An Economy-wide Material Flow Analysis to Develop Circular Economy Indicators for South Africa

Reference report

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An Economy-wide Material Flow Analysis to Develop Circular Economy Indicators for South Africa

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EXECUTIVE SUMMARY

INTRODUCTION

The circular economy (CE) concept is gaining increasing traction as a comprehensive environmental-economic strategy in line with sustainable development imperatives. It however risks being empty talk if not grounded in firm evidence. For this purpose, systematic comprehensive empirical assessments are required, to understand the status-quo and to be able to develop robust guidance without simply shifting problems. A team at BOKU, Vienna, developed a suitable accounting and calculation framework to capture and describe the state of circularity of a national economy.

The Department of Science and Innovation, through the Waste RDI Roadmap contracted the University of Cape Town, in partnership with the BOKU team, to adapt this framework to the South African situation and to develop economy-wide indicators of circularity for the South African economy. The team chose the year 2017 as base year for the analysis, as this was the year with both the most recent and the most robust data in a variety of data sources.

METHODOLOGY

The objectives of this study were:

- To adapt the comprehensive economy-wide monitoring framework to the South African situation;
- To quantify all materials and energy use, as well as resulting waste and emissions;
- To derive policy-relevant indicators on the state of circularity of the economy;
- To present systems-level guidance for improving the sustainable circularity of the South African economy.

To achieve these goals, information was compiled for 82 materials, organized in 6 main categories and 12 sub-categories, tracking for each material domestic extraction, imports, exports, transformations, additions to stock, demolition, generation of wastes and fate of wastes, all for the calendar year 2017.

Table E1: Categorization of materials enumerated in this study

Main category (1-digit)	Subcategories (2-digit)	Materials (natural)	Materials (synthetic)
Biomass	5	21	0
Metals	3	19	1
Geo-extractive waste	2	19	0
Industrial minerals	0	4	1
Construction minerals	0	5	3
Fossil fuels	2	8	1

Synthetic materials studied are steel, glass (flat and container), concrete, asphalt and plastics.

It is important to note that 'Unused extraction' was not counted in this study; i.e. the study only quantified materials leaving the mine or the field to go into further processing, from which 'extractive waste' arises.

MAIN RESULTS

South Africa's extraction of all food, feed, minerals, metal ores and fossil energy carriers (coal) amounted to 875 million tonnes in 2017 (see Figure E1). 66% of this extraction are metal ores and coal. Compared to this, imports are relatively small (32 Mt). Exports are large (170 Mt) and consist predominantly of ores, refined metals and coal, while leaving the associated extractive waste in South Africa. Altogether, waste flows are relatively high. Solid and liquid outputs returned to nature are about 310 Mt of which 171 Mt are extractive waste from mining activities.

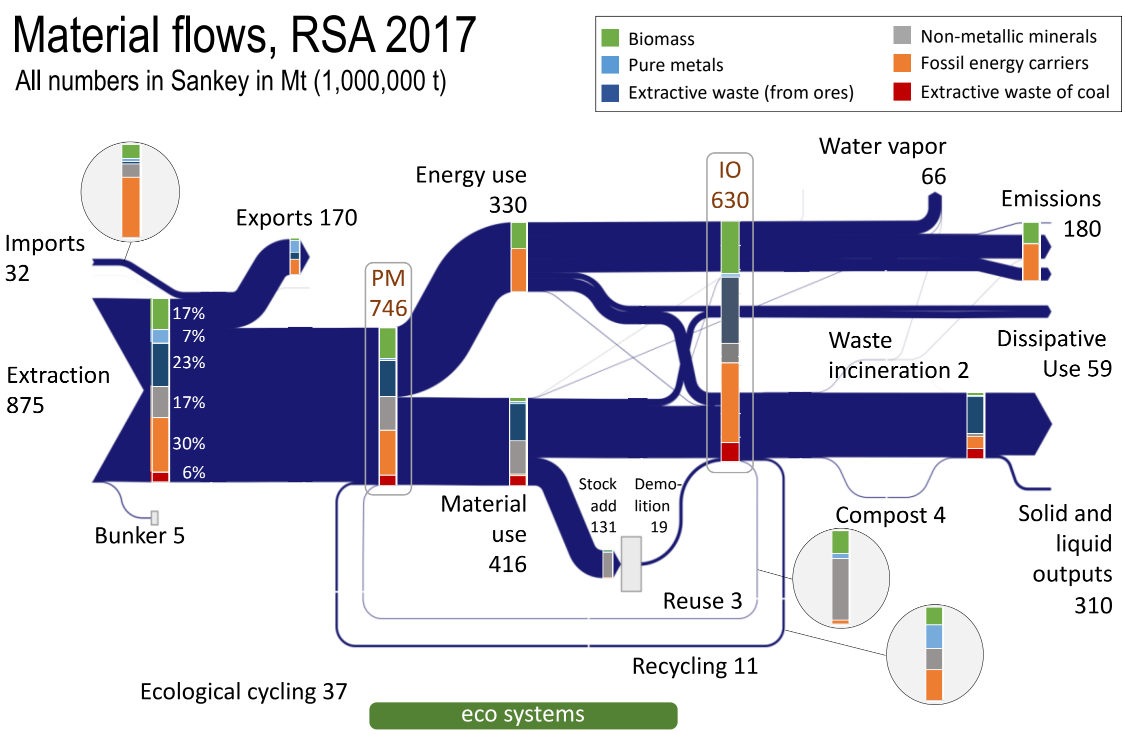

Figure E1: Estimate of material flows in South Africa in 2017. Width of arrows is proportional to flow size. Processed materials (PM) and interim outputs (IO) form the basis for the calculation of circularity indicators.

Emissions to air from technical processes, humans and livestock were estimated at 180 Mt; in this number carbon related emissions are only accounted as carbon amount (which came to 175 Mt). If oxygen taken from air is included, this results roughly in 650 Mt of emissions, of which 36% are of biogenic origin. In addition to the amounts reported in the national greenhouse gas inventory reports, these numbers include (due to mass balancing) all carbon emissions stemming from biomass extracted from nature and released to nature within a year. Thus, breathing of humans and livestock is included.

Mass balancing for the study year means that everything that goes into the South African economy has to be either a net-add to stocks or an export or output to nature. Numbers also include an estimate of informal flows like waste from un-serviced households.

The circular economy indicators were estimated at the input and the output side of the economy (and they differ because of the accumulation of stock). Results for the input side are shown in Figure E2. The socio-economic cycling rate, which is the ratio between the sum of recycled and reused materials to the domestically processed materials, is just under 2%. Ecological cycling is significantly larger at 5%, but highly uncertain due to a lack of knowledge as to the fraction of the input biological materials that can be regarded as a sustainable harvest. This fraction was estimated to lie somewhere between between one quarter and two thirds.

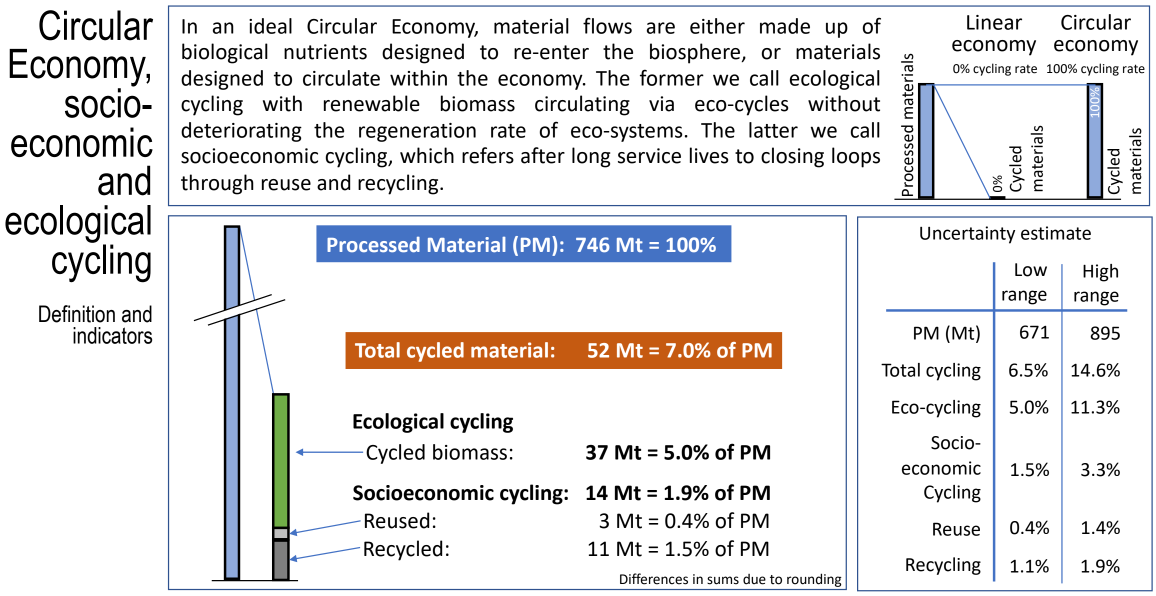

Figure E2: Estimated input cycling rates for South Africa, 2017

On the output side, cycled materials are reported as the ratio to all 'interim outputs' from the economy (solid and liquid End-of-Life waste, emissions, water vapor and dissipative use), which are smaller than the processed materials entering the economy, and hence output cycling indicators in percentage terms look marginally bigger, as shown in Table E2.

Table E2: Cycling rates for South Africa, 2017

	Input side	Output side
Basis	Processed materials 746 Mt	Interim outputs 630 Mt
Socio-economic cycling	1.5% recycled; 0.4% reused	2% recycled; 0.6% reused
Ecological cycling	5.0% of all processed material is considered to be cycled via eco-systems	5.9% of all interim outputs is considered to be cycled via eco-systems
Total cycling rate	7.0%	8.5%

FINDINGS

The picture of material flows that was developed gives rise to 5 key findings:

1. The economy is materially dominated by export-oriented extractives.
2. The economy is energetically dominated by fossil fuels, notably domestic coal supported by imported oil.
3. There is a low rate of domestic stock building of infrastructure (buildings, roads, etc.).

4. There are pockets of high circularity in the domestic economy and significant informal activity around cascade use, reuse and recycling, but the overall socio-economic cycling rate is very low at 2%.
5. Bio-based flows are sizeable at 17% of domestic extraction, but there are significant sustainability concerns about ecological cycling.

CONCLUSIONS

This study has shown that circular economy goes well beyond more recycling of end-of-life materials. Of the 875 Mt materials extracted, only 327 Mt eventually became waste and of these about 221 Mt are extractive wastes with very limited cycling potential, if any. So reuse and recycling can only target 105 Mt, which is 12% of what has been extracted, or 14% of processed materials and 17% of interim outputs. While improved waste management is essential, its reach to increase circularity is limited. For increased circularity it is key to reconfigure resource flows through the economy as a whole. While the numerical results in this study are subject to uncertainty, this statement can be considered robust for both the lowest and the highest value of the uncertainty band.

Thus, the South African economy needs to develop a new national development model which entails phasing out its extractive orientation of non-renewable resources for export and power generation. This would both make it more sustainable and prepared for changes on the world market to be expected due to unfolding effects of already existing global environmental policies. These global developments will increasingly limit the gains of the present economic orientation, which dominates South Africa’s inherited resource use pattern. Only such a pro-active strategy enables the country to seize the opportunities a circular economy potentially offers: new businesses in the service sector, decent jobs for all skill levels directed at a stronger domestic economy and lower environmental impacts. However, this means a substantial change across several sectors including mining, agriculture, transport, urban planning, construction and power generation. The astute observer will notice that fast-moving consumer goods and its associated packaging, which have thus far attracted much of the circular economy discussion focus, are not explicitly listed. This is not to discount efforts made in these sectors, but rather to highlight that they only represent a small proportion of the overall circular economy challenge.

TABLE OF CONTENTS

Table of Figures

List of Tables

Glossary

Notion	Description
Cycling rates (input and output as well as socioeconomic and ecological cycling rates)	Input socioeconomic cycling rate is defined as the share of recycled and reused materials in processed materials. Input ecological cycling rate is defined as the share of sustainably produced primary biomass inputs (excluding socioeconomic cycling) in processed materials. Output cycling rates same as above, but as share in interim outputs.
Domestic extraction	All materials (other than liquid water) taken from nature within the boundaries of the Republic of South Africa; reported as fresh weight
Domestic material consumption (DMC)	Domestic extraction + Imports - Exports
Domestic material input (DMI)	Domestic extraction + Imports
Domestic processed output (DPO)	All materials released to nature (solid, liquid and gaseous outputs to nature). In contrast to some conventions (e.g. UNEP), landfilled waste even if controlled is considered as output to nature. This is done for practical reasons, as there is a lack of data on emissions to water or air from controlled landfills, and as landfilled materials sooner or later end up in nature.
Dry weight	Weight of a material excluding any moisture
End-of-life waste (EoL)	Sum of demolished stocks, discarded throughput materials and solid and liquid residues of energy use (ashes, faeces etc.)
Emission	Material emitted as gas during energy use or a conversion step. Carbon is counted as C, not CO_2. Also includes S and H in fuels, and O from reduction of metal ores to metals
Energy use (EU)	Comprises materials used to provide technical energy (fossil energy carriers, fuel wood and biofuels) but also feed and food, the primary energy sources for livestock and humans
Extractive waste	Waste arising from processing of extracted materials, includes all chemical elements in an ore other than the desired material like coal or metal (e.g. O, S, Si, Ca etc.)
Fresh weight	Weight of a material including moisture
Interim outputs (IntOut)	All emissions and vapor as well as EoL waste (all potential outflows before any socioeconomic cycling like recycling and reuse)
Material use (MU)	All materials not used for energy conversion
Net addition to stocks (NAS)	Stock add - Demolition
Processed materials (PM)	Sum of domestic material consumption and recycled materials
SASoW	South African State of Waste Report (for the year 2017, published by the Dept. of Environment, Forestry and Fisheries in 2020 (DEA, 2018)
Solid and liquid outputs (SLO)	All solid and liquid outputs stemming from extraction, imports or demolition including moisture but excluding added water (e.g. toilet water)
Unused extraction	Materials extracted but not processed or used; left next to the mine (overburden) or on the field (unused residues)
Vapor	Water in gaseous form; Moisture emitted during processing

1 Introduction

The circular economy (CE) concept is gaining traction as a comprehensive environmental-economic strategy towards a more sustainable economy (Ghisellini et al. 2016). In South Africa, it is increasingly being discussed as an advancement on the "green economy", as prominently agreed to in the Green Economy Accord (South African Government, 2011), and has been referred to in several policy papers since 2018. However due to competing claims and high expectations, it now has to prove its validity (Blomsma and Brennan 2017). For this purpose, systematic comprehensive empirical assessments are required, to understand the status-quo and to be able to derive robust guidance without simply shifting problems (Pauliuk 2018). Many attempts have been reported at developing indicators of circularity, with Saidani *et al.*, 2019 also having attempted a taxonomy for these. Recently, the indicator discussion was supplemented by a discussion on the appropriate formulation of targets (see Morseletto, 2020).

A comprehensive economy-wide monitoring framework covering all materials and energy use, as well as resulting waste and emissions has been developed by BOKU (Haas et al. 2015; Jacobi et al. 2018; Mayer et al. 2019; De Wit *et al.*, 2020; Haas *et al.*, 2020). This economy-wide CE monitoring framework has been adopted into the European Commissions' circular economy policy package as their macro-level headline approach (European Commission 2018a, 2018b) and has become part of the raw material score board (European Union et al. 2016, 2018). From this CE monitoring framework, policy indicators on the state of the circular economy and systems-level guidance for improving the sustainable circularity of an economy are systematically derived.

The Waste RDI roadmap contracted the Environmental & Process Systems Engineering Research Group at the University of Cape Town to work with the BOKU team to adapt this this framework to the South African situation and to develop economy-wide indicators of circularity for the South African economy. The team chose the year 2017 as base year for the analysis presented in this report.

2 Research scope and framework

The CE framework used in this study is depicted in Figure 1. It enables linking all biophysical material and energy flows of an economy, from extraction and imports to the dynamics of production and consumption, construction of buildings, infrastructure and machinery and all resulting waste and emissions.

The assessment has three key characteristics[1] (Haas et al. 2020, Haas et al. 2015a; Mayer et al. 2019): Firstly, it utilizes the harmonized system boundaries developed for researching the socio-economic metabolism and economy-wide material and energy flow accounting, which is defined along political-administrative boundaries (usually national territories) and covers all biophysical

[1] Please note that this CE assessment follows a 'production-based' perspective, which means that extraction, trade and consumption of materials and energy carriers, as well as waste and emissions, are measured when they are biophysically occurring within and across political-administrative system boundaries, e.g. national borders.

resource flows managed and mobilized through societal activities, as well as the resulting waste and emissions (Krausmann et al. 2018, 2017). Secondly, it provides two headline indicators on the biophysical scale of the socio-economic system, providing information on the quantity and composition of all primary and secondary '*Processed Materials (PM)*' and their major uses, as well as all '*Interim Outputs (Int-Out)*', consisting of all solid and liquid end-of-life materials (before re-, downcycling and reuse), emissions, water vapor and dissipative use (e.g. mineral fertilizers). Thirdly, from these indicators on the physical scale, two CE-rates are derived, covering the degree of socio-economic 'restorative' loop closing as well as the degree of ecological 'regenerative' cycling potential:

- *Input-circularity* is defined as the ratio of all recycled, reused and potentially 'ecologically regenerative' materials in total primary and secondary processed materials and energy carriers (PM).
- *Output-circularity* is defined as the ratio between all recovered and potentially 'ecologically regenerative' materials kept in loops and the total amount of all end-of-life materials, products and emissions (Int-Out).

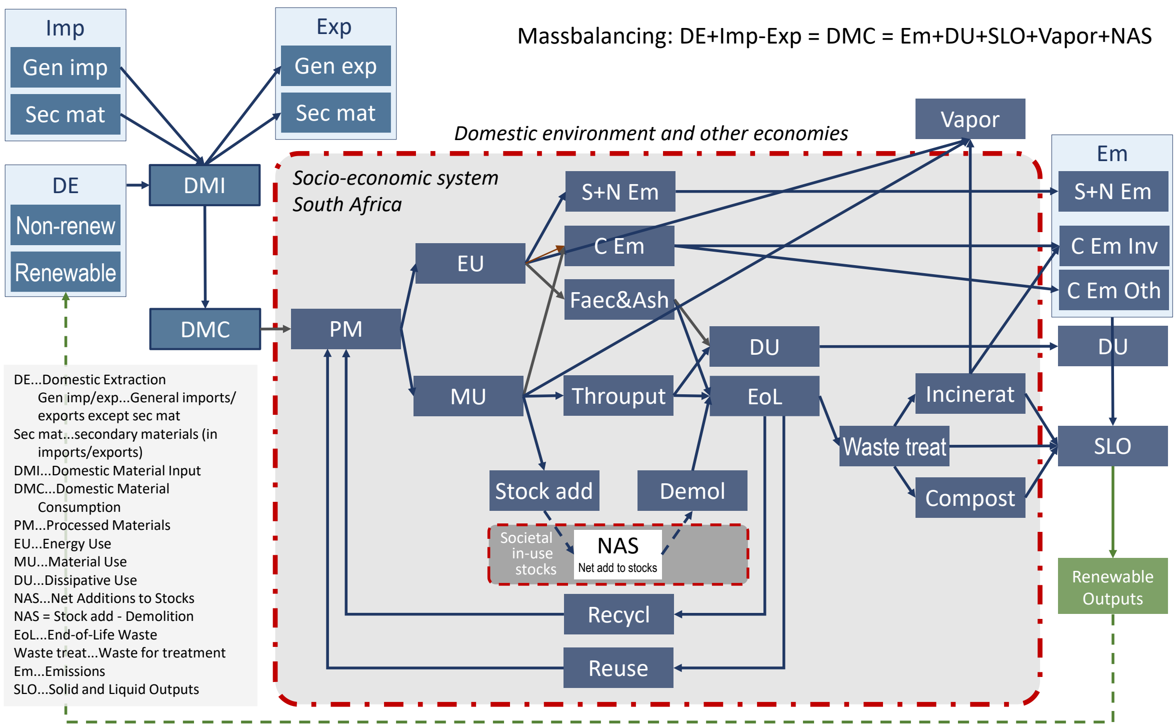

Figure 1: Framework for the economy-wide monitoring of the circular economy in South Africa adapted from (Mayer et al. 2019). The different data sources used are fully mass-balanced in the framework. For further details and technical descriptions, please see Mayer et al. (2019).

The key difference between the input- and output-perspective is that substantial amounts of processed materials are utilized to expand and maintain societal in-use stocks of products and structures, which are in-use for years to decades and only then become available as end-of-life waste materials, making their explicit representation crucial to understanding the potentials and limitations for closing loops. For more detailed discussions we refer to the respective publications by BOKU (Haas et al. 2020, Haas et al. 2015a; Mayer et al. 2019; Jacobi et al. 2018).

This monitoring framework enables:

- assessing the degree of circularity vis-à-vis the overall size and dynamics of the physical economy, thereby providing headline indicators for policy and communication efforts;
- providing systems-level insights into potentials for improving circularity and sustainability;
- investigating the nexus between climate relevant emissions and circularity; and
- providing robust and comprehensive information even in the case of missing data, e.g. on waste flows, due to its data triangulation and mass-balancing approach.

The use of this framework, and the derivation of input and output circularity indicators are illustrated in Figure 2 and Figure 3, which show the summary of all material flows in the EU28 countries in 2014, and estimate 9.6% of inputs to derive from socioeconomic cycling and 14.8% of outputs to undergo socioeconomic cycling. Combined with potential ecological cycling, circularity was estimated to be 34.2% of inputs and 50.1% of outputs.

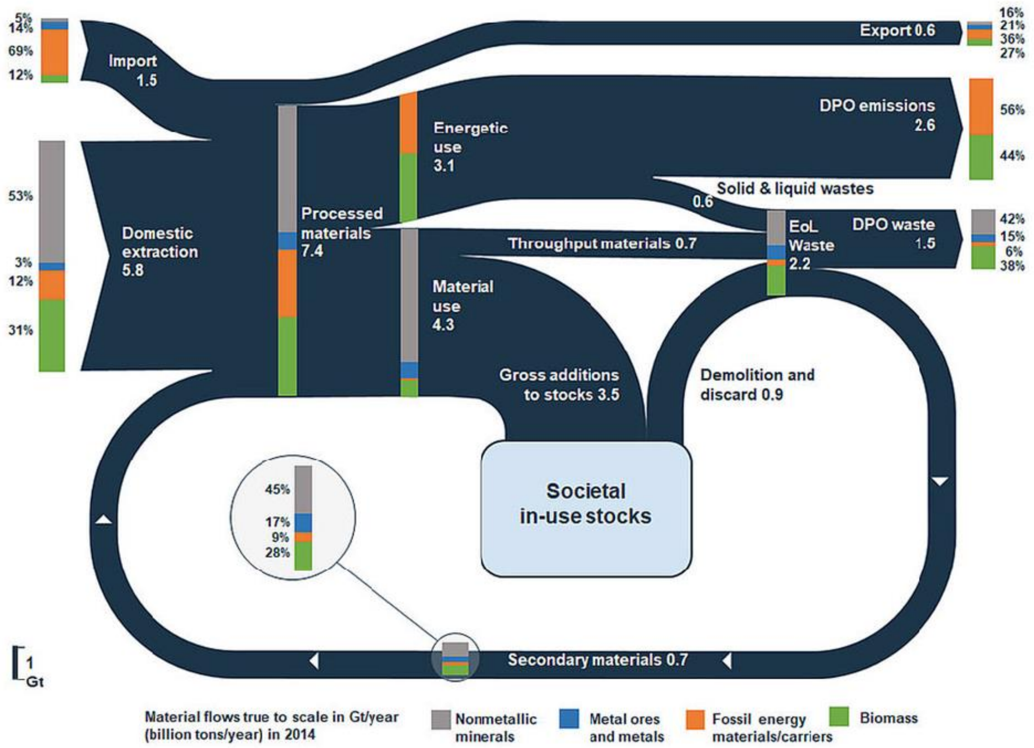

Figure 2: Material flows through the EU28 economy in 2014 (Mayer et al. 2019). In this Sankey diagram, the width of the arrows is proportional to the size of the material flows (dark blue); the numbers show the size of the material flows in Gt/yr and the bars their composition.

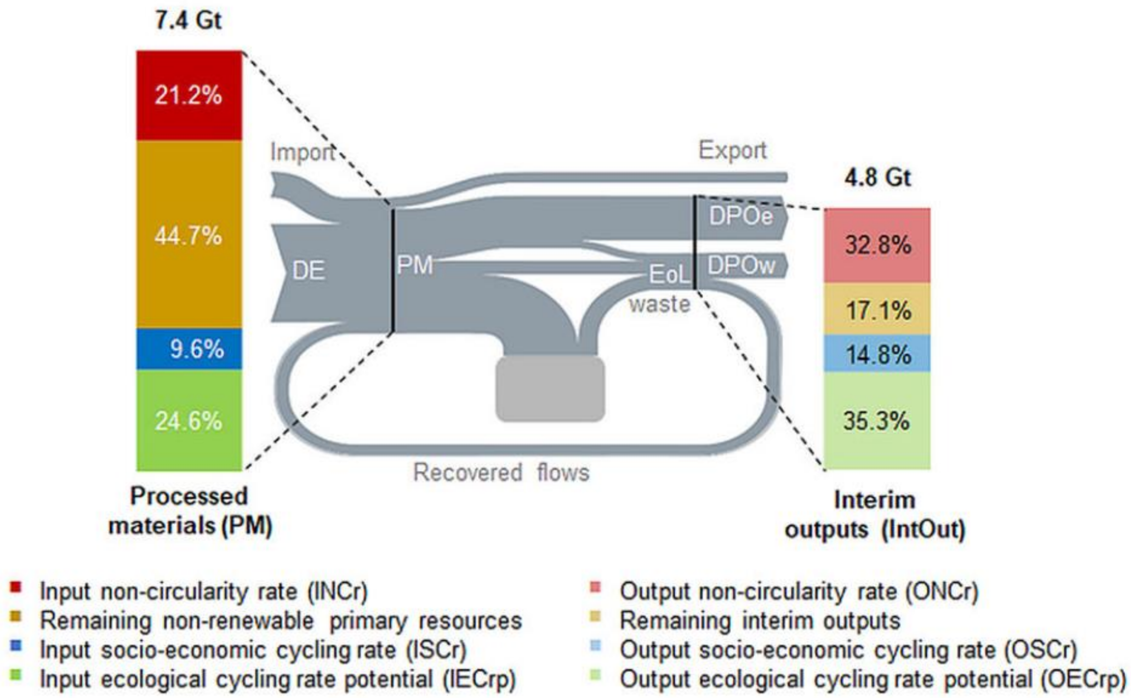

Figure 3: Systematic circularity assessment for the EU28, for the year 2014. Please see text and literature for a detailed discussion and interpretation of indicators and findings (Mayer et al.*, 2019).*

At the outset of this project, it was postulated that this monitoring framework could be used to inform and guide strategies to increase the sustainable circularity of the South African economy. In South Africa, resource use, as well as waste quantities and subsequent waste management policies have rapidly expanded in the past years and the circular economy has been proposed as a new sustainable resource use and waste management paradigm (Godfrey and Oelofse 2017). However, a comprehensive assessment of the current state from all inputs to all outputs and prospects for increasing the circularity of the South African economy has not been conducted yet.

Herein, we report how we utilized and adapted the previously developed CE-monitoring framework as applied for the EU-28, to investigate the case of South Africa. This report should allow various South African stakeholders, e.g. national and local government, business, NGOs, etc., to identify opportunity areas for increasing circularity within the South Africa economy, in an effort to domesticate the CE to the South African developing country context. It provides an evidence-based approach to identify strategic intervention areas within the South African economy to increase circularity, with the intention of supporting local economic development and job creation.

3 Methods, data sources, challenges

The key strength of the economy-wide CE monitoring framework introduced above is that it follows a mass-balancing approach: all flows of materials and energy have to either end up in material stocks of infrastructure, buildings, machinery, or become waste, emissions, water vapor or dissipative use. Therefore, data gaps can be bridged via triangulation of existing data of different points of flows through the economy, mass-balancing and process information respectively case study data. The economy-wide CE monitoring approach utilizes and combines national official statistical data on economy-wide material and energy flows (ew-MEFA), national energy consumption, emissions and national waste (construction & demolition waste, extractive waste, industrial processing waste, municipal household waste, etc.).

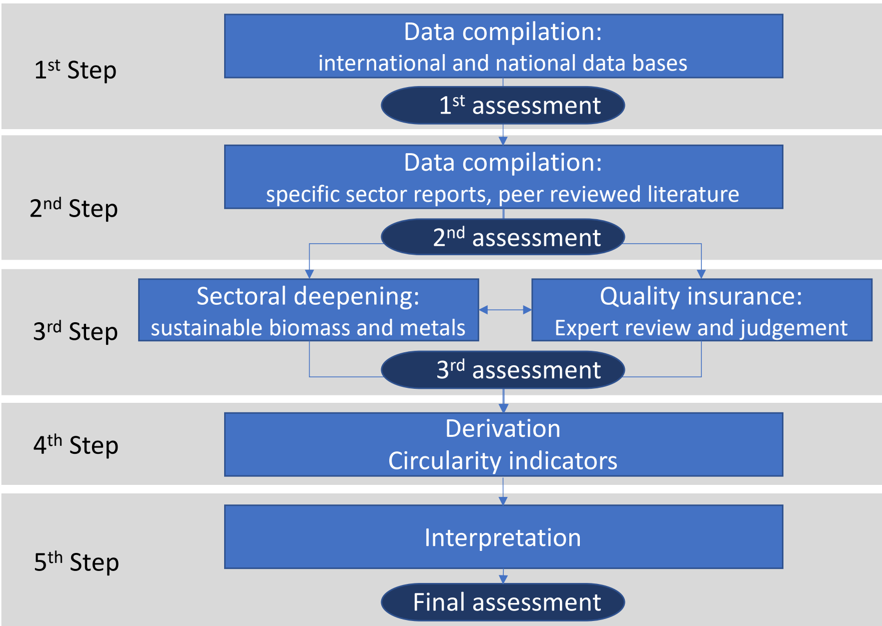

Figure 4: Step-wise approach for the generation of a circularity assessment

We followed a 5-step procedure to populate and amend the framework so as to derive and interpret circularity indicators (Figure 4):

1. Use of readily available data from reliable international and national sources, yielding an incomplete 1st assessment.
2. Refining of estimations by using additional South-African specific information, from sector-specific annual activity reports (e.g. for mining, forestry, agricultural subsectors), industry information and peer-reviewed literature, culminating in a 2nd assessment.
3. This assessment was presented as quality insurance to invited experts for their judgement and a sectoral deepening, focused on sustainability of biomass extraction and use on the one hand, and a better representation of the intertwined nature of flows related to minerals extraction and metals production on the other, yielding the 3rd estimate.
4. Derivation of the circularity indicators based on this estimate generated the 3rd assessment.
5. Interpretation of the overall flow pattern and their indicators and the circularity indicators (final assessment).

3.1 Readily available data sources for the 1st estimate

As a first step, we used readily available data from the following international and national sources:

1) Data for economy-wide material and energy extraction, trade and consumption at the national level were sourced from the recently established UNEP database, which robustly covers 1970-2017 and is based on nationally reported data and aggregates and harmonizes information from international databases such as FAO, IEA, Comtrade and others (Schandl *et al.*, 2018; UNEP 2016).
2) Data for energy consumption and emissions were sourced from the national greenhouse gas emissions inventories established under climate reporting obligations (UNFCC & Paris Agreement) and from international databases such as EDGAR and IEA.
3) Data for national waste and recycling flows were taken from the South African State of Waste (SASoW) report for 2017 (DEA, 2018). It estimated total waste managed to be 55.07 Mt of general waste (of which 34.5% recycled and 62.5% disposed in landfills), plus 52.19 Mt of hazardous wastes (of which 6.6% recycled and 92.7% disposed in landfills).
4) The combination and triangulation of all data sources for the first step was be based on the established procedures from (Haas *et al.*, 2015, 2020; Jacobi *et al.*, 2018; Mayer *et al.*, 2019).

3.2 Harnessing South African data sources and expertise for a 2nd estimate

In a second step, we refined the estimations by using additional South-African specific information, from technical reports, industry information, peer-reviewed literature and expert judgement. We specifically also paid attention to trying to estimate flows into the informal economy.

3.2.1 Data sources

Table 1 shows for which materials uncertainties existed in the data found internationally, which South African sources were consulted, and how the uncertainty was resolved.

Table 1: South African data sources used to complement international data sets

Material flow	Nature of uncertainty	Sources used	Resolution
Mining	For several metals, combination of USGS data for extraction and Comtrade for imports and exports yielded negative DMC	MCSA 2018, SAMI (2017)	Comparison of combination of local vs. International data sources for extraction and trade on a metal by metal basis to determine arrive at positive DMC
Construction minerals	Official and industry sector national estimates for sand and gravel lower than in UNEP	SAMI 2017 MCSA 2018	Stayed with higher UNEP estimate; an earlier industry claim was found that official statistics under-report; could not balance construction materials recipes with lower sand & gravel.
Energy	Some flows in international sources	DMRE Energy Balance 2017	Big discrepancies in domestic fuel use required attention

	questionable or disaggregation missing		
Polymers and chemicals from coal	A uniquely South African practice	Plastics MFA by (von Blottnitz, Chitaka and Rodseth, 2018); Lubricants, paraffin wax, bitumen from energy balance	Inserted a line in the calculations for plastics from coal, equivalent to plastics from oil
IPPU emissions	Not immediately available from international sources	SA GHGI 2017	Used for cement sector, only for comparison

3.2.2 Estimating informal flows

The official waste statistics are silent on informal waste management practices. They do not explicitly show the fate of the waste of the 31% of households not receiving waste collection services. We thus used the estimates of Rodseth, Notten and von Blottnitz (2020) for the household portion of the waste. It is noteworthy that an estimated quantity of 3,67 Mt of household waste undergoes 'self-help' disposal which may include dumping, burying, burning, resource recovery or feeding to animals.

Additionally, the category of construction & demolition (C&D) waste appears to be strongly under-estimated in the SASoW (as in most waste statistics world-wide), due to informal waste and recycling activities and under-reporting of waste amounts from formal economic activities. Additional expert estimation and mass-balancing were necessary to complement these data.

In order to estimate the C&D waste quantities, two approaches were used: one based on estimated construction material volumes and likely lifetimes of in-use stocks, and the 2nd using a scale-up from one municipal data source deemed trustworthy to the full population.

Method 1: Estimating primary construction materials and their stock life

The first approach is based on input quantities and estimated lifetimes. C&D waste is taken to consist of concrete and masonry, asphalt, wood, plastics, metals and gypsum plus miscellaneous materials (European Commission, 2011) – in the European case concrete and masonry (69%) and asphalt (16,3%) are reportedly dominant, thus these need to be well-quantified. We added flat glass as a separate material, and separated the fraction for concrete and masonry into "reinforced concrete" and "Bricks, mortar, paving, tiling".

For estimates of new construction materials, the following data sources and assumptions were used:

- Reinforced concrete is made of cement, sand, gravel and steel. These figures are based on half of the total cement (0.5 x 14.7 Mt), and a cement-to-sand-to-gravel ratio of 1:2:4. The steel is taken to be half of the 40% of the total steel assumed to go into construction uses (0.5 x 0.4 x 5.76 Mt) – with the other half going into frames, fittings, cables etc.
- Clay bricks and tiles, cement bricks (a.k.a. concrete blocks) and mortar.

  - Clay bricks are taken to be 7.4 Mt (CBA – insert reference!).
  - Cement bricks are found from 1/8 of total cement (14.7 Mt / 8), as well as sand (8 x cement mass).
  - Mortar uses the remaining cement (3/8 of 14.7 Mt) and sand (3 x cement mass).
- Flat Glass: Flat glass is assumed to be half of total production mentioned in SASoW, i.e. 0,5 x 0.36 Mt. (DEA, 2018)
- Asphalt: This includes bitumen and aggregate and is assumed to be 3.5 Mt (sabita, 2017).
- Plastic pipes, frames, furnishings: This is assumed to be 50% of the 0.81 Mt of plastics used durably in 2017 (von Blottnitz, Chitaka and Rodseth, 2018).
- For gypsum, the ratio of gypsum to concrete & masonry in European wastes was assumed to hold for construction amounts in South Africa.
- Miscellaneous materials were assumed to be 5% of the total construction materials.

The fraction of new construction materials that become waste directly is not documented, here we assumed a value of 1%. For demolition, a waste to input ratio was calculated for each item based on material service life (Cochran & Townsend, 2010). The service life for flat glass and plastics is assumed to be 30 years. The C&D estimate is found from this ratio and an assumption that the use of building materials in the long run in South Africa grows at 3% p.a.; the "rule of 72" then gives a doubling of use, and waste, every 24 years. This means that for a material with a 24-year life-span there would now be double the amount used as construction material as there was 24 years ago, and (simplistically) the material deployed 24 years ago would now all become waste and be 50% of the new construction materials by mass. In reality, of course, there would be life-time distributions and the estimation of waste quantities would be computationally more complicated.

Method 2: Per Capita – Cape Town Population

The second method scales up from fairly reliable waste reporting in Cape Town to the national total on a per-capita basis, taking urban vs. rural population into account.

- The population of Cape Town is assumed to be 3,8m and the national population is assumed to be 57 million.
- Annual C&D waste generation in Cape Town is assumed to be 1.09 Mt (City of Cape Town, 2017).
- In order to include the impact of both urban and rural population, it is assumed that the rural population has a fifth of the intensity of Cape Town consumption, while the urban population's consumption is the same as Cape Town.
- It is further assumed that the population is 60% urban and 40% rural.
- Therefore, the average citizen annual building waste relative to Cape Town is 68%.
- The total C&D waste generation is then found (1.09/3.8 x 57 x 68% = 11.12 Mt).

Next, the quantities of C&D wastes to different possible fates were estimated. Five options were considered: informal reuse, formal recycling, informal dumping, use of cover material in landfills (downcycling), and landfill together with other wastes (formal disposal).

For informal reuse the attractiveness is qualitatively described and then assigned a fraction, as per our own assessment and shown in

- Table 2.

- For formal recycling, fractions were estimated to be consistent with waste statistics.
- A fraction of 20% of was assumed to be informally dumped, based on widespread reports of informal dumping of building rubble, with a lower fraction used for materials highly desirable for informal reuse and also for asphalt (10%) where more controls were assumed to be in place.
- The amount of concrete and asphalt used as landfill cover material was varied to be 50% higher than the total amount officially reported.

Table 2: Estimated attractiveness of C&D constituents for informal reuse

Material group	**Attractiveness for informal reuse or recycling**	**informal reuse**
Wood products & offcuts	High	0,8
Flat glass	Low (mostly broken)	0,1
Metal frames, furnishings	High	0,5
Concrete	Very unlikely (difficult to separate)	0
Bricks, mortar, paving, tiling	Medium to high for clay, low for cement	0,143
Plastic pipes, frames, furnishings	Medium to high	0,500
Gypsum	Low	0,1
Asphalt	Very unlikely	0
Miscellaneous	medium	0,333

It may be noted that this part of the work was done late in the project, after the expert inputs presented in the following section, when it became clear that there was no better data available for C&D waste quantities and for informal reuse of such materials. The estimates produced remain expert estimates have since undergone further refinement, undertaken as part of the Masters level research of Sally Berge, ongoing at the time of writing and expected for completion in the 2nd half of 2022. A publication is under review (Berge and von Blottnitz, 2021).

3.2.3 Co-production with sector experts

Once the team was confident that the 2nd estimate was nearing completion, plans were made to present it to a small group of invited experts with deep knowledge of material flows in specific sectors. The aim was to seek critique on the choices made and representation of results, and to obtain guidance on alternate datasets where numbers remained either illusive or highly uncertain. The workshop was held via video-conferences on the Zoom platform, between 3 and 5 November 2020. A 2-hour plenary session to explain the approach and methods was attended by 14 guests, all of whom participated again in one of the four specialist sessions, focusing on:

- Fossil & biomass fuels,
- Food & feed flows,
- Waste & recyclables with additional focus on construction material stocks and flows,
- Minerals & metals.

In these specialist sessions, the results obtained to date for the material classes workshopped were presented in the form of a Sankey diagram, and the research team also prepared a list of questions. This resulted in a semi-structured discussion in which points raised by the contributors could be explored before returning to the loosely prepared agenda. The participating experts are gratefully acknowledged and their names are listed in addendum 1. Notes were taken and used to structure follow-up activities. Four types of improvements were identified:

i. Important flows in terms of quantities
ii. Flows that receive heightened attention in the political and expert debates
iii. Low hanging fruit for improving data
iv. Methodological refinements to better reflect specific South African realities, esp. in the minerals extraction sector and regarding end-of-life materials.

Regarding large flow items, improvements and clarifications were made to construction minerals (as mentioned in 3.2.1 and 3.2.2 above), biomass (in particular maize 'straw' and grazing, see section 3.3.1 below) and mining-related flows, clarifying the difference between 'unused extraction' and 'extractive waste' (see glossary) and attending to flows between metal sub-sectors, in particular between iron ore, iron and steel, and the chromium and manganese ferroalloys (see section 3.3.2 below).
Flows that according to the expert consultations receive heightened attention and were thus reconsidered include:

- Plastics (for which we use the UCT E&PSE plastics MFA by von Blottnitz, Chitaka and Rodseth (2018); an updated version is under review (Goga *et al.*, under review));
- Mismanaged waste streams (outputs to nature) – open burning, plastics to ocean, informal dumping;
- Food waste which formed the topic of a final year student research project by Cridge and McDonic in 2022 (report available on request);
- Composting as an alternative to organic waste to landfill;
- Waste data where adaptions were made to the State of waste report data;
- Alien species;
- E-waste and recovery of scarce or toxic metals.

Several methodological improvements were made to the calculation engine in the Excel spreadsheet. One pertains to complexity in the minerals and metals sub-sectors (section 3.3.2 below); others related to the re-use, cascading and down-cycling of materials which is a feature of industrial symbioses, but also prominent in the highly unequal South African society. Reuse was specifically added as an end-of-life option, with the prime example being for bottle glass, for which the final year student project by Musselwhite and Douglas compiled a substance flow analysis with Sankey diagram, available on request. Incineration and composting were also added to the end-of-life options. Importantly, in order to capture cascadic use and reuse of certain compound materials that are not extracted from nature in the form used, such as asphalt, concrete, glass or steel, a transfer between materials was introduced. This way, specific amounts of extracted materials could be combined into one compound material (e.g. sand and gravel and bitumen becoming asphalt). Thereafter, reuse- and recycling-flows could be included for the compound material category.

Food and feed are part of the energy use as they are metabolized in order to provide energy. Within this process, food is transformed into emissions, vapor and excreta and leaves the socio-economic system as output. A small part, however, is never metabolized but emerges as waste even before consumption. Data on the amounts of primary crops and fish lost before consumption is available from FAO, as well as from Oelofse and Nahman (2013). This amount of food waste was included as a separate flow, in order to account for the difference of metabolized vs. non-metabolized food and to explicitly show how this flow reports from energy use back to solid and liquid outputs. The 2021 revision of food waste estimates for South Africa (Oelofse *et al.*, 2021) was published after the calculations for our study had been completed and are not reflected in our results. Cridge and McDonic in their final year research report illustrate how the MFA could be adapted with these newer numbers.

3.3 Deepening on specific material flows

Two specific material flows, namely biomass and metal ores, were selected for further analysis. They both relate to the prominence of extractive activities in the South African economy and their link to environmental sustainability.

3.3.1 Sustainability of biomass extraction and management of organic wastes

South Africa is known for its mining sector, so it was somewhat surprising to the research team and to many of the invited experts that biomass extraction appeared to make up of the order of 20-25% of total domestic extraction (at the time of the 2nd estimate). Circularity and ecological cycling of biomass are dependent on the sustainability of agricultural production and disposal; as to what extent it interfers with ecosystems viability and interrupts geochemical cycles (carbon, nitrogen, phosphorus). The team thus decided to take a closer look at both the sustainability of biomass harvesting (production) and the management of organic wastes – and whether there is potential ecological cycling of nutrients in the outputs back into the inputs via ecosystems. Methodologically we followed conceptual considerations as outlined in Haas *et al.* (2020) and in Navare *et al.* (2021).

To gauge the fraction of inputs sustainably harvested, and thus reliant on ecological cycling, we sourced sustainability or annual reports from sector associations and looked for indicators of sustainable performance, such as FSC certification for wood products and the SASSI scorecard for fishing. For grain agriculture, the fraction of land managed according to conservation agriculture principles was sourced, though it is acknowledged that there may be other indicators of sustainability. We also cross-checked quantities relative to those obtained from FAO data.

For grazing, livestock feeding and manure management we worked with livestock numbers obtained from the agricultural statistics report (DAFF, 2019)**.** Animal feed is predominantly maize based, including grain, silage, chop and screening (Russo *et al.*, 2018). This food is used for concentrated feeding/feedlots. The daily intake of food, both grazing and feedlot, was found for the respective livestock subcategories (Du Toit et al., 2014; Russo and von Blottnitz, 2017; Niedertscheider, 2011). For sustainability of grazing, we relied on an expert estimate (Blignaut, 2021).

For manure quantities, we used the quantities of volatile solids per animal per day from the study of Moeletsi and Tongwane (2015). These were adjusted for a typical manure ash content of 27% (Matthiessen *et al.*, 2005) to obtain total dry matter.

For fates of manures, a report on Nitrogen Inputs to Agricultural Soils From Livestock Manure allocates a % of Total Manure available to a Manure Management System (MMS) for each livestock group (FAO, 2018). The MMS's include manure burning for fuel, manure left on pastures and manure stored. The livestock groups include cattle, goats, sheep, pig and chicken. Results are summarized in

Table 3.

Table 3: Fates of animal manures (FAO, 2018)

Fate	Cattle	Goats	Sheep	Pig	Chicken
Fuel	12 %	0 %	0 %	0 %	0 %
Pasture	38 %	87 %	80 %	4 %	14 %
Stored	50 %	13 %	20 %	96 %	86 %

A more detailed list of manure fates was considered in a study focused on estimating greenhouse gas emissions from manures (Moeletsi and Tongwane, 2015), though for 2004 livestock populations. The report gives a clear indication of the methane and nitrous oxide emissions associated with relevant MMS as well as MMS % usage for different livestock categories. MMS include Lagoon, Liquid/Slurry, Daily Spread, Compost, Pasture, Manure with Bedding, Poultry Manure with and without Litter. The livestock categories include sub-categories and thus are complex; we grouped them into cattle, goats, sheep, pig and poultry for simplification purposes. To estimate manure quantities, we multiplied by 2017 livestock population as reported by department of agriculture.

In a final step we compared the total annual feed and grazing intake to the manure production, for each major livestock class, to check for plausible ratios of the inputs to the outputs.

3.3.2 Methodological enhancements for minerals extraction and metals production

Given the prominence of a diverse mining and metals production sector, it was found that the available methods which are built on the assumption that each sub-sector produces one metal were insufficient to represent the reality of inter-subsector flows. A methodological improvement to allow for transfer of byproduct metals between sectors was therefore made, upon advice by experts consulted. Also, key products of metallurgical processing often are alloys containing multiple metals. Steel was thus introduced as a technical material to facilitate better accounting. At the same time, high domestic recycling rates for metals had been observed, so these analyses were done not just for extraction, but for the entire metals chain. Four metallic elements were focused on, viz. Iron, manganese, chromium and copper, as shown in Figure 5, with the mining sub-sectors from which they originate.

Mining sector	Key metals	Intermediates	Metal products	Extractive waste
Iron Ore	Fe	Pig iron	Iron	Oxygen, Silicon +
		(Pig iron from other sectors)	**Steel**	
Manganese	Mn, Fe	Ferro-Manganese		Oxygen, Silicon +
Chromium	Cr, Fe	Ferro-Chromium		Oxygen, Silicon +
PGM	Fe, Cr	Chromite concentrate		
	Pt, Pd, Rh, Au	Precious metal concentrate	Pt, Pd, Rh	Sulphur +
	Cu, Co, Ni	Base metal concentrate	Nickel, Cobalt	Sulphur +
Copper	Cu, Fe		Copper	Sulphur, Iron, Silicon +

Figure 5: Relationships between selected mining sectors, metallic elements and key products

The investigation was done in two stages. First, a pair of chemical engineering 4th year students, Ayanda Mafunda and Ongezwa Mbaba, dedicated their 2020 capstone research project to developing value chain flowsheets, obtaining data and structuring these into mass balance stream tables (report available on request). Thereafter, the project team refined this work to fit into the MFA accounting logic, also making expert choices to balance flows where inconsistencies arose. The new methods developed in this component of 'sectoral deepening' were not extended systematically to all metal value chains in South Africa. Some metals sub-sectors are thus still presented in oversimplified form, incl. the heavy mineral sands (Titanium, Zirconium) and the platinum group sector (although the production of byproduct chromite concentrate from this sector has been captured, as well as the Copper (Cu), Cobalt (Co) and Nickel (Ni) byproducts which are contained in regular mineral sector production statistics).

3.4 Final estimate and derivation of circularity indicators

The improvements discussed in sections 3.2.3 and 3.3 were implemented into the main calculation spreadsheet and the supporting spreadsheet with South Africa specific data. Upon their completion, a number of regular balance checks were performed by controlling the mass-balance for certain interactions between material flows within the model to arrive at a mass-balanced final estimate. For example, total inputs minus outputs and minus net additions to stock (considering additions to bunker and transfers to other material groups) have to equal zero for every material subcategory. The final estimate was mass balanced at primary, secondary and tertiary level of detail (e.g. metals, non-ferrous metals, aluminium) and for all process steps in the model where inputs and outputs have to balance (see Figure 6).

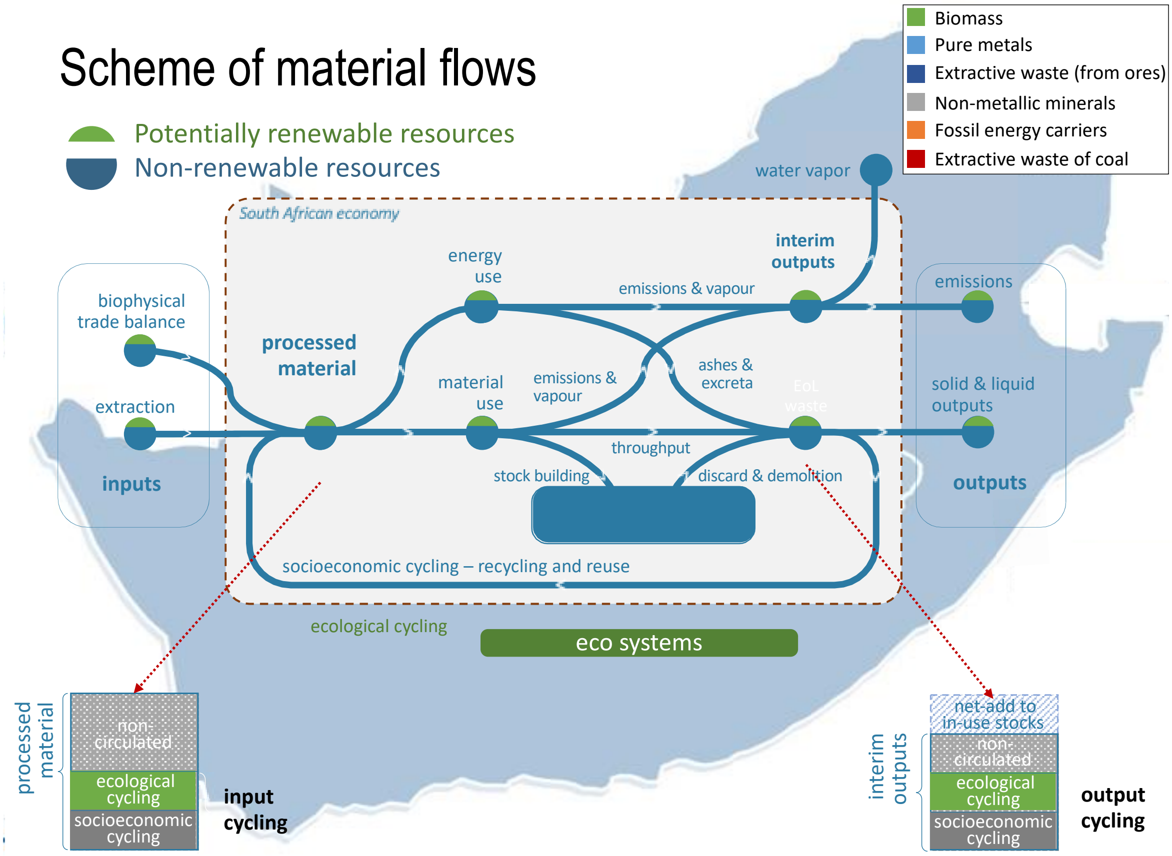

Figure 6: Scheme of material flows through the South African economy: all nodes (e.g. processed materials) need to be balanced for all material categories and thereafter ecological and socioeconomic cycling flows can be related to processed materials and intermediate outputs

Thereafter, Sankey diagrams were developed, and the input and output side circularity indicators (as defined in section 2 above) were enumerated. Likely ranges for the indicators were also estimated by varying major contributing flows between likely highest and lowest values.

3.5 Interpretation of circularity indicators

When discussing circularity, most commentators focus recycling rates. These look into a certain waste flow (e.g. steel) and relate collected material to overall EoL waste in this material (collected steel scrap to EoL steel). Recycling rates are important for understanding what increases are still possible. However, for various reasons they do not indicate if this is having a positive effect on circularity overall, since e.g. additional energy or material requirement for recycling activities might exceed the gains from replacing primary materials (e.g. the difference in transport distances between transporting C&D waste and primary materials can turn net-gains in energy use into net-losses).

Circularity indicators by contrast conceptually measure on the output side all interim outputs before recycling and reuse and thus relate collected materials or products that become secondary materials or reused products to outputs including emissions, other wastes, water vapor and dissipative use. Thus positive and adverse effects are reflected and shifts from less material use but more energy use are considered. This can help to lead a discussion on overall circularity strategies. However, this indicator is not specific enough to understand which specific recycling activity has what potential for increase.

Our model presents circularity indicators as key indicators, but also provides results on recycling rates. To interpret our circularity indicators, we first evaluated the nature and underlying drivers for material and energy flows, and evaluated stock addition. Since circularity indicators overall were very low (as will be revealed in the results chapter), we looked for material classes with high socio-economic cycling. Lastly, given the importance of relying on both socioeconomic and ecological cycling, we tried to interpret extraction from and return of flows to the biosphere in relation to sustainable harvesting and sustainable disposal practices.

4 Results

This results chapter proceeds by presenting findings firstly organized by the four major material groups, followed by a section on waste data and finally summarizing the overall result. Mineral wastes are grouped with ores and metals, whilst industrial minerals and construction minerals are grouped together as non-metallic minerals. The results in this chapter are accompanied by explanations; an interpretation and discussion follow in chapter 5.

4.1 Ores and metals

These flows are made up of the metals themselves plus the extractive waste which together constitute the ores. Most of the extractive waste remains in the country, whereas 4 times more metal is exported than domestically used.

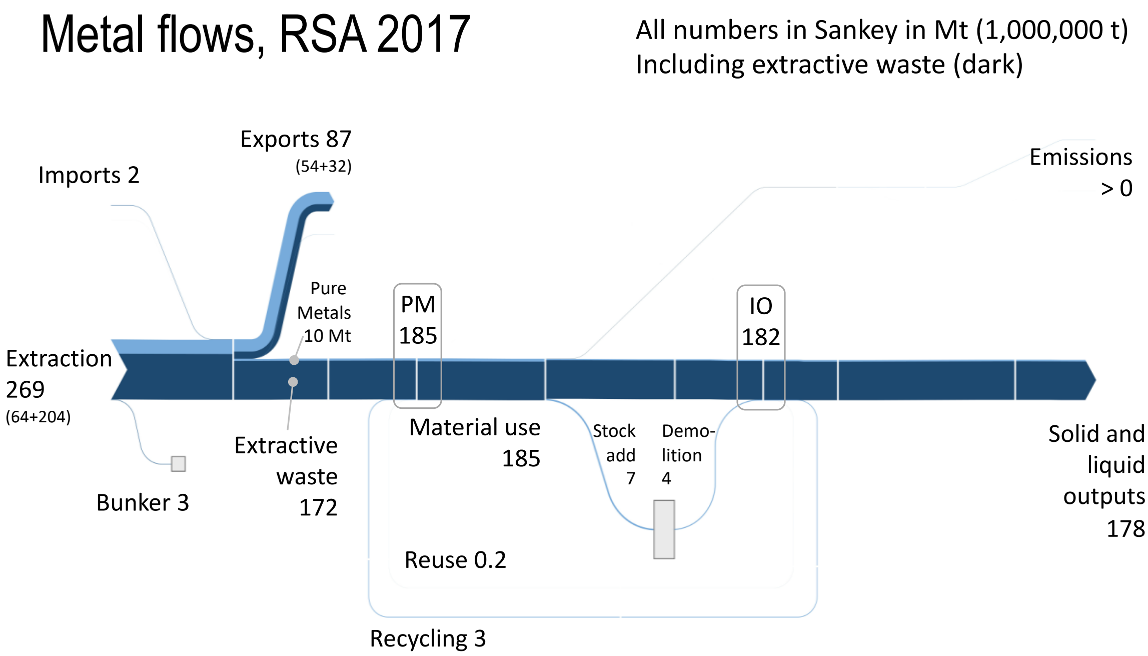

Figure 7: Flows of metals and associated extractive waste (numbers in Mt)

Metals use in the economy appears to be 13 Mt (as of the 185 Mt of PM, 172 Mt is extractive waste), however this amount includes ~ 5 Mt of metallic elements (mainly Fe, Cr and Mn) lost in tailings or slags during processing, with actual metal use consisting of some 7 Mt of stock-add and less than 1 Mt of short-lived use (e.g. packaging). Over 90% of the metals used, by weight, are iron and steel, though when accounting in the category of processed materials, this fraction is lower at 84%, due to significant amounts of chromium and manganese being processed domestically.

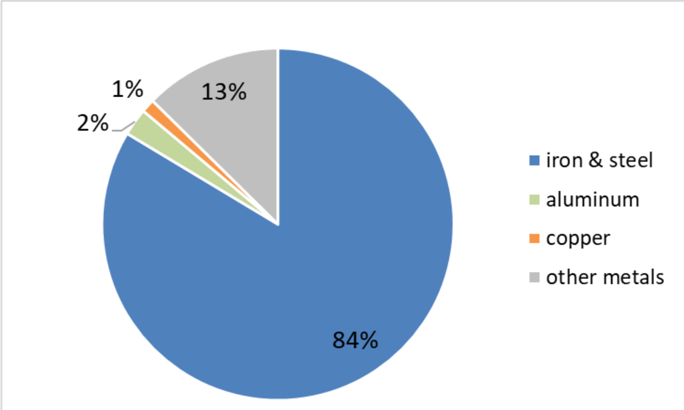

Figure 8: Breakdown of metals in the category 'processed materials'

The relationships between iron and the other two major so-called 'ferrous metals' chromium and manganese, for which South Africa is a major global supplier, are shown in Figure 9. When interpreting this figure, care should be taken that is does not differentiate the exports into beneficiated and non-beneficiated forms.

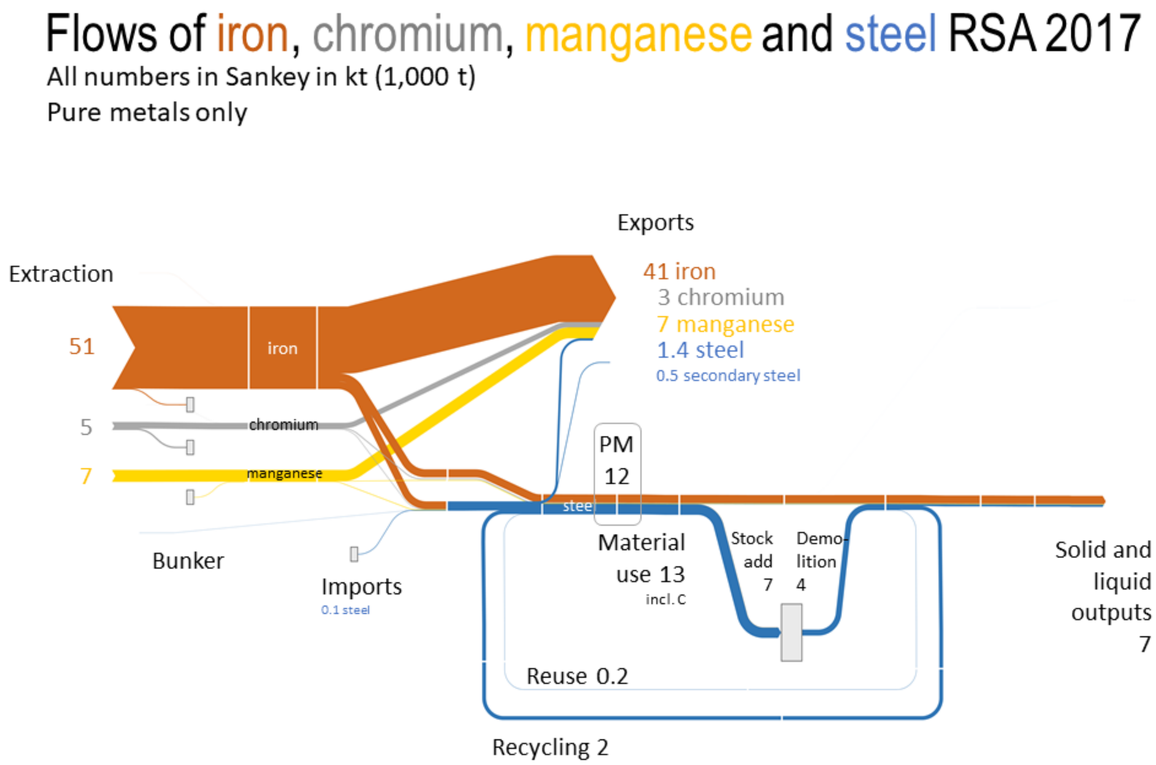

Figure 9: Flows of iron, chromium, manganese and steel

To understand the amounts of extractive waste, of course, ore grade matters, so e.g. the 136 t of gold produced do produce 42 Mt of tailings, whereas 60 kt of Cu at 1% head grade would produce 6 Mt of tailings. Overall the average ore grade across all metals mined in South Africa is 24%.

We observe one result where there is a high degree of circularity, possibly to the detriment of economic development:
For the non-ferrous metals, and in particular for aluminium and copper (the two largest uses), possibly also for lead, there are very low additions of virgin metal into the domestic economy. In the case of copper only 23 kt of the total use of 156 kt is virgin material. Additionally, there are fairly significant outflows of scrap metal exports. This result is only possible if the ratio of end-of-life metals becoming available is high relative to stock additions (75% for Al, and 120% according to our numbers for copper) coupled to high recycling rates of end-of-life metals (which is assured by their high value making them preferred collectibles for informal waste reclaimers). Whilst this is a positive result in terms of circularity, the low additions to stock, or possibly even stripping of infrastructure, means that society's built capital is growing very slowly, either undermining prospects of economic growth and service provisioning, or reflecting a structural transition in the economy. The latter is a possible explanation, given the strong reduction in gold mining and processing during the 2nd decade of the 21st century, a former mainstay of South Africa's industrial economy. Old metal infrastructure may now be stripped from defunct mines at significant rates.

4.2 Non-metallic minerals

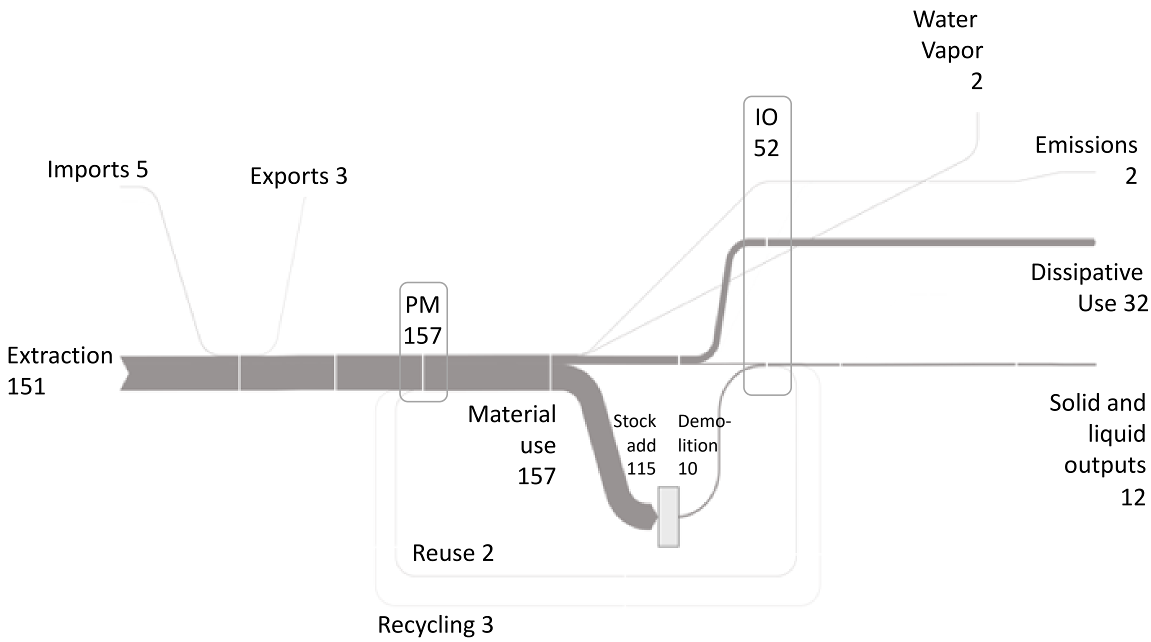

Figure 10: Flows of industrial and construction material (numbers in Mt)

This is a material category which is mainly extracted and used domestically. About 21% (31 Mt) are industrial minerals which are predominantly chemical and fertilizer minerals (97%). This category is dominated by the 120 Mt of minerals that find their way into the construction sector as shown in Figure 11.

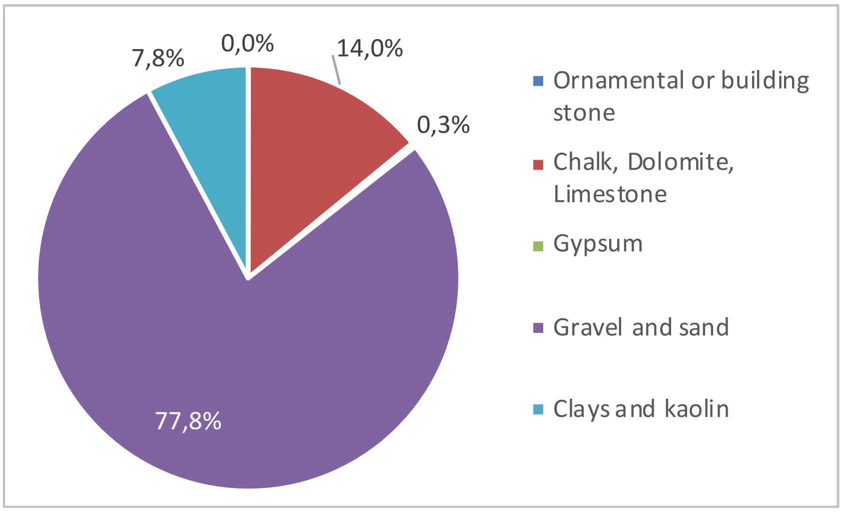

Figure 11: Breakdown of the domestic extraction of construction minerals

Roughly 50% of sand and gravel and of chalk, dolomite and limestone are used for producing concrete. Of all construction minerals about 95% or 115 Mt are used to expand and maintain stocks. Demolition respectively C&D waste is with 10 Mt relatively low. This number is based on waste statistics but was corrected upwards by applying two different estimation methods. The method finally applied took a case study for Cape Town (City of Cape Town, 2017) and extrapolated it with per capita values for South African urban inhabitants and by using 20% of the urban value for inhabitants of rural areas (see sub-section 3.2.2). It can be assumed that there is a substantial amount of stocks which are neither in use anymore nor demolished. In literature this is called hibernating stocks. This refers to abandoned above ground construction and mostly dysfunctional below ground infrastructures, where the demolition is too costly. Out of the 12 Mt EoL waste of construction minerals about 1.7 Mt are recycled (based on waste statistics). According to our own estimate clay bricks are informally reused adding another 0.4 Mt to the reuse. Together with 0.3 Mt of concrete reused this adds up to 0.7 Mt reused construction minerals.

For ornamental or building stone we used the UNEP data, they are 24 698 t, SAMI has 248 681 which is a significant discrepancy. However, altogether these are small amounts (given that construction minerals add up to roughly 119 000 000 t).

In the case of industrial minerals recycling and reuse is reported for glass. Thus 1.4 Mt of glass is reused (container glass) and 0.9 Mt is recycled. Thus, altogether 4.7 Mt of 16.4 Mt EoL waste of non-metallic minerals is recycled and reused.

4.3 Fossil energy carriers

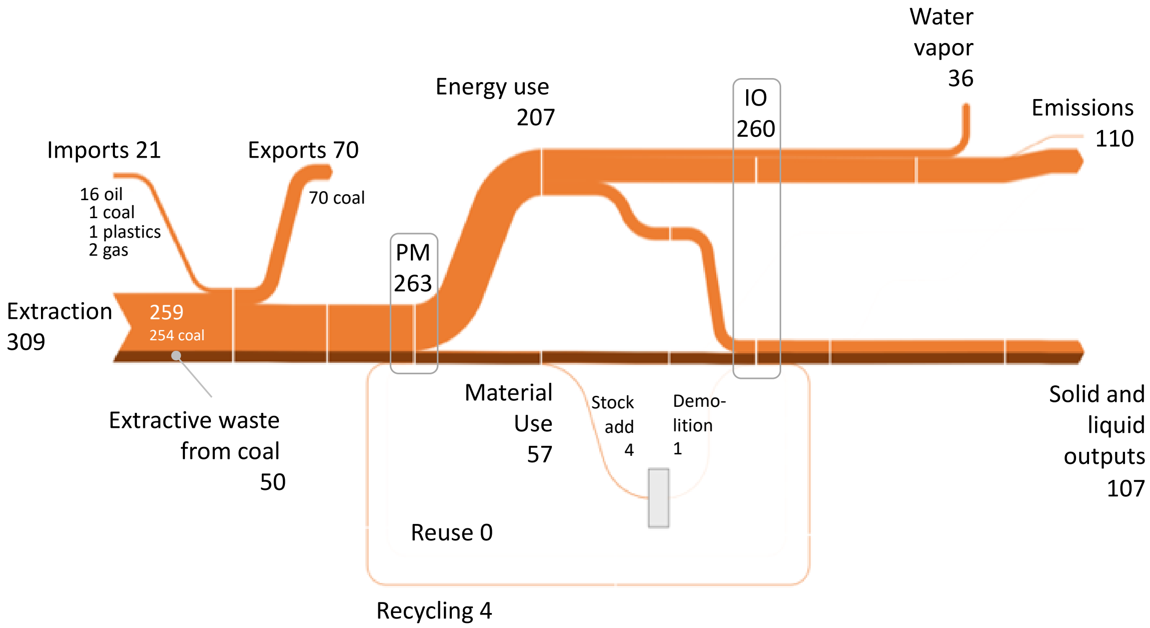

Figure 12: Flows of fossil energy carriers (numbers in Mt)

South Africa has abundant coal reserves, and 98% of the 259 Mt of domestic extraction of fossil energy carriers is hard coal, the rest oil and natural gas. Most oil used is imported, whilst of the 250 Mt of extracted coal, 180 Mt are used domestically and 70 Mt are exported. We account for 50 Mt of extractive waste associated with coal mining in the form of annual additions to discard piles (interestingly, this number is not reported in the production statistics provided by the minerals council nor of the Department of Mineral Resources, and represents an informed guess).

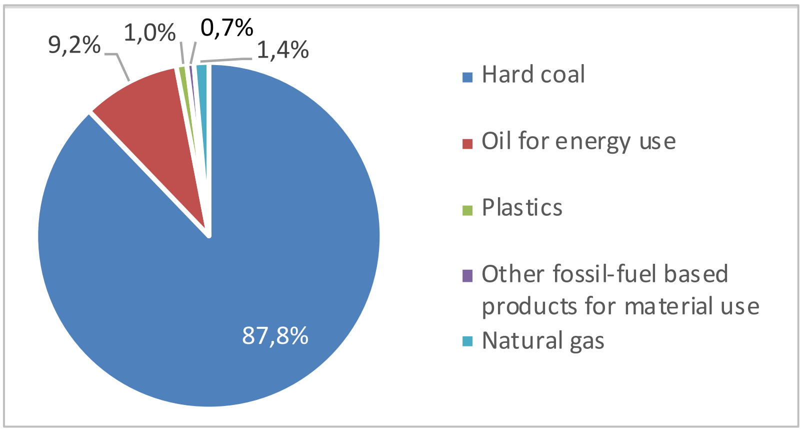

Figure 13: Domestic use of fossil energy carriers in South Africa

Hard coal, mainly use for power generation, is a large part of the use of fossil energy carriers in South Africa. Oil, mainly imported, is mainly used for transport and in industry. The 184 Mt of coal consumed result in 57 Mt of ashes, 91 Mt of C emissions (about 330 Mt CO_2), about 2 Mt of other emissions and 32 Mt of water vapor. A small fraction of ashes from coal burning and coal to liquid processes, 3 Mt, is recovered and processed for use in construction materials, shown as part of 'recycling' in Figure 12. Thus, coal for energy use and associated extractive waste, which amounts to 32% of all processed materials, is in mass terms the single biggest obstacle to circularity.

Plastics is with 2.1 Mt a relatively small flow. 1.7 Mt of plastics become EoL waste of which 0.34 Mt are recycled and 0.15 Mt are possibly informally reused.

4.4 Biomass

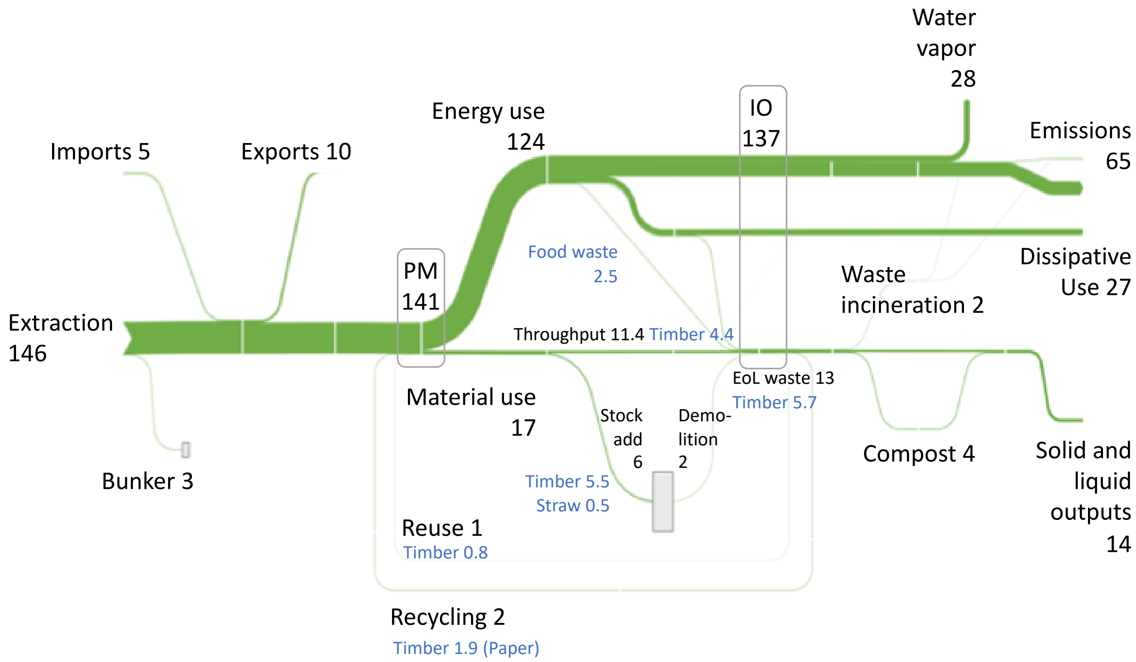

Figure 14: Flows of biomass (numbers in Mt)

Biomass extraction through farming and forestry, and to a lesser extent fishing and hunting is sizeable at 146 Mt, mainly for the feed, food and technical biomass energy carriers. Figure 15 shows how dominant grazing and primary crop production are. Exports are relatively modest at 10 Mt and imports are half that amount.

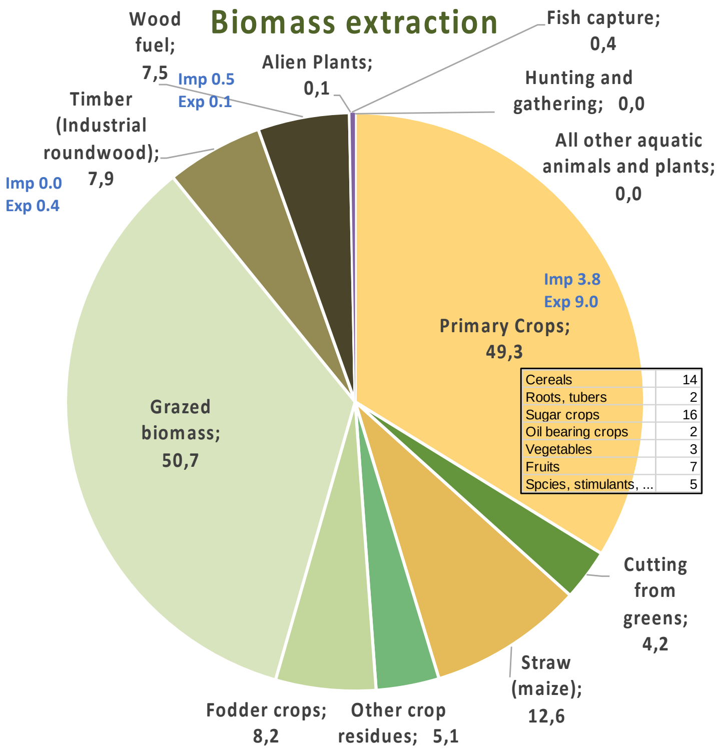

Figure 15: Breakdown of biomass extraction

The food system is heavily geared towards providing 77 Mt of animal feed (grazing, fodder crops and crop residues fed to animals), which become just less than 9 Mt for human food consumption (28% of the 31 Mt of food provided is animal-based; the other 72% are of plant origin).

On the material use side, paper and cardboard are short-lived and regarded as 'throughput' whereas timber products are long-lived and contribute to stock-add, and to demolition. Recycling is dominated by paper and cardboard, with the reuse of timber products and materials not well recorded and more uncertain.

On the output side, the 120 Mt of water vapor, biogenic carbon emissions and dissipative uses are theoretically all returned to the ecosphere and available for ecological cycling. However, in order to develop ecological cycling indicators, a more detailed look is necessary at the sustainability of extraction on the one hand, and of disposal practices on the other.

4.4.1 Sustainability of biomass extraction and harvesting

For input ecological cycling potential, the following results were obtained:

1. **Forestry**: 80% of commercial plantations/forestry are FSC Certified. A higher estimate for sustainable harvest of 96% would arise if considering that ~ 4% of timber is produced in communal land without strong governance systems (FSC Southern Africa, 2018).

2. **Grain**: Thus far around 20% of commercial grain farmers have adopted conservation agriculture (CA), whether that equates to 20% of the harvest would have to be confirmed by a calculation (GreenCape, 2018). Commercial grain farming is heavily dependent on input of synthetic fertilizers and whilst precision agriculture improves short and medium-term performance, the sustainability of this sector remains in question, also in the light of the

dependence of dryland agriculture on rainfall and drought periods which are predicted to become more variable as a result of climate change.

3. **Fisheries**: A widely used indicator is the SASSI scorecard. Green fish makes up 76% of the 2016 harvest. If one excludes small pelagic fish (sardines) from the red code, the sustainable harvest would be 95%. However, these data only accounted for legally caught fish. It is important to note that the majority of illegally caught fish will most likely be onshore easily accessible fisheries (line fishing, crayfish, abalone etc.). The method of trawling is generally less sustainable. The hake industry 100 % MSC certified; this is 26% of the total industry (Andrews, Groeneveld and Pawson, 2015). This is a very complex foodweb to gauge, even if 1% of catch is definitely red, it is important to note that the majority of red species have small mass and may thus be important in food webs and for biodiversity. A better indicator might be whether a critical fraction of the South African coastline is declared and managed as marine reserves.

4. **Grazing and livestock feed:** The numbers of livestock are shown in Table 4**.** Animal feed (other than grazing) is predominantly maize-based, contributing ~5.2 million tons in 2017 in the form of grain, silage, chop and screening (Russo *et al.*, 2018). This food is mainly used for concentrated feeding/feedlots and on dairy farms. The total volume of feed (excluding for chicken) was calculated to be ~8.1 million tons. The volume of grazed biomass is estimated to be ~ 52.6 million tons, dominated by beef cattle at 66%, dairy cattle at a modest 7%, and sheep and goats accounting for 27%. One expert estimates that only about 10%, at best 20% of grassland grazing is sustainably managed (Blignaut, 2021). This would translate to the sustainably grazed fraction to be 5-10 million tons.

Table 4: Livestock herds and their feed intake in 2017

Livestock Numbers	**Herd size**	**Grazing**	**Commercial feed**
Cattle	13 000 000	38 495 182	6 287 840
Commercial cattle herd	7 920 000	24 143 674	6 287 840
Subsistence cattle herd	5 080 000	14 351 508	0
Commercial dairy herd	*1 210 000*	*3 932 915*	*3 217 840*
Commercial beef herd	*6 710 000*	*20 210 758*	*3 070 000*
Pigs	2 897 000	0	1 876 677
Sheep	20 348 000	11 140 530	0
Goats	5 437 500	2 977 031	0
Chicken	125 282 096	0	
Total		52 612 743	8 164 516

Note: Chicken feed not quantified here.

5. **Invasive alien plants (IAPs)**: the CSIR assessment recommends to view these as standing stocks, not sustainable harvest (Le Maitre, Forsyth and Stafford, 2011). They are spread over 44 million ha, average density of 3.7 t/ha, range from 0-228 t/ha (p. 23, (Le Maitre, Forsyth and Stafford, 2011). The working for water report has a much lower area of 10 million ha of land invaded by woody biomass (Stafford, 2017) (mentioned by WfW and in CSIR value added industry report, 2017, page 6/46.). If one multiplies that average density with the new hectares cleared in 2016/7 of 120 kha, one would get an 'extraction' of ~450 kt. Real harvest would be fraction of that (so the undocumented 83 kt looks reasonable). One small-volume, high value product stream deriving from this are the school desks made from wood of harvested IAPs, estimated at a mass 4 kt in 2017.

4.4.2 Potential for ecological cycling of organic wastes

On the output side, our investigation of ecological cycling potential focused on uses and fates of maize harvest residues, management of animal manures, and on the extent of composting of municipal and industrial organic wastes.

Maize residues differ significantly from wheat/oat/rye 'straw' and in the South African context make up much larger amounts. They consist of 20% corn cobs, with the remaining material being leaves, husks, tassel and stalks (Stephen, 2011). It was estimated that 48% of the material is left on fields, 48% is grazed, 2% is burnt and 2% collected for other uses (Tongwane *et al.*, 2016). Using production figures for the 2016/2017 season of 16.7 million tons (GrainSA, 2020), we calculated the wet and dry mass of maize residue to be 25 and 22 Mt, respectively. There may be significant potential for biofuel production from the non-extracted portion of the residues, but this would have to be carefully planned in relation to cycling of nutrients contained therein and for the changes this may bring to soil organic-carbon.

Animal manures contain important nutrients that can be cycled back to soils. We estimate that ~ 26 million tons (dry weight) of livestock manure were produced in 2017. Manure Management Systems (MMS) systems vary, and our two data sources differ strongly on the amount of cattle manure left in the field between 38% (FAO, 2018) and 81% (Moeletsi and Tongwane, 2015). We thus estimate that between 46,8% and 80,5 % of manure was left in the pastures. According to IPCC definitions this means that the manure from the pasture/range/grassland of grazing animals is allowed to lie as deposited, and is not managed. Despite the methane emission factor only being 1.5 % for this particular MMS (Moeletsi and Tongwane, 2015), there is no guarantee that the nutrients left in the manure are being absorbed into pastures for optimal regeneration. Other fates are to storage at 45% if using (FAO, 2018), made up of dry-lots (10.1%) and lagoons (2.4%) when working with the data from Moeletsi and Tongwane (2015).

The daily intake was then compared to the manure production, yielding a ratio of 0.30 between manure (VS) and feed intake across the categories of cattle, pigs, goats and sheep.

Of the estimated 14 Mt of solid and liquid outputs of biogenic origin, the majority (10 Mt) ends up in landfill sites, a practice known to generate the greenhouse gas methane. Composting of municipal and industrial wastes at an estimated 4 Mt is starting to direct a portion of these materials for ecological cycling.

4.5 Wastes and their fates

As mentioned in section 3.2, we complemented the latest available national waste estimates (DEA, 2018) with other sources. Table 5 shows our estimates for waste quantities arising (local generation plus imports minus exports) relative to those of the SASoW. We arrive at a slightly larger amount of MSW, a significantly larger amount of C&D waste and we add sewage sludge to the general municipal (and household) wastes. Our industrial biomass estimate is slightly larger, whilst for other general industrial and hazardous wastes we do not deviate from SASoW estimates.

Table 5: Estimation of waste quantities in 2017

Waste main category	**Waste sub-category** Quantities in kilo-tonnes	**Waste managed (SASoW)**	**Waste generated (this study)**
General municipal waste	Municipal solid waste	21 608	24 272
	Construction & demolition	4 483	11 128
	Sewage sludge	-	2 537
	Total	*26 090*	*37 937*
Industrial General waste	Biomass	12 552	14 408
	Fly ash, dust & bottom ash	10 835	10 835
	Other general waste	5 589	5 589
	Total	*28 975*	*30 832*
General waste	*Total general waste*	*55 066*	*68 770*
Hazardous waste	Fly ash, dust & bottom ash	39 160	39 160
	Organic material	1 067	1 067
	Inorganic/inert materials	11 960	11 960
	Total hazardous waste	52 187	*52 187*
All waste	***Overall Total***	***107 253***	***120 956***

It is worth noting that a large portion of the industrial biomass residues reported in SASoW as waste (and re-estimated by us) are burnt in pulp & paper or sugar mills, to contribute to the energy requirements of these mills. As such, when transferring these numbers into the CE calculation, only the quantities known to be directly disposed, composted or used for material purposes were retained as 'end-of-life' materials, and the portion combusted was replaced with its ash (5% of 11.21 Mt) in the end-of-life category. If one follows this definition then the quantity of general waste would have to be revised downwards to 58.1 Mt.

The fates of the general wastes also merited some reinterpretation. Figure 16 contrasts the fates as per the official state of waste report with our estimates. Informal reuse (of C&D waste) has been grouped with recycling in the lower chart.

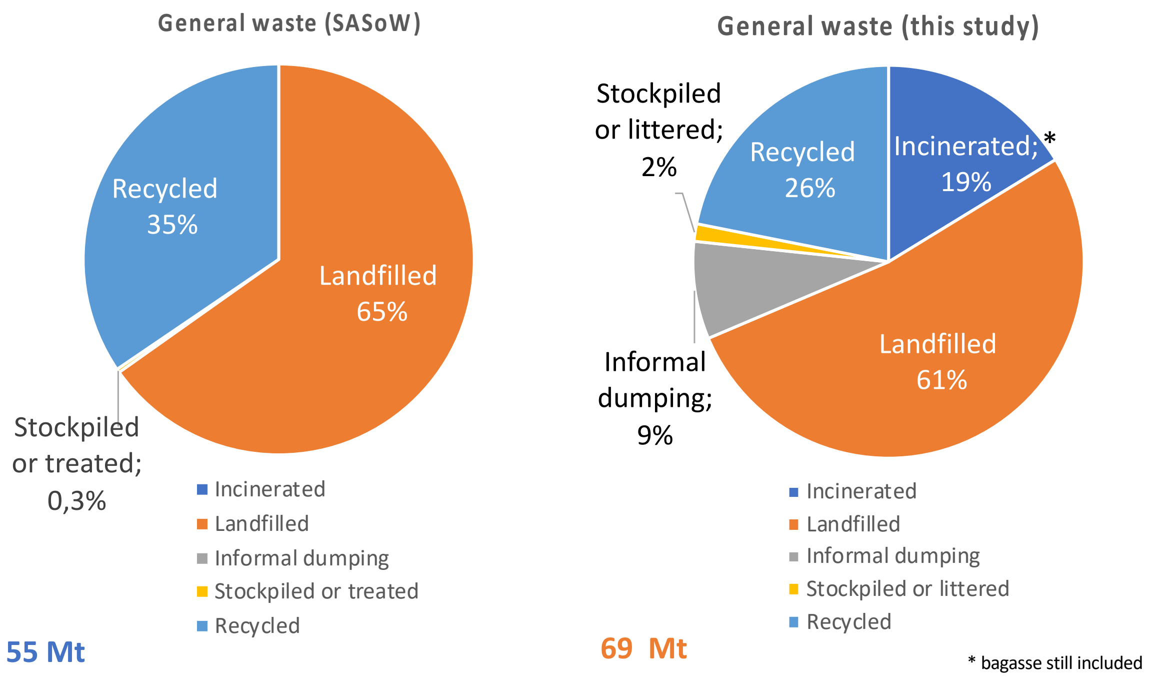

Figure 16: Fates of general waste in South Africa according to the SA State of Waste Report (DEA, 2018) and own calculations. For hazardous waste the split in the SA State of Waste Report (6.6% recycled, 92.7% disposed) was applied.

It is worth noting that most of the extractive waste generated in the mining sector is not recorded in the waste statistics, with only metallurgical residues such as slags and ashes recorded.

Table 6: End-of-life waste of this study derived via mass-balancing and presented by material category contrasted by the coverage of the SASoW study

Quantities in kilo-tonnes	this study	SASoW
Biomass	18 432	partly
Metals	9 889	fully
Extractive Waste	171 328	no
Industrial minerals	4 113	fully
Construction minerals	12 268	partly
Fossil energy carriers	60 501	partly
Extractive Waste of coal	50 000	no
Totals	**326 531**	**107 523**

4.6 Overall flows and circularity indicators

South Africa's extraction of all food, feed, minerals, metal ores and fossil energy carriers (coal) amounted to 875 million tonnes in 2017 (see Figure 17). 66% of this extraction are metal ores and coal. Compared to this, imports are relatively small (32 Mt). Exports are large (170 Mt) and consist predominantly of refined metals and coal, while leaving the associated extractive waste in South Africa. Altogether, waste flows are relatively high. Solid and liquid outputs returned to nature are about 310 Mt of which 171 Mt are extractive waste from mining activities.

Emissions from technical processes, humans and livestock accounted to 180 Mt; in this number carbon related emissions are only accounted as carbon amount. If oxygen taken from air is included, this results roughly in 650 Mt of GHG emissions, of which 36% are of biogenic origin. In addition to the amounts reported in the national inventory reports, these numbers include due to mass balancing all carbon emissions stemming from carbon extracted from nature and released to nature within a year. Thus, breathing of humans and livestock is included. Mass balancing for the study year means that everything that goes into the South African economy has to be either a net-add to stocks or an export or output to nature. Numbers also include an estimate of informal flows like waste from un-serviced households.

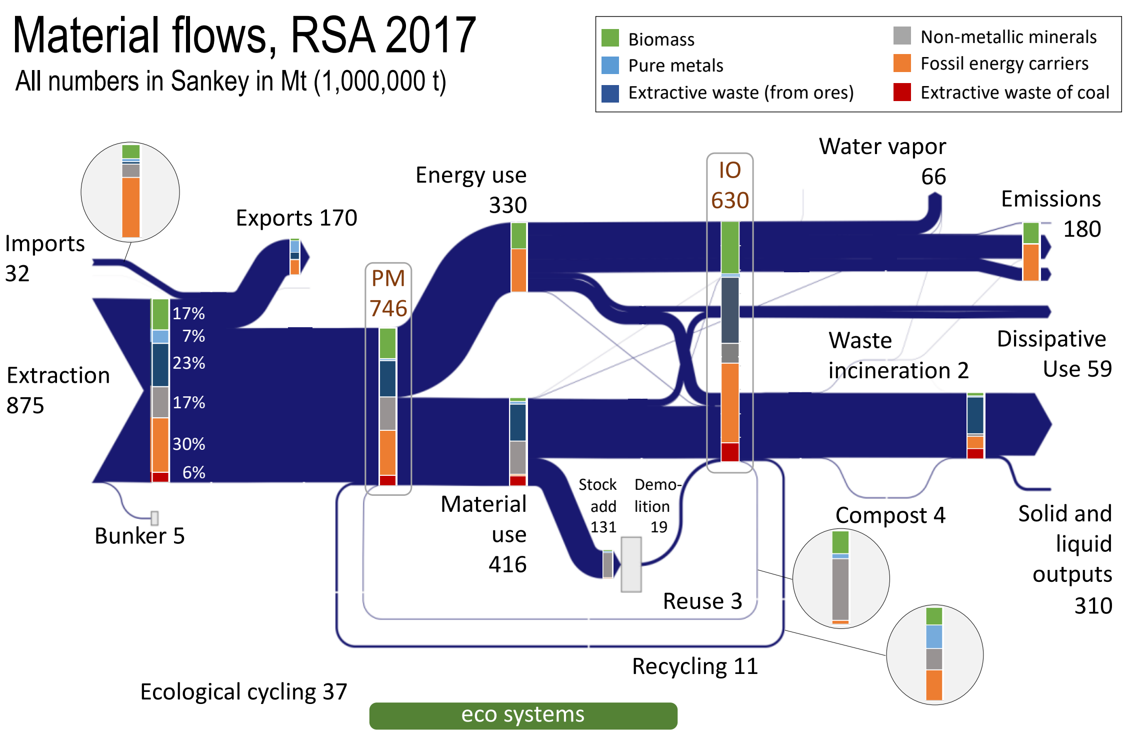

Figure 17: Summary of all material flows in South Africa in 2017

The circular economy indicators were estimated as shown in Table 7. The socio-economic cycling rate, which is the ratio between the sum of recycled and reused materials to the domestically processed materials, is just under 2%. Ecological cycling is significantly larger at 5%, but highly uncertain, with anything between one quarter and two thirds of the input biological materials that can be regarded as a sustainable harvest.

Table 7: Summary of cycling indicators

	Input side:	Output side:
Socioeconomic cycling		
Recycling	1.52%	1.98%
Reuse	0.43%	0.56%
Sum	**1.95%**	**2.55%**
Ecological cycling		
All biomass	19%	22%
Sustainably produced biomass	5.0%	5.9%

5 Discussion and Interpretation

In this section, we offer interpretations of the findings, but first discuss the coverage and quality of the assembled data, as well as uncertainties.

5.1 Coverage and quality of assembled data

To our knowledge, this is the first completed attempt of producing an economy-wide material flow account for South Africa. Data had to be assembled from a range of sources, which are not always consistent in their conventions for what to measure and how to report it. We are confident that we have covered all large and important flows at the input side of the South African economy, and that we have worked with the best available data for the output side. Our results are presented as summed total weights, from the weights in the 4 major material groups, which in turn are disaggregated into one, or two, further levels of disaggregation. We note that holders of data in particular industries may hold data at deeper levels of detail which they may struggle to directly reconcile with the levels of aggregation we have worked with. Our model also does not need, and thus did not assemble, data on the output of manufacturing activities, beyond tracking whether the input materials are used for energy or material purposes, and for the latter whether they are throughput or become stock. Table 8 names some of the data challenges we faced and how we resolved these.

Table 8: Summary of data challenges and their resolution

Challenge	Solution
Quality and coverage of official waste reporting data for South Africa	The SA State of waste report covering 2017 (and finalized in 2020) is a major advance on understanding waste flows in South Africa, and is one of the main reasons we chose 2017 as the year of study for this work. We applied mass-balancing techniques to check its results and to close data gaps for waste and emissions.
Quality of the international database on economy-wide material and energy flows as regards South Africa, especially for mining & other resource extraction activities	BOKU has been a key player in developing the economy-wide MFA approach and we combined its expertise for refining estimations based on nationally specific data with UCT's ability to source these locally, e.g. from dissertations and technical reports. The critique of our 2nd estimate by national sector experts enabled improvements and deepening as discussed in section 3.2 and 3.3.
Trade: representing the imports and exports of waste for recycling challenges the notion of circularity at a national scale	Information on such trade flows were derived from trade statistics and the SASOW; additionally some methodological enhancements were made to the accounting framework to capture these flows whilst maintaining mass balances.
Officially reported data and its quality versus informal activities.	Here we focused on likely informal reuse of waste from construction and demolition activities as discussed in section 3.2.2, and also paid attention to informal gathering of firewood. Our data is likely incomplete for informal mining and for subsistence farming (though it does contain estimates of livestock).
Overall data quality and uncertainty	Applying the economy-wide CE monitoring requires in-depth data quality assessments, cross-checks, data triangulation and mass-balancing, to ensure robust conclusions. Systematic tests were conducted to check the sensitivity of key indicators to specific data sources and assumptions (see Mayer et al. 2019 for details).

5.2 Uncertainties

Estimating the circularity of the South African economy relies on many different data sources. To get an understanding of the uncertainty of the findings, based on literature and our expertise we made an expert judgement for the lower and higher range of key flows. We double checked MFA data from international sources with national sources and corrected them with the most plausible data. For the uncertainty we looked at the variance between these different data and how other studies were assessing the uncertainty (Wiedenhofer et al., 2013; Mayer et al., 2019; Haas et al., 2020).

We finally established that the processed materials might range between 10% lower and 20% higher than our compilation of data. Additions to stocks, which might involve an error propagation of processed materials, might have an additional uncertainty due to inaccuracies in the assignment of flows to energy/material use and to throughput/stock add. For this reason a low/high range was added with +/-10% of our calculation. The estimate of EoL waste was then assessed. We assumed that it might only be slightly lower than what we calculated, however, waste amounts might be underreported. This followed the discussion in literature, where it is assumed that especially those wastes where recycling or proper treatment takes place, is reported with a far higher probability than for uncontrolled waste flows (Tisserant et al., 2017). So we assumed a range of -10% and +20%. Further, in terms of recycling we assumed that flows might only deviate by -10%, especially when collected recyclables are used for reporting instead of secondary materials used in the production cycle. Given findings of Haupt, Vadenbo and Hellweg (2016) this is possibly an optimistic approach. However, we assumed that recyclables might be 10% higher, when informal recycling activities are not captured. For reuse we assumed a higher uncertainty since there is no discussion of economy wide reuse quantities in literature and this was to our knowledge the first attempt to do so. Therefore, we were assessing that our estimate is the lower limit and reuse might well be three times higher. Due to the low quantities, this is not adding a high uncertainty to the overall assessment. Biggest uncertainty exists with the sustainability of biomass flows (Haas et al., 2020; Navare et al., 2021). Since these flows are significant compared to all flows, we put more attention to the uncertainty assessment of biomass.

The effects of this uncertainty analysis on key cycling indicators are summarized in Table 9.

Table 9: Uncertainty ranges for cycling indicators (input side)

	Uncertainty estimate	
	Low range	High range
PM (Mt)	671	895
Total cycling	6.5%	14.6%
Eco-cycling	5.0%	11.3%
Socio-economic cycling	1.5%	3.3%
Reuse	0.4%	1.4%
Recycling	1.1%	1.9%

5.3 Findings

Despite the limitations imposed by data constraints, and the resulting uncertainties discussed above, it was possible to extract five major findings from the results. These are introduced and discussed in the following paragraphs.

Finding 1: An economy materially dominated by export-oriented extractives
Global resource use is known to be unsustainable. South Africa is implicated as it exports non-renewable resources that are unsustainably used in a mostly linear manner. By mass these exports are dominated by coal, iron ore and other ores needed for steel-making. The large volumes of extractive waste associated with these exports remain in South Africa, causing environmental and social harm. Sooner or later this growing global resource use will have to be downsized significantly due to intentional global policies or by looming disasters. A plan to deal with the anticipated slowing demand for export coal is urgently needed as part of a just transition in the coal-mining areas. For iron ores and other metals, the transition is expected to occur over longer time-spans. In the short to medium term, the global energy transition may in fact bolster demand for certain metal exports.

Strategic option: South Africa can anticipate these developments and the sooner it reacts to likely global policy effects, the larger the attractive option space for business, employment and reduction of inequalities.

Finding 2: An economy energetically dominated by fossil fuels, notably domestic coal supported by imported oil
Domestic coal extraction and use for power generation is the largest linear flow in the current configuration of the economy, at 120 Mt/a, with another 60 Mt/a of coal used (mostly) for other energetic purposes. Oil accounts for 65% of all imports into South Africa.

Strategic options:
Coal: Reducing and phasing out coal-based power generation is not only the single largest measure to reduce GHG emissions, but would also result in improving circularity indicators. A back of the envelope estimate for abandoning coal use shows that this would improve socio-economic circularity from 1.5% to 2.6% (a 40% increase).
Oil: A significant improvement here in terms of climate mitigation and circularity is only feasible, if a decisive greening of mobility is envisaged in which road mileage is considerably reduced, rail-bound traffic is refurbished and all urban planning for new developments is designed to shorten daily commutes allowing for walking, cycling and public transport. This improves health (less air pollution and more exercise), saves both resources for material-intensive roads and energy for transport activities. Further it ameliorates South Africa's monetary trade balance. As a clear second priority after active mobility and public transport, e-mobility can supplement such a strategy.

Finding 3: Low rate of domestic stock building
The material used domestically for building and maintaining stocks like roads, buildings, dams, factories or artefacts needs to be critically discussed as to whether it is sufficient to deliver the required services to the population. By comparison: In per capita terms the EU's material consumption is just 10% higher than in South Africa, but building and maintenance of stocks is three times higher.

Table 10: Indicators of stock-building

	Tons per capita	% of DE	Source
South Africa (2017)	2.3	15%	This study
EU28 (2014)	8.0	60%	(Mayer *et al.*, 2019)
China (1995)	6.7	71%	(Wang *et al.*, 2020)
China (2015)	20.7	87%	Ditto

Strategic option: Sooner or later metal ore and coal mining activities will face sales problems in global markets due to international policies like on climate, sustainability and/or circularity. Phasing out these linear export-oriented activities offers the opportunity to reuse and refurbish stocks used for the extractive sector for communities in need of infrastructure, housing and durable consumer goods, thus stimulating alternative businesses in construction, repair and other service sectors. International examples for such a redistribution are promising, and with careful planning they can provide decent jobs (better than waste picking).

Finding 4: Pockets of high circularity in the domestic economy and significant informal activity around cascade use, reuse and recycling
Recycling: Many post-consumption materials are recycled. Loops are relatively well developed for some metals, mainly lead, copper, aluminium and steel with recycling rates of 70% and above. Material recycling of paper products and container glass is well developed as well.
Reuse: Container glass shows high reuse at significant scale, and it was estimated (but highly uncertain) that significant informal reuse of certain construction and demolition waste happens in the context of informal settlements.

Strategic options:
A few domestic recycling loops like the ones of some metals are already partly closed. This can be further improved and they can become learning models for other loop-closing initiatives (including industrial symbiosis). Learning can focus on the link between loop-closing and creating decent jobs. In a circular economy, recycling activities are of a lower priority; well-managed nationwide reuse corners might be a better option. Such low hanging fruits can be used to make the circular economy more appealing.
In the transport sector, combined leasing and car sharing options could contribute to improving circularity, with service providers required by law to maintain long service times and, as far as possible, closed loops for all car parts be it through reuse or recycling.

Finding 5: Sizeable bio-based flows at 17% of domestic extraction, but with significant sustainability concerns about ecological cycling
Of the 146 Mt of extracted biomass about 57 Mt are crops (for food and feed), 51 Mt grazed biomass, 18 Mt residues, 16 Mt wood and 4 Mt cutting from greens. Despite biomass to be considered as a renewable resource, biomass use can interrupt geochemical cycles and impair quality of ecosystems (e.g. loss of species and landscape diversity, habitat loss). Estimating the sustainable fraction of biomass that qualifies for ecological cycling faces both lack of data and disagreement between different fields of science (agricultural sciences and ecology), as discussed above.

Strategic option: On a global level there is sufficient evidence that the biogeochemical nutrient cycle (of nitrogen and phosphorus) has already transgressed the planetary boundaries of a safe operating space for humanity. This has been caused by industrial and agricultural processes. Hence, an assessment of a system's capability to close the biological nutrient cycle and maintain the ecosystem's regenerative capacity is essential. The Natural Capital Accounts initiative (Statistics South Africa, 2021) is extremely important and other scientific assessments should help generate better evidence for tailor-made strategies to improve circularity and sustainability. Meanwhile, attention needs to be paid to sustainable farming practices especially for grasslands, livestock and primary crop farming (see also Erb and Gingrich, 2022).

Beneficial no-regret measures include: Improved manure management, less use of mineral fertilizer reduced, replaced by compost derived from organic waste treatment, and unsafe pesticides should be phased out. On the demand side food waste should be minimised and the separation of materials of biotic and abiotic origin should be improved to enhance the biodegradability of bio-based materials.

5.4 Resource efficiency through industrial symbioses

As a final point in this interpretation of results, it is worth recording that we have observed significant symbioses between industrial sub-sectors, which result in resource efficiency gains and thus lower volumes of wastes than if these sub-sectors were fully independent of each other. In some cases we needed to introduce methodological improvements to the accounting methods used to capture these transfers of flows between sectors. Some examples are: transfer of chromite-rich residue from the PGM sector to the ferrochromium sector; use of sugarcane bagasse in paper-making; pig iron byproduct from smelting of heavy mineral sands transferred to the steel industry; and the use of steel-making slags to substitute clinker in cement products. However, enhancing such mitigating synergies demands to complement the procurement, engineering and sales knowledge of industries from a linear production to an industrial ecology expertise.

6 Conclusion

This study has shown that circular economy goes well beyond more recycling of end-of-life materials. Of the 875 Mt materials extracted in South Africa in 2017, only 327 Mt eventually became waste and of these about 221 Mt are extractive wastes that are largely unsuitable for any use. Thus, reuse and recycling can only target 106 Mt, which is 12% of what has been extracted. While improved waste management is essential, its reach to increase circularity is limited. For increased circularity it is key to reconfigure resource flows overall through the economy.

The five major findings of the study are:

1. The economy is materially dominated by export-oriented extractives.
2. The economy is energetically dominated by fossil fuels, notably domestic coal supported by imported oil.
3. There is a low rate of domestic stock building of infrastructure (buildings, roads, etc.).
4. There are pockets of high circularity in the domestic economy and significant informal activity around cascade use, reuse and recycling, but the overall socio-economic cycling rate is very low at 2%.
5. Bio-based flows are sizeable at 17% of domestic extraction, but there are significant sustainability concerns about ecological cycling.

Thus, the South African economy needs to develop a new national development model which entails phasing out its extractive orientation of non-renewable resources for export and power generation. This would both make it more sustainable and prepared for changes on the world market to be expected due to unfolding effects of already existing global environmental policies. These global developments will increasingly limit the gains of the present economic orientation, which dominates South Africa's inherited resource use. Only such a pro-active strategy enables the country to seize the opportunities a circular economy potentially offers: new businesses in the service sector, decent jobs for all skill levels directed at a stronger domestic economy and lower environmental impacts. However, this means a substantial change across several sectors, including mining, agriculture, transport, urban planning and power generation.

7 Recommendations

We offer the following recommendations:

1. Use the findings of this research to shape science and innovation policy.
2. Plan to update this study in 5-year intervals (initially) to ascertain the effect of global economic shifts and whether there are changes in the domestic economy.
3. Develop capacity to predict what the circularity indicators would be if certain policies and measures for circular economy and for a low carbon economy were to be implemented.
4. Work through the strategic options (structured by the 5 findings as discussed in section 5.3) to develop more concrete interventions, either for policy action or for further research.

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ANNEXURE 1

TITLE – Participants in expert workshops of 3-5 November 2020

We gratefully acknowledge the input of the following colleagues in our expert workshops in which we presented the 2nd estimate and workshopped unknown and uncertain flows with them.

Prof Linda Godfrey, CSIR: Project client and participant in all sessions.

Fossil & biomass fuels:

Prof Anne Stark, SA Research Chair in Sugarcane Bio-refining, UKZN
Mr Bruno Merven, Energy Systems Research Group, UCT

Food & feed flows:

Prof Anne Stark
Dr Yvonne Lewis, The Green House
Mr Mkhululi Silandela, WWF South Africa
Ms Anel Blignaut, Blue North Consultants
Ms Luanne Stevens, North West University

Waste & recyclables with additional focus on construction material stocks and flows:

Prof Cristina Trois, SA Research Chair Waste & Climate Change, UKZN
Mr Saliem Haider, GreenCape
Mr Sam Smout, GreenCape
Mr Paul Currie, ICLEI Africa

Minerals & metals:

Prof Jochen Petersen, SA Research Chair in Minerals Beneficiation, UCT
A-Prof Jenny Broadhurst, Minerals-to-Metals, UCT
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ANNEXURE 2

TITLE – IF ANNEXURES ARE NEEDED FOR SUPPORTING DOCUMENTATION

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