of national economies (Huang *et al.*, 2012).

Until now, research in material flow analysis has largely focussed on quantifying and comparing economy-wide material accounts at the national scale. The first record of a national material flow analysis can be traced back to 1969, when Robert Ayres and Allen Kneese developed a physical account of the economy in the United States to complement the standard monetary analysis (Fischer-Kowalski *et al.*, 2011). The conceptual basis and methodological standards of material flow analysis were advanced in the 1990s by research institutions in Japan, Germany, and Austria; first independently and then as a collective (Fischer-Kowalski *et al.*, 2011). Following this development, a methodological guide to EW-MFA was published by the Statistical Office of the European Union (Eurostat) in 2001, which provided a standardised approach to account for the physical dimension of the economy (Fischer-Kowalski *et al.*, 2011; Krausmann *et al.*, 2017). Since then, the methodology has been widely applied, predominantly in the Global North, and it has been adopted into national and international environmental reporting mechanism's including that of the European Union, the Organisation for Economic Co-operation and Development and the United Nations System of Environmental-Economic Accounting (Fischer-Kowalski *et al.*, 2011; Krausmann *et al.*, 2017).

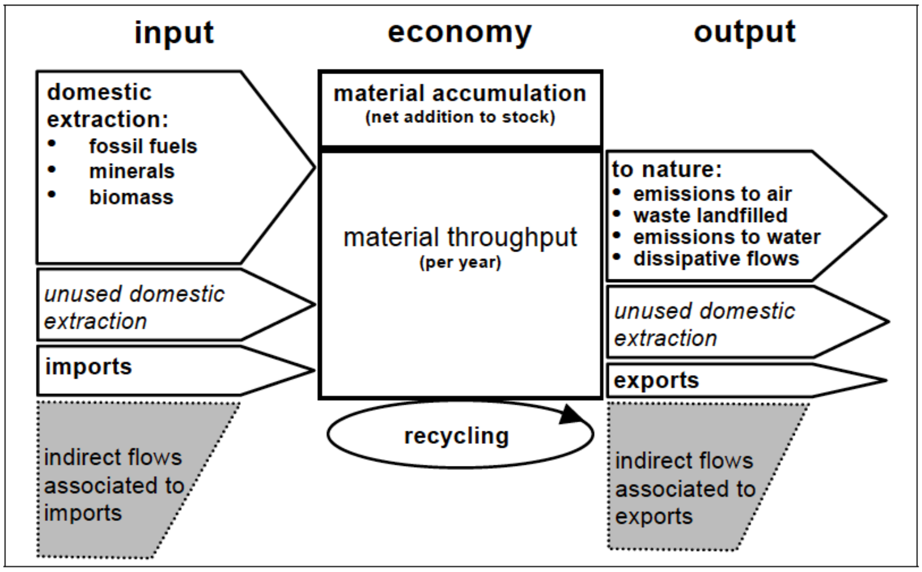


Figure 2-4: Material balance scheme for economy wide material flow analysis (EW-MFA) (excl. air and water); taken from Eurostat (2001).

The Eurostat EW-MFA framework accounts for direct and indirect flows coming into and out of the economy as well as material accumulation within the economy, see Figure 2-4 (Eurostat, 2001). Biomass, fossil fuels and minerals form the basis of the material inflows while emissions to air, emissions to water, dissipative flows and waste landfilled form the basis of material outflows. Bulk flows of liquid water are excluded from the framework due to their much larger relative size and it is recommended that they be presented in separate water flow accounts (Eurostat, 2018). Aggregated indicators derived from material flow analysis (e.g. domestic material consumption

[DMC] and total material requirement [TMR]) have provided valuable insights into society's material consumption, resource intensity and efficiency as well as environmental pressures (Krausmann *et al.*, 2017). However, material flow analysis has received criticism for aggregating a wide range of materials with different impacts on the basis of mass (Krausmann *et al.*, 2017). Despite the criticism, material flow indicators have been highlighted as invaluable for natural resource management and sustainable development (Bringezu *et al.*, 2016; Krausmann *et al.*, 2017; Haberl *et al.*, 2019). In the past decade, material flow analysis studies have started to focus more on strategies for decoupling resource use and economic growth, dematerialisation of the economy and promoting the circular economy (Huang *et al.*, 2012; Krausmann *et al.*, 2017; Haberl *et al.*, 2019).

While the EW-MFA framework was initially designed for national scale assessments, it has been adapted for application at sub-national scale including cities, towns and regions (Xu *et al.*, 2008; Barles, 2009; Kovanda, Weinzettel and Hak, 2009; Hoekman and von Blottnitz, 2017; Voskamp *et al.*, 2017; Wiedmann, Athanassiadis and Binder, 2023). Given the fact that biogeographical factors and resource endowment can vary significantly within countries, application at lower spatial scales is recommended to enable a better understanding of area-specific impacts (Krausmann *et al.*, 2008, 2017; Kovanda, Weinzettel and Hak, 2009). Such, in turn, can inform spatially-explicit sustainability debates like water scarcity, biodiversity loss and land-use conflicts as well as unequal regional development (Krausmann *et al.*, 2017). However, no mature standardised methodology exists for material flow analysis at sub-national scale, and a study by Patrício and colleagues (2015) indicated that lower scale accounts are generally accompanied by higher levels of uncertainty due to data limitations; data availability, sparsely spread data, aggregation of uncertainties and low confidence values (Patrício, Kalmykova and Rosado, 2015). These challenges are re-iterated in a more recent study by Wiedmann, Athanassiadis and Binder (2023).

2.3.2. Widening the Scope of Material Flow Analysis

It has been argued that focussing solely on material flows is insufficient to holistically promote and inform sustainable development. Widening the scope of material flow analysis, through combining socio-metabolic approaches, can facilitate a deeper understanding of social metabolism, which in turn can increase the applicability of the results and reduce the risk of shifting problems (Haberl, 2001a; Huang *et al.*, 2012; Bringezu *et al.*, 2016; Voskamp *et al.*, 2017).

Haberl (2001a) states that in order fully exploit the metabolic approach, it is necessary to understand both the energetic metabolism of society as well as the material dimension. Afterall, human society is reliant on both energy and material flows to maintain its metabolism. While a number of energy accounting frameworks and models exist, they focus predominantly on technical energy and provide indicators on the primary energy use by society (Haberl, 2001a). Haberl argues that these conventional energy balances omit a significant component of society's energy throughput: nutritional energy for livestock and humans (Haberl, 2001a). To address this gap, Haberl details an energy accounting framework that is consistent with the economy-wide material flow analysis to account for both nutritional and technical energy components of society's metabolism (Figure 2-5) (Haberl, 2001a).

The methodology has since been applied in a number of different socio-metabolic studies (Haberl, 2001a, 2006; Krausmann and Haberl, 2002; Haberl *et al.*, 2004). It has been recommended that material and energy flow accounting should be applied with the Human Appropriation of Net Primary Production (HANPP) to successfully assess land use changes, thereby strengthening the linkages between energy policy and land-use policy for sustainable development (Haberl *et al.*, 2004). Long-term studies looking at the energetic metabolism of society have provided insights into the sustainability implications of society's unprecedented rise in energy throughput, namely a reduction in energy available for ecosystem processes and a change in the global carbon cycle (Haberl, 2006). Haberl's method for analysing the energetic metabolism of society is, however, not without criticism and has been questioned for its reductionist approach, which simplifies a complex array of energy forms and processes into a single measurement, potentially overlooking the nuanced differences and impacts of various energy types (Giampietro, 2008).

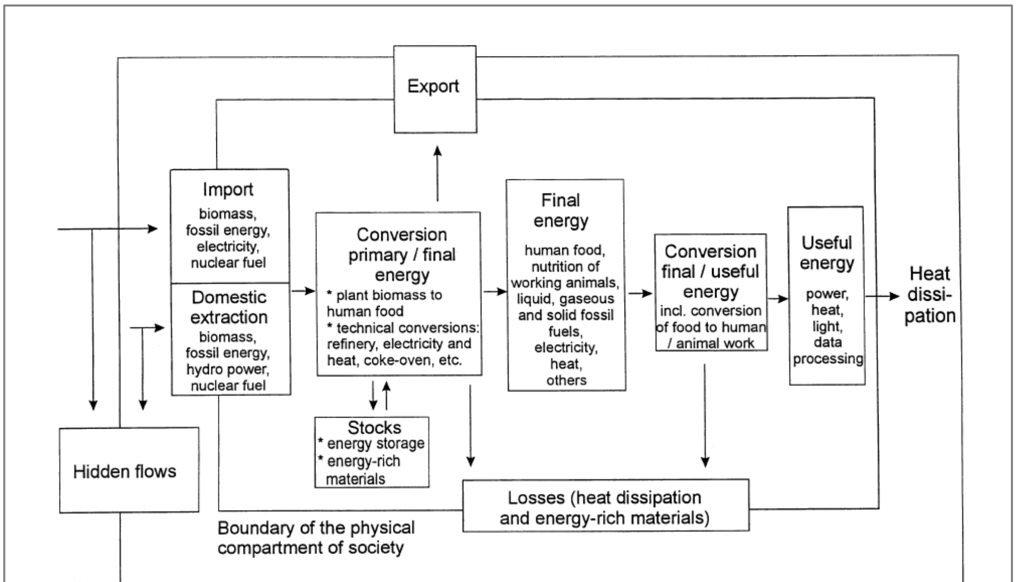


Figure 2-5: Energy accounting balancing scheme, taken from Haberl (2001a).

The Eurostat methodology excludes bulk water flows, which include drinking water and wastewater accounts, despite the crucial role water plays in sustaining all life on earth. Although the Eurostat material flow analysis recommends assessing water flows separately, reports on water flows within the same socio-metabolic studies are limited (Voskamp *et al.*, 2017). Voskamp and colleagues (2017) have argued that this is a major shortfall of the standard material flow analysis framework and they have subsequently proposed an adjusted method to account for water flows. In their study of the city of Amsterdam, including water flows facilitated a deeper understanding of the city's metabolism (Voskamp *et al.*, 2017). Water footprint guidelines also argue that water flows are insufficiently reported on in material flow analysis and highlight the need to strengthen the linkages between water footprints and material flow accounts (Hoekstra, 2011).

2.4. Socio-Metabolic Studies in South Africa

In South Africa, socio-metabolic studies at the sub-national scale are limited to urban metabolism studies for Cape Town and one failed regional study. This can be partially attributed to limited data availability, the difficulty of defining system boundaries as well as estimating informal flows (Culwick *et al.*, 2017; Currie, Musango and May, 2017; Hoekman and von Blottnitz, 2017). The latter, however, is also faced in national level studies (von Blottnitz *et al.*, 2022).

Paul Hoekman and Harro von Blottnitz (2017) conducted a material flow analysis for the City of Cape Town for the year 2013 using the Eurostat accounting framework. The study aimed to not only characterise the physical dimension of Cape Town's economy but also to provide an indication on the levels of uncertainty associated with the data (Hoekman and von Blottnitz, 2017). Results from this study were then combined by Currie and colleagues (2017) in a multi-layered approach to examine the spatial and temporal dimensions of Cape Town's metabolism. The results of this study highlighted several sustainability prospects for the city relating to interventions in water, energy, food, waste, housing and transportation (Currie, Musango and May, 2017). Both studies highlight the city's reliance on food imports, among other materials, and recommend that further investigation into Cape Town's metabolism is needed (Currie, Musango and May, 2017; Hoekman and von Blottnitz, 2017).

In 2017 Culwick and colleagues set out to quantify the metabolism of Gauteng's city-regions with the objective of identifying where resource efficiency and sustainability gains could be achieved. The chosen method of analysis was an adapted version of the Eurostat EW-MFA framework, though water flows were also included due to major water deficits in the region (Culwick *et al.*, 2017). The quantitative metabolic analysis could however not be completed due to severe data constraints (Culwick *et al.*, 2017). Consequently, the study focussed on the linkages between material flow analysis and urban political ecology, providing insight into institutional barriers and the systems that govern flows (Culwick *et al.*, 2017).

At the national level, two different material flow analysis studies have been conducted. The first of these was published in 2016 by Beyers and Swilling and it provides a time series account of South Africa's physical economy between 1980 and 2012. The primary objective of the study was to provide an empirical basis of South Africa's resource extraction that could be used to develop alternative growth pathways. The study corroborates the consensus that the South African economy is inherently unsustainable, with an economic growth trend that results in high income disparity and a heavy reliance on non-renewable resources. A more recent study by the University of Cape Town and the University of Natural Resources and Life Sciences in Vienna (BOKU) reached similar conclusions in terms of resource and energy intensity, but also provided an indication on the state of circularity of the economy (von Blottnitz *et al.*, 2022). von Blottnitz and colleagues conducted a comprehensive national material account for the year 2017 using the accounting framework developed by BOKU, which builds on the standardised EW-MFA framework but makes provisions for waste flows, recycling and downcycled materials (von Blottnitz *et al.*, 2022). The study set out to provide systems-level guidance on how to improve the circularity of South Africa's economy and to this effect, a number of recommendations were made that holistically culminated in "a new national development model which entails phasing out its extractive orientation of non-renewable resources for export and power generation" (von Blottnitz *et al.*, 2022). While the national EW-MFA provides a comprehensive assessment of the country's input-output material balance and circularity as a whole, it does not provide the level of disaggregation necessary for applying insights and evaluating local impacts fully.

A handful of studies also exist that analyse different aspects of social metabolism in the South African context. Strydom and colleagues investigated Cape Town's energetic metabolism at the household level, although they focussed solely on technical energy (Strydom, Musango and Currie, 2020). Material flow analysis in isolation and in combination with life cycle assessment have also been used to characterise the flows and stocks of plastics in the South African economy (Olatayo, Mativenga and Marnewick, 2021; Goga *et al.*, 2022). Additionally, a water metabolism to complement the urban metabolism accounts for Cape Town has also recently been completed (Atkins, Flügel and Hugman, 2021).

2.5. Summary

The literature review highlights the potential value of a baseline metabolic assessment for Mpumalanga. Such an assessment, as indicated by literature, could be a useful tool to assist in addressing the region's sustainability challenges and aiding the transition towards a low carbon economy. Given the region's heavy reliance on coal, the assessment could facilitate the quantitative capture of socio-economic and environmental risks and opportunities associated with transitioning from coal dependency. It could also help shed light on the effects of current practices on public health and the environment, including air and water quality, soil integrity and biodiversity.

The social metabolism framework is identified as a promising method for this analysis, allowing for an examination of material, energy and water exchanges within the region and their wider ecological impacts. This dissertation aims to bridge the gap in comprehensive socio-metabolic research within Mpumalanga, offering a systemic evaluation that can guide sustainable policy decisions and support the province’s resilience in the face of both current and future ecological and economic shifts.

Chapter 3 : Research Methodology

A quantitative research approach was chosen to assess the metabolism of Mpumalanga. The methodology presented in this chapter closely follows the most recent EW-MFA framework for South Africa (von Blottnitz *et al.*, 2022). However, the scope was extended beyond the standard physical dimension of the economy. Given the province's role in providing both nutritional and technical energy to the rest of the country, the material flow accounts were converted to energetic equivalents, as prescribed by Haberl (2001a) and conventional energy balances, to quantify the energetic metabolism. In light of the province's water challenges, water flow accounts were also included in the material analysis, but they are reported separately. This comes with the intention of providing a comprehensive understanding of Mpumalanga's social metabolism and addressing the noted shortfalls in utilising solely material flow accounts to inform and promote sustainable development (Haberl, 2001; Huang *et al.*, 2012; Bringezu *et al.*, 2016; Voskamp *et al.*, 2017).

To quantitatively account for material, energy and water flows through a system, in accordance with the chosen methodologies, it was essential to first set the system's spatial and temporal boundaries. Typically for EW-MFA, the spatial boundary is set to the national political borders as specified in the Eurostat Methodological Guide (2001). This ensures consistency with national accounts (and compatibility with international accounts), as is the case in the most recent national study. However, this study diverges by setting its boundary to the provincial confines of Mpumalanga as seen in Figure 3-1. Such a choice posed challenges from the outset. While there are existing sub-national studies, they often encounter issues including:

1. A scarcity of empirical data at the sub-national scale, which can be further complicated by the limited data resources of developing nations (Wiedmann, Athanassiadis and Binder, 2023).
2. Questions regarding the appropriateness of the methods originally designed for national datasets when applied to more granular geographical scales (Wiedmann, Athanassiadis and Binder, 2023)

For harmonisation purposes, the temporal scope for this research was set at one year, 2017, which aligns with the national EW-MFA (2022). This facilitated a seamless comparison and assisted in filling data gaps that arose (Wiedmann, Athanassiadis and Binder, 2023).

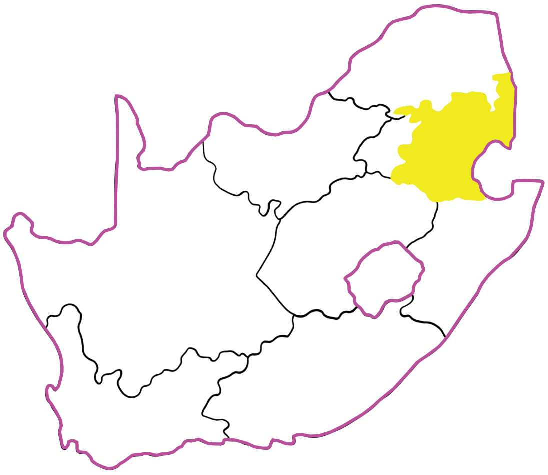


Figure 3-1: Spatial boundary of Mpumalanga delineated in yellow, set within the context of the national borders depicted in pink.

Table 3-1 below offers a snapshot of the province of Mpumalanga, against the broader South African backdrop, capturing key metrics like population size, surface area, household dynamics, land allocation and economic contributions. This table establishes a basis for the forthcoming analysis, and provides a comparative lens through which to assess Mpumalanga's metabolic profile in relation to the national context.

Table 3-1: Contextual information for Mpumalanga in 2017.

Metric	South Africa	Mpumalanga	Allocation	Source
Population	56 520 000	4 444 200	7.9%	(StatsSA, 2018)
Surface area (km^2)	1 219 090	76 495	6.3%	(StatsSA, 2018)
Population density (cap/km^2)	46	58	-	(StatsSA, 2018)
Households	16 199 000	1 248 000	7.7%	(StatsSA, 2018)
GDP* (Rand million)	4 653 579	348 987	7.5%	(StatsSA, 2019)
GDP** primary industry (Rand million)	453 554	83 688	18.5%	(StatsSA, 2019)
GDP** secondary industry (Rand million)	879 900	74 992	8.5%	(StatsSA, 2019)
GDP** tertiary industry (Rand million)	2 839 874	154 341	5.4%	(StatsSA, 2019)
Eskom Thermal Installed Nominal Power Capacity (MW)	37 868	28 463	75.2%	(Eskom, 2018)
Agricultural land (Ha)	7 614 392	943 163	12.4%	(StatsSA, 2020)

*At market prices

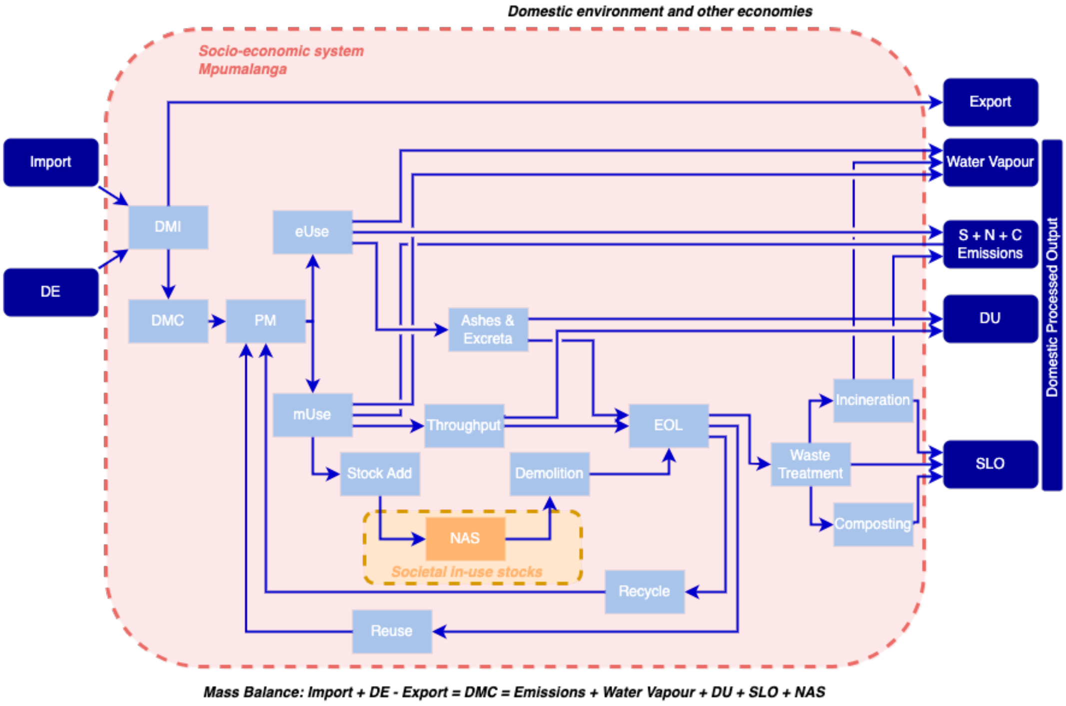
**At basic prices

Baseline assessments for the province's material, energy and water flows were undertaken in the aforementioned sequence, followed by an integrated interpretation of the province's social metabolism. The following sections unpack the strategy adopted to regionalise and interpret the material, energy, and water accounts for Mpumalanga, detailing the data gathering and processing techniques as well as assumptions made concerning various flows.

3.1. Material Flow Accounts

3.1.1. Accounting Framework

The accounting framework followed in this study was adapted from the national EW-MFA (2022), which in turn was adapted from Mayer *et al.* (2019) and builds on the established Eurostat EW-MFA framework. The framework is illustrated in Figure 3-2 and tracks materials by main material category (biomass, metals, non-metallic minerals, and fossil energy carriers) from extraction to material use within the socio-economic system towards discard and either recovery or deposition to nature (Mayer *et al.*, 2019; von Blottnitz *et al.*, 2022). Material inputs into the socio-economic system include domestic extraction and imports, while the material outflows are exports and domestic processed output to the environment in the form of emissions, water vapour, solid and liquid output, and dissipative use. The principle processing stages within the socio-economic system are processed materials, in-use stocks of materials and waste treatment (Mayer *et al.*, 2019).



Mass Balance: Import + DE - Export = DMC = Emissions + Water Vapour + DU + SLO + NAS

DE = Domestic extraction; DMI = Domestic processed inputs; DMC = Domestic material consumption; PM = Processed material; eUse = Energetic use; mUse = Material use; NAS = Net additions to stock; EOL = End-of-life waste; DU = Dissipative use; SLO = Solid and liquid outputs

Figure 3-2: Framework for the EW-MFA in Mpumalanga; adapted from Mayer et al. (2019) and von Blottnitz et al. (2022).

The throughput indicators are illustrated in Figure 3-2 by boxes while the arrows illustrate the flow of materials. Direct Material Input (DMI) consists of domestic extraction (DE) and imports, including raw materials and finished products. Any extracted material that is stored and not used for the year concerned (i.e. bunkered) is subtracted from DE prior to calculating DMI. To determine the domestic material consumption (DMC), exports are subtracted. Processed materials (PMs) equal the combined total of DMC and secondary material (SM) inputs. SMs comprises materials recovered through recycling and reuse.

The PMs are then split into either energetic use (eUse) or material use (mUse). The latter involves resources used for both technical energy and nutritional energy. Fossil energy carriers are primarily allocated to eUse, barring a few exceptions like petrochemical base materials. Other resources not used for energy are allocated to mUse. These include metal ores, minerals, and certain biomass materials such as industrial roundwood. Material use is further divided into extractive waste produced during the initial processing phases of domestically mined ores, stock building materials and throughput materials. Throughput materials don't accumulate in stocks and include resources used in a short-lived or dissipative manner, as well as wastes produced during processing.

All materials, if not added to stocks or recovered, get transformed into gaseous, solid, or liquid outputs within a year. Combined with resources from demolished stocks reaching their lifespan's end, these outflows are labelled interim outputs (IntOut). IntOut are categorised into emissions and End-of-life (EoL) waste. Emissions directly contribute to the domestic processed output (DPO) while some EoL waste re-enters as SMs. The remaining EoL waste is then treated either via incineration, composting or landfill and returned to the environment as DPO in the form of either solid and liquid output (SLO), emissions or water vapour.

Given that the framework described above adheres to a mass balancing approach, all material and energy flows must either contribute to stocks or transition into waste, emissions, water vapour, or dissipative use (DU) (Krausmann *et al.*, 2018; Mayer *et al.*, 2019; von Blottnitz *et al.*, 2022). Achieving a balanced account of flows is challenging solely with statistical data on waste and emissions (Krausmann *et al.*, 2018). Thus, to ensure a closed material balance between input and output flows, data from statistical reports is integrated with modelling techniques. This allows for any missing data to be filled by triangulating available data from various flow points within the economy, mass balancing and process information (von Blottnitz *et al.*, 2022).

Figure 3-3 illustrates the application of the framework to South Africa as a whole, detailing the summary of all material flows for the year 2017. In addition to covering all material flows through the socio-economic system, the framework has two key features. Firstly, it introduces two indicators on the biophysical scale of the socio-economic system: *Processed Materials* and *Interim Outputs* (von Blottnitz *et al.*, 2022).

The former offers insights into the volume and makeup of all *'Processed Materials'* as well as their uses, while the latter provides similar insights for all solid and liquid materials at their lifecycle's end as well as emissions, water vapor, and dissipative usage (Mayer *et al.*, 2019; von Blottnitz *et al.*, 2022). Secondly, based on these indicators, the methodology derives two circular economy rates. These rates signify the extent of socio-economic 'restorative' loop closing and the potential for ecological 'regenerative' cycling (Mayer *et al.*, 2019; von Blottnitz *et al.*, 2022).

The study found that 1.9% of inputs originated from socio-economic cycling, while 2.6% of outputs underwent the same process (von Blottnitz *et al.*, 2022). When considering potential ecological cycling, the circularity was estimated to be 7% for inputs and 8.5% for outputs (von Blottnitz *et al.*, 2022). These figures are notably lower than those in the Mayer et al. study on the EU28, which estimated circularity at 34.2% for inputs and 50.1% for outputs (Mayer *et al.*, 2019).

The aforementioned framework utilised in the 2017 South African material account (von Blottnitz *et al.*, 2022) underwent revisions in Haas *et al.* (2023). The latter authors shifted the export origin to after processed materials, recognising that materials undergo some form of processing prior to export (Haas *et al.*, 2023). This shift led to changes in balance equations and the subsequent results. While these accounting differences are noted, the adjustments made by Haas *et al.* (2023) have not been incorporated into this study, owing to their publication late in 2023.

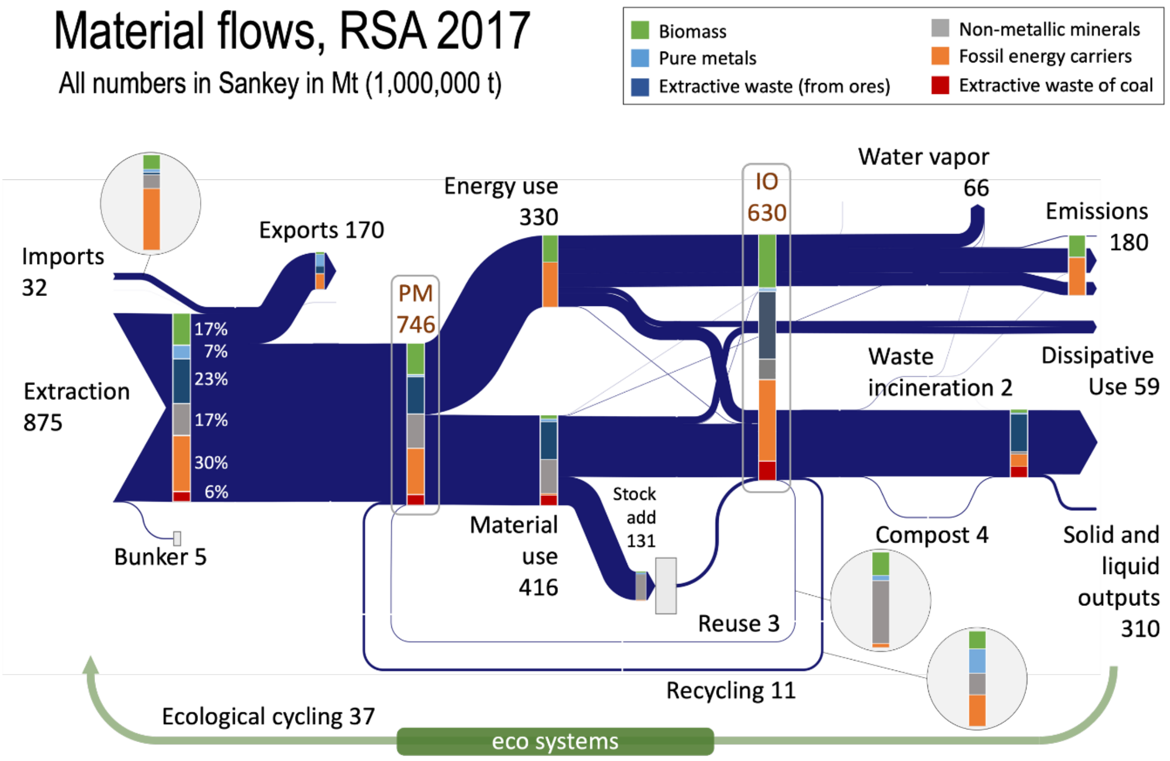


Figure 3-3: National EW-MFA for the year 2017; taken from von Blottnitz et al. (2022).

3.1.2. Regionalising the Economy-Wide Material Flow Analysis for Mpumalanga

The accounting framework outlined above was initially developed for application on a national scale, amalgamating official national statistical data on material and energy flows, energy consumption, emissions, and various waste streams (including construction and demolition waste, extractive waste, industrial processing waste, and municipal household waste) (von Blottnitz *et al.*, 2022). For its application at the sub-national level, the framework required certain adaptations, despite the majority of the accounting principles remaining consistent.

Wiedmann and colleagues regionalised the EW-MFA for the Swiss Cantons where several data sets were identified from the national EW-MFA with cantonal resolution, which were repurposed for the research (Wiedmann, Athanassiadis and Binder, 2023). When this was not the case, alternative data sources at a cantonal scale were used, or data from the national level were downscaled to cantonal level using proxies; indirect measures or indicators that are used to estimate material flows or stocks when direct data are not available or are hard to obtain; can be based on related data sets, statistical correlations, or other forms of empirical evidence that provide a reasonable approximation of the desired value. In the South African case, none of the data sources identified in the national level study were disaggregated to the provincial level, requiring the use of other data or proxies. The main data and associated sources used to regionalise the South African EW-MFA for Mpumalanga are provided in the following subsections and further details can be found in Appendix A.

3.1.2.1. Domestic Extraction (DE)

In order to account for domestic extraction of the main material groups, primary data, conversion factors and top-down estimates were needed. If a material was not reported to be domestically extracted in the national level EW-MFA, it was automatically excluded in the provincial analysis. The portion of domestically extracted material that was stored or set aside for use elsewhere, *bunkered*, was assumed to be the same for the province (i.e. if 10% of domestically extracted primary crops was bunkered nationally, it was assumed that 10% of Mpumalanga's domestic primary crop production was bunkered).

3.1.2.1.1. Biomass extraction

Biomass extraction encompasses primary crops, crop residues (used), fodder and grazed biomass, wood, and wild fish catches, as well as hunting and gathering. It does not account for cultivated livestock, but does consider the biomass they consume.

An agricultural census was completed for the year 2017 by Statistics South Africa (StatsSA), which was the main data source for primary crops. The census detailed provincial and national level crop production (tons) and area planted (hectares). Although crop production quantities were used, when these were not available (i.e.

spices, stimulant crops, tobacco, rubber and other crops), the national values were scaled down based on planted area as a proxy. Should the national reported crop production differ greatly from the EW-MFA value, the provincial values were either scaled up by the difference or growing association values were used. For example, the sugar cane production volumes reported in the census were less than half those reported in the EW-MFA: this difference was scaled up to match the EW-MFA reported value and checked against South African Cane Growers' Association reported production values.

To account for fodder crop production and grazed biomass, the national EW-MFA was scaled down based on the reported number of livestock and farming practices in the province in relation to the national. This was done to maintain consistency with the demand-side approach taken in the national EW-MFA. The downscaled value for fodder crops was further refined to ensure that maize cultivated for animal feed was included. No data at the provincial level were available for crop residues. As a result, used crop residues were estimated using the same harvest factors and recovery rates as the national EW-MFA (this method aligns with Eurostat and can be used in the absence of data).

Wood extraction is categorised into industrial roundwood, fuel wood and alien plants. The Forestry Association of South Africa published an annual forestry and forestry product industry report for 2017, which provides plantation area, production and value statistics per roundwood (softwood/hardwood) and product (sawlogs, pulpwood, poles and other). The forestry reported production quantity for the national level is around twice that of the EW-MFA. As a result, the national production values were scaled down using the forestry reported roundwood and product splits for the province as proxies. No data on fuel wood extraction or alien plant extraction for the province were found. Consequently, fuel wood was estimated using a demand-side approach based on the number of households in the province that rely on wood as their primary and/or secondary fuel for cooking and heating. These values were obtained from StatsSA's General Household Survey (GHS) for the year 2017. Alien plant extraction was assumed to be correlated to the quantity of alien plants present in the province, thus the portion of the nation's alien plants present in Mpumalanga (12.6%, as estimated by Maitre, Versfeld and Chapman [2000]) was used as a proxy to downscale the EW-MFA account of alien plant extraction.

Given the geographical location of the province, as well as the small quantity of biomass extraction from wild natural biological resources relative to other material flows in the national, it was assumed that negligible amounts of fish catch, aquatic plants and animals, and via hunting and gathering were extracted in the province (i.e. null).

3.1.2.1.2. Metals and extractive waste extraction

Domestic extraction of metal ores encompasses the pure metal component as well as the extractive waste. The metal ore subcategories include iron and non-ferrous metals (copper, nickel, lead, zinc, tin, gold, silver, platinum and other precious metals, bauxite and other aluminium, uranium and thorium, other metal).

The DMRE reports annually on national level metal extraction in the South African Mineral Industry (SAMI) Report. However, this information is not available at a disaggregated level due to the protection of sensitive information related to mines and their operations, which if released could confer a competitive advantage. Consequently, the main data source used was the United States Geological Survey (USGS) of South Africa's mineral industry, which details the annual capacity of main mines and processing facilities at a disaggregated level. The listed operating companies and associated facilities located in Mpumalanga were cross-checked with the DMRE's directorate of operating mines. Given that the USGS only reports on main facilities and associated capacities, it was assumed that whatever was not reported on equated to negligible quantities. It was assumed that the ore grades for the province were the same as those reported in the national EW-MFA.

3.1.2.1.3. Non-metallic minerals extraction

Domestic extraction of non-metallic minerals includes both industrial (e.g. chemical and mineral fertilisers and salt) and construction minerals (such as gravel and sand, clays, and limestone). No data were found for provincial level non-metallic minerals for the reason given above, except for a handful reported by USGS. As a result, the materials from the national EW-MFA were downscaled using the portion of mines operating in the province for each material commodity, as per DMRE mining directorate and associated reports, as a proxy. While this assumes all mines for a specific material commodity have the same annual production capacity, which is highly unlikely, an alternative was not found.

3.1.2.1.4. Fossil energy carrier extraction

Fossil energy carrier extraction includes solid energy carriers (e.g. coal) as well as liquid and gaseous energy carriers (crude oil and natural gas). While the province has no crude oil or commercially viable natural gas reserves (extraction taken as null), coal is abundant. SAMI reports the Mpumalanga coal basin extraction accounted for 81.62% of the total extraction in 2017. This percent was used as a proxy to downscale the national EW-MFA quantity for hard coal. This was cross-checked against (1) the production volumes for coal extracted outside of the province as reported by DMRE's operating and developing coal mines directorate and (2) the global coal mine trackers production volumes for outside the province. It is assumed that the balance of coal that is not extracted in other province's, is extracted in Mpumalanga. While the DMRE's directorate was incomplete on production volumes, the global coal mine tracker was able to complete the gaps, constituting a refinement in the production quantity used. These three methods to estimate coal extraction quantities had <3% statistical difference.

3.1.2.2. Imports and Exports

Imports and exports are materials that come into and go out of the economy. These traded goods can be finished products, semi-finished products, or raw materials. Usually, trade data are available at a national level from sources like the United Nations Commodity Trade Statistics Database, the United Nations Environment Programme as well as customs and border control. These data include quantities of traded commodities between countries. When looking at imports and exports on a sub-national level, this includes material flows within the country (i.e. between provinces) and with other countries.

Official sub-national trade flow statistical reporting is, however, not a usual practice. While these flows can be estimated using data on freight or transported goods as is illustrated by Wiedmann and colleagues (2023), the lack of publicly available data for Mpumalanga prevented this. Consequently, import and export flows for the province were calculated using predominantly top-down estimates. Unlike the national EW-MFA, these were not split into primary and secondary materials, nor were they differentiated as intra-national or international flows.

For everyday household materials like food, glass containers and plastics, it was assumed that domestic consumption per capita was the same as the national. Thus, the DMC for these products was downscaled from the national EW-MFA using the province's population as a proxy. The reasoning for this is that even as household income and consumption in the province appears to be below the national average in monetary terms (as suggested by GDP and specifically tertiary sector GDP), physical quantities of food consumed are set by biological needs. Similarly for animal feed, the demand-based feed estimate provided the necessary animal food requirements. It was then assumed that any shortage or excess was either imported or exported.

For not-so-regular materials like industrial minerals, construction materials, industrial roundwood, and metals, it was assumed that the domestic consumption is related to the GDP. So, the DMC for these materials was downscaled from the national EW-MFA using the province's GDP as a proxy, and again, any shortage or excess was either imported or exported.

Some adjustments were made to the imported and exported quantities when more detailed data were found or when the found data contradicted the aforementioned assumptions. This was mostly related to processing/production capacities within the province. In this instance, the imports also reflected the processing capacity of the province, and the exports pertained to the semi-/finished products that leave the province once the province's requirements are met (estimated as above). This applied to the following industries: sugar, maize, coal, oil for energy use, natural gas and ferro-alloys.

3.1.2.3. Net Addition to Stock (NAS)

Krausmann and colleagues define three types of stock: manufactured capital, livestock and humans (2018). Only the former was accounted for in this study, which aligns with the national EW-MFA. Manufactured capital encompasses all in-use artifacts such as infrastructure, buildings, and durable goods. Net addition to stock (NAS) is the difference between the materials accumulated in stocks of manufactured capital (Stock Add) and the outflows of waste from processing of stock building materials as well as from discarded stocks at the end of their lifetime (Demolition).

In the case of the national EW-MFA (2022) and Mayer et al. (2018), NAS was calculated as the difference between Stock Add and demolition, the latter derived from national waste statistics. No information on NAS, Stock Add or Demolition in Mpumalanga was available. Consequently, the share of stock building materials in mUse was assumed to be the same as the national EW-MFA, as well as the portion of stock that was discarded/demolished. This assumes consistent losses, lifetime distribution and recycling rates for stock building materials; industrial roundwood, ores, sand and gravel, raw materials to produce plastics, bricks, glass, concrete, and asphalt.

3.1.2.4. Domestic Processed Output (DPO)

Outflows of solid and liquid waste, emissions, water vapour and intentional material applications to the environment are all encompassed in domestic processed output (DPO) (Krausmann *et al.*, 2018; Mayer *et al.*, 2019; von Blottnitz *et al.*, 2022). In order to account for DPO of the main material groups, a combination of primary data, material compositions, top-down estimates and mass balancing with input flows were needed.

3.1.2.4.1. Solid and liquid outputs (SLO)

Solid and liquid outputs comprise processing and manufacturing waste including extractive waste and ash, end of life waste after recycling (waste treated) and excreta from humans. The primary data source used in the national EW-MFA was the South African State of Waste (SASoW) report for 2017, which provided national accounts of general and hazardous waste as well as recycling flows (DEA, 2018).

Detailed provincial level waste accounts were not found for Mpumalanga, with the exception of the South African Waste Information Centre (SAWIC). Both hazardous and non-hazardous waste streams can be found in the SAWIC's tonnage reports, however, the reports contain generic and unverified statistics reported by the registered waste facilities and excludes accounts from unregistered and non-reporting waste facilities. To check the validity of SAWIC's accounts, they were compared to those reported in the SASoW report. The results of this data-check indicated significant underreporting from SAWIC, with a few exceptions for hazardous waste streams. Consequently, predominantly top-down estimations were used to evaluate waste streams.

Municipal solid waste for both serviced and un-serviced households was estimated as per Rodseth *et al.* (2020), utilising provincial household dynamics. Food waste stemming from production, processing and household waste was scaled down from the national EW-MFA, using the number of households as a proxy. The same logic was applied to garden waste. Feed waste was not considered given the demand based estimate (Krausmann *et al.*, 2018). Estimates for human excreta were based on the population of the province and the associated digestibility metabolic rates which were assumed to be consistent with the national EW-MFA. Ash stemming from thermal combustion of energy carriers and waste incineration were evaluated using material compositions consistent with the national EW-MFA. Commercial and industrial waste (hazardous and general) was downscaled from the national EW-MFA using GDP as a proxy unless information on known processing capacities and resultant waste could be found.

Official waste statistics typically report waste materials that encompass multiple material categories within the EW-MFA framework (i.e. battery waste contains a combination of metals, industrial minerals, and fossil energy carriers) (Krausmann et al., 2018; Mayer et al., 2019). Consequently, to ensure a closed material balance, an allocation of output to input flows was required (Mayer *et al.*, 2019; von Blottnitz *et al.*, 2022). It was assumed that the composition of reported waste categories was consistent with the national EW-MFA along with the waste treatment types.

3.1.2.4.2. Emissions to air

The emissions to air were calculated as per the national EW-MFA and stem from technical processes including thermal energy generation and waste incineration, in addition to those from humans and livestock, and are all accounted for in DPO. The energy carriers/fuel composition, limestone calcination stoichiometry as well as human and livestock respiration rates remained consistent with the national. In the calculation scheme of Mayer *et al.* (2018), oxygen drawn from air is omitted and emissions to air only include what was extracted; thus, e.g. in tons of C (carbon) rather than tons of CO_2. This convention was followed to remain consistent with the national EW-MFA.

3.1.2.4.3. Water vapour

As with emissions to air (above), water vapour was calculated as per the national EW-MFA. Water vapour outflows from humans and livestock, brick production, and thermal combustion of energy carriers were all considered, though again the oxygen content of vapour formed was excluded where such oxygen originates from the atmosphere.

The moisture content of clay and energy carriers as well as the change in moisture content from respiration remained consistent with the national study.

3.1.2.4.4. Dissipative use (DU)

The dissipative use of products stems from the application of manure, fertilisers and seeds. Estimates for the dissipative use of (organic) manure were based on the numbers of livestock present in the province and the associated digestibility metabolic rates which were assumed to be consistent with the national EW-MFA. Similarly to estimate dissipative use of seeds, the portion of primary crop material use allocated to seeds was assumed to be consistent with the national EW-MFA. The national EW-MFA overestimates dissipative use of fertilisers, reporting just under 32 Mt (a matter corrected in the subsequent publication by Haas et al. [2023]), consequently a different method was used. To estimate dissipative use from fertilisers, including pesticides, the national application of both pesticides (FAO) and fertilisers (fertiliser association) was downscaled based on the annual spend for the province (as a proxy) and as listed in the commercial agricultural census (2019).

3.2. Energy Accounts

The energy accounting framework utilised in this study drew from Haberl (2001a), as well as conventional energy balances. In accordance with Haberl (2001a), both technical and nutritional energy flows were considered while maintaining compatibility with the EW-MFA approach. However, while Haberl (2001a) employs gross calorific values for both technical and nutritional flows, ultimately summing them to provide an aggregated account of energy inputs, internal energy transformation and energy utilisation for a socio-economic system, this study did not.

Giampietro (2008) argues that metabolic systems possess a distinct identity that delineates what constitutes energy and what does not within them: e.g. fruit is a source of energy for humans, but not for cars (Giampietro, 2008). To account for these differences, this study elected to keep nutritional and technical energy flows separate, as advocated by Giampietro (2008). In line with this argument, it was chosen to assess nutritional energy using gross calorific values (GCV) and technical energy using net calorific values (NCV). This provides a more realistic indication of usable energy while maintaining harmonisation with ecological trophic-dynamics and conventional energy balances.

The approach adopted to quantify the technical and nutritional energy flows for Mpumalanga in 2017 is described in the following subsections, detailing the main methodological assumptions, data sources and processing techniques. Further details on the technical energy methodology are provided in Appendix B.

3.2.1. Technical Energy

The framework used to account for technical energy flows aligns closely with conventional energy balances and is illustrated in Figure 3-4. In South Africa, energy statistics at the national level are published annually by the DMRE and follow international standards. These national energy accounts encapsulate commodity flows of technical energy in both native units and energetic equivalents, along with an overarching energy balance for the country (DMRE, 2018).

Technical energy flows in Mpumalanga primarily encompassed fossil energy carriers, with a minor inclusion of biomass such as wood, which is used for cooking and heating. Only the material flows designated specifically for techno-energetic purposes were included in the energy account, diverging from Haberl's (2001) framework which accounts for all flows of energy-rich materials irrespective of their intended use. Only accounting for energetic use aligns with the national energy statistics and strengthens the case for comparison and harmonisation (small non-energy uses of materials are accounted for in national statistics generally understood to be mainly energy carriers).

The depicted framework accounts for all technical energy flows transitioning into and out of the socio-economic system, alongside all primary energy conversions, conversion losses, and final energy use within the system (Figure 3-4). Consistent with the national energy balance, the final use of energy flows was categorised into sectors: industry; transport; and commerce, residential and other. Final energy in this instance refers to the energy delivered to final consumers, including all economic sectors that use the energy to produce energy services, rather than converting it into another form of energy, such as what happens in the generation of electricity (Schandl *et al.*, 2002).

Domestic energy input for the system is the sum of domestic extraction and imports, while domestic energy consumption is domestic energy input minus exports (Haberl, 2001a; Krausmann and Haberl, 2002; Haberl *et al.*, 2008). Domestic energy consumption is comparable to total primary energy supply (Haberl *et al.*, 2008).

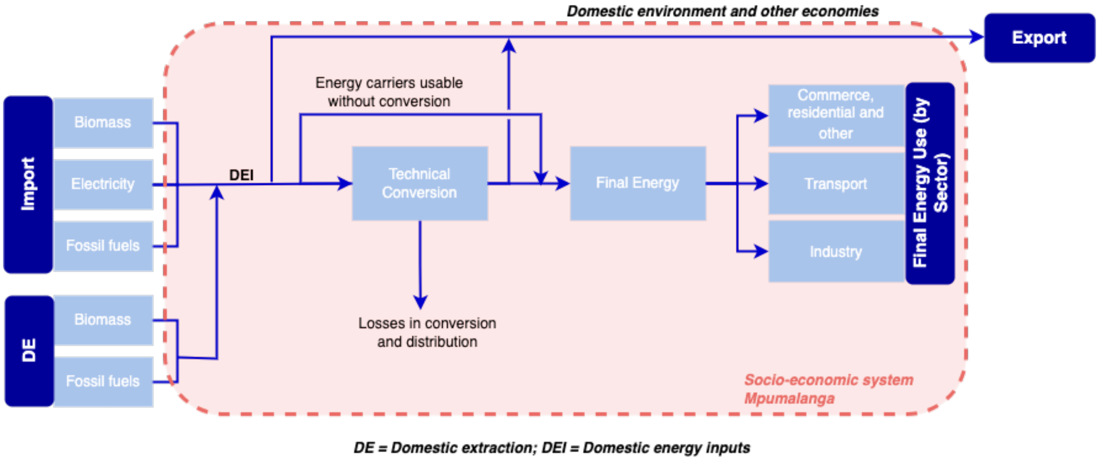


Figure 3-4: Technical energy accounting framework; adapted from Haberl (2001a, 2001b).

To assess imports, exports and domestic extraction of technical energy flows, data for biomass and fossil energy carriers in the province were sourced from the regionalised EW-MFA. The disaggregated material flows in mass were converted to energy equivalents using the net calorific values outlined in Table 3-2, where only the portion of material flows related to technical energy use were converted.

Table 3-2: Net calorific values (NCVs) used to convert material flows to energy equivalents for Mpumalanga.

Energy Flow	NCV (MJ/kg)	Source
Aviation gas	50	(DEA, 2017)
Biomass (wood)	17	(DEA, 2017)
Biomass (bagasse, fresh weight)	7.6	(Mashoko, Mbohwa and Kekana, 2008)
Coal (domestic export)	22	(DMRE, 2018)
Coal (international export)	28	(DMRE, 2018)
Coal (other)	27	(DMRE, 2018)
Coal (power generation)	20.1	(DMRE, 2018)
Coal (synfuels)	21.9	(DMRE, 2018)
Diesel	45.1	(DEA, 2017)
Furnace oil	42	(DEA, 2017)
Gas	48	(DEA, 2017)
Jet Fuel	47.5	(DEA, 2017)
LPG	46.1	(DEA, 2017)
Paraffin	47.5	(DEA, 2017)
Petrol	45.6	(DEA, 2017)

Technical energy conversions in the province encompassed primarily coal to electricity and coal-to-liquid processes, with no crude-oil refineries present in the province. The allocation of coal to electricity generation and coal-to-liquid processes was assessed using primary data from annual Eskom and Sasol reports, in conjunction with the national commodity and energy balance. Within the province, biomass conversion into heat and electricity occurs on a smaller scale, primarily at two sugar mills (Komati Mill and Malalane Mill), as well as at the Ngodwana Pulp Mill. The technical energy generated at these mills is primarily utilised to satisfy their own onsite demands for process heat and electricity. In this context, the conversion of biomass to process heat and electricity was not depicted alongside coal to electricity and coal-to-liquid processes. Instead, it was integrated within the industry's final use sector, reflecting that the conversion takes place at the point of final consumption.

To evaluate the amount of electricity generated from coal, a thermal efficiency of 31.2% was used, as reported by Eskom for 2017 (Eskom, 2018). The volume of liquid fuel produced from coal-to-liquid processes within the province was obtained from Sasol reports and converted to energetic equivalents using net calorific values (Sasol, 2017, 2020). Sasol reports also showed that gas was produced during the coal-to-liquid processes within the province, which was also converted to energetic equivalents (Sasol, 2017, 2020).

The final technical energy use within the province comprised electricity, liquid fuels, gas, coal and biomass, which were subsequently allocated to the respective sectors as illustrated in Figure 3-4. The quantity of coal utilised in the province as final energy was evaluated by applying proxies to downscale the national energy accounts. A combination of proxies was used depending on the sector; for industry, processing capacity and GDP contribution were used, while for domestic use, the number of households was utilised.

The electricity distributed for final use within the province was documented by StatsSA, with the remainder of electricity generated in the province, post transmission and distribution losses, presumed to be exported (StatsSA, 2021). Losses incurred during the transmission of electricity were applied to all electricity generated within the province (including exports), whereas losses incurred during distribution were solely applied to final electricity use within the province. In the absence of provincial specific factors, the transmission and distribution loss factors were assumed to align with Eskom’s reported average for 2017 (Eskom, 2018).

As per the 2017 report on the State of Renewable Energy in South Africa, Mpumalanga procured a capacity of 30 MW in renewable energy from biomass; however, this capacity was not operational during the year (DoE, 2017). As a result, the generation of renewable energy within the province for distribution was assumed to be null. The quantity of electricity imported and consumed from renewable sources such as solar and wind within the province was not quantified; nonetheless, Mpumalanga is recognised as a net exporter of electricity.

To evaluate the final electricity use by sector within the province, the national energy accounts were downscaled using GDP, based on sector energy (electricity) intensity (DMRE, 2018). Negligible amounts of electricity were presumed to be used in the transport sector. The final use of liquid fuels in the province per sector was calculated employing the same rationale used for electricity, while the final use of gas in the province was attributed entirely to the industrial sector, assuming negligible consumption in other sectors. Given the demand-driven allocation for wood fuel extraction in the material analysis, it was assumed that 100% of the final use was allocated to households. The portion of biomass burned to produce process heat and generate electricity (co-generation) comprising primarily wood waste, sugarcane bagasse and black liquor was allocated to industry.

3.2.2. Nutritional Energy

The approach taken to account for nutritional energy flows followed the methodology developed by Haberl (2001a) and detailed in the Handbook of Physical Accounting (2002), with a few differences as previously mentioned. The nutritional energy accounting framework used is depicted in Figure 3-5.

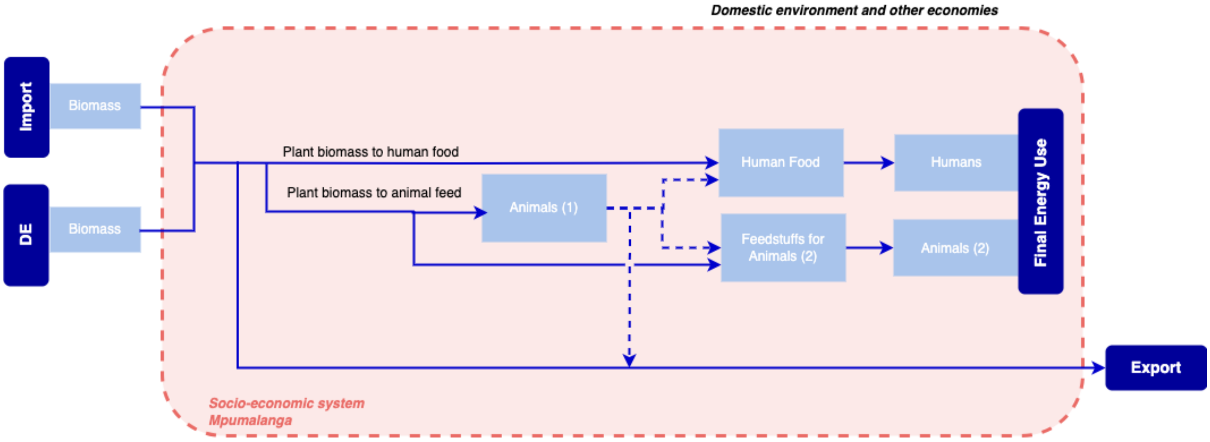


Figure 3-5: Nutritional Energy Accounting Framework; adapted from Haberl (2001a) and Schandl et al. (2002).

Primary energy in the context of nutritional flows is derived from plant biomass, sourced either through domestic extraction or imports. Adopting a trophic-dynamic perspective, the consumption of food by humans and animals is categorised as final energy (Krausmann and Haberl, 2002). Haberl recommends accounting for the animal component as two hypothetical sub-components: livestock as converters of nutritional energy (animals 1) and domesticated animals as consumers of feedstuff (animals 2) (Schandl *et al.*, 2002). Given the demand-side approach for feed utilised in the national EW-MFA, the number of livestock in the country is known. However, the national EW-MFA did not extend to quantify the animal-derived products such as dairy, meat and wool; and neither did the regionalised EW-MFA. Although the agricultural census offers some figures on the quantity of animal products sold, it lacks specificity on whether these goods are consumed locally, are destined for export, or are imported. The uncertainty surrounding the data and not wanting to increase the research scope beyond manageable limits within the timeframe, I excluded the analysis of animal product flows for nutritional energy, concentrating instead on plant-based biomass. This methodological decision is represented in Figure 3-5, where omitted flows are denoted by dotted lines and included flows by solid lines.

The conversion from final energy to useful energy, such as useful drive power, was not considered. There are two reasons for this omission: firstly, the technical balance did not include useful energy; and secondly, a precise evaluation of the mechanical work performed by humans and working animals would necessitate an analysis of annual working hours by species and workload intensity (Schandl *et al.*, 2002). The lack of such data impedes the ability to derive meaningful results, hence its exclusion from the study (Schandl *et al.*, 2002).

To evaluate the imports, exports and domestic extraction of plant-based nutritional energy flows, biomass data for the province were obtained from the regionalised EW-MFA. The material flows, quantified in mass, were converted into energy equivalents using the gross calorific values and moisture contents listed in Table 3-3. Only the material flows associated with food and feed were converted to energy equivalents (i.e. material use of plant biomass was excluded). The quantity of primary crops cultivated in the province for animal feed, principally maize, was reassigned as fodder crops within the provincial material account. As a result, the balance of primary crops was assumed to be harvested for human consumption (food), whereas crop residues, fodder crops and grazed biomass were for animal consumption (feed). The unused extraction was not accounted for in the material account and was also omitted in the nutritional energy account (i.e. unused crop residues).

The energy content of biomass varies depending on the species and even the specific tissues or organs of an organism, both in plants and animals (Schandl *et al.*, 2002). As this is the initial assessment of a nutritional account for the province, typical calorific values were employed. For more accurate evaluations, it is crucial to have detailed information about major biomass flows, especially the quality of materials and, most importantly, their water content. The energy content of dry biomass can fluctuate by a factor of about 2, while water content can range extensively from 10% to 95% (Schandl *et al.*, 2002). In this instance, the gross calorific values were kept consistent regardless of export, import or extraction, however, this is unlikely given that food and feed products are likely to be dryer in comparison to raw materials (Haberl *et al.*, 2008).

Table 3-3: Gross Calorific Values (GCVs) for nutritional flows, utilising average moisture and energy contents; taken from Schandl et al. (2002).

Material	Moisture Content (%)	GCV (MJ/kgDM)
Cereals	14%	18.3
Roots, tubers	83%	16.3
Sugar crops	80%	16.0
Pulses	10%	20.0
Nuts	4%	25.0
Oil bearing crops	10%	25.0
Vegetables	86%	18.5
Fruits	86%	20.0
Fodder crops	15%	18.5
Straw and other crop residues	15%	18.0
Grazed biomass	15%	17.5

3.3. Water Accounts

Several water accounts have been developed for South Africa at the national level with varying levels of detail, including works by StatsSA (2006), Middleton and Bailey (2009), Bailey and Pitman (2012), Pahlow, Snowball and Fraser (2015) and Maila, Crafford and Mathebula (2018). Additionally, the Department of Water and Sanitation (DWS) publishes an annual report detailing the national status of water resources. Provincial accounts are less common, with national accounts rarely providing disaggregated provincial level water statistics, which can be partially attributed to the institutional structure of the water sector.

In South Africa, water management is organised around Water Management Areas (WMAs), which are overseen by Catchment Management Agencies (DARDLEA, 2019; Simpson *et al.*, 2019). Three of the nine WMAs overlay wholly or partially with Mpumalanga's borders: the Inkomati-Usuthu, Olifants and Vaal WMAs. The configuration of WMAs, as shown in Figure 3-6, demonstrates that they extend beyond provincial boundaries, illustrating the complex overlap between water governance territories and provincial borders.

The methodology adopted to quantify water flows in Mpumalanga is based on the United Nations integrated environmental and economic accounting for water resources (SEEAW). This framework has been applied by StatsSA to establish national water resource accounts for South Africa, with Maila, Crafford and Mathebula (2018) providing specific guidelines for its application at the national level. Employing this methodology not only aligns with the principles of harmonisation and comparability of national accounts but also integrates with the boundaries of EW-MFA. In alignment with the approach taken by StatsSA for the national accounts, various adjustments to the SEEAW framework were done to improve the integration of data sources within Mpumalanga.

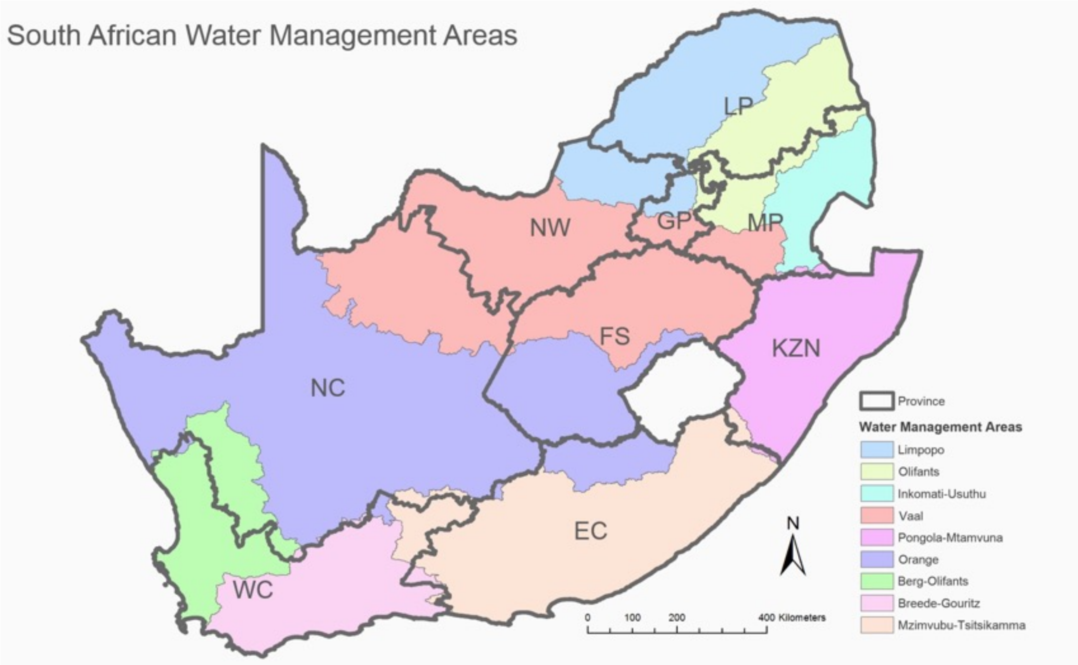


Figure 3-6: South African Water Management Areas (WMA); taken from StatsSA, WRC and Prime Africa Consultants (2017).

The water framework used is illustrated in Figure 3-7 and facilitates tracking of water flows across and within the economy and the hydrological system. The framework makes use of supply and use tables, accounting for the water abstracted from the environment, both surface and groundwater, and its allocation across various economic sectors. Additionally, it tracks the water that is discharged back into the environment, either as treated effluent or as part of return flows to groundwater and surface water systems. The framework’s primary objective is to monitor water extractions utilised for economic activities. Consequently, it does not encompass water dynamics that occur entirely within natural settings, such as interactions between the atmosphere, surface water and groundwater sources that involve processes like precipitation, seepage or direct evaporation from bodies of water (StatsSA, 2006; Maila, Crafford and Mathebula, 2018). Likewise, indirect economic water uses that do not involve direct withdrawal, such as for recreation or transportation, are omitted (StatsSA, 2006; Maila, Crafford and Mathebula, 2018).

Due to various data gaps and challenges in classifying data across provincial borders and water catchment regions, certain water flows could not be quantified and were therefore excluded. Where feasible, estimations were made and where possible, for areas with data deficiencies, qualitative descriptions were provided. The water flow omissions included the specific supply routes through which water reaches end-users, whether through direct user licenses or water boards, as well as the stream flow reduction activity (SFRA) due to forestry plantations. These water flows are illustrated in Figure 3-7 by dotted lines.

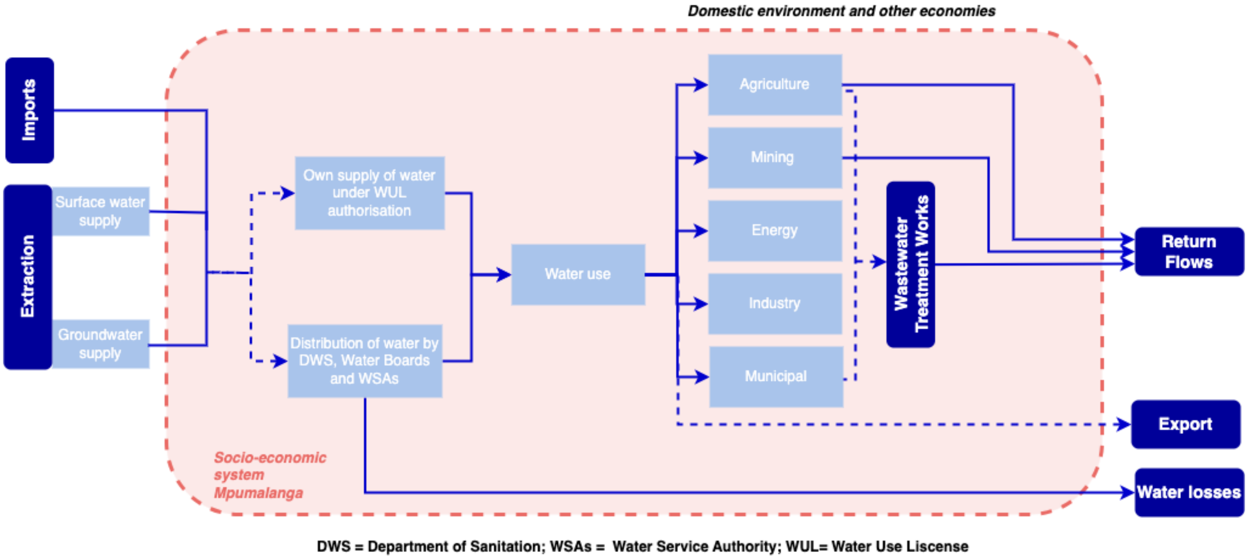


Figure 3-7: Water flow accounting framework; adapted from Maila, Crafford and Mathebula (2018).

To account for water input into the socio-economic system, only surface water abstractions and groundwater abstractions were considered (i.e. “blue” water). The water users accounted for in the framework include agriculture, mining, energy, industry and municipal. Municipal water users comprise urban-based industries, services and domestic users (StatsSA, 2006). The only water distribution losses considered were those from the municipal supply system, given a lack of readily available data. Return flows were evaluated based on wastewater treatment works design capacity, irrigation efficiencies and national top-down estimates.

Concerning water quality, data were collected on the levels of pollutants such as total dissolved solids (TDS), nitrates and phosphates for the WMAs within the province. Measurements of nutrient levels in both surface and groundwater resources for the province were also included. These quantitative metrics were then integrated with qualitative reports on water quality to give a general indication of water pollution within the province. Given the complexities involved in pinpointing specific causes for changes in water quality, these quality accounts serve primarily to record the overall fluctuations within a specified accounting period, without delving into the root causes (Maila, Crafford and Mathebula, 2018). Water quality was then evaluated against the Total Water Quality Ratings (TWQR) to gauge the condition of the province's water resources.

The compilation of the water accounts necessitated data acquisition from a variety of sources. Table 3-4 illustrates the principal physical water flows for both supply and usage, along with the corresponding data sources and the methodologies employed for data processing. During the data collation process, several data inconsistencies emerged that warranted additional scrutiny, these issues are further examined and addressed in the results section of this study. Further details on the methodology are provided in Appendix C.

Table 3-4: Water flow data sources and processing techniques.

Water Flow	Source
Groundwater abstraction	Primary data; (DARDLEA, 2019)
Surface Water abstraction	Data gap; estimated using balance equation (supply = use + losses)
Agriculture	Primary data; (Van Niekerk, Jarmain and Goudriaan, 2018)
Wastewater treated	Primary data; (DWS, 2013a, 2013b, 2013c, 2022)
Return Flows	Estimation and primary data; (Maila, Crafford and Mathebula, 2018)
Municipal	Primary data; (DWS, 2017)
Mining	Estimation; (DWS, 2016)
Industry	Primary data; (Sasol, 2020)
Energy	Primary data; (Roselt and Mpofu, 2021)
Water Quality	Primary data; (Maila, Crafford and Mathebula, 2018; DARDLEA, 2019)

3.4. Derivation of Metabolic Profile

Following the completion of the provincial material, energy and water accounts, several balance checks were conducted. These were primarily related to the material accounts to ensure that the sum of all inputs, minus the outputs and net additions to stock, equalled zero for each material category. Subsequently, Sankey diagrams were constructed to visualise the flow of materials, energy and water, and a series of metabolic indicators were calculated. Further detail on the metabolic indicators is provided in Appendix D.

3.5. Interpretation

The 2017 data from the material, energy and water accounts were collated and analysed to construct an integrated portrayal of the province's metabolic function. This entailed a comprehensive review of all inputs, transformations and outputs within the provincial boundaries. The principal flows identified were viewed in relation to overall trends and linked, where feasible, to the respective economic sectors.

Furthermore, the data were compared against the national material flow analysis for 2017, underscoring the patterns in resource extraction, processed materials, consumption and output to the environment at a finer spatial scale. The applicability of the national resource trends to Mpumalanga’s patterns was also assessed. The intention of this comparison was to shed light on the provincial nuances within the broader context of the country’s socio-economic metabolism, considering the region’s unique natural features and the availability of resources.

Chapter 4 : Results

This chapter presents the results from the baseline metabolic analysis for Mpumalanga in the year 2017. The outcomes from regionalising the EW-MFA for Mpumalanga are provided first, including an overview of all material flows as well as an individual account of the main material groups: biomass; metals; non-metallic minerals; and fossil energy carriers. Following this, the nutritional and technical energy accounts are presented, culminating with the findings from the water account. The primary focus of this chapter is descriptive, with the interpretation of these results reserved for the subsequent chapter, Chapter 5.

The Sankey diagrams incorporated herein are designed such that the proportional widths of the arrows represent the relative size of the flows, be they material, energetic, or water. The numerical data have been rounded to the nearest unit as displayed, which may introduce minor variances between the aggregates of individual entries and the consolidated totals presented.

4.1. Material Flow Analysis

Regionalising the EW-MFA framework for Mpumalanga in 2017 revealed that roughly 291 million metric tons (Mt) of materials were sourced through domestic extraction, while around 99 Mt were net exports and 3.8 Mt were bunkered, as illustrated in Figure 4-1. Of the 190 Mt of processed materials, 2.3 Mt originated from secondary materials. The processed materials in the province were used predominantly for energy purposes, amounting to 121 Mt, while 69 Mt were used for material purposes (Figure 4-1). The majority of material use resulted in throughput materials, totalling just under 58 Mt, while 11 Mt were allocated to expanding and maintaining the province's manufactured capital, leading to a net increase in in-use material stocks of 10 Mt. Consequently, around 5% of all processed materials in 2017 contributed to the expansion of infrastructure, buildings and durable products within Mpumalanga. Of the throughput materials, around 90% consisted of extractive waste from metal ores and coal.

A total of 93 Mt of end-of-life waste resulted from various sources including demolition and discard, throughput materials and solid waste from energetic use. Among these, just under 3% was recovered and reused as secondary materials, while the remaining 97% was either disposed of in landfills, composted or incinerated, ultimately released into the environment. Carbon, nitrogen and sulphur emissions to air amounted to roughly 63 Mt, with roughly 56 Mt originating from fossil energy carriers and 6 Mt from biomass sources such as food and feed, as depicted in Figure 4-1. Fossil energy carriers also accounted for around 19 Mt of water vapour. The total domestic processed output for Mpumalanga in 2017 was sizable, at just under 178 Mt which included 2.8 Mt of materials for dissipative use.

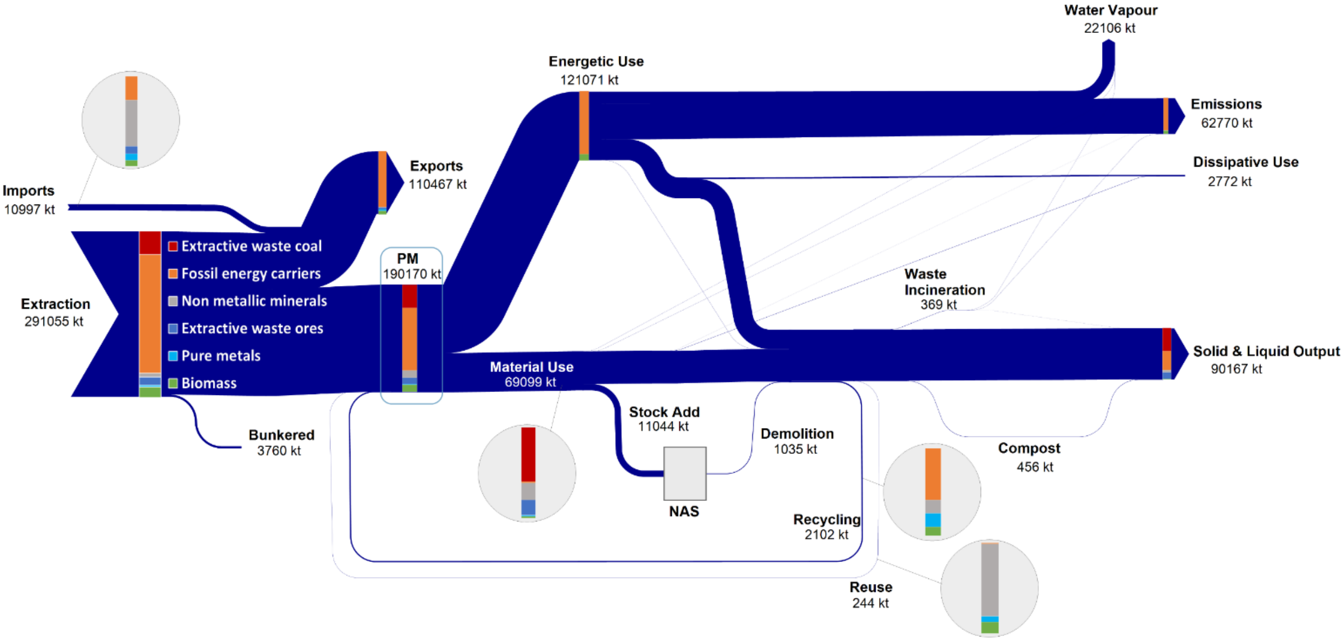


Figure 4-1: The regionalised economy-wide material flows for Mpumalanga in 2017 in kilotons (kt).

Fossil energy carriers by mass, primarily hard coal, overwhelmingly dominated the material flows within Mpumalanga in 2017. The subsequent sections present the results for the biomass, metals, non-metallic minerals and fossil energy carrier material flows for the province.

4.1.1. Biomass

The biomass material flows are illustrated in Figure 4-2. Biomass extraction was sizeable at just under 19 Mt, with a notable portion being exported (33%), while there were minimal biomass imports into the province. Thus, most of the processed material was sourced from extraction within the province, of which around one-tenth was for material use; primarily forestry products (0.6 Mt). A portion of the material use was added to stocks, totalling 0.41 Mt, while a fraction of stocks was discarded and demolished (0.12 Mt), resulting in a net addition to stock of 0.28 Mt (Figure 4-2). The remaining processed material served as a source of nutritional energy for livestock (as feed) and humans (as food), and to a lesser extent technical energy. The dominant energetic use of biomass led to 6 Mt of biogenic emissions, 2.7 Mt of water vapor and 2.4 Mt of dissipative use through manure. In terms of biomass recycling and reuse, roughly 12% of the end-of-life waste was recovered, leaving around 1.2 Mt of waste to be disposed of through landfills, composting or incineration (Figure 4-2).

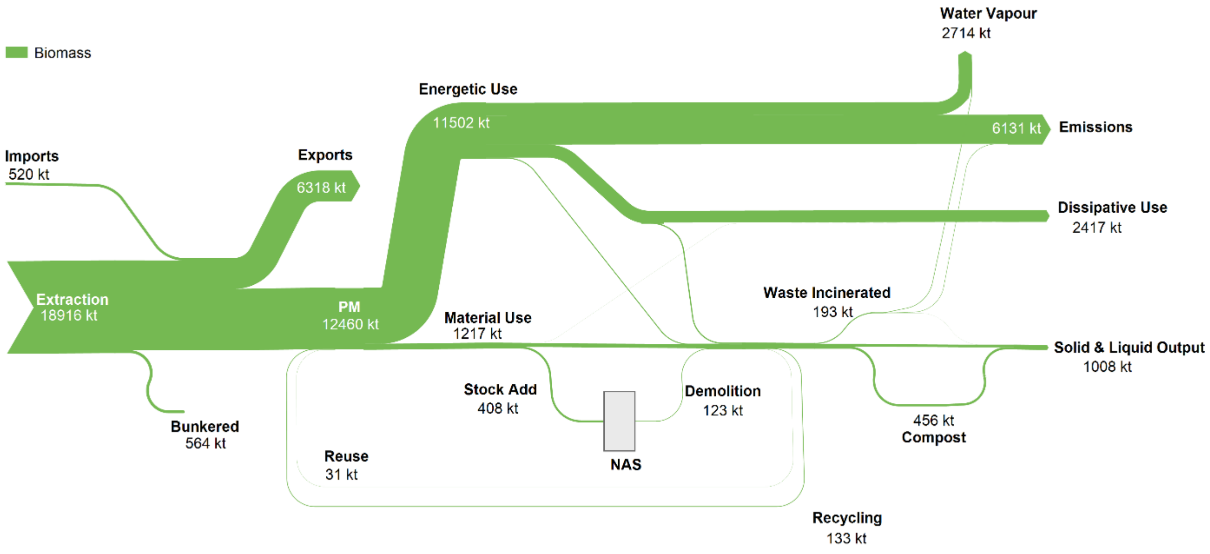


Figure 4-2: Biomass material flows through Mpumalanga for the year 2017 in kilotons (kt).

The dominance of primary crop production, biomass grazing and forestry in the province is highlighted in Figure 4-3. Farming of sugar crops and cereal crops dominated primary crop extraction (6.3 Mt), accounting for around 46% and 34%, respectively. Extraction of crop residues, fodder crops and grazed biomass for animal feed collectively surpassed that of primary crops. Meanwhile, industrial roundwood accounted for 84% of total wood extraction (4.5 Mt), comprising roughly 80% pulpwood and 20% sawlogs.

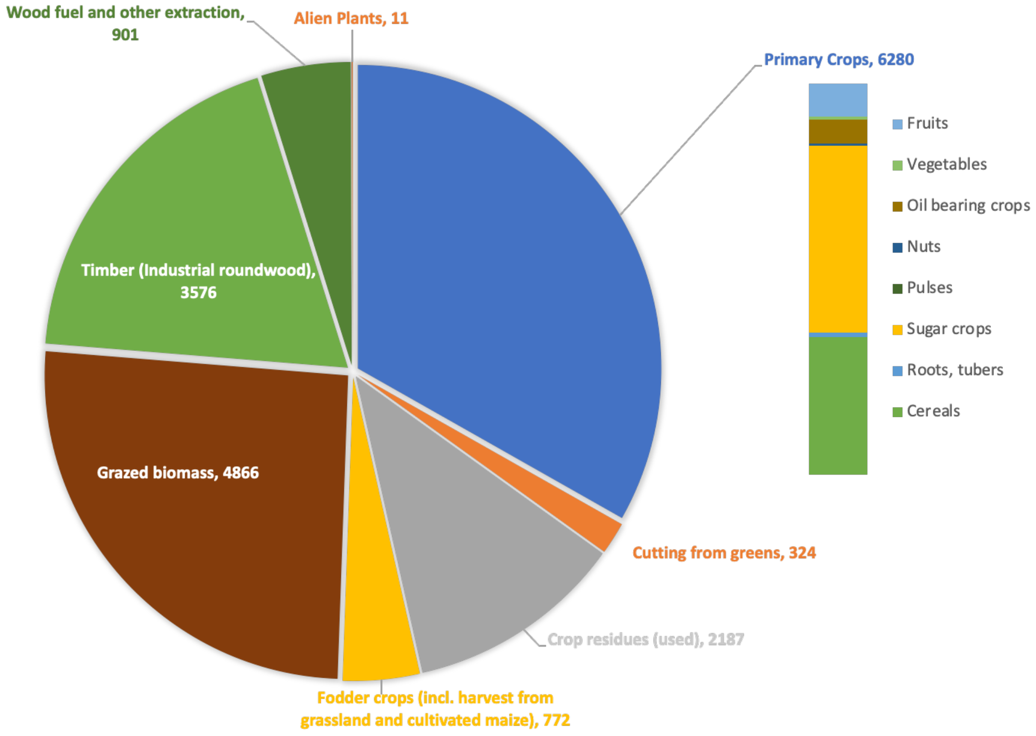


Figure 4-3: Breakdown of biomass extraction in 2017 for Mpumalanga in kilotons (kt).

4.1.2. Metals

The metal flow accounts for Mpumalanga are shown in Figure 4-4 and depict both the pure metal component and the extractive waste component of metal ores. In 2017, the province extracted approximately 3 Mt of pure metal, while the accompanying extractive waste was over four times that, amounting to 14 Mt (Figure 4-4). Most of the extractive waste remained within the province and returned to the environment as solid and liquid waste, totalling 11.4 Mt, as illustrated in Figure 4-4.

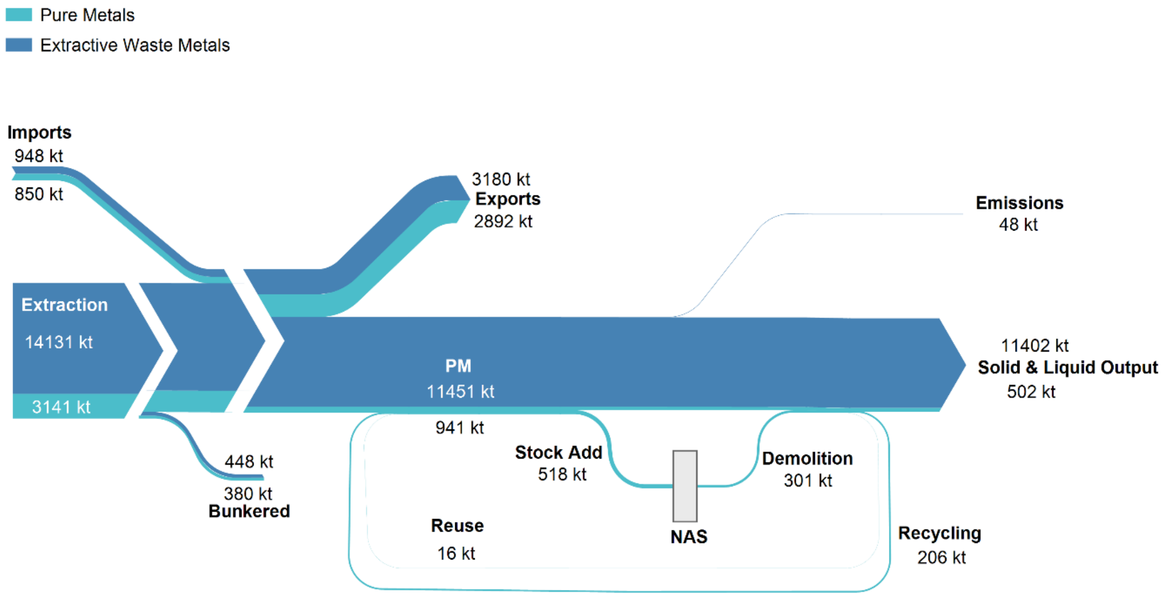


Figure 4-4: Metal material flows through Mpumalanga for the year 2017 in kilotons (kt).

Chromite was the primary metal ore extracted in the province, totalling around 6.6 Mt, of which a large portion was exported. In terms of pure metal component, chromite comprises primarily chromium and iron. The quantities of chromium and iron extracted in the province are shown in Figure 4-5. Interestingly, it was estimated that no iron ore extraction occurred in the province. Thus, the reported iron extraction solely arose from chromite extraction, with no extractive waste attributed to it. All extractive waste was instead ascribed to chromium, given its dominance as a pure metal.

Other metals such as copper, nickel, and vanadium were also extracted, along with smaller amounts of gold and platinum group metals. These latter metals notably contributed to the extractive waste, as illustrated in Figure 4-5. In 2017, the total processed metal material in the province (both extractive and pure) stood at approximately 12 Mt.

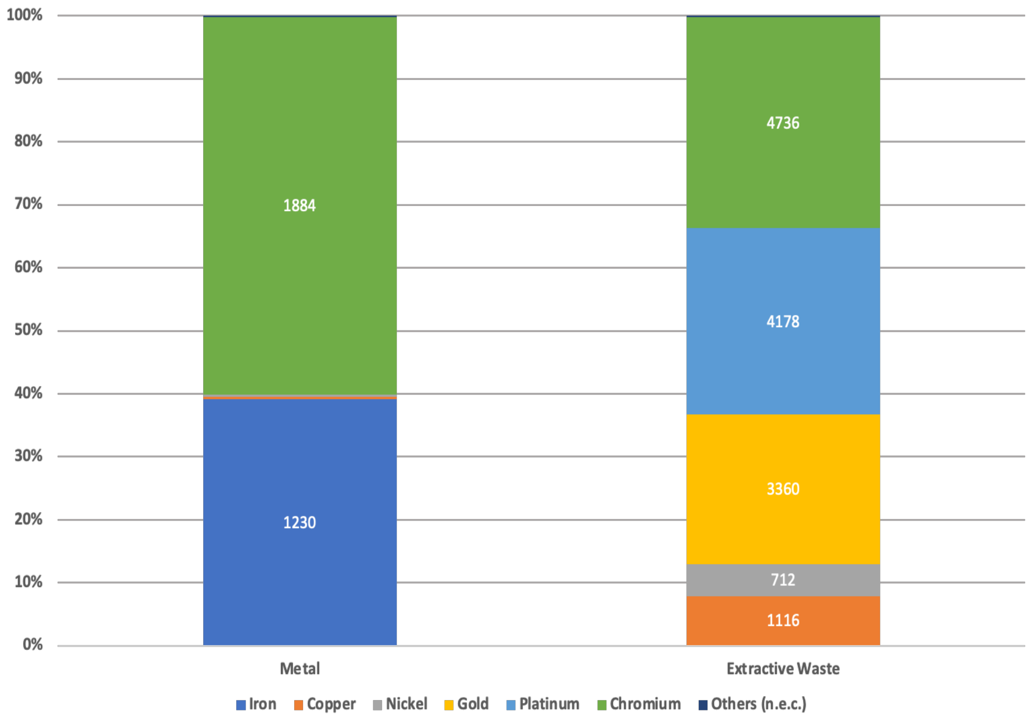


Figure 4-5: Metal ore extraction for Mpumalanga in 2017, split into pure metal (left) and extractive waste(right); the numbers show the size of metal material flows in kilotons (kt) as well as the percentage composition of materials.

In terms of domestic processing, ferroalloy production in the province was dominant. As a result, notable amounts of chromium and manganese were processed. While no manganese ore was extracted within the province, it was imported for local processing. Notably, about 80% of the locally processed chromium and manganese was used for steel production, facilitated by two steel plants in the province. To meet the production capacity of these plants, iron ore (or scrap) was also estimated to be imported. All the metals processed in the province were assumed to be utilised for material purposes, however small amounts of the organometallic compound methylcyclopentadienyl manganese tricarbonyl (MMT) have been used as an octane-booster in Sasol's petrol. The pure metal contribution to material use was 941 kt, with iron and steel constituting nearly 90%. The dynamics between steel, iron, chromium, and manganese for the province are illustrated in Figure 4-6.

More than half of the total metal material use within the province was allocated to expanding and maintaining manufactured capital in the province, as illustrated in Figure 4-4. Meanwhile, 301 kt of societal in-use stocks reached their end-of-life and were discarded/demolished, leading to a net-addition to stocks of about 217 kt. Metal throughput and demolition amounted to a total of 724 Mt, from which approximately 30% or 222 Mt was recovered, with the highest recoveries estimated for steel (70%), lead (100%), copper (70%) and bauxite and other aluminium (80%). However, these figures were interpreted with caution since they were based on top-down estimates without primary data from the province.

Lastly, solid and liquid outputs from the pure metal component totalled 502 kt, while emissions from the imported iron ore were approximately 48 kt (Figure 4-4).

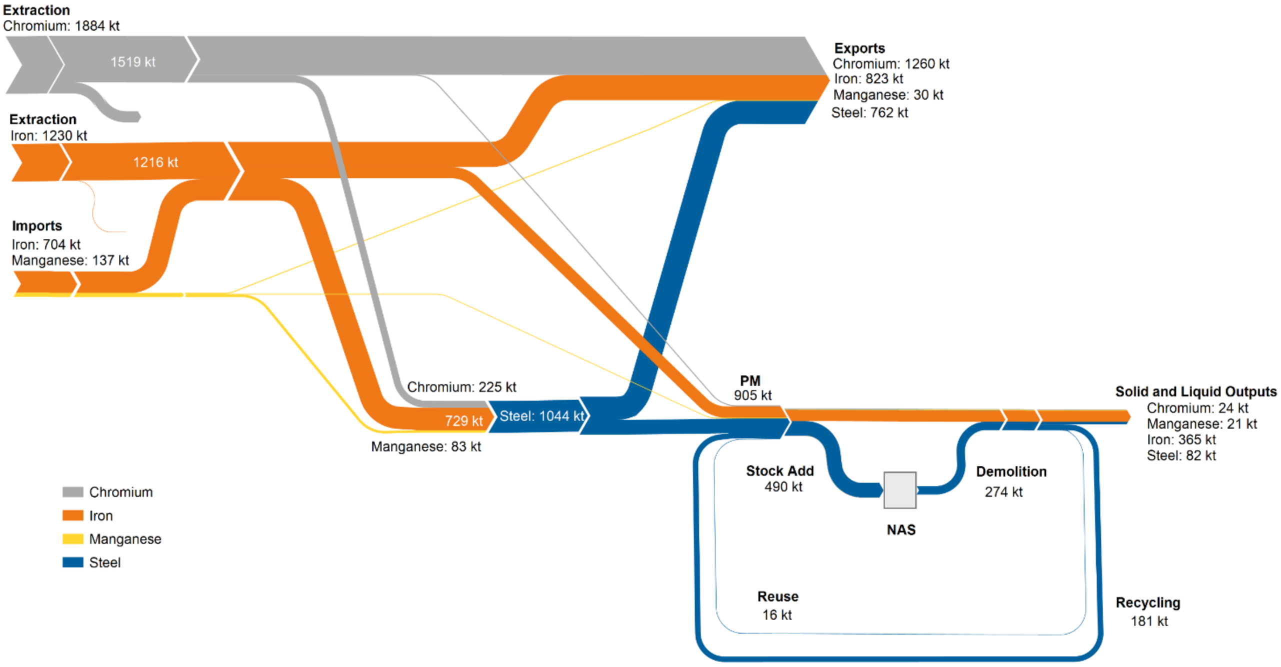


Figure 4-6: Material Flows of chromium, manganese, iron and steel within Mpumalanga for the year 2017 in kilotons (kt).

4.1.3. Non-metallic minerals

The flows of non-metallic minerals, which encompass construction and industrial minerals, for Mpumalanga in 2017 are illustrated in Figure 4-7.

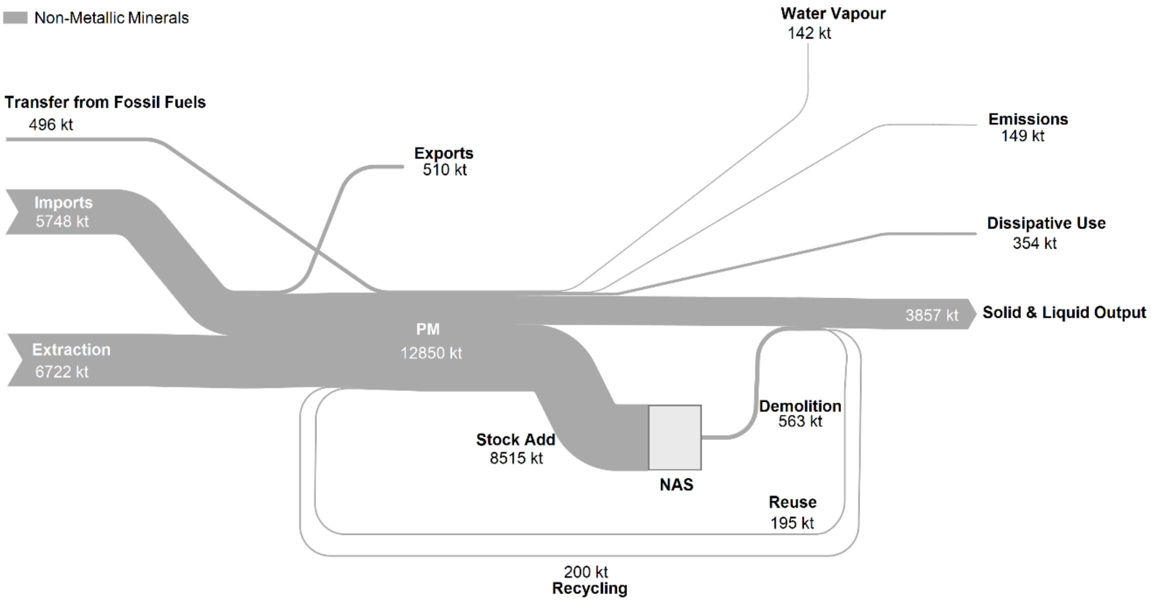


Figure 4-7: Non-metallic mineral material flows through Mpumalanga for the year 2017 in kilotons (kt).

The domestic extraction amounted to just under 7 Mt, as shown in Figure 4-7, of which approximately 98% was construction minerals. The small portion of industrial minerals, totalling 0.1 Mt, extracted in the province was from chemical and fertiliser minerals, specifically talc and magnesite (Figure 4-8). Gravel and sand dominated the construction mineral extraction in the province, amounting to just under 5 Mt, followed by chalk, dolomite and limestone at 1 Mt for 2017 (Figure 4-8). Meanwhile, the province was a net importer of non-metallic minerals (5.2 Mt), an amount almost equivalent to that of domestic extraction. Imports into the province, consisted primarily of gravel and sand, contributing to 36%, and chemical and fertiliser minerals, contributing 55%, as seen in Figure 4-8.

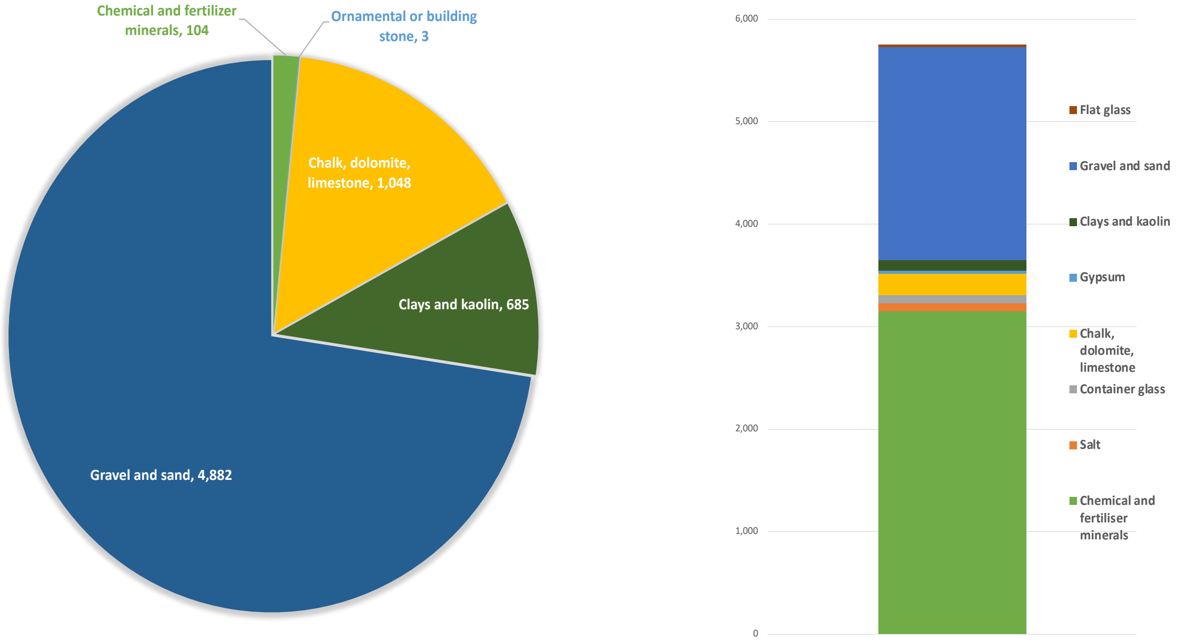


Figure 4-8: Breakdown of domestic extraction (left) and imported (right) non-metallic minerals in Mpumalanga for 2017 in kilotons (kt).

Processed materials in this category in the province amounted to around 12.8 Mt, 100% of which was utilised for material purposes, as illustrated in Figure 4-7. This included roughly 0.5 Mt of petrochemically derived ammonia and sulphur as well as bitumen, all of which were transferred from the fossil energy carrier material group. Around half of the sand, gravel, chalk, dolomite and limestone was dedicated to concrete production. It warrants mention that within Mpumalanga, there is only one cement grinding plant with an annual capacity of 1.4 Mt. Approximately 8.5 Mt or 95% of construction minerals were allocated to expanding and maintaining manufactured capital in the province, while the amount of construction and demolition waste was relatively low in comparison at 563 kt, resulting in a net-addition to stocks of about 7.9 Mt. Out of the 1 Mt of end-of-life waste from construction minerals, around a quarter was recovered as secondary materials. Water vapour stemming from brick production and carbon emissions from the calcination of limestone as well as cement production amounted to 142 kt and 149 kt, respectively (Figure 4-7).

On the other hand, industrial minerals accounted for just under 30% or 3.6 Mt of non-metallic mineral processed materials in the province. Interestingly, the province heavily relied on imported glass and salt. Negligible amounts of industrial minerals were added to stocks, meanwhile end-of-life waste amounted to roughly 3.2. Mt. The recovery of glass through recycling and reuse was notable at 66%.

The domestic processed output for non-metallic minerals was primarily solid and liquid outputs, totalling around 3.9 Mt, followed by dissipative use from fertiliser application at 354 kt, as illustrated in Figure 4-7.

4.1.4. Fossil Energy Carriers

In Mpumalanga, the sole fossil energy carrier extracted in 2017 was hard coal, accounting for a dominating quantity of approximately 207 Mt, as depicted in Figure 4-9. The accompanying extractive waste amounted to slightly less than 41 Mt, all of which was returned to the environment as solid and liquid waste. The province exhibited a net export of hard coal, totalling 91 Mt, as well as liquid fuels amounting to 1.6 Mt. The latter result stemmed from coal-to-liquid processes within the province, which also generated various co-products, consequently establishing the province as a net exporter of both primary and secondary petrochemicals. In contrast, the province recorded a net import of gas, amounting to 0.8 Mt.

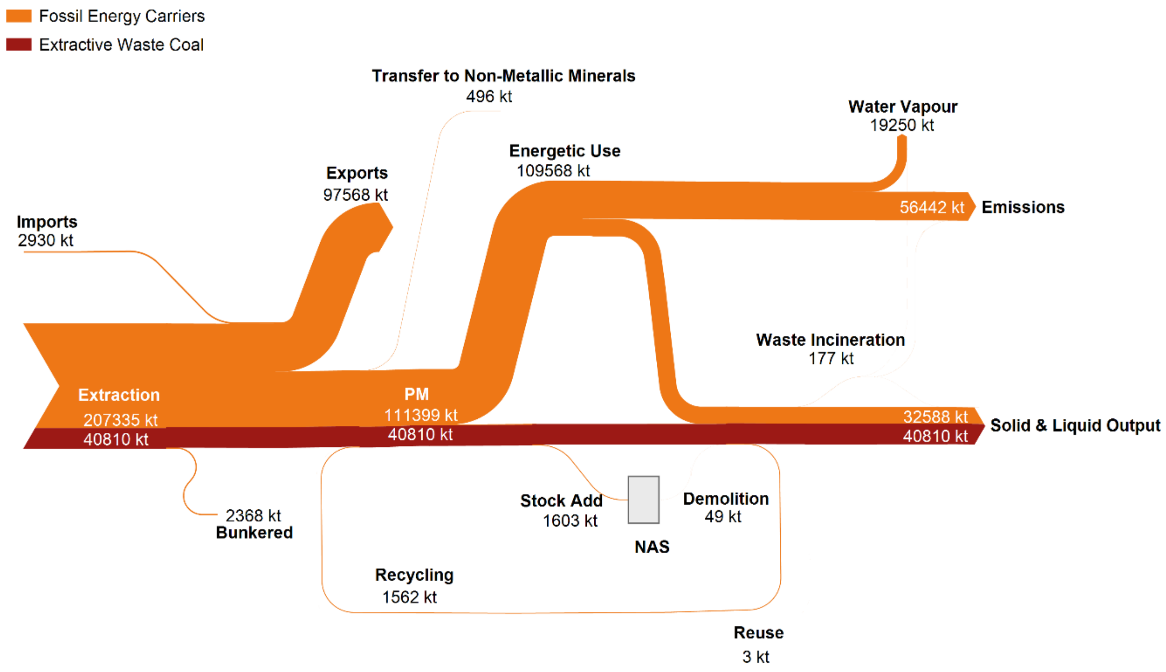


Figure 4-9: Fossil energy carrier material flows through Mpumalanga for the year 2017 in kilotons (kt).

Out of the total processed fossil fuel material of 111 Mt within the province, only a small fraction was allocated for non-energetic purposes. The utilisation of fossil energy carriers for material purposes encompassed petrochemical-derived products such as plastics, bitumen and tyres, of which 15% was reclaimed as secondary materials. The remaining processed material served energetic purposes, leading to the combustion of approximately 110 Mt of fossil energy carriers in the province, as illustrated in Figure 4-9, with hard coal accounting for 97% of this total. Hard coal combustion in the province generated 34 Mt of ash, 51 Mt of carbon emissions, about 2 Mt of other emissions and 18 Mt of water vapor. A portion, approximately 1.5 Mt, of the ash produced from hard coal combustion and coal-to-liquid processes was recovered and repurposed for material-use in the construction sector.

The dominant material transfers within the province occurred during the coal-to-liquid processes, where hard coal was transformed into a range of materials. Given that these materials were not extracted from nature in the same form that they were used, introducing transfers facilitated better accounting principles (von Blottnitz *et al.*, 2022). A breakdown of the coal-to-liquid processes within the province is depicted in Figure 4-10. Roughly 39 Mt of hard coal was utilised, which included hard coal for feedstock, steam and electricity generation. The transfers from hard coal amounted to about 7.8 Mt, this reflected the weight of products produced as a result of the coal-to-liquids processed (Figure 4-10). The major product was liquid fuels at 4.5 Mt, followed by organic petrochemicals at 1.5 Mt. Liquid fuels and methane-rich gas were utilised predominantly for energetic purposes, while plastics, organic and inorganic petrochemical are utilised for material purposes. Furthermore, the inorganic petrochemicals comprising ammonia and sulphur were transferred to the industrial minerals' material class of chemical and fertiliser minerals. As previously mentioned, Mpumalanga was a net exported of these products, bar gas.

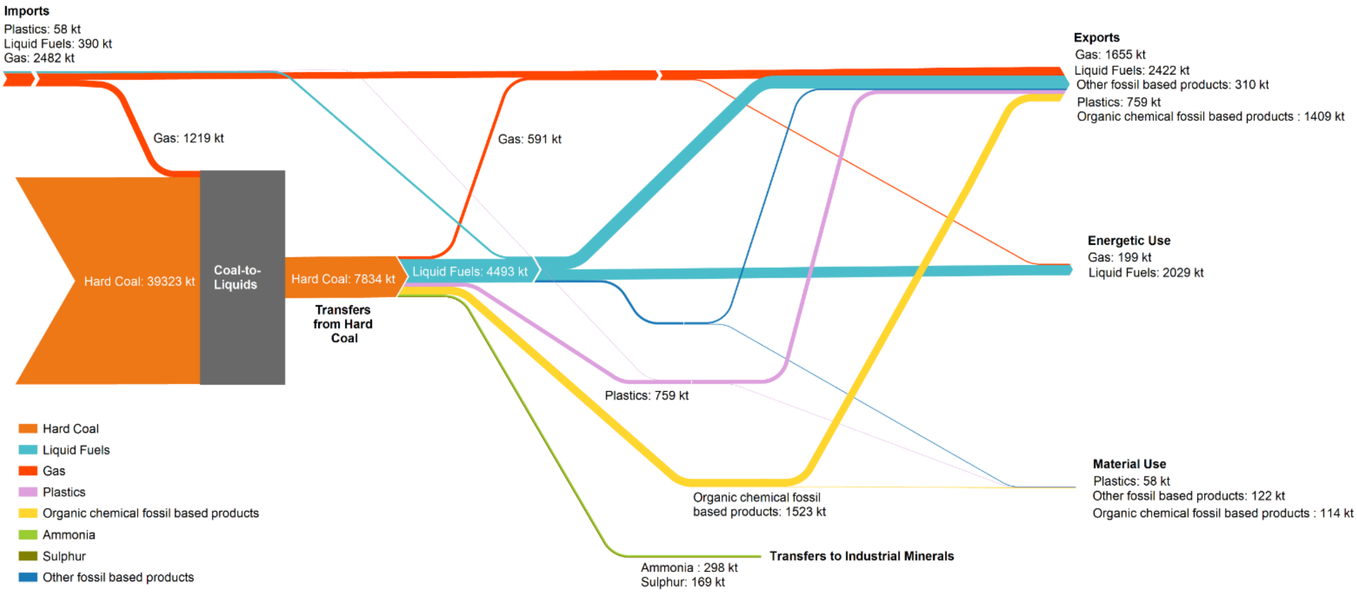


Figure 4-10: Breakdown of Coal-to-liquids material flows and transfers in Mpumalanga for the year 2017, in kilotons (kt).

4.2. Energy Balance

The results from the technical and nutritional energy accounts for the province are reported below.

4.2.1. Technical Energy

The technical energy flows within the province of Mpumalanga for the year 2017 are depicted in Figure 4-11. The extraction of technical energy in the province was primarily driven by coal, contributing to 4 788 Petajoules (PJ), while a minor share of biomass was also extracted, amounting 22 PJ. The imports of gas and liquid fuels to the province were approximately 137 PJ, whereas the exports of technical energy reached about 2 924 PJ. As a result, the province emerged as a net exporter of coal, electricity and liquid fuels during the year 2017. The exportation of technical energy was predominantly from coal (82%), followed by electricity (12%), liquid fuels (4%) and gas (3%).

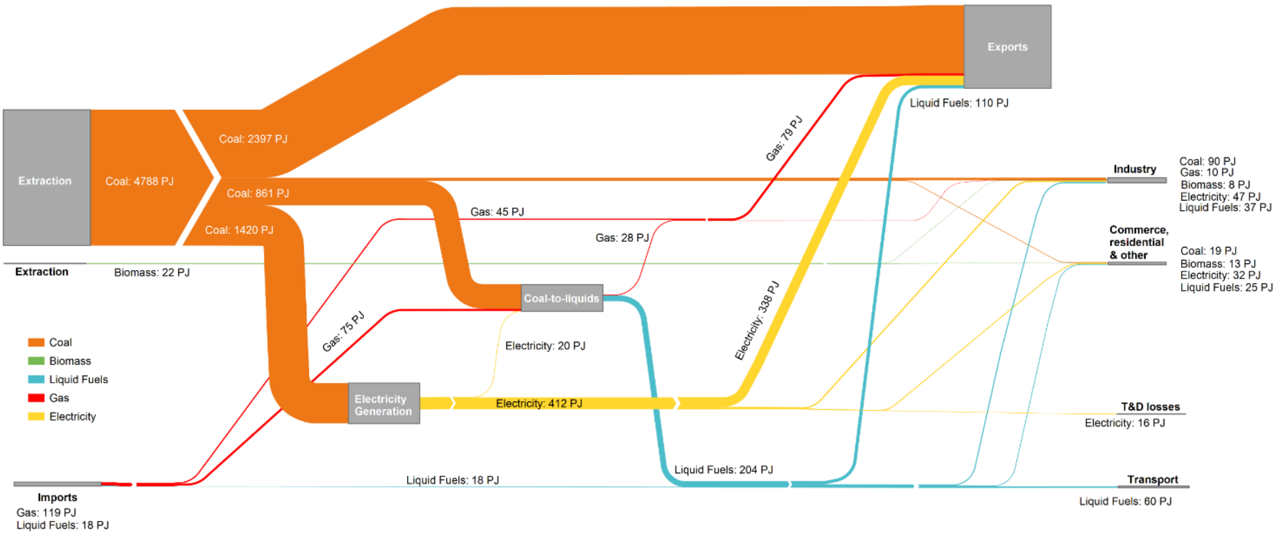


Figure 4-11: Technical energy flows for Mpumalanga in 2017 in Petajoules (PJ).

The predominant utilisation of coal within the province was for electricity generation, whereby around 1 420 PJ of coal was converted to approximately 443 PJ or 123 200 GWh (1 PJ = 278 GWh) of electricity. Of this, 11 PJ (3 056 GWh) was used onsite, while 16 PJ (4 520 GWh) was lost during transmission and distribution. The value for electricity generated in the province was marginally higher than the 120 158 GWh generated by Eskom's coal-fired power stations in Mpumalanga, as reported in the province's environmental outlook for 2017/2018 (DARDLEA, 2019).

Coal-to-liquid processes represented the second largest utilisation of coal within the province. The total energetic inputs for coal-to-liquid processes approximated to 956 PJ, with coal constituting 90%, or 861 PJ, of this input. The coal was employed for both feedstock and steam generation (237 PJ), alongside electricity generation (17.8 PJ). The coal-to-liquid processes yielded about 204 PJ of liquid fuels and 28 PJ of gas, respectively, as seen in Figure 4-11. Notably, the fossil energy carrier materials including plastics and chemical by-products are not reflected in the coal-to-liquid energy output quantities.

A breakdown of the final use by sector within the province for 2017 is illustrated in Figure 4-12. The industrial sector emerged as the primary consumer of technical energy, with a total consumption of approximately 191 PJ. This was followed by the combined consumption of the commerce, residential, and other sectors at 89 PJ and the transport sector at 60 PJ.

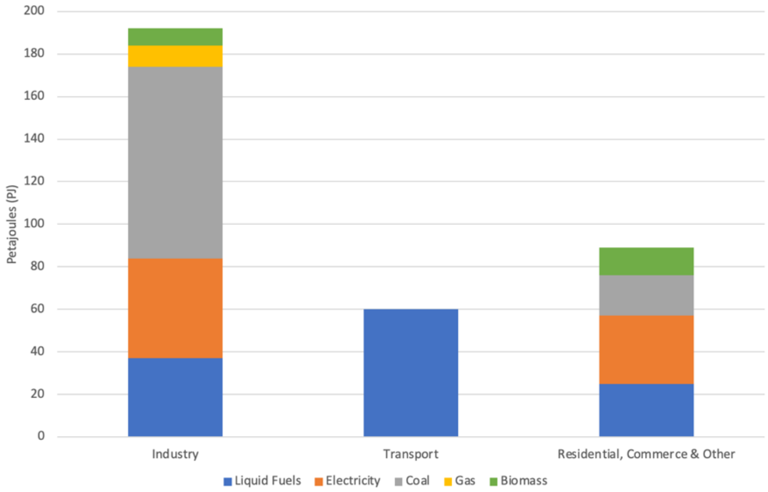


Figure 4-12: Breakdown of final technical energy use by sector for Mpumalanga in 2017 in Petajoules (PJ).

The utilisation of liquid fuels was dominated by the transport sector, which accounted for approximately 48% of the total final use within the province. In contrast, the predominant consumer of coal, excluding its use for power generation and coal-to-liquids processes, was the industrial sector, with a consumption rate of about 83% of the total final use in the province. Moreover, the industrial sector emerged as the principal consumer of both electricity and gas, accounting for around 60% and 100% of the total final use, respectively. Regarding biomass used for technical energy, the residential, commercial, and other sectors were the major consumers, constituting about 60% of the final use in the province. Biomass utilised for co-generation in the industry sector amounted to around 8 PJ.

4.2.2. Nutritional Energy

The results from the nutritional energy account for Mpumalanga in 2017 are shown in Figure 4-13. The province's extraction of primary nutritional energy was approximately 157 PJ, with grazed biomass being the predominant source at 46%, followed by primary crops at 26%, crop residues at 20% and fodder crops at a minimal 8%. It is noteworthy that although primary crops surpass grazed biomass in mass, which can be partially attributed to their high moisture content and that they are reported in wet-weight, unlike fodder crops and grazed biomass which are reported in dry-weight, as is required by EW-MFA general guidelines (Haberl *et al.*, 2008).

In terms of nutritional imports, Mpumalanga imported around 1 PJ of primary crops in 2017. As expected, the region was a net exporter of nutritional energy with approximately 20 PJ of primary crops and 6 PJ of fodder crops being exported, as shown in Figure 4-13. Of the maize processed in the province, 45% is intended for human food and 55% for animal feed. Notable portions of maize for animal feed and human food were exported to meet demand outside the provincial borders.

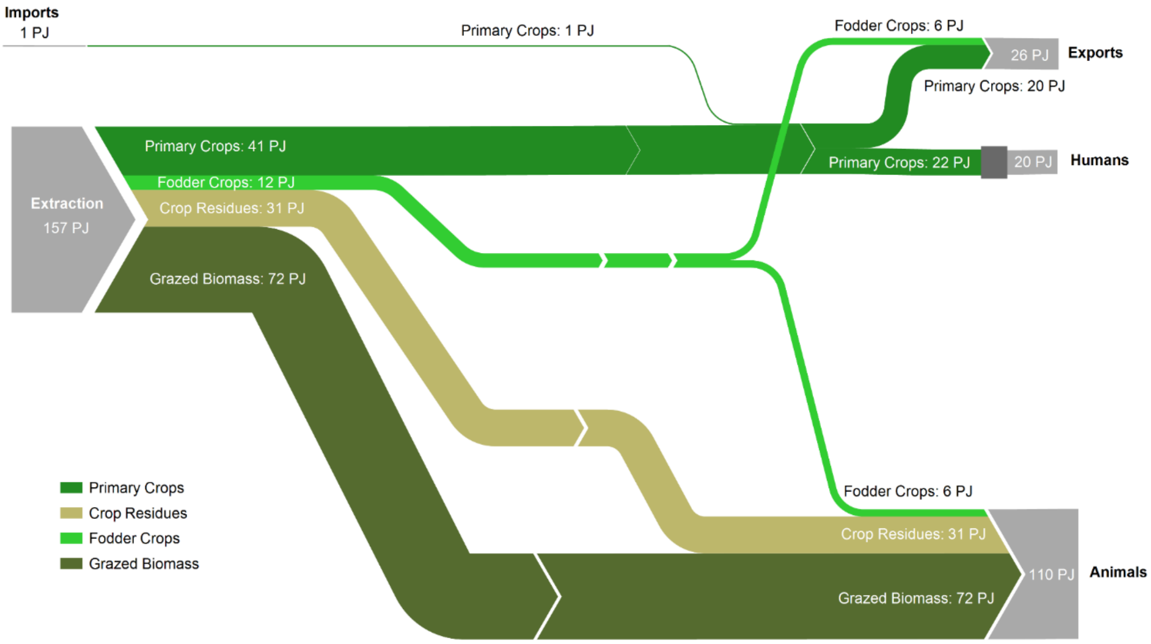


Figure 4-13: Nutritional energy flows in Petajoules (PJ) for Mpumalanga in 2017.

The final utilisation of nutritional energy for animal feed totalled approximately 110 PJ, predominantly from grazed biomass (65%) and crop residues (28%), aligning with the estimate that 96% of the animals in the province were grazers. The analysis did not account for losses in feed supply leading up to the final use, adhering to the demand-based approach taken in the EW-MFA. Human food from plant-derived nutrition, in comparison, was much lower at 20 PJ which accounted for an estimated 2 PJ of losses due to processing and consumer waste. The nutritional energy value for human consumption of 20 PJ translates to approximately 12.6 MJ per capita per day, not accounting for the energy from animal-derived food products. This per capita figure is slightly above the FAO's reported daily caloric supply of 12.1 MJ for South Africans in 2018 (Roser *et al.*, 2023), which includes animal derived food products. It also surpasses the daily caloric availability for South African households documented by Rose *et al.* in their 2002 study, which is approximately 10.4 MJ per adult female equivalent (including animal derived food products).

A further breakdown of primary crops extracted, imported, exported, and used in the province can be seen in Figure 4-14. Extraction was dominated by cereal crops followed by oil and sugar crops; a large portion of these nutritional flows were exported as illustrated in Figure 4-14. This was expected given the favourable Highveld climate as well as the fact that Mpumalanga is one of two province's that grows and processes sugarcane. The largest import in terms of nutritional energy into the province was sugarcane at 0.52 PJ, which is for further processing within Mpumalanga, followed by vegetables at 0.4 PJ. In terms of primary crops for final use, cereals dominated at 58% followed by oil bearing crops at 18% and sugar crops at 14% and to a lesser extent pulses (1%), roots and tubers (2%), vegetables (2%) and fruits (3%).

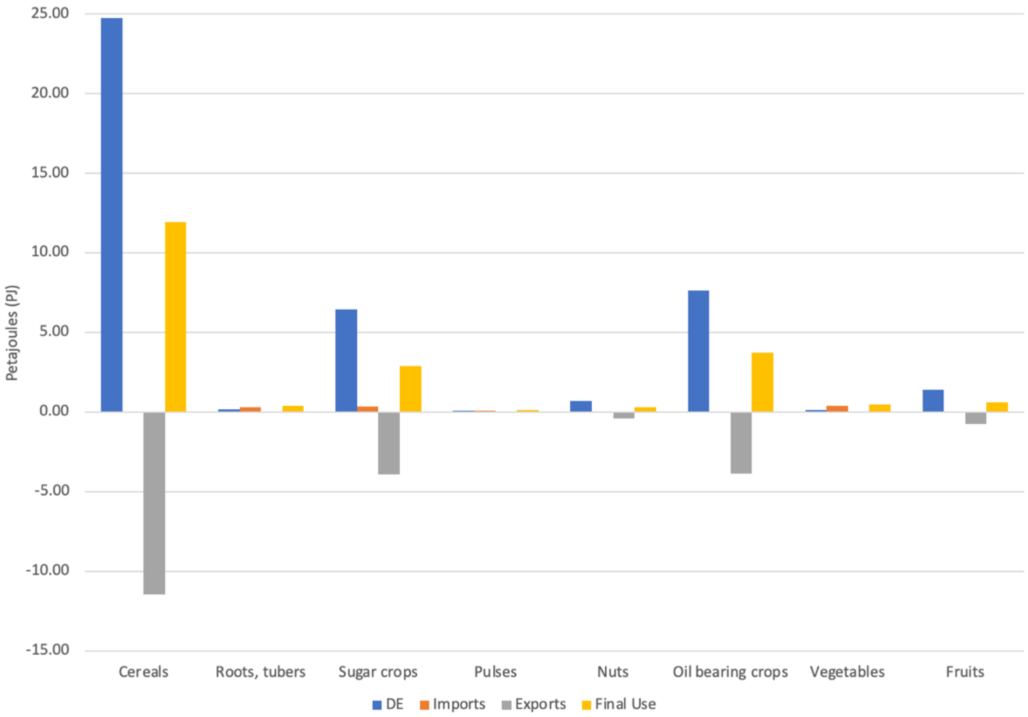


Figure 4-14: Primary crop breakdown in Petajoules (PJ) for Mpumalanga in 2017.

When interpreting the results, it is crucial to understand that the reported final energy use represents the gross energy content of food, which does not consider the losses incurred during digestion and absorption. The usable portion of gross energy is known as metabolizable energy, which is typically 5-10% less than the gross energy (Egan and Collins, 2022). Furthermore, it is important to recognise that the aggregated nutritional energy flows are not representative of quality (Giampietro, 2008). This means that 1 MJ from cereal crops may not provide the same nutritional value or energy service as 1 MJ from fruits. The distinction here emphasises that equal energy values from different food sources do not necessarily offer equivalent nutritional benefits or functionality.

4.3. Water Account

The results of the physical water flow account for Mpumalanga in 2017 are depicted in Figure 4-15. The total water supply for the period was estimated to be approximately

2 095 million cubic meters (Mm^3), which is comparable to DEDT's 2017 report of 2 037 Mm^3 (2019). This encompassed imports and the abstraction from surface and groundwater resources. The imports from inter-basin transfer schemes were assumed to be 77 Mm^3, which was the reported provincial deficit for 2017 (DEDT, 2019). The abstraction from surface and groundwater sources was estimated at 1 729 Mm^3 and 289 Mm^3, respectively. It is noteworthy that the groundwater figure is based on data from only one of the three WMAs in the province; that managed by the Inkomati-Usuthu Catchment Management Agency (IUCMA). Therefore, the actual groundwater abstraction might surpass the reported value. However, the data from IUCMA are considered a reliable indicator of the province's water resources, according to the DARDLEA, both qualitatively and quantitatively (DARDLEA, 2019). While no data on water exports was found for the province, it is noted that around 350 Mm^3 of water flowed from the Inkomati Basin to Mozambique in 2017 (DWS, 2017).

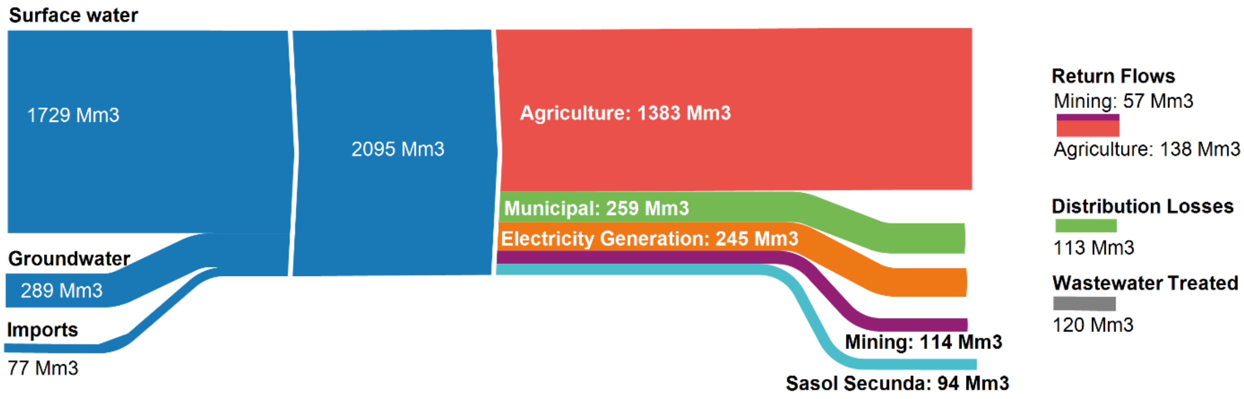


Figure 4-15: Water account for Mpumalanga in 2017 in million cubic metres (Mm^3).

A breakdown of water-use within the province for 2017 can be seen in Figure 4-16. Agriculture emerged as the predominant water consumer in Mpumalanga for 2017, accounting for around 66% of water use. Van Niekerk et al. (2018) estimated irrigation water use at 1 245 Mm^3 for the 2014/15 season. Considering irrigation inefficiencies and assuming a 90% efficiency rate for drip irrigation, the actual water usage approximated to 1 383 Mm^3 (Van Niekerk, Jarmain and Goudriaan, 2018). Given the consistency in rainfall patterns between 2014 and 2017, and corroborated figures of 1 011 Mm^3 and 1 120 Mm^3 for irrigation agriculture by IUCMA (2023) and DEDT (2019) respectively, these estimates are assumed to be relevant for this analysis.

In 2017, approximately 59 676 ha of field crops were irrigated in Mpumalanga, constituting about 9% of the total field crop area (StatsSA, 2020). Sugarcane, a water-intensive crop, which was almost exclusively irrigated had a median water usage of 906 mm/yr, with other significant crops being citrus (911 mm/yr), maize (737 mm/yr), and wheat (658 mm/yr) (Van Niekerk, Jarmain and Goudriaan, 2018). Notably, the Stream Flow Reduction Activity (SFRA) from forestry plantations was approximately 420 Mm^3, although not represented in Figure 4.15 (IUCMA, 2023).

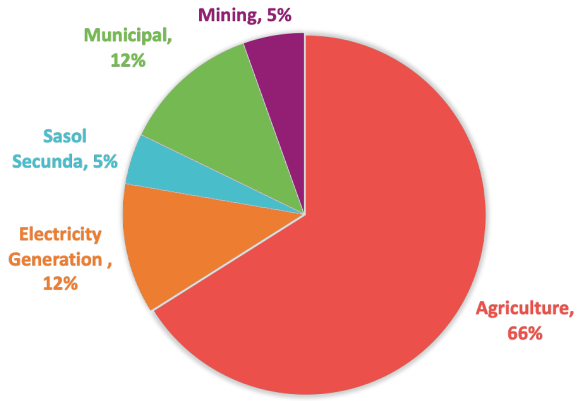


Figure 4-16: Breakdown of water usage per sector within Mpumalanga.

Municipal water supply in the province was recorded at 259 Mm^3 by the DWS for 2017, equating to approximately 160 litres per capita per day (l/c/d). This value is slightly higher than the reported 10% or 204 Mm^3 for domestic use in 2017 as reported by DEDT (2019). Non-revenue water (NRW) accounted for 118 Mm^3, out of which 113 Mm^3 was distribution losses with the remainder as non-billed authorised consumption (DWS, 2017). The municipal water use was below the national average (191 l/c/d), with local municipalities exhibiting varied consumption and loss rates (DWS, 2017). Emalahleni had the highest municipal supply with 38 Mm^3, followed closely by the City of Mbombela, Bushbuckridge and Govan Mbeki (DWS, 2017). The highest NRW losses were recorded in Dr JS Moroka at 77.1%, with Bushbuckridge, Nkomazi and Thembisile Hani each reporting 58% losses (DWS, 2017).

The third largest water user in the province for 2017 was Eskom. In one report, water usage for power generation in the province was reported to constitute 26% of the total provincial use, or approximately 530 Mm^3 in 2017 (DEDT, 2019). This figure contrasts with Eskom's reported net raw water consumption of 276 Mm^3 for all its coal-fired power stations, leading to a revised estimate of 245 Mm^3 (equating to around 12%) for the province in 2017 (Roselt and Mpofu, 2021). Among these, the plant at Arnot consumed the most at 37.5 Mm^3, with those at Kriel and Tutuka each using about 34.2 Mm^3 (Roselt and Mpofu, 2021).

The mining sector, as per DEDT (2019), utilised 3% of the total water, estimated at 61 Mm^3. However, this figure appears to be an underestimate given that, on average approximately 431 litres of water are used per ton of coal produced (CER, 2018). Based on national benchmarks for water conservation and demand management in the mining sector, the consumptive water use for coal mining is benchmarked at 380 litres per ton of run-of-mine coal (DWS, 2016). Using the national benchmark, this suggests an annual consumption of about 94 Mm^3 for coal mining in Mpumalanga for the year 2017, which exceeds the DEDT's reported figure by around 33 Mm^3.

The methodology used by DEDT in 2019 to arrive at the 61 Mm^3 figure was not disclosed. Consequently, the national benchmark figures were applied for coal to estimate the province's water use, based on the provincial accounts for domestic extraction. The same approach was employed for gold, platinum, and other metals mined in the region. The estimates place the total consumptive water use for mining in the province at 114 Mm^3 for 2017. When compared to the national water usage of 600 Mm^3 in 2014, this estimate appears reasonable. Regarding mining return flows, which in the national account constitute about half of the water use, the same proportion was applied in this study for lack of data, estimating that 60 Mm^3 of water was returned to the system (Maila, Crafford and Mathebula, 2018).

Industry water use in this account was limited to Secunda's coal-to-liquid processes, as reported by Sasol, which amounted to around 94 Mm^3 for 2017 which was comprised of river (93%) and potable (7%) water (Sasol, 2020). This value is higher than the reported manufacturing water use of 41 Mm^3 for 2017 in the province (DEDT, 2019), and lower than the IUCMA cumulative report for domestic and industry users of 548.8 Mm^3 (IUCMA, 2023).

In terms of water treatment, Mpumalanga has 76 municipal wastewater treatment works (WWTW), supplemented by 11 owned by the DWS, along with a number of private treatment facilities. Nonetheless, the oversight of water flows in and out of these WWTWs is hindered by significant data shortages. For instance, the 2022 provincial Green Drop report revealed that 46% of municipal treatment plants did not record daily inflow rates, a slight improvement from the 54% unrecorded in the 2013 report (DWS, 2013a, 2013b, 2013c, 2022). Discrepancies are evident, as the Green Drop reports from 2013 and 2022 indicate that only half of the facilities' designed capacities are in use, while other accounts suggest some facilities are operating beyond their intended capacity (DWS, 2013a, 2013b, 2013c, 2022; Roselt and Mpofu, 2021). Due to these data limitations and variances, assessments of the volume of water treated are based on the designed capacities of the WWTWs, which is regarded as the most dependable metric available. However, it is acknowledged that the actual volume of wastewater treated may deviate from this estimate.

Water quality in Mpumalanga has been a growing concern, with nutrient levels in both surface and groundwater showing a rising trend. According to the provincial Environmental Outlook Report (DARDLEA, 2019), the trend analysis from 2009 to 2017 showed a 10% increase in groundwater nitrate and nitrite concentrations, now at 5.09 mg/L, and an 8% increase in sulphate levels, now at 44.50 mg/L. In surface waters, there was a 12% increase in Chlorophyll-A, an indicator of algal growth, while phosphorous levels showed a potential 26% decrease (DEDT, 2019). A similar decrease in phosphate loading has been reported in other areas in South Africa and is believed to be related to the voluntary removal of phosphate from detergents by the dominant brand owner in the country around 2010 (Quayle, 2010; Chong *et al.*, 2019).

Table 4-1 outlines the three dominant contaminants in the three WMAs within the province. The data, which is from 2016, also suggests an increasing trajectory of total dissolved solids (TDS) and nitrate levels compared to 2011 values. According to the TWQR, most values fall within the ideal (green) and acceptable (grey) ranges, with the exception of phosphates (yellow) in the Vaal and Olifants WMA's. Although these figures suggest that water quality in the province is within acceptable limits, contrasting reports indicate otherwise (CER, 2018).

Table 4-1: Water pollutants for 2016 WMA's; adapted from Maila, Crafford and Mathebula (2018).

	Olifants WMA	**IUCMA**	**Vaal WMA**
TDS (mg/L)	490	498	553.8
PO_4 (mg/L)	0.0713	0.026	0.051
NO_3 (mg/L)	0.093	0.3	0.0793

The rise in nitrate and nitrite levels is likely linked to agricultural practices in the province, along with the influence of human settlements. At the same time, increases in sulphate concentrations can be attributed to the region's extensive coal mining activities. Empirical data from the Olifants River catchment area in Mpumalanga substantiates this, showing that observed sulphate loads increased by one to two orders of magnitude at monitoring sites, particularly during episodes of elevated runoff (Maila, Crafford and Mathebula, 2018). Deposits of sulphates and nitrates arising from Eskom's approximate 1.6 Mt of SO_2 and 0.8 Mt of NO_2 annual emissions (Eskom, 2023) are likely exacerbating the degradation of water quality in the province. This situation is further aggravated by the consistent inefficiency of wastewater treatment facilities in the province (DEDT, 2019). In 2017 approximately 200 000 households in Mpumalanga were affected by water pollution (StatsSA, 2018).

4.4. Metabolic Indicators

The metabolic indicators presented below, derived from the aforementioned material, energy and water findings, provide an aggregated view of Mpumalanga's resource patterns for 2017. A range of input, output and consumption indicators, as well as measures of intensities, are included. While gathering complete and reliable data presented significant challenges, the indicators assembled below are believed to be a reasonable representation of Mpumalanga's metabolic profile. It's important to note that this constitutes the province's first baseline metabolic assessment constituting material, energy and water flows, and as such, it represents a substantial first step in understanding and documenting its resource patterns.

Table 4-2: Material indicators for Mpumalanga in 2017.

Indicator	**Value (kt)**	**Per Capita (t)**
Domestic Material Input	302 051	68.0
Domestic Material Consumption	187 824	42.3
Physical trade balance	-99 471	-22.4
Processed Material	190 170	42.8
NAS	10 009	2.3
DPO	175 043	39.4
Interim Output	180 161	40.5

Table 4-3: Material input and output cycling rates for Mpumalanga in 2017.

	Input-side	**Output-side**
Basis	Processed Material	Interim Output
Socio-economic Cycling	0.13% re-use; 1.11% recycling	0.14% re-use; 1.17% recycling
Ecological Cycling	3.25%	3.45%
Total Cycling rate	4.48%	4.73%

Table 4-4: Material intensity indicators for Mpumalanga in 2017.

Indicator	**Value**	**Unit**
Material Intensity of economic activity	0.5	kt/Rand million
Material Productivity (GDP/kt)	1.9	Rand million/kt
Material Area Intensity	3.8	kt/km^2
Domestic resource intensity (DE/DMC)	1.5	-

Table 4-5: Energy Indicators for Mpumalanga in 2017.

Indicator	**Value (PJ)**	**Per Capita (TJ)**
Domestic Technical Energy Input	4,946	1.11
Domestic Technical Energy Consumption	2,023	0.46
Domestic Nutritional Energy Input	158	0.04
Domestic Nutritional Energy Consumption	132	0.03

Table 4-6: Water Indicators for Mpumalanga in 2017.

Indicator	**Value (Mm^3)**	**Per Capita (kl)**
Total water supply	2445	550
Net water use	1666	375
	Value (%)	
Water Return Rate (return flows/total supply)	18%	

Chapter 5 : Interpretation

The baseline metabolic assessment of Mpumalanga yields a variety of interesting and anticipated outcomes that offer a comparative lens with national figures, and that shed light on the province's resource flows. This section attempts to interpret the results, examine their broader significance, and, where possible, deduce what they indicate about Mpumalanga's sustainability prospects.

5.1. Nature of Mpumalanga's Metabolism

The interactions between nature and society are often predicated on the available natural capital. This concept has underpinned global economic activities for centuries. Given Mpumalanga's well-known extensive coal reserves, it is no exception to this historical pattern. The findings from the metabolic analysis underscore the central role of coal and its associated industries within the province, which overshadow other forms of natural capital, such as the region's high potential agricultural land. This dominance is discussed below, alongside other notable resource patterns that characterise the region's dynamics.

5.1.1. Electricity Generation

As anticipated, the material and technical energy analyses substantiate Mpumalanga's role as the cornerstone of South Africa's electricity generation. The province produces approximately 123 000 GWh of electricity annually. Of this output, around 102 000 GWh is exported, supplying an extensive network that extends to neighbouring countries Mozambique and Eswatini, alongside adjacent provinces Gauteng, Limpopo, Free State and KwaZulu-Natal; as delineated by South Africa's grid architecture.

This principle provincial output is reliant on the supply of roughly 71 Mt of coal and 245 Mm^3 of water, which equates to about 26% of the provincial non-renewable extractives and 12% of its water usage (most of which is lost to evaporation). These resources power the operations of the 12 coal-fired power stations owned by Eskom, which are strategically situated across the Highveld region in close proximity to the coal mines.

Notwithstanding its sizable electricity exports, Mpumalanga has a disproportionately high consumption of electricity. Despite being the second smallest of South Africa's nine provinces and home to only 7.9% of the nation's population, it ranks as the country's third-largest consumer of electricity. This elevated consumption is likely due to the aggregation of energy-intensive industries within its borders, which contribute a not insignificant portion of the country's primary industry GDP (18.5%).

However, the heavy dependence on coal for electricity generation imposes clear environmental repercussions. The emissions resulting from these power stations considerably degrade air quality, as evidenced by significant high priority air pollutant emissions. Reports confirm high levels of air pollution in areas surrounding the power plants, accompanied by human health and livelihood implications. Furthermore, there are reports of increased sulphate and nitrate levels on the already strained provincial water supply. The province also produces considerable quantities of ‘hazardous’ ash as a result of its power generation, with only a small fraction (6%) being repurposed as secondary material in the construction sector.

5.1.2. Coal-to-liquids

Sasol’s coal-to-liquids plants and broader Secunda complex stand as distinct industrial features, unique to the province and arguably the rest of the world.

The coal-to-liquids facilities plays a critical role in producing and supplying liquid fuel to the scale of 204 PJ, which significantly addresses the fuel requirements of the provincial transportation and industrial sectors, as well as meeting the needs of neighbouring inland regions (exporting 110 PJ). This production is pivotal, particularly given the recent closure of three crude oil refineries and one gas-to-liquids facility in South Africa, serving as substitute for international imports; further solidifying its market role (Bergh *et al.*, 2022).

Additionally, the Secunda complex serves as a central node for the country’s gas imports through the ROMPCO pipeline, synergising these imports with its own methane-rich gas production (a by-product of the coal-to-liquid processes). From here, the gas is distributed to industrial users within the province (10 PJ) and across provincial borders (79 PJ). Furthermore, Secunda’s operations are the foundation of South Africa’s petrochemical industry, manufacturing essential chemicals used in a range of products including plastics, fertilisers, synthetic rubbers and various industrial chemicals.

Annually, the complex processes around 39 Mt of coal, supplied largely from Sasol’s own mining operations, rendering it the largest single source of GHG emissions in South Africa. Alongside these emissions, the process generates significant amounts of ash and liquid effluent, contributing to its environmental footprint. In terms of water use (94 Mm^3), it remains slightly less than that of the mining sector, yet it is by no means insignificant within the province’s overall water consumption profile.

5.1.3. Heavy Industry

In addition to power generation and coal-to-liquid processes, a notable portion of South Africa’s ferro-alloy production occurs in the province. While its scale has varied over time, approximately 48% of the country’s ferro-chrome and 27% of its ferro-manganese production capacities are located in Mpumalanga (Yager, 2022). Concentrated around Middelburg and Emalahleni in the Highveld region, these heavy industries play an important role in the province’s export revenue.

The intense energy and reductant demands of ferro-alloy smelting necessitate the location of these industries in close proximity to sizeable energy sources, highlighting their strategic placement in the province. This is further underscored by the area's large chromite extraction (7.9 Mt). However, the province's limited mining of manganese and iron ore implies that it is more feasible to import these ores to the coal-rich region.

Ferro-alloys are a central material for steel making, another energy-intensive industry. Consequently, Mpumalanga is also home to 16% of the country's steel production capacity, predominantly stainless steel. This figure might vary slightly, especially considering the operational status of Evraz Highveld Steel in 2017, which remains ambiguous in the literature.

Although not precisely quantified, it is likely that a substantial portion of the electricity and coal designated for industrial use in the province is consumed by ferro-alloy production and steel making. The water consumption of these industries in the province is not well-documented, but it might be integrated into the municipal supply system. Despite high socio-economic cycling rates for steel, the metal industry is notorious for being 'dirty', with substantial emissions of dust and particulate matter linked to the smelters and furnaces (Hallowes and Munnik, 2017). Moreover, these processes produce significant amounts of slag as an output. While a small fraction of this slag is repurposed, the majority contributes to slag heaps and waste that remain within the province.

5.1.4. Coal Exports

Although coal mining is extensive in the province, not all the coal mined in Mpumalanga is consumed within the province's boundaries. Despite the presence of the aforementioned coal intensive users, approximately 91 Mt or 2 397 PJ is designated for export. This places coal as the largest material and technical energy export from the province. Further investigation into Mpumalanga's coal dynamics revealed that about 72% of the coal is exported to international markets, while the remaining 28% serves the domestic market (based on weight).

Coal exported to international markets is primarily of a higher grade, sourced from the best outputs of washing plants. This coal commands a high price and thus assists in furthering the financial viability of coal mines. In contrast, the thermal coal burned domestically is generally unwashed. It is important to note, however, that the environmental costs of mining coal for export remain within the province and country. Included in these costs are water pollution, with increased sulphate loads and acid mine drainage, along with large quantities of extractive waste.

5.1.5. Other

Mpumalanga’s economy is materially and energetically dominated by fossil-fuels. However, the biological withdrawals from the province are not insignificant (18.9 Mt). The climate of the Lowveld is favourable for the cultivation of fruits, nuts and sugarcane and for the growth of forestry plantations. This environment has fostered the development of a strong sector that includes the manufacturing of pulp and paper and various wood products. Conversely, the Highveld, with its fertile soils located above the province’s coal reserves, is the predominant region for field crop cultivation, juxtaposed with the aforementioned mining and heavy industry operations.

The field crop cultivation plays a major role in supplying nutritional energy to the province’s population (20 PJ) alongside exports (20 PJ). Livestock in the region primarily rely on grazing, yet there is also a considerable cultivation and export of maize for animal feed. The agricultural practices in Mpumalanga are the predominant consumers of water resources, an impact magnified by the stream flow reduction from forestry activities. Furthermore, they are also likely to account for a large portion of the chemical and fertiliser use within the province, with ensuing environmental concerns. While the exact energetic and coal reliance of the agriculture and forestry sectors was not specifically quantified, bio-energy linked to sugarcane bagasse and black liquor from the pulp and paper industry are partially supplying these sectors’ process heat and electricity needs.

The region's dependence on imports for non-metallic mineral materials is apparent as the largest imported material group, however these results are highly uncertain. Interestingly, no clinker plants exist within the province, which is vital for cement and, by extension, infrastructure development.

5.2. Comparison Against the National EW-MFA

In this section, the findings are examined in relation to the outcomes of the national EW-MFA for 2017. A number of the main findings from the national EW-MFA are also reflected in Mpumalanga’s socio-economic metabolism. The first finding from the national EW-MFA highlights the economy’s material dominance of export-oriented extractives, which largely occurs in a linear fashion (von Blottnitz *et al.*, 2022; Haas *et al.*, 2023). This finding talks primarily to the extraction and export of coal, iron ore and other ores used in steel making (von Blottnitz *et al.*, 2022; Haas *et al.*, 2023). Although Mpumalanga’s overall metal ore extraction was relatively modest compared to the national figures, representing about 5% of pure metal extraction and 7% of extractive waste, its contribution to chromium (38%), nickel (27%) and copper (15%) extraction is noteworthy. Conversely, the province extracts negligible quantities of iron ore.

On the other hand, coal extraction and exports are concentrated in Mpumalanga with 82% of the county’s coal extracted in the province, of which around 44% is exported. However, it is important to note that the exports (and imports) for the province cannot be directly compared to the national EW-MFA given that the provincial study incudes inter-provincial trade. Nonetheless, Mpumalanga emerges as a net material exporter, with a significant volume of extractive waste, primarily from coal, staying within its borders. This is underscored by the fact that extractive waste constitutes around 27% of all processed material in the province.

The second finding from the national EW-MFA underscores an energetic reliance primarily on fossil fuels, especially domestic coal, supported by significant quantities of imported oil (von Blottnitz *et al.*, 2022; Haas *et al.*, 2023). Interestingly, while Mpumalanga is heavily reliant on coal for energetic use, materially comprising 96% of the fossil energy carriers energetic use, only a fraction of liquid fuels for energetic purposes are imported. This stems from the coal-to-liquid processes in the province, reducing the need for imported oil. Consequently, Mpumalanga supplies other regions of the country, especially inland areas such as Gauteng, with liquid fuels, since the coastal regions house three of the four oil refineries. This dynamic is captured in Mpumalanga's technical energy account where approximately 71 Mt of coal, equivalent to 1 420 PJ, is used for electricity generation, with another 43 Mt (or 970 PJ) used for mainly technical energetic purposes (including the technical conversion of coal-to-liquid fuels). A large portion of coal-based electricity (338 PJ) is also exported to the rest of the country, highlighting that much of the country's reliance on domestic coal stems from Mpumalanga.

Thirdly, the discernible low rate of domestic stock building identified in the national EW-MFA is marginally higher in Mpumalanga. Net additions to stock in South Africa and Mpumalanga for 2017 amounted to around 2 t/cap and 2.3 t/cap, respectively. The slightly higher estimate regarding NAS in the province can be attributed to ash from hard coal utilised in other industries along with construction minerals, however, these values are highly uncertain. Similar concerns regarding the provision of services to the province apply, such as inadequate infrastructure, inconsistent service quality, and insufficient resources, all of which ultimately hinder human well-being (von Blottnitz *et al.*, 2022; Haas *et al.*, 2023).

The fourth finding in the national EW-MFA revealed pockets of high circularity in the domestic economy, characterised by substantial informal activities around cascade use, reuse and recycling of materials (von Blottnitz *et al.*, 2022; Haas *et al.*, 2023). While the same could be said from the baseline results in the province, these are highly uncertain as they are based predominantly on top-down estimations. However, it is reasonable to assume that high-value recyclables such as lead, copper, aluminium and steel are recycled at high rates within the province.

The fifth and final finding from the national EW-MFA points out the sizable bio-based flows, constituting 17% of domestic extraction, but raises significant sustainability concerns regarding ecological cycling. In 2017, Mpumalanga accounted for roughly 13% of the total country's biomass extraction by mass. The province was particularly notable for its industrial roundwood production, comprising nearly half (45%) of the nation’s total. Additionally, it made substantial contributions to the extraction of primary crop flows, including cereals (18%), sugar crops (17%) and oil-bearing crops (16%), while fodder crops and grazing only contributed 10%. Despite Mpumalanga’s favourable climatic conditions for agriculture and the presence of almost half of the country’s high potential arable land, the province’s contribution to biomass extraction is smaller than might be expected. With respect to ecological cycling, the apprehensions expressed at a national level concerning geochemical cycles and ecosystem integrity are presumed to be equally, if not more, salient in Mpumalanga, given the province’s significant wetland areas and biodiversity hotspots.

The domestic extraction (A) and domestic processed outputs (B) in (i.) absolute value, (ii.) per square kilometre, and (iii.) per capita for Mpumalanga and South Africa are illustrated in Figure 5-1. Solid and liquid outputs were added to dissipative use due to the misallocation of certain dissipative use flows in the national EW-MFA.

Figure 5-1 underscores the pivotal role that coal plays in the economy of Mpumalanga, as well as the consequent environmental impacts. The province accounted for a substantial proportion, over half (51%), of the nation’s emissions, with specific contributions including 58% of coal-based emissions, 11% for oil and 48% for natural gas. Additionally, Mpumalanga is a significant contributor to solid, liquid and other wastes, primarily due to coal extractive waste and ash production.

When evaluated on intensity metrics per unit of surface area and per capita, Mpumalanga’s figures surpass the national averages, barring those for metallic and non-metallic minerals. Specifically, the fossil fuel extraction intensity and the accompanying extractive waste, as well as biomass flows, are higher in Mpumalanga than the national figures when measured against surface area. This pattern holds when the metrics are adjusted for per capita impact. The environmental output of the province is markedly higher than the national average in both area intensity and per capita terms, emphasising the substantial environmental footprint of Mpumalanga’s economic activities, most notably from the extraction, processing and consumption of fossil fuels.

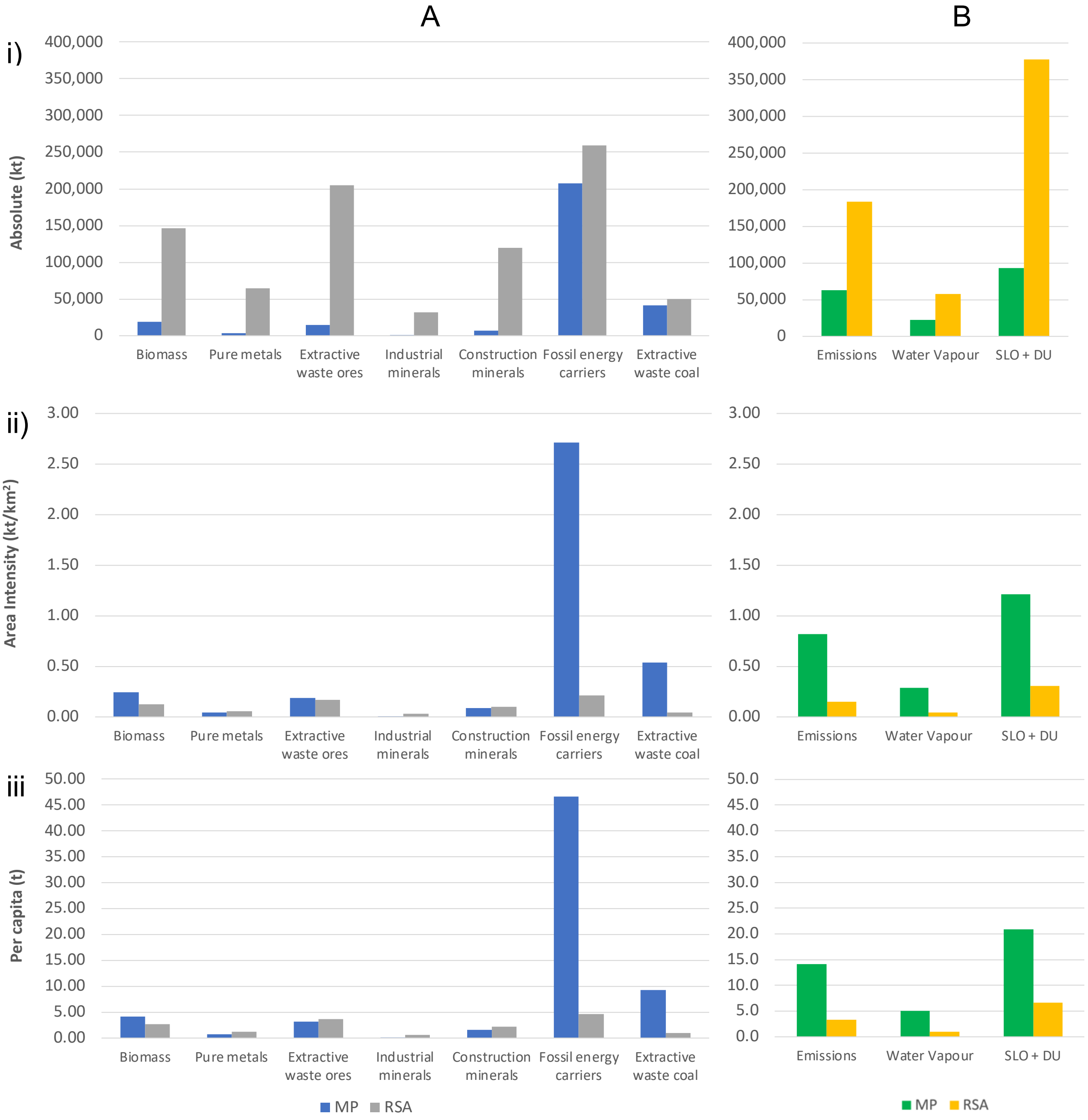


Figure 5-1: Domestic extraction (A) and domestic processed outputs (B) in (i.) absolute value (kt), (ii.) per square kilometre, and (iii.) per capita for Mpumalanga and South Africa for 2017.

5.3. Metabolic Crossroads

The metabolic profile of Mpumalanga reveals a resource-intensive industrial economy underpinned by four dominant coal-based activities. The intensive mining of coal and other non-renewable resources and the accompanying waste and emissions have had, and will likely continue to have, profound environmental implications for the province. The low rates of socio-economic cycling within Mpumalanga further underscore this reality.

The province is largely self-reliant, able to provide for its own nutritional and technical energy demands while also supporting those of neighbouring provinces and countries. However, this comes at an additional cost, with most of the extractive waste and pollutants remaining within provincial borders. As eluded to by Simpson *et al.* (2019), land conflicts between agriculture and mining are apparent with primary crop production at risk in the Highveld from existing and prospective mining rights. The precarious balance between technical and nutritional energy is further threatened by the existing water deficits and decreased water quality. Although the use of water for electricity generation is deemed strategic, the prioritisation of water for agricultural purposes is not similarly recognised. This renders the province susceptible to the impact of water scarcities or droughts, which are increasingly likely due to climate change. Such water challenges pose a significant threat to the province's capacity to produce nutritional energy.

This metabolic analysis, while not offering a time series to fully gauge the sustainability implications for the province, does establish an initial measure of its resource flows and consumption. Unfortunately, being the first complete assessment of its kind on a provincial level in South Africa, it lacks data to compare to other provinces. Nevertheless, it lays the groundwork and emphasises the necessity of prioritising the province in the energy and broader sustainability-orientated transition.

Chapter 6 : Conclusion & Recommendations

The province of Mpumalanga confronts various challenges in any transition towards a low carbon economy, with a noticeable gap in research to facilitate systematic evaluation for informed sustainable development. Social metabolism has gained recognition for its utility in sustainability assessments, yet its application in South Africa, and specifically within Mpumalanga, remains limited.

It should be remembered that this study set out to provide an empirical contribution to the research informing the inevitable transition away from coal in Mpumalanga: the nation's power house. The primary objective of the study was to conduct a baseline metabolic analysis of the province for the year 2017.

Aligned with the research objective, this study sought to answer the following key question: *What insights can a baseline metabolic analysis of Mpumalanga provide that could potentially be used to inform and guide strategies to increase the sustainability of the province?*

As this research was largely exploratory, aimed at quantitatively characterising the province's material, energy and water flows, this chapter will attempt to summarise the key findings for these accounts and draw conclusions from these. The chapter will conclude by identifying areas for improvement and suggesting directions for future research.

6.1. Summary of Key Findings

To fulfil the primary objective of the research, established socio-metabolic methodologies were adapted and employed to quantitatively document the province's flows of materials, energy, and water. Conducting such a study at a sub-national level presented considerable data challenges, as suggested by the literature. The completion of this assessment within the constrained timeframe was only possible by the strategic use of downscaled national accounts and proxies to bridge data gaps and resolve inconsistencies. However, some flows, in the absence of data had to be omitted as noted in the body of this research. Despite these challenges, the primary flow quantities deduced from the study appear within range of those documented in the literature, yielding no results that are particularly unexpected.

Regarding material flows, domestic extraction for 2017 was around 65 t per capita, predominantly consisting of coal mined in the Highveld region of the province. Extractive waste from both coal and metal ores constituted 12 t per capita, the majority of which remained within the province. Mpumalanga was a net exporter of materials to the scale of 22 t per capita. The limited imports consisted mainly of non-metallic minerals, whereas fossil energy carriers, notably coal, dominated exports. Of all the processed materials in the province (43 t per capita), around 63% were allocated to energy use, with the remainder for material use. Only a small portion of the material use was dedicated to the construction and maintenance of manufactured capital (2.5 t per capita). The domestic processed outputs were significant (39 t per capita) and primarily derived from coal mining and combustion.

When compared to the national EW-MFA, Mpumalanga's per capita domestic extraction of fossil energy carriers is tenfold greater, while its domestic processed output to nature is sevenfold greater. When adjusted for provincial land area, Mpumalanga's extraction of fossil energy carriers is thirteen times the national average, and its domestic processed output from fossil energy carriers is eight times higher. This disparity is even more pronounced given that Mpumalanga is one of only five provinces with coal reserves.

The technical energy extracted in the province is chiefly from coal, resulting in an energy use profile heavily reliant on fossil fuels, constituting coal, coal-derived electricity, and coal-based liquid fuels. Over half of the 1.1 TJ per capita domestic technical energy input to the province, which includes imports and extraction, is exported. This export predominantly comprises coal, followed by coal-derived electricity and coal-based liquid fuels. Around 60% of the coal-based technical energy consumed in the province is for electricity generation.

Although they cannot be directly compared, the nutritional energy flows in the province are significantly lower than the flows of technical energy. Domesticated animals are the leading nutritional consumers in the province, depending mainly on grazed biomass. Locally grown primary crops satisfy approximately 95% of the nutritional energy needs of Mpumalanga's population, with an estimated nutritional supply of 12.6 MJ per capita per day. Mpumalanga is also a net exporter of nutritional energy, constituting predominantly cereal, sugar and oil crops alongside maize for animal feed.

The water account for the province shows a dependency on surface water abstractions, with additional imports necessary to meet local needs. Agriculture is the largest user, consuming about 66% of the province's yearly water supply. Significant quantities are also used by Eskom's coal-fired power stations and Sasol Secunda operations, accounting for roughly 12% and 5% of the water supply, respectively. Municipal water supply systems are plagued by inefficiencies, with losses accounting for nearly half of their total provision. The rising levels of nitrates, sulphates, TDS, and Chlorophyll-A signal a decline in the quality of the province's water resources.

6.2. Conclusions

A number of critical conclusions emerge from the analysis conducted, foremost of which is the notable deficiency in sufficient and adequate sub-national data. While this study has successfully conducted the first metabolic assessment of Mpumalanga, detailing the flows of materials, energy, and water, along with various metabolic indicators, it has underscored the lack of publicly available, comprehensive and reliable data on resource flows at the sub-national level. In the case of Mpumalanga, this is particularly concerning, considering the substantial resources dedicated to pinpointing strategic intervention areas within the province for economic diversification and job creation.

The challenges in data acquisition were not entirely unexpected, echoing similar issues encountered in Gauteng province as reported by Culwick *et al.* (2017). Nevertheless, the extent of data limitations in this research was considerable and included, inter alia, the absence of official national statistics broken down by province, the lack of official provincial statistics, discrepancies between government and industry reports, incomplete statistical accounts, and inconsistencies between the geographical delineations of resource flows and provincial boundaries.

Secondly, decades of coal extraction within Mpumalanga have established coal and its related activities as the dominant metabolic pathway in the province. The dominance of coal in Mpumalanga's socio-economic metabolism is striking, although not entirely unforeseen. Energetically, coal represents 97% of the domestic technical energy input to the province, with the majority of technical energy demands being met by coal, coal-generated electricity and coal-based liquid fuels. Materially, coal and its related waste make up approximately 85% of the province's domestic extraction, 82% of its processed materials, and 81% of its domestic processed output. Furthermore, 17% of the water use in the Mpumalanga is directly associated with coal-based energy infrastructure. The primary means through which the province 'metabolises' these resource flows include power generation, coal-to-liquid processes, heavy industry and coal exports. Collectively, these findings demonstrate that coal's influence extends well beyond the economic framework of Mpumalanga, critically shaping its environmental footprint, directing the allocation of resources and determining the course of its infrastructural development.

Thirdly, the dominance of coal within the province has likely led to the suppression of other resource flows and their associated industries, with agriculture being the most obviously affected. Agricultural activities make up a smaller proportion of the province's socio-economic metabolism than might be expected, given its suitable soils and favourable climate. The province, home to nearly half of South Africa's high potential arable land, sees only 13% of national primary crop extraction, suggesting untapped agricultural capacity. Coal's dominance in the agriculturally rich Highveld, has led to the conversion of 12% of this land for mining as of 2012, a trend that has likely worsened with ongoing mining pursuits (DARDLEA, 2019). The substantial allocation of water to energy further highlights the competitive tension between agriculture (predominantly cereal crops) and coal-derived energy.

Building on this, it is worth noting that the province’s technical energy mix included little to no presence of renewable energy. In this regard, South Africa as a whole was also still at the early stages of the energy transition and generated only 9 000 GWh from utility scale renewable sources (Pierce and Le Roux, 2023). Mpumalanga’s conditions are conducive to solar and wind energy production, though they are somewhat less ideal than those in the Western Cape, Eastern Cape and Northern Cape. That said, the province’s geographic position offers a strategic advantage for the distribution of electricity.

Fourthly, a significant portion of the changes and the risks linked with the country’s shift toward low carbon energy sources will be concentrated in Mpumalanga. The intensity metrics, both per capita and per area, in comparison to national figures, highlight the disproportionate concentration of coal reliance, GHG emitting infrastructure and resulting environmental pressures within the province. This validates the rationale behind designating Mpumalanga as a high-priority region for the country's just transition efforts.

Lastly, expanding the scope of the material flow analysis to include water and energy facilitated a closer examination of the flows that shape the province’s metabolism beyond the overall scale and intensity of material use in the province. A prime example was the integration of the water account, which revealed an unusually high use of water by the coal-based activities of Sasol and Eskom, significantly above the reported national average of 2% for the energy sector (Sparks *et al.*, 2014). This indicates that coal’s dominance materially and energetically, is also reflected in water flows. The water analysis also highlighted the province’s vulnerability, especially in terms of agriculture and food supply, as exacerbated by climate-induced droughts, posing substantial threats to regional food security.

Furthermore, the technical energy account provided a more nuanced understanding of coal’s function as a primary technical energy source, contributing to a better grasp of how coal flows through the various economic sectors within the province and how it is transformed within those sectors. Similarly, the nutritional account highlighted the critical role of certain biomass flows in maintaining stock of humans and livestock in the province and its surrounding regions.

In the context of nature-society interactions, physical geography emerges as a key determinant in the metabolic function of socio-economic systems. Mpumalanga's Lowveld, with its warm subtropical climate, is optimised for forestry and tropical fruit cultivation, while the Highveld's cooler, higher altitudes are better suited for growing field crops and are also rich in coal reserves. These distinct geographic areas drive region-specific resource use, agricultural practices, infrastructure development and water flows and availability, all of which influence the province's overall socio-economic metabolism.

Although faced with considerable data constraints, this study has corroborated numerous recognised features of the province, including its roles in generating electricity, producing liquid fuels, and supplying both nutritional and technical energy to the country and adjacent provinces. Overall, the metabolic analysis has provided a number of insights concerning both the physical and energetic dimensions of the province, alongside critical data that supports the transition to a low carbon economy in the province. The precise outcome of the inevitable transition to a low carbon economy remains highly uncertain. However, it is evident that as this shift gains momentum in the coming years, the nature of Mpumalanga’s metabolism will likely undergo, or need to undergo, very significant transformation.

6.3. Recommendations

To address the conclusions of this study, a series of recommendations are proposed for improved practices and further research. The initial recommendation addresses the shortage of publicly available, comprehensive sub-national data. It is recommended that the monitoring and reporting of resource flows, which pose no confidentiality issues, at the sub-national level be improved. This improvement should encompass the frequency of publishing data, the completeness of data, the level of disaggregation of data and the cross-checking of data with relevant industry associations. Notable areas requiring data enhancements include water management, waste disposal and mining operations. For flows where confidentiality concerns exist, it is recommended that government or industry publish aggregated results at the provincial level that can then be used as proxies (for example, stating that ‘5% of copper is mined in Mpumalanga’). Given the high stakes associated with the impending socio-metabolic transition, accurate and thorough data is essential to effectively inform planning and decision-making processes within the province.

The second recommendation, in anticipation of the province’s inevitable transition towards a low carbon economy, is to strategically reduce Mpumalanga’s coal dependency. This should be undertaken alongside actively planning for and pursuing supressed and/or alternative metabolic pathways. This is particularly crucial, considering Mpumalanga’s vulnerability to the fluctuations of global energy markets, the effects of climate change and the pressures from international climate policies. Reducing the province’s reliance on coal entails a fundamental re-orientation of the province’s dominant resource flows, energy infrastructure and primary industries. It is imperative that the phasing out of existing coal-dependent industries and the emergence of new industries is managed in a way that is both just and sustainable. Enhancing the understanding of the province’s resource flows, interdependencies and physical geography is essential to this, as is the optimal reallocation of flows that are likely to be repurposed due to the departure from the current coal-centric paradigm.

Economic diversification will not only contribute to a more dynamic socio-economic metabolism but also strengthen the province’s resilience against prospective economic and environmental challenges. While it is not the place of this thesis to make recommendations about the most suitable alternative pathways for the province, opportunities clearly exist in the areas of water, agriculture and renewable energy.

Given its identified unfulfilled potential in the province, agriculture represents an important alternative pathway. Repurposing water from the energy sector to agriculture for example could be a silver lining considering water deficits, realigning land use with regional capacities and mitigating environmental impacts for sustainable agricultural viability. However, further research is necessary to identify and investigate strategic opportunities within the province's biomass, non-metallic and metallic materials, as well as renewable energy and water sectors.

Examining the socio-economic metabolism of the province through the lens of the national EW-MFA enabled the discernment of spatially specific insights concerning resource trends and environmental pressures. Furthermore, expanding the scope of traditional material flow analysis to encompass energy and water uncovered synergistic opportunities and provided a clearer indication of how the province metabolises resource flows. Thus, it is recommended that similar metabolic studies be performed for other provinces in the country, especially in the context of the energy and wider sustainability-orientated transition. These studies should be performed periodically, so that resource flows and trends can be continuously tracked and assessed, furthering the potential to aid resource management, policy formulation, opportunity identification, and assess progress towards sustainability.

For these future socio-metabolic studies at the sub-national level, it is recommended to adopt the methodological improvements suggested by Haas et al. (2023) for a more accurate estimation of processed materials. This refinement will ensure that material flow analyses are in line with the most recent and academically reviewed standards. Additionally, it is important to allocate adequate planning and time for navigating governmental channels to access confidential data, including mining production volumes from each province, for a more accurate analysis. Differentiating between international and interprovincial exports could also provide deeper insights into the province’s economic interactions and dependencies.

Lastly, this study's scope was limited to a metabolic analysis using quantitative descriptive indicators of the resource flows necessary to sustain the province’s economy, omitting the regulatory mechanisms that oversee these flows. These mechanisms are especially pertinent for understanding how changes may occur within the province as which would be beneficial for informing policy development for resource allocation and sustainability. Therefore, it is recommended that future studies of this nature should consider both the dynamics of resource utilisation and the regulatory frameworks that will shape Mpumalanga's future.

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Appendix A : Material Flow Account

Assessing material flows for the province posed a challenge due to the scarcity of publicly accessible, sufficiently detailed data at the provincial level. The available data often necessitated additional processing to align with the requirements for EW-MFA categorisation. Various data sources, processing techniques and estimates were employed to compile the material flow account. Consequently, more comprehensive information on the methodology employed for the material flow analysis of Mpumalanga in 2017 is provided below.

Table A-1 provides an overview of the main data and associated data sources used to regionalise the South African EW-MFA for Mpumalanga, further detail will be provided in the following subsections.

Table A-1: Main data sources used and data processing techniques to carry out the EW-MFA for Mpumalanga.

Material Categories	**Type of data used and main data sources**
Domestic Extraction Biomass	Primary data and top-down estimates; (Godsmark and Oberholzer, 2019) (StatsSA, 2020) (Maitre, Versfeld and Chapman, 2000)
Metal Ores	Primary data and top-down estimates; (Yager, 2022) (von Blottnitz *et al.*, 2022)
Non-metallic Minerals	Top-down estimates; (DMRE, 2022) (Yager, 2022) (von Blottnitz *et al.*, 2022)
Fossil Energy Carriers	Primary data; (Eskom, 2018) (Sasol, 2020) (Sasol, 2017)
Imports and Exports All material groups	Top-down estimates; (StatsSA, 2019) (DMRE, 2021a) (von Blottnitz *et al.*, 2022)
Net Addition to Stocks All material groups	Top-down estimates; (von Blottnitz et al., 2022)
Solid and Liquid Outputs All material groups	Primary data and top-down estimates; (DEA, 2018) (StatsSA, 2018) (SAWIC, 2017)
Emissions All material groups	Estimations based on Digestibility (metabolic reactions), Mass balanced stoichiometric calculation based on material composition and assumptions on combustion technology, stoichiometric relations
Water Vapour All material groups	Estimations based on moisture content change (respiration), moisture content of energy carriers and certain minerals
Dissipative Use All material groups	Primary data and top-down estimates; (FAO, 2019) (StatsSA, 2020)

A.1. Material Extraction

The primary data, conversion factors and overarching estimates employed to assess the extraction of materials including biomass, metals (both pure and extractive waste), non-metallic minerals, and fossil energy carriers (including extractive waste), that are not elaborated in Chapter 3, are described below.

Biomass Material Flows

The primary data extracted from StatsSA's 2017 commercial agricultural census are presented in Table A-2. Subsequently, these values were aggregated into primary crop sub-material groups: cereal crops; oil bearing crops; pulses; fodder crops; sugar crops; vegetables; fruits; and nuts. A comparison between the national production quantities reported in the census and those used in the national EW-MFA (as reported by the FAO) revealed significant discrepancies. These discrepancies were presumed to stem from underreporting in the StatsSA data. As a result, for sugar crops and fodder crops, where the discrepancies were most pronounced, the census figures were adjusted. This adjustment involved scaling up the data based on the percentage of underreporting, as illustrated in Table A-3.

Table A-2: Agricultural crop production tonnages and hectares for South Africa and Mpumalanga for 2017; values taken from StatsSA (2020).

	Planted Hectares		**Production (metric tons)**	
Crop	SA	MP	SA	MP
Cereals	2666646	434128	12146020	2479284
White maize	1262434	167701	5627514	852502
Yellow maize	910937	255123	5173511	1604042
Grain sorghum	48168	7798	81471	11703
Wheat	325910	2396	1011705	9124
Barley	61879	500	145700	850
Oats	57318	610	106119	1063
Oil bearing crops	892993	208681	1519599	369156
Sunflower seeds	355661	1351	555995	2114
Ground-nuts (peanuts)	32145	0	65928	0
Soya beans	470169	207150	842550	366677
Canola	35018	180	55126	365
Pulses	20471	2155	37856	4129
Dry beans	20471	2155	37856	4129
Fodder Crops*	273001	15192	2200042	50212
Grass	129358	13182	263850	26695
Lucerne/Alfalfa	87003	360	1312662	2567
Maize for silage	56640	1650	623530	20950
Sugar Crops	186484	23933	7534550	1439383
Sugarcane**	186484	23933	7534550	1439383
Vegetables	43816	1313	1671755	49705
Beetroot	2889	105	87087	3138
Cabbages	4041	303	153268	13583
Carrots	6111	103	226017	3086
Green beans	1505	21	9473	155
Onions	14832	2	602612	50
Pumpkins (excluding melons)	2119	31	57983	894
Tomatoes	5638	166	362167	10963
Butternut	3746	291	99022	7681
Peppers	2935	291	74026	10155

Roots and Tubers	46763	1547	2116734	69161
Potatoes	43703	1431	1975046	62361
Sweet potatoes	3060	116	141688	6800
Citrus Fruit	105864	8410	2613198	277211
Oranges	49371	4447	1372238	159794
Naartjies	11926	673	201618	6209
Lemons	19441	1035	388005	34606
Grapefruit	17349	1774	482181	73936
Other soft citrus	7777	481	169156	2666
Subtropical fruits	68491	16516	702058	214361
Banana	10408	5745	219573	147258
Pineapples	10188	0	227667	0
other subtropical fruits	24442	5388	-	-
Avocado	13367	2922	132098	34150
Berries (all kinds)	2520	40	20399	22
Paw Paw	1716	1090	27296	17362
Melons	1271	0	26455	0
Mango	4579	1331	48570	15569
Deciduous fruits and viticulture	134558	377	2595224	7424
Apple	26160	367	907133	7224
Pears	11709	0	355882	0
Peaches	8751	10	143973	200
Table grapes	22597	0	328177	0
Wine-grapes	59935	0	783298	0
Plums	5406	0	76761	0
Tree Nuts***	54450	16727	74519	28994
Macadamia	34431	16237	49170	28121
Pecan	20019	490	25349	873

*Fodder crops adjusted

**Sugarcane adjusted

***Nuts values reported is higher than national EW-MFA

Table A-3: Major discrepancies in fodder crops and sugarcane production quantities and adjusted production values for Mpumalanga.

			% of National EW-MFA	**Adjusted Value MP (t)**
Fodder	StatsSA Census (StatsSA, 2020)	2,200,042	26%	193,740
	National EW-MFA (von Blottnitz *et al.*, 2022)	8,488,716		
Sugarcane	StatsSA Census (StatsSA, 2020)	7,534,550	50%	2,879,819
	National EW-MFA (von Blottnitz *et al.*, 2022)	16,485,000		

To calculate crop residues within the province, the methodology mirrored that of the national EW-MFA, employing the same harvest factors and recovery rates, as illustrated in Table A-4. These rates are the default standard values established by Krausmann *et al.* (2015).

Table A-4: Harvest factors and recovery rates for primary crops; values taken from Krausmann et al. (2015) and von Blottnitz et al. (2022).

	Harvest Factor	Recovery Rate
Wheat and products	2.3	0.9
Barley and products	2.3	0
Maize and products	1.5	0.48
Rye and products	2.3	0.9
Oats	2.3	0.9
Millet and products	3.5	0.9
Sorghum and products	3.5	0.9
Cereals, Other	2.3	0.9
Sugar cane	0.7	0.1

To estimate the demand for grazed biomass and fodder crops within the province, a demand-driven feed balance approach was adopted. This aligns with the methodology used in the national EW-MFA. For fodder crops, it's assumed that any imbalance between fodder crop extraction and demand is rectified through imports or exports. However, given the uncertainties surrounding the StatsSA census data, the reported livestock composition was accepted as accurate, while the actual livestock numbers were considered likely to be underestimates, as detailed in Table A-5.

Consequently, the composition data from StatsSA were used to proportionally adjust the provincial figures down from the values reported in the national EW-MFA, maintaining the same annual food intake per head. Following this, the distribution of grazing versus pasture-fed livestock was assumed to be the same as the national; all sheep and goats were presumed to graze, while all chickens and pigs were assumed to rely on fodder crops. Cattle were divided between the two categories, and live game was considered negligible in this context.

Table A-5: Livestock numbers and associated farming practices, values taken from StatsSA (2020) and von Blottnitz et al. (2022).

Livestock	MP	SA	Portion of RSA livestock in MP	Grazing	Fodder
Pig	81,382	1,465,774	5.6%	-	100%
Chicken (broilers)	19,400,036	134,545,022	13.9%	-	100%
Chickens (layers)	2,572,248	22,979,702		-	100%
Sheep	378,571	8,041,577	4.7%	100%	-

Goat	28,767	627,603	4.6%	100%	-
Cattle beef	623,630	5,066,038	12.3%	83%	17%
Cattle diary	13,828	861,760	1.6%	55%	45%

The composition of industrial roundwood production in the province, encompassing both roundwood type and products, was presumed to align with the those reported by the Forestry Association of South Africa. However, significant variations were noted between the total production quantities for the country as reported by forestry association and those detailed in the national EW-MFA. As a result, the national figures were downscaled to reflect these discrepancies, while maintaining the compositions of the forestry association, as illustrated in Table A-6. Since the Forestry Association of South Africa did not provide data on wood fuel, the estimation of wood fuel extraction was instead based on household demand. This estimation process and its outcomes are depicted in Table A-7.

Table A-6: Industrial roundwood adjustments.

	Value	**UOM**	
Total production forestry association (Godsmark and Oberholzer, 2019)	15,600,000	t	
Total production national EW-MFA (von Blottnitz *et al.*, 2022)	7,895,491	t	
% of Forestry Production Values	51	%	
Softwood conversion	0.96	m^3/t	
Hardwood conversion	1.35	m^3/t	
Forestry Association Reported Production	**Volume (m^3)**	**Quantity (t)**	**Adjusted Quantity (t)**
Pulpwood MP	3,736,000	5,650,798	2,859,989
Pulpwood softwood	1,113,328	1,066,286	539,670
Pulpwood hardwood	3,388,552	4,584,512	2,320,319
Sawlogs MP	1,851,000	1,393,516	705,288
Sawlogs softwood	1,277,190	1,223,224	619,100
Sawlogs hardwood	125,868	170,292	86,188
Other MP	459,000	20,800	10,527
Other softwood	5,508	5,275	2,670
Other hardwood	11,475	15,525	7,858

Table A-7: Wood fuel estimations based on household demand.

Mpumalanga Wood Fuel Demand		**Source**
No of household main cooking fuel	207,000	(StatsSA, 2018)
No of households second cooking fuel	109,445	(StatsSA, 2018)
No of household main heating fuel	197,000	(StatsSA, 2018)
No of households second heating fuel	58,997	(StatsSA, 2018)
Assume average kg/household/day main cooking	8.8	Alison Hughes personal communication
Assume kg/household second cooking	5.28	Alison Hughes personal communication

Assume kg/household/day main heating	1.2	Alison Hughes personal communication
Assume kg/ household second heating	0.72	Alison Hughes personal communication
Total ton wood/annum cooking	875,807	Calculation
Total ton wood/annum heating	25,099	Calculation
TOTAL ton wood/annum	900,906	Calculation

Metals (ores and extractive waste)

Data pertaining to metal extraction was sourced from the United States Geological Survey (USGS), as illustrated in Table A-8. Meanwhile, the extractive waste fraction, or ore grade, was estimated to be consistent with the national study, which utilised a blend of USGS data and other sources (Table A-9). It's important to note that not all listed facilities are involved in mining; some are purely processing facilities. In such cases, these figures were not included in the extraction data but were considered in the assessment of processed materials as well as in the analysis of imports and exports.

Table A-8: Primary data extracted from from Yager (2022) for metals.

Commodity	**Major Operating Company and Equity owners**	**Annual capacity**		**Location of main facility**
Ferro Chromium	Glencore & Merafe	396	kt	Lydenburg Plant
Ferro Chromium	Samancor Chrome Pty Td	1200	kt	Middelburg, Steelport, Witbank
Ferromanganese	Assmang	290	kt	Machadodorp Plant
Silicomanganese	Transalloys	180	kt	Witbank
Ferrosilicon	Ferroglobe Pc	40	kt	Emalahleni
Ferro-Vanadium	Vanchem Vanadium Products	12500	t	Witbank
Crude Steel	Evraz Highveld Steel	815	kt	Witbank
Crude Steel	Columbas Stainless	750	kt	Middelburg
Copper	Nkomati Joint Venture	10	kt	Mpumalanga Nkomati Mine
Nickel Mine (Not Refined)	Nkomati Joint Venture	21	kt	Mpumalanga Nkomati Mine
Gold	Sibanye Still Water Ltd	3100	kg	Burnstone Mine MP
Gold	Pan African Resources	3000	kg	Barberton Mine
Gold	Pan African Resources	3000	kg	Evander Mine
Gold	Pan African Resources	930	kg	Retreatment Tailings Project
Gold	Pan African Resources	930	kg	Retreatment Tailings Project
Vanadium Pentoxide	Evraz Steel	17500	t	Mapochs Mine
Vanadium Pentoxide	Evraz Steel	10800	t	Plant Witbank
Vanadium Pentoxide	Vanchem Vanadium Products	5000	t	Plant Witbank
Silicon Metal	Ferroglobe	12	kt	Emalahleni Plant
PGM	Nkomati Joint Venture	4300	kg	Nkomati Mine
Manganese Metal	Manganese Metal Co	30	kt	Electrolytic Plant
Cobalt	Nkomati Joint Venture	1200	t	Nkomati Mine

Chromite	Glencore	1200	kt	Magareng Mine
Chromite	Samancor	2000	kt	Eastern Chrom Mines
Chromite	Assore	1400	kt	Dwarsrivier Mine
Chromite	Nkomati Joint Venture	500	kt	Nkomati Mine
Chromite	ASA Metals	800	kt	Dilokong Mine

Table A-9: Metal ore grades used; values taken from national EW-MFA.

Metal	Ore grade
Iron	0.4817
Copper	0.0104
Nickel	0.0183
Lead	0.1186
Zinc	0.0834
Gold	0.000003
Silver	0.0003
Platinum	0.000006
Uranium and thorium	1.0000
Other metal	0.1835
Chromium	0.2846
Manganese	0.3704
Others (n.e.c.)	0.1225

Table A-10: Metal processing capacities in Mpumalanga; estimated from Yager (2022).

Metal Processing Facilities	% or Tons processed
Ferro-chromium processing plant capacities	48% or 2316 kt
Ferro-manganese processing plant capacities	27% or 290 kt
Steel processing capacity	16%

Non-metallic Minerals: Industrial and construction minerals

A summary of the mines per commodity in Mpumalanga and South Africa, as reported by the DMRE operating mine directorate for 2022 are illustrated in

Table A-11. The portion of mines operating in the province for each material commodity were then used as proxies to downscale the national (Table A-12).

Table A-11: Operating mines per non-metallic mineral commodities mined in Mpumalanga; taken from DMRE (2022).

Commodity	Total Mines RSA	Total Mines MP	EW-MFA Material Category
Aggregate	421	24	Gravel and Sand
Attapulgite	4	1	Clays and kaolin
Bentonite	5	1	Clays and kaolin
Clay Brickmaking	135	11	Clays and kaolin
Dimension Stone Granite	61	9	Ornamental or building stone
Dimension Stone Slate	9	1	Ornamental or building stone

Lime	36	3	Chalk, Dolomite, Limestone
Limestone	48	3	Chalk, Dolomite, Limestone
Magnesite	4	1	Chemical and fertilizer minerals
Sand Natural	642	29	Gravel and Sand
Semi-Precious Stones	32	1	Chemical and fertilizer minerals
Shale Brickmaking	120	10	Clay and Kaolin
Shale For Cement	9	1	Sand and Aggregate
Silica	31	4	Sand and Aggregate
Sulphur	50	6	Chemical and fertilizer minerals
Talc	1	1	Chemical and fertilizer minerals

Table A-12: Resultant proxies for downscaling non-metallic minerals.

EW-MFA Material Category	**Proxy**
Chemical and fertilizer minerals	1.4%
Salt	0.0%
Container glass	0.0%
Ornamental or building stone	12.3%
Chalk, Dolomite, Limestone	6.3%
Gypsum	0.0%
Clays and kaolin	8.1%
Gravel and sand	5.3%

Fossil Fuels

The coal extraction in the province was evaluated by assessing the volume of coal extracted in other provinces, as illustrated in Table A-13, and subtracting it from the value reported in the national EW-MFA. Table A-13 illustrates data from the global coal mine tracker and from the DMRE operating coal mine directorate.

Table A-13: Coal production outside of Mpumalanga

Mine Name	**Production** (t) **(Global Coal Mine Tracker)**	**Production** (t) **(DMRE operating coal mine directorate)**	**Location**
Aviemore Colliery	400,000	486,191	KwaZulu-Natal
Chelmsford Colliery	480,000	375,244	KwaZulu-Natal
Grootegeluk Coal Mine	29,700,000	25,500,000	Limpopo
Khanye Coal Mine	2,800,000	2,800,000	Gauteng
Kliprand Colliery	318,734	318,734	KwaZulu-Natal
New Vaal Coal Mine	15,100,000	15,100,000	Free State
Sigma Mooikraal Operations	1,200,000	1,817,573	Free State
Total	49,998,734	46,397,742	Outside of Mpumalanga
Total	203,734,023	207,335,015	Mpumalanga

A.2. Transfers

The national EW-MFA accounts for 'transfers' - materials flowing between sectors and material groups within the socio-economic system, often undergoing transformation processes. These are materials that are not extracted in their useful or utilised form, examples being steel, synfuel and glass. Incorporating transfers enhances accounting principles, particularly for tracking cascading use and reuse at the national level. To align with the national EW-MFA, this approach was also adopted.

Table A-14 outlines the principal material transfers and the resulting compound materials specific to Mpumalanga. Notable deviations from the national data include the omission of glass (both container and flat glass) and the inclusion of sugarcane bagasse in paper production, as well as coal's conversion to synfuels and its by-products. These differences are attributable to the absence of facilities or manufacturing centres for these processes within the province. The estimated transfer quantities were derived from a mix of primary data and top-down estimates.

Table A-14: List of transfer materials.

Compound Material	Material Source	Estimation procedure
Asphalt	Gravel and sand; bitumen	Top-down estimation
Concrete	Gravel and sand; chalk, dolomite and limestone; and clays and kaolin	Top-down estimation
Fossil based-products for mUse	Synfuels (oil for energy use)	Primary data from SASOL and eco-invent allocations
Methane-rich natural gas	Hard coal	Primary data from SASOL and eco-invent allocations
Organic petrochemicals	Hard coal	Primary data from SASOL
Plastics	Hard coal	Primary data from SASOL
Steel	Iron; Nickel; Chromium; Manganese	Top-down estimation
Sulphur and ammonia	Hard coal	Primary data from SASOL
Synfuels (oil for energy use)	Hard coal	Primary data from SASOL

Waste associated with these transfers was categorised according to its origin, such as coal-related waste remaining within the coal category. However, certain transfers recognised in the national EW-MFA did not apply at the provincial level. For instance, the transfer from sugar mills to paper production was excluded since such facilities are located outside the province. Similarly, transfers related to chemicals, fertilisers, and the conversion of gravel, sand and limestone to glass were omitted due to the absence of manufacturing plants for these materials within the province—both Consol and PG glass factories are situated elsewhere.

Conversely, additional transfers were accounted for, including those from coal to chemicals and fertilizers, such as ammonia and sulphur produced at Secunda, as well as other petrochemicals including alkenes and ketones.

A.3. Domestic Processed Output

More detailed information regarding the approach taken to estimate domestic processed output stemming from processing and manufacturing, humans, livestock and technical energy carriers is provided below.

Waste

The estimation procedures taken to account for general and hazardous waste flows in the province are illustrated in Table A-15. The composition of the waste streams and associated waste treatment method (i.e. incineration, landfill, recycling) are assumed to be the same as the national average obtained from the EW-MFA, with the exception of primary data from SAWIC which specifies the method of waste treatment.

Table A-15: Waste streams and associated estimation procedures

Waste Stream	Estimation Procedure
MSW Household	Estimated, Rodseth *et al.* (2020), adjusted and calculated
Commerce and light industry	Proxy, GDP
Garden waste	Proxy, households
Food waste	Proxy, households
Construction and demolition	Proxy, GDP
Sewage sludge	Estimate, 0.13 kg/cap/day (dry weight)
Sugar mills	Estimate, production capacity; 30% bagasse
Saw mills	Estimate, production capacity; 9% bark, 20% sawdust, 52% lumber, 19% chips (DEA, 2018)
Pulp and paper	Estimate, production capacity;
Fly ash, dust and bottom Ash (non-hazardous)	Primary data, SAWIC
Fly ash, dust and bottom Ash (hazardous)	Proxy and waste report, portion of Eskom’s coal burnt in MP
Other	Primary data, SAWIC
Gaseous Waste	Proxy, GDP
Mercury containing waste	Proxy, GDP
Batteries	Proxy, GDP
POP waste	Proxy, GDP
Inorganic hazardous waste	Primary data, SAWIC
Asbestos containing waste	Proxy, GDP
Waste oils	Proxy, GDP
Organic solvents (some with halogens)	Primary data, SAWIC
Organic hazardous waste	Primary data, SAWIC
Tarry & bituminous waste	Proxy, liquid fuels capacity
Brines	Estimate, assumed 100% Eskom and Sasol
Hazardous mineral wastes	Primary data, SAWIC
WEEE	Proxy, GDP
Health care wastes	Proxy, population
Miscellaneous	Proxy, GDP
Non-hazardous slags	Primary data, SAWIC
Hazardous slags	Primary data, SAWIC

Livestock

The direct processed output (DPO) from animals includes gases (carbon dioxide and methane), water vapor from normal breathing and methane production, as well as their solid and liquid waste. Table A-16 outlines the share of animal feed dry matter that goes into building up animal bodies and products, waste as well as the processes of breathing and producing methane.

Table A-16: *Breakdown of dry matter feed intake for livestock; values taken from Krausmann et al. (2018).*

	Grazers	Non-grazers
Moisture	20%	20%
% of dry matter feed intake		
Excreta solid	37%	16%
Excreta liquid	4%	1%
Bodies	3%	20%
Methanogenesis	5%	1%
Respiration	51%	63%

Humans

Actual human food intake was calculated as gross food supply minus food waste, the latter derived by downscaling the national by number of households while maintaining the same food waste composition as the national. Table A-17 outlines the share of food intake to body mass increase, waste and respiration.

Table A-17: Breakdown of dry matter food intake for humans; values taken from Krausmann et al. (2018).

	Humans
Moisture	20%
	% of dry matter food intake
Excreta solid	6%
Excreta liquid	1.7%
Bodies	0.2%
Respiration	91.8%

Technical Energy Carriers

The quantification of solid and gaseous by-products from the use of technical energy carriers was determined based on the data presented in Table A-18. Specifically, the figures for hard coal refer to Eskom's steam coal, whereas the other data points are taken from the work of Krausmann *et al.* (2018). This table lays out the elemental composition of the fuels, including elements such as carbon (C), nitrogen (N), oxygen (O), sulphur (S), and hydrogen (H), along with their ash and moisture levels. In considering the resultant outputs, the oxygen that combines with hydrogen during the combustion process is initially sourced from the fuels themselves, as detailed in the relevant table (Krausmann *et al.*, 2018). Oxygen that goes beyond this internal supply is considered surplus O_2 and is excluded from the DPO calculations. The DPO takes into account the ash residue and the unburned portions of carbon and sulphur, which are not emitted but remain as part of the solid outputs. For further information refer to Krausmann *et al.* (2018).

Table A-18: Fossil fuel composition and associated outputs.

		Fuel	Crude oil	Gasoline	Natural gas	Burning wood	Hard coal SA
Fuel	Elementary composition	C	85.1%	86.6%	71.0%	40.1%	49.4%
		H	11.9%	13.0%	27.5%	4.8%	3.7%
		O	0.5%	0.0%	0.0%	35.1%	6.1%
		N	0.5%	0.0%	1.5%	0.0%	1.2%
		S	1.2%	0.1%	0.0%	0.2%	0.9%
		H_2O moisture	0.4%	0.0%	0.0%	15.0%	7.7%
		Ashes	0.5%	0.3%	0.0%	4.8%	31.0%
		Total	100%	100%	100%	100%	100%
Outputs excl. oxygen from air	Water vapour	**H_2O material	0.56%	0.00%	0.00%	39.55%	6.9%
		H_2O moisture	0.36%	0.00%	0.00%	15.00%	7.7%
		Total	0.92%	0.00%	0.00%	54.55%	14.57%
		H	11.84%	12.96%	27.50%	0.39%	2.93%
			12.74%	12.96%	27.50%	54.93%	17.50%
	Solid outputs	Ashes	0.50%	0.30%	0.00%	4.81%	31%
		S (PM)	1.07%	0.09%	0.00%	0.00%	0.00%
		C	0.85%	0.00%	0.00%	0.40%	1%
		Total	2.42%	0.39%	0.00%	5.21%	31.99%
	Emissions to air	C	84.22%	86.64%	71.00%	39.70%	48.4%
		N	0.50%	0.00%	1.50%	0.00%	1.2%
		S	0.12%	0.01%	0.00%	0.16%	0.9%
		Total	84.83%	86.65%	72.50%	39.86%	50.51%
		Check	100.00%	100.00%	100.00%	100.00%	100.00%

Appendix B : Energy Accounting

B.1. Technical Energy

Table B-1 illustrates the installed and nominal capacities of Eskom's coal-fired power stations in Mpumalanga, shedding light on the province's energy production capabilities. Table B-2 provides a breakdown of the total liquid fuel sales in Mpumalanga for 2017, a crucial metric for estimating the province's liquid fuel exports, imports, and overall consumption. Lastly, Table B-3 displays the electricity distributed within Mpumalanga, which is assumed to represent the final consumption in the province, with any excess accounted for as exports after adjusting for losses and onsite utilisation.

Table B-1: Installed Capacity and Nominal Capacity of Eskom Coal-Fired Power Stations Located in Mpumalanga.

Eskom's Coal-Fired Power Stations	Installed MW	Nominal MW
Arnot power station	2352	2232
Camden power station	1600	1481
Duvha power station	3600	2875
Grootvlei power station	1190	1120
Hendrina power station	2000	1638
Kendal power station	4116	3840
Komati Power Station	1000	904
Kriel power station	3000	2850
Kusile Power Station	4800	720
Majuba power station	4143	3843
Matla power station	3600	3450
Tutuka power station	3654	3510
Total	47522	37868

Table B-2: Liquid Fuel Sales in Mpumalanga for 2017; taken from DoE (2019)

Liquid Fuel Sales	Jet Fuel	Aviation Gasoline	Diesel	Furnace Oil	LPG	Paraffin	Petrol
1st Quarter	472	138	347,217	79,999	50,034	40,423	220,665
2nd Quarter	40,756	192	390,631	57,817	36,500	32,505	225,727
3rd Quarter	2,272	119	415,307	8,751	59,196	40,406	230,778
4th Quarter	1,731	77	392,893	23,206	47,125	40,648	285,610
Total (kL)	45,231	525	1,546,049	169,773	192,854	153,981	962,780
Density (kg/L)	0.79	0.71	0.85	0.99	0.56	0.79	0.75
Total (kt)	36	0.373	1,306	168	107	122	722

Table B-3: Electricity Distributed in Mpumalanga and South Africa in 2017; taken from StatsSA (2021).

Electricity distributed	**Mpumalanga**	**South Africa**
	GWh	**GWh**
January	2760	18586
February	2475	17334
March	2744	19083
April	2709	18212
May	2842	19766
June	2727	19372
July	2710	19648
August	2719	19563
September	2641	18376
October	2798	19073
November	2768	18609
December	2813	18229
Total	32706	225851

To account for biomass utilised for co-generation at the two sugar mills and pulp mill, it was assumed that the quantity of bagasse was 30% of the total sugarcane crushed in the province, while for every tonne of pulpwood processed, approximately 52.6% of black liquor is generated. Of the bagasse, it is further assumed that only 80% is used for cogeneration as bagasse is also sold to be for animal feed. Of the black liquor generated, it is assumed to contain 17% solids, all of which used for cogeneration. The resultant co-generated electricity quantities were obtained from annual SAPPI and RCL reports (RCL, 2018; SAPPI, 2019).

Appendix C : Water Accounting

More detail on the water usage pertaining to certain sectors is provided below. Table C-1 details mining water usage factors sourced from DWS (2016), presenting data on the water consumption for coal, gold, platinum, and other mining activities. It shows both the total specific use and the total consumptive use, although only the consumptive water use was applied in this account. Table C-2 illustrates the breakdown of water usage per power station located in the province. Table C-3 lays out the municipal water supply data for Mpumalanga in 2017, as reported by DWS (2017). It breaks down the system input volume and differentiates between revenue water and non-revenue water, including water losses, across various regions within the province.

Table C-1: Mining Benchmark Water Usage Factors; taken from DWS (2016).

Mining	**Run of Mine**	**Total specific use factor**	**Total consumptive use factor**	**Total Specific use**	**Total Consumptive Use**
Units	t	m^3/t ROM	m^3/ton ROM	Mm^3	Mm^3
Coal	248,145,014.50	0.70	0.38	174	94
Gold	3,360,141.36	2.09	2.02	7	7
Platinum	4,178,462.82	1.85	1.82	8	8
Other	8,503,250.55	0.96	0.65	8	6
Total				197	114

Table C-2: Power Station Water Usage; taken from Roselt and Mpofu (2021).

Eskom Power Station	**Mm^3**
Kriel	34.2
Kendal	5.7
Tutuka	34.2
Duvha	22
Matla	37.5
Arnot	25.5
Majuba	22.1
Kusile	2.1
Camden	17.9
Grootvlei	9
Komati	15.1
Hendrina	19.5
Total	244.8

Table C-3: Municipal Water Supply for Mpumalanga in 2017; taken from DWS (2017).

Region	% Non-Revenue Water	% Water Losses	System input volume (m^3)	Revenue water (m^3)	Non-Revenue water (m^3)	Water Losses (m^3)
Bushbuckridge	58	58	33074748	13891394.15	19183353.85	19183354
Chief Albert Luthuli	58	58	11366684	4774007.28	6592676.72	6592677
City of Mbombela	40.19	40.17	37482900	22417200	15065700	15055700
Dipaleseng	36.1	35.9	2715116	1734959.12	980156.88	974727
Dr JS Moroka	77.1	77.1	23380000	5354020	18025980	18025980
Dr Pixley Ka Isaka Seme	36.1	35.9	5331537	3406851.97	1924685.03	1914022
Emakhazeni	55	55	3545711	1595570.09	1950140.91	1950141
Emalahleni	47.4	50	37713000	19837038	17875962	18856500
Govan Mbeki	20.7	20.7	32565196	25824200.43	6740995.57	6740996
Lekwa	36.1	35.9	7408442	4733994.62	2674447.38	2659630
Mkhondo	36.1	35.9	11015810	7039102.77	3976707.23	3954676
Msukaligwa	38.9	38.3	7100000	4338100	2761900	2719300
Nkomazi	58	58	24017391	10087304.06	13930086.94	13930087
Steve Tshwete	30.9	30.9	15966634	11032944.09	4933689.91	4933690
Thaba Chweu	36.1	35.9	6302097	4027039.87	2275057.13	2262453
Thembisile Hani	58	58	18971517	7968037.33	11003479.67	11003480
Victor Khanye	36.1	35.9	4832984	3088276.78	1744707.22	1735041
Mpumalanga	45.6	43.81	258656000	140707000	117949000	113310000

Appendix D : Metabolic Indicators

The metabolic indicators for the province are further elucidated in this appendix, which includes the equations employed and an elaboration of the significance of each indicator.

To quantify the per capita indicator for material, water and energy flows, the absolute value was ratioed over the population in the province for the year 2017 (4 444 200 people).

Given the limited sub-national studies in South Africa, the use of these indicators is limited as they are particularly useful to show resource trends over time as well as for benchmarking and comparing resource use between regions.

D.1. Material Indicators

Domestic Material Input (DMI) Measures the total amount of materials extracted in Mpumalanga, plus all physical imports into the province, representing the total materials coming into the socio-economic system.

$$DMI = Extraction + Imports$$

Domestic Material Consumption (DMC) Represents the total amount of material used by an economy after exports and addition to bunker are subtracted from the DMI, indicating actual material consumption.

$$DMC = DE - Addition\ To\ Bunker + Imports - Exports$$

Physical Trade Balance (PTB) Calculated as the difference between the imports and exports of Mpumalanga’s economy, showing whether it is a net importer or exporter of materials.

$$PTB = Imports - Exports$$

Processed Material (PM) Quantifies the materials consumed in the province plus the addition of secondary materials which get processed and consumed again in the province.

$$PM = DMC + Reuse + Recycling$$

Net Addition to Stock (NAS) Represents the increase in the amount of materials accumulated in Mpumalanga's socio-economic manufactured capital, indicating growth or expansion.

$$NAS = Stock\ Add - Demolition/Discard$$

Domestic Processed Output (DPO) Illustrates the total mass of materials that leave the socio-metabolic system, excluding exports but including waste and emissions.

$$DPO = Solid\ and\ Liquid\ Waste + Dissipative\ Use + Emissions + Water\ Vapour$$

Interim Output (IntOut) The sum of all materials that have reached their end-of-life, prior to cycling back into the system, and all emissions, water vapour and dissipative use materials.

$$IntOut = PM - Stock\ Add + Demolition$$

Input Socio-Economic Cycling Rate The ratio of all recycled and reused materials in total processed materials.

$$Input\ SocioEconomic\ Cycling = (reuse + recycling)/PM$$

Output Socio-economic Cycling Rate The ratio of all recovered materials kept in the system and the systems Interim Output.

$$Output\ SocioEconomic\ Cycling = (reuse + recycling)/IntOut$$

Input Ecological Cycling Rate The ratio of all potentially 'ecological regenerative' materials in total processed materials.

$$Output\ Ecological\ Cycling = Sustainable\ portion\ of\ biomass\ DE\ /PM$$

Output Ecological Cycling Rate The ratio of all 'ecological regenerative' materials kept in the system and the systems Interim Output.

$$Output\ SocioEconomic\ Cycling = Sustainable\ portion\ of\ biomass\ DE/\ IntOut$$

Total Input Cycling Rate The sum of the input ecological and socio-economic cycling.

Total Output Cycling Rate The sum of the input ecological and socio-economic cycling.

Material Intensity of economic activity Indicates the amount of material used per unit of economic output, reflecting how material-intensive the socio-economic system is.

$$Material\ Intensity\ of\ economic\ activity = DMC/GDP$$

Material Productivity The ratio of economic output to material input, which shows how efficiently materials are used.

$$Material\ Productivity = GDP/DMC$$

Material Area Intensity Measures the amount of materials used in relation to a geographical area, often indicating the pressure on resources.

$$Material\ Area\ Intensity = DE/Total\ Area$$

Domestic Resource Intensity Evaluates the amount of domestic extracted materials used per unit of economic activity, highlighting the dependency on domestic versus imported materials.

$$Domestic\ Resource\ Intensity = DE/DMC$$

D.2. Energy Indicators

Domestic Technical Energy Input Measures the total amount of technical energy extracted in Mpumalanga, plus all technical energy imports into the province, representing the total technical energy coming into the socio-economic system. All technical energy flows considered here were known to be extracted and imported for technical energy needs (i.e. exclusion of non-energetic fossil energy carriers).

$$\text{Domestic Technical Energy Input } = Extraction + Imports$$

Domestic Technical Energy Consumption Represents the total amount of technical energy used by an economy after exports are subtracted from the domestic technical energy input, indicating actual material consumption. All technical energy flows considered here were known to be extracted and imported for technical energy needs (i.e. exclusion of non-energetic fossil energy carriers and addition to bunker).

$$\begin{aligned}&\text{Domestic Technical Energy Consumption}\\&\qquad = \text{Domestic Technical Energy Input} - Exports\end{aligned}$$

Domestic Nutritional Energy Input Measures the total amount of nutritional energy extracted in Mpumalanga, plus all nutritional energy imports into the province, representing the total nutritional energy coming into the socio-economic system. All nutritional energy flows considered here were known to be extracted and imported for either food or feed (i.e. exclusion of timber and other non-nutritional biomass based products).

$$Domestic\ Nutritional\ Energy\ Input = Extraction + Imports$$

Domestic Nutritional Energy Consumption Represents the total amount of nutritional energy used by an economy after exports are subtracted from the domestic nutritional energy input, indicating actual nutritional consumption. All nutritional energy flows considered here were known to be extracted and imported for either food or feed (i.e. exclusion of timber and other non-nutritional biomass based products as well as addition to bunker).

$$\begin{aligned} &Domestic\ Nutritional\ Energy\ Consumption \\ &\qquad = Domestic\ Nutritional\ Energy\ Input - Exports \end{aligned}$$

D.3. Water Indicators

Total Water Supply Illustrates the sum of all blue water abstracted in the province along with the imports of water into the province.

$$\begin{aligned} &Total\ Water\ Supply \\ &\qquad = Surface\ Water\ Abstraction + Groundwater\ Abstraction + Imports \end{aligned}$$

Net Water Use Refers to the balance of the total water supplied and the water returned to the environment. Indicating non-returnable water. Return flows encompass flows from mining, water losses from municipal system, water effluent from WWTW and agricultural return flows.

$$Net\ Water\ Use = Total\ Water\ Supply - Total\ Return\ Flows$$

Water Return Rate Highlights the ratio of water returned to the environment and the total water supply.

$$Water\ Return\ Rate = Total\ Return\ Flows/Total\ Water\ Supply$$