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How circular is an extractive economy? South Africa's export orientation results in low circularity and insufficient societal stocks for service-provisioning

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ABSTRACT

The circular economy is a major topic in import-dependant nations like Japan, China or the European Union, where supply security, strengthening domestic value chains and greening economic growth are key concerns. In contrast, extractive economies, mostly in the Global South, provide resources to the world market and thus exhibit inherently linear resource use while struggling for sustainable development. Circularity in resource importing regions could undermine extraction-based development modes, but such effects have rarely been studied yet.

Herein, we analyse economy-wide circularity for all flows of materials, energy, waste and emissions in South Africa, for the year 2017. We advance an established methodology regarding interlinked metals mining, constraints to sustainable biomass cycling, and informal disposal, waste picking and informal and formal reuse. Data were developed from national and international sources, and reviewed and co-produced with national experts in an online workshop series.

Cornerstones of South Africa's biophysical economy in 2017 are a domestic extraction of 875 Mt, low imports of 32 Mt dominated by oil, 170 Mt of exports dominated by coal and metal ores, resulting in 496 Mt of total waste and emissions. Processed material is 917 Mt or 16 t/cap (EU27: 16 t/cap). Materials use for stock-building is very low at 130 Mt (2.3 t/cap). Socioeconomic input cycling is only 2 % [1.4–2.8 %] and ecologically sustainable biomass cycling is only 4 % [3.9–6.1 %], totalling 6 % input circularity. Given the low circularity, we conclude on leverage points for a transformation towards increased circularity to yield socio-economic benefits in a highly unequal society.

1. Introduction

The circular economy (CE) is often described as a new development pathway and umbrella concept (Blomsma and Brennan, 2017; Ghisellini et al., 2016). As early as the 1980′s, Walter Stahel noted about his conceptual predecessor to the CE, that it creates "an economy based on a spiral-loop system that minimizes matter, energy-flow and environmental deterioration without restricting economic growth or social and technical progress" (Stahel, 1982). With these multiple promises, the CE has found a foothold especially in resource-importing economies such as Japan, China and the European Union, where greening economic growth under conditions of resource constraints is considered to be a priority, making resource use more sustainable and mitigating the climate crisis (Lazarevic and Valve, 2017). Consequently, these countries have widely adopted the CE concept into policy (Bleischwitz et al., 2022; McDowall et al., 2017; Ogunmakinde, 2019; Wright et al., 2019). In Japan for example, circularity monitoring was introduced in the year 2000 to move toward a 'sound material-cycle society' (Hashimoto, 2009; Japanese Ministry of the Environment, 2018; Moriguchi, 2007; Takiguchi and Takemoto, 2008). In addition, since there is a widespread expectation that the CE will contribute to rapid emissions reductions (Cantzler et al., 2020), circularity ambitions might be accelerated.

Sooner or later, increasing circularity in the Global North will inevitably have consequences for extractive economies, such as South Africa. There, extractive industries have played a pivotal role in economic development at least since the discovery of diamonds in the 1870s

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(Janse, 2007). In the 1970s and 80′s, the South African mining sector contributed ~20 % to the national gross domestic product (GDP) (Lehohla, 2015), which has steadily declined since to about 8 % in 2020 (Fedderke, 2002; Khan et al., 2021). Its economic, but even more so its material significance might be higher, with claims that mining has high indirect multipliers due to induced effects in the construction, transport and electricity sectors as well as mining-induced salaries (Roe and Round, 2017; Sorensen, 2011). The Global North's circularity ambitions therefore might challenge national economic development models focused on supplying the world market, raising the question whether the CE in countries like South Africa can be conceptualized not only as an economic threat, but also as a new development opportunity (Godfrey, 2021; Wright et al., 2019).

The context for implementing a CE in South Africa differs fundamentally from the one in industrialised higher income countries. South Africa is one of the most unequal countries, struggling with legacies of Apartheid, such as very high levels of chronic poverty, an unemployment rate of 30 % (Stats SA, 2022), a small middle class and only a few high-income earners (World Bank Group, 2018). After the democratic transition of 1994, the formal economy and national policy embraced globalization, foregoing the previous self-sufficiency paradigm necessitated by sanctions imposed by many countries. Imports of consumer goods and oil are paid for by earnings from extractive industries. At the same time, very few investments are aimed at providing local benefits and improving the wellbeing of the entire population (Godfrey, 2021). Another legacy are the Apartheid spatial patterns of the built environment in residential areas characterized by sprawl, low-density and mono-functional neighbourhoods, locking in high mobility demands with little options for public transport, high land demand and resource-intensive infrastructure networks (Nahman et al., 2021). However, South Africa also has one of the most progressive constitutions (Francis and Webster, 2019), which offers unique opportunities for reconfiguring the economy towards the needs of its population. Regarding circularity, there are already both informal and formal activities, like reuse, repurposing, repair and recycling, driven by an environmental-entrepreneurial spirit on the one hand, and by poverty and unemployment on the other. Often, materials and commodities are recovered by waste picking from bins and landfills (Wright et al., 2019; Yu et al., 2020).

Despite the long-standing extractivist mode of development in South Africa, a transition to a low-carbon economy yielding a more sustainable economic growth path is aimed for by a number policies like the National Development Plan (National Planning Commission, 2012), adoption of the Sustainable Development Goals (SDGs), and the climate change mitigation commitments put forward in its Nationally Determined Contribution (South Africa NDC, 2021), which promise GHG-emission reductions of 13–28 % in 2030 relative to 2017.

The CE could become a key lever to support these South African policies and, in the context of the post-COVID economic recovery, is nationally seen as an opportunity with growing political support (Nahman et al., 2021), having been proposed as a new sustainable resource use and waste management paradigm (Godfrey and Oelofse, 2017). It is even seen as leverage for a 'just transition', which is inclusive, yields benefits for economically marginalized members of society and creates jobs and small business opportunities (Potgieter et al., 2020). It is a grand societal challenge for the CE to minimize resource use, waste and emissions while also solving social issues and promoting economic growth. National discussions and strategies therefore need an evidence-base, as well as capacity building towards robust and harmonized monitoring, delivering policy-relevant headline indicators.

For this purpose, comprehensive empirical assessments on national level are required to understand the status-quo, develop systems knowledge and to derive robust guidance without simply shifting problems (Pauliuk, 2018). A CE monitoring framework covering economy-wide materials and energy use as well as resulting waste and emissions has been developed and extended previously (Haas et al., 2015, 2020; Jacobi et al., 2018; Mayer et al., 2019; Wang et al., 2020). This yields policy-relevant indicators on the state of the CE and provides systems-level guidance towards more sustainable circularity. The framework was previously applied globally (De Wit and Haigh, 2022; Haas et al., 2015, 2020), to high income nations (Jacobi et al., 2018; Mayer et al., 2019), China (Wang 2020) and an island (Noll et al., 2021). National level assessments in the context of the Global South have not been conducted. In this article, we provide a comprehensive biophysical baseline assessment of the South African biophysical economy and its circularity, for the year 2017.

2. Methods, materials and data

2.1. Methodology of the economy-wide CE assessment

The Circular economy South Africa (CeSA) assessment is an extension and adaptation of a previously developed economy-wide CE monitoring framework (Haas et al., 2015, 2020), already utilized by the European Union (Mayer et al. (2019). In our investigation we rely on the definition of a CE as "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops" (Geissdoerfer et al., 2017). At the same time we expect a CE to contribute to sustainable development (for defintions see: Nobre and Tavares, 2021).

The assessment has three key characteristics[1] (Haas et al., 2015; Mayer et al., 2019): Firstly, it utilizes the harmonized system boundary developed for researching the socio-economic metabolism and economy-wide material and energy flow analysis (Haberl et al., 2019). This boundary is defined along political-administrative lines as established in the system of national accounts and covers all biophysical resource flows managed and mobilized through societal activities, as well as the resulting waste and emissions (Krausmann et al., 2017, 2018). Secondly, it provides two headline indicators on the biophysical scale of the socio-economic system, these being quantity and composition of all primary and secondary *'Processed Materials (PM)'* by major uses, as well as all *'Intermediate Outputs* (*IO*)', consisting of all end-of-life materials (before recycling/reuse) and emissions. 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 (Table 1).

The system definition for the methodology utilized herein follows Mayer et al. (2019) and can be found in Fig. S1 in the supplementary information (SI1), showing all flows traced through the economy, including nodes where flows are accounted for and where they branch off to other nodes. All flows are mass balanced at the level of nodes and at the macro-level of the socioeconomic system (see SI2). A detailed list of material categories and materials can be found in Table S1 (SI1).

We refined and adjusted the method to the data availability and general situation in South Africa, tracing 84 material input and 38 outflow categories (see Table S1 in SI1), being:

- Biomass, 21 materials,
- Metals, 19 materials plus their respective associated extractive waste,
- Industrial minerals, 4 materials plus one extractive waste category
- Construction minerals, 5 materials,
- Fossil energy carriers, 8 materials,
- 7 compound materials,
- Reported waste, 34 materials,
- Emissions, 4 categories.

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[1] CeSA follows a 'production-based' perspective, which means that extraction, trade and consumption of materials and energy carriers are measured when they cross national borders or system boundaries to nature.

Table 1

Scale and rate indicators to measure circularity at the macro level. Summarized from Mayer et al. (2019) and Haas et al. (2015, 2020).

	Input	Output
	Scale indicators	
In- and output flows (t)	*Processed Materials* (PM) are the sum of all extracted and imported materials and energy carriers plus all cycled materials (recycling and reuse).	*Interim Outputs (IO)* are the sum of all outflows of solid and liquid waste, as well as emissions and water vapour, before socioeconomic cycling comes into play.
	Rate indicators	
Socio-economic cycling (%)	*Input Socioeconomic Cycling rate (ISCr)* is defined as the share of recycled and reused materials in processed materials. $\text{ISCr} = \frac{\text{recycled} + \text{reused}}{\text{PM}}$	*Output Socioeconomic Cycling rate (OSCr)* is defined as the share of recycled and reused materials in interim outputs. $\text{OSCr} = \frac{\text{recycled} + \text{reused}}{\text{IO}}$
Ecological cycling (%)	*Input Ecological Cycling rate (IECr)* is defined as the share of sustainably produced primary biomass inputs (renewables excluding socioeconomic cycling) in processed materials. $\text{IECr} = \frac{\text{renewables}}{\text{PM}}$	*Output Ecological Cycling rate (OECr)* is defined as the share of sustainably produced primary biomass outputs (renewables excluding socioeconomic cycling) in interim outputs. $\text{OECr} = \frac{\text{renewables}}{\text{IO}}$

We introduce categories for 7 compound materials: steel, container and flat glass, asphalt, concrete, plastics and other fossil fuel based products. These flows are either significant in quantity (steel, asphalt and concrete), the materials are recycled as compounds or their products are reused (plastics, steel, flat and container glass), or the materials are mainly fossil fuel based but materially used (plastics, lubricants, bitumen and tyres). We also introduce cutting from greens and alien plants as new biomass categories in the material flow accounts, as they appear in waste statistics (cuttings) or are partly used (alien plants).

2.2. *Combining international and national data sources and estimates for informal activities*

As a first step, data for economy-wide material and energy extraction, trade and consumption for South Africa were sourced from the UNEP material flow accounts database, which covers the period 1970–2017, is based on nationally reported data and summarizes information from international databases such as FAO, IEA, Comtrade and others in a harmonized manner (Lenzen et al., 2021; Schandl et al., 2018; UN IRP, 2020; UNEP, 2021). For trade we calculated materials inherent in traded commodities using more detailed information from bilateral trade data (UNSD, 2019) for iron & steel, aluminium, copper, lead, zinc and plastics and by following methods already established in prior research (see SI1 Section 2.2).

In a second step, these international data were improved with data from other mainly South African sources for extraction and trade of specific materials (see table S2). Data for energy consumption and emissions were sourced from the national energy balance statistics and the greenhouse gas emissions inventories (DFFE, 2021) established under climate reporting obligations (UNFCC & Paris Agreement), and from international databases such as EDGAR and IEA (see publications: IEA, 2020; JRC, 2020). Data for national waste and recycling flows were taken from the South African State of Waste (SASoW) report for 2017 (Department of Environmental Affairs, 2018). The combination and triangulation of all data sources was based on the established procedures from Haas et al. (2020), Haas et al. (2015), Jacobi et al. (2018) and Mayer et al. (2019).

Third, since residues from the mining sector are only partially reported in the official waste reports (SASoW), data had to be estimated. This applies specifically for concentrator residues, which arise after processing and thus are regarded as extractive waste, contrary to the unused extraction from mining (e.g. of overburden and waste rock). We combined available data from different sources on amounts of mined metal ores, on production of concentrates and pure metals and on ore and concentrate grades to establish best estimates (MCSA, 2018; USGS, 2020).

Fourth, waste from agricultural and forestry activities is only partially reported in waste statistics, though sometimes waste statistics include intermediate outputs such as sugarcane bagasse prior to onsite incineration for energy generation. These amounts were estimated based on mass balancing. Intake of feed for livestock and food for humans was converted to outputs following the calculation procedure established in Krausmann et al. (2018, see SI p3–5). Additional expert estimation were necessary to complement these data.

Data sources used to fill gaps related to informal economic activities, inconsistencies in waste inventories and for sectoral deepening in the important geo-extractive sector as well as biomass are listed in Table S2 and discussed below.

2.3. *Knowledge co-production with sector experts*

South Africa's national statistics for production and trade are reasonably robust, especially regarding the formal sector, but less reliable to even silent on informal production and on wastes from extractive industries and production processes. To compensate for these data deficiencies and to improve overall robustness, we consulted experts from academia and non-governmental organisations who have in-depth knowledge on a variety of topics in a series of four workshops, followed by personal communications afterwards (see Fig. S2 on the stepwise approach). These workshops were organised to receive critique on our draft assessment and solicit advice on alternative data sets, improved assumptions, as well as validity checking. Due to COVID-19 related restrictions, the workshops were held via video-conference, starting with an introductory workshop to explain the approach and initial findings, attended by 14 external experts. Four specialised workshops followed, with 2–5 experts each, focusing on the topics fuels, food and feed, waste and recycling respectively minerals and metals.

In all workshops we had a focus on quantitatively important flows, on issues debated in South Africa, on improvements due to readily available data and methodological refinements appropriate for South Africa (see SI1).

2.4. *A novel sub-module for geo-resources*

South Africa has the world's largest resources of platinum group metals (PGM), manganese and chromium, whilst its once globally dominating gold industry has declined sharply due to resource depletion. Mining-based exports include PGMs, iron-ore, steel, coal, gold, manganese ore and semi-processed derivatives, chromite ore, ferrochromium, vanadium, titanium slag and zircon. Significant volumes of aluminium oxide are imported for processing, based on historically cheap coal-based electricity, a practise now under threat.

Given the economic prominence of this diverse mining and metals production sector, the existing method and procedures were adapted, replacing the previous assumption that each sub-sector produces one metal, to more closely represent inter- & intra-sectoral flows. A methodological improvement to allow for transfer of by-product metals between sectors was 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 better model this flows in CeSA. At the same time, high domestic recycling rates for metals had been observed, so these analyses were beyond extraction to the entire metals chain. Four metallic elements were focused on, viz. iron, manganese, chromium and copper, illustrated in Fig. S3, with the mining sub-sectors from which they originate.

The investigation was done in two stages. Mafunda and Mbaba (2020), developed value chain flowsheets, obtaining data and structuring these into mass balance stream tables. Thereafter, the project team refined this work to fit into CeSA, including mass-balancing of flows where inconsistencies arose. This new sub-module for the CeSA method was not extended 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 PGM sector (although the byproduct chromite concentrate from this sector has been captured, as well as the copper, cobalt and nickel byproducts).

2.5. *Coal mining and its uses*

South Africa is the 7th largest coal producing country, serving both export and domestic markets. Data for coal mining, trade and use for power, heat and steel-making were readily available from the national energy balance statistics and the national GHG inventory (DFFE, 2021). Data for discards from coal processing were not available and were derived by mass balance. Interestingly, coal ash is the single largest officially recorded waste stream in the official waste report (Department of Environmental Affairs, 2018). Of the total of nearly 50 Mt, some 3 Mt is utilised for brick-making and in other construction materials. Uniquely in the world, South Africa converts a significant quantity of coal into liquid fuels and chemicals, including monomers for polymer production supplying the plastics value chain. For these activities, we used data compiled for the ecoinvent life cycle database (Russo et al., 2018)

2.6. *Biomass, ecological cycling and its ecological sustainability thresholds*

South Africa is known for its mining sector, but biomass extraction contributes sizeably to material flows and economic activity (Niedertscheider et al., 2012). More sustainable ecological circularity is an important topic in the CE discussion (Morseletto, 2020), which is dependant on the ecological sustainability of harvesting and the disposal of biomass waste, as both may interfere with ecosystems viability and interrupt geochemical cycles (carbon, nitrogen, phosphorus). We 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) (see SI1).

2.7. *Waste, recycling and treatment*

Official waste statistics are silent on informal disposal of household wastes, despite 31 % of households not receiving waste collection services (Statistics South Africa, 2016). We used the estimate of Rodseth et al. (2020) to quantify this flow, and expert judgement to apportion it between fates associated with 'self-help' disposal, which may include dumping, burying, burning, resource recovery or feeding to animals.

The majority of resource recovery from commerce and household waste occurs due to informal waste pickers, where further processing of glass, paper and cardboard, metals and plastics then occurs in facilities that report recycling quantities. No further estimation efforts were thus necessary to capture the socio-economically cycled quantities of these materials, in contrast to informal reuse of wastes from construction and demolition (C&D). As a novelty for economy-wide circularity assessments, we included formal and informal reuse flows next to recycling.

2.8. *Construction and demolition waste quantities and fates including informal reuse*

The category of construction & demolition (C&D) waste is strongly under-estimated in the official waste reporting (Department of Environmental Affairs, 2018); which is actually a globally under-reported issue (see Tisserant et al., 2017). To still provide a first estimate of C&D waste quantities, we refined the estimates made by Berge and von Blottnitz (2022), by reconciling the life-time stock-flow method and the scaling-up method from a fairly reliable municipal data source from Cape Town (see SI1).

We then validated those first estimates with national experts in the above mentioned workshops, further refining them based on expert interviews (Berge and von Blottnitz, 2022).

2.9. *Uncertainty and sensitivity*

We tackled data uncertainty and model sensitivity in several steps. Through discussing critical data questions in expert workshops, comparing data sources as well as mass-balancing, we developed a good understanding of major uncertainties and critical data points. Building on previous work (Mayer et al., 2019), we then applied a one-at-a-time sensitivity analysis for the most important data-based nodes, by increasing each parameter/data point by +20 % and displaying its effect on the headline indicators (Fig. S4), generally assuming an underestimation for these data points. The most important aspects are total extraction, exports, net additions to stock, End-of-Life (EoL) waste, reuse and recycling, as well as the sustainable fraction of biomass (Table S3). Based on this, we developed specific lower and higher uncertainty ranges for those data points which are most influential (see Fig. 2 and SI1).

3. Results

3.1. *Scale and circularity of material flows through an extractive economy*

Metal ores[2] and coal dominate extraction, making up 31 % respectively 35 % of the 875 Mt of resources domestically extracted in 2017 (run through Fig. 1 from left to right). Amongst exports of 170 Mt, 51 % are metals or ore concentrates and 41 % is coal. Imports of 32 Mt consist to 65 % of fossil fuels (mainly oil) to fuel the economy. The domestic material consumption (DMC), a key indicator of material flow accounting used in the SDGs, is 731 Mt. The processed materials (PM), which in addition includes exports and cycled materials and products, are 917 Mt or 16 t/cap (EU27: 18 t/cap). PM is then divided into exports (19 %), energy use (36 %) and the material use fraction (45 %). Material use of 417 Mt is split into a large throughput flow, which consists of 78 % extractive wastes from coal and metal mining, and 130 Mt (31 %) of additions to stocks, which is low in comparison to other countries. In the centre of Fig. 1 we display the flow of food waste (thin line running down), carbon emissions that stem from extracted materials used in steel and cement production (left thin line running up) and water vapour from brick production.

Altogether, interim outputs (IO) amount to 633 Mt before cycling and waste treatment. Of these, 4 Mt are reused, 12 Mt are recycled and 4 Mt are composted. Waste incineration leads to a split into emissions and solid waste. The final outputs are water vapour (66 Mt), dissipative use (29 Mt) which is manure (83 %) and mineral fertilizers (17 %) in agriculture, solid and liquid outputs (340 Mt) and emissions excluding

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[2] Metals ores are the sum of pure metals and extractive waste.

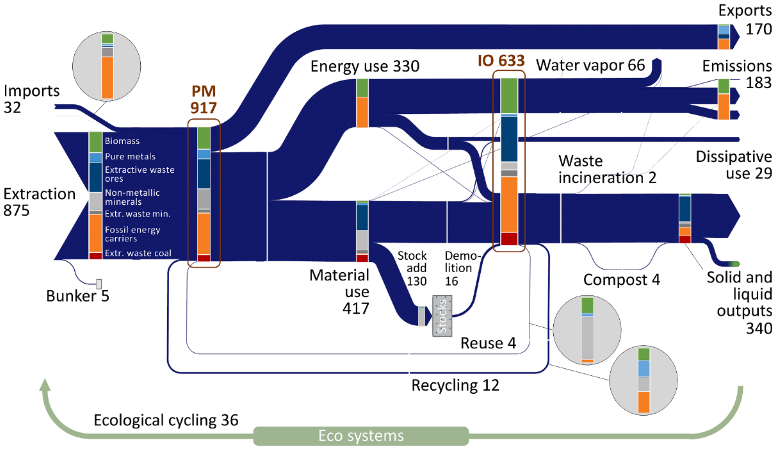

Fig. 1. Economy-wide circularity of the South African socio-economic system in 2017. This Sankey diagram of material flows is expressed in Megatons (Mt). Arrow width is proportional to flow size.

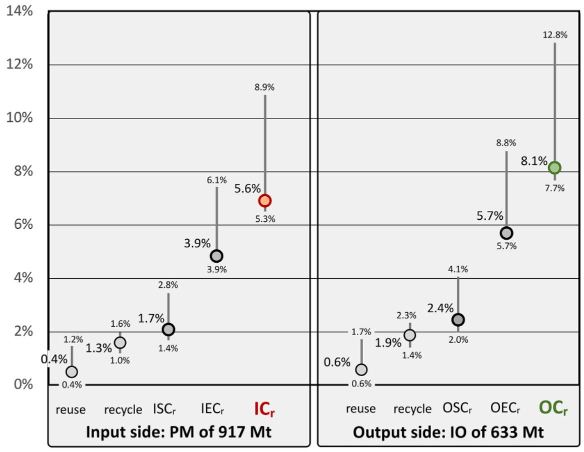

Fig. 2. Derived circularity rate indicators, including their uncertainty ranges for the South African economy in 2017. SCr = socio-economic cycling rate; ECr = ecological cycling rate; Cr = cycling rate (total); definition of indicators see Table 1.

oxygen taken from air (183 Mt). The emissions are dominated by carbon emissions (95 %). Due to the mass balancing approach they include human and livestock respiration as well as carbon emissions accounted in the official South African emissions inventory.[3]

The fraction of sustainably produced biomass was assessed to be 24 % or 36 Mt of all primary biomass extraction of 146 Mt. Consequently, the *ecological input cycling rate* (IECr) is 4.0 %, while 4 Mt reuse and 12 Mt recycling amount to a *socioeconomic cycling rate* (ISCr) of 1.7 % leading to an overall *input circularity rate* (ICr) of 5.7 %. Similar results can be seen for the output side in Fig. 2. Here, all uncertainties are displayed, whereby the one for ecological cycling is particularly large, as it is difficult to assess the degree of sustainable biomass production.

3.2. The circularity of material flows by major category

The circularity of South African resource use in the established main categories of metal ores, fossil fuels, biomass and non-metallic minerals is shown in Fig. 3 (see SI1 for details).

Biomass (Fig. 3a)*:* For many of the South African experts involved in the workshops, the relatively high amount of extracted biomass of 146 Mt was a surprise. It is roughly composed by 34 % of primary crops, 12 % of used crop residues, 6 % of fodder crops, 35 % of grazed biomass and 11 % of wood. Imports of 5 Mt, 60 % of which are cereals, play a lesser role. Exports amount to 10 Mt and consist of products like citrus fruits, wine and cereals. 124 Mt of biomass was used for food, feed and for technical energy. We could detect 0.5 Mt of reuse, which is timber, and 2.1 Mt of recycling which is mainly related to paper and cardboard. The 151 Mt of processed materials fate can be described as 7 % exports, 3 % net additions to stocks, 2 % are cycled within the economy and 3 % are composted. Thus, three quarters are ending up in nature as water vapour, emissions and solid and liquid outputs, 16 % as dissipative use.

Metal ores (Fig. 3b): The majority of metals, 87 Mt, is destined for export, while only a small fraction of 7 Mt was used to expand and maintain societal material stocks in South Africa. Most notably is the flow of extractive wastes from metal mining amounting to 204 Mt; about two thirds of which stem from gold, platinum, chromium, manganese and titanium extraction, and another 27 % are due to iron mining (see Table S7 for underlying factors).

Fossil energy carriers (Fig. 3c): 309 Mt of fossil fuels dominated by coal were extracted, of which 70 Mt were exported. 190 Mt were mainly used for domestic thermal power plants and 39 Mt was supplied to the synthetic fuels complex. Coal extraction was accompanied by about 50 Mt of extractive waste. At the same time 21 Mt of oil was imported mainly to fuel transport and industries.

Non-metallic minerals (Fig. 3d): Non-metallic minerals[4] (the sum of industrial and construction minerals) are mainly extracted domestically, 151 Mt, while imports and exports are of minor relevance with 4.6 respectively 3.5 Mt. Together with recycled and reused material, they add up to 162 Mt of processed material. Roughly ¼ of these are industrial minerals, primarily mineral fertilizer. The other ¾ are construction minerals, mainly gravel and sand (93 Mt), followed by chalk, dolomite and limestone (17 Mt) and clays and kaolin (10 Mt). These are directly used as sand and gravel in construction (44 Mt) or as bricks (7 Mt), but also further processed as compound materials like concrete (54 Mt) and asphalt (4 Mt). Cement production causes about 1 Mt of carbon

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[3] If expressed in C, these emissions relevant for the inventory amount to 110 Mt, if oxygen from air is included, it amounts to 404 Mt CO_2 emissions, which is about 12 % lower than the reconciliation of reported and modelled energy and industrial GHG emissions in the technical analysis to support the update of South Africa's 1st NDC mitigation target (Marquard et al., 2021). Considering the typical difference between CO_2 and GHG emissions it is a plausible value.

[4] The material category non-metallic minerals is the sum of industrial and construction minerals.

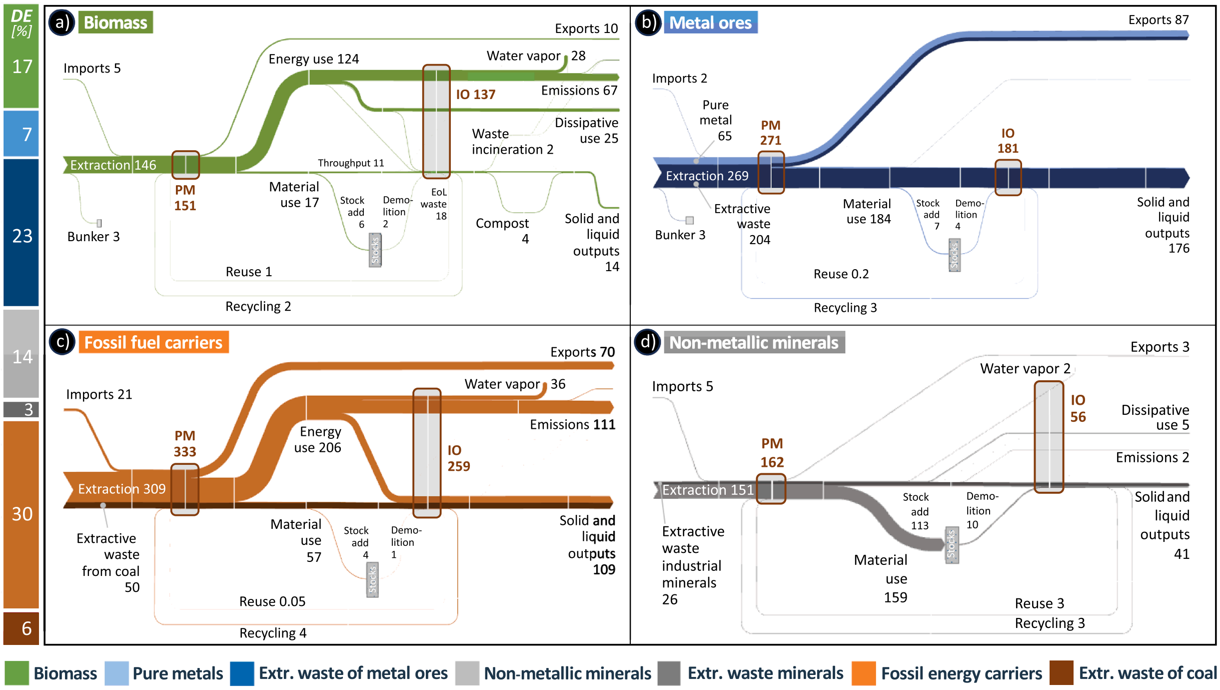

Fig. 3. Sankey diagram for biomass, metal ores, fossil fuel carriers and non-metallic minerals flows (in Mt); the vertical bar on the left shows the proportion of domestic extraction for all material categories including extractive wastes.

emissions stemming directly from the raw materials. Brick production emits about 2 Mt of water vapour from the extracted clay. 113 Mt is added to stocks (69 % of PM). While demolition amounts to about 10 Mt, the end-of-life waste adds up to 21 Mt. Reuse and recycling are relatively low with 3 Mt each. The dissipative use of 5 Mt is mineral fertilizer applied to the fields. The further processing of mined phosphate rock is associated with 26 Mt of extractive waste. In sum, industrial minerals by and large became dissipative use plus extractive waste and the bulk of construction minerals became stockpiled in the built environment.

3.3. The steel complex of iron-chromium-manganese

South Africa is a leading supplier of steel-alloying elements chromium and manganese. To shed more light on this complex of metal flows, we developed a novel sub-module for the CeSA method, detailing the intertwined flows of iron, chromium and manganese, resulting in steel as a compound material (Fig. S5). The iron extracted from the various mining sectors (iron, chromium, manganese and PGM) amounted to about 51 Mt, of which a big quantity was exported (41 Mt) and a small amount was bunkered. 5 Mt was used for domestic steel production and about 5 Mt were further processed for other iron uses including manufacturing losses. 7 Mt of chromium ore (5 Mt pure chromium) and 16 Mt of manganese ore (7 Mt pure) were mined, most of which were exported and only a small part went into steel production. 1.8 Mt of domestically produced steel was exported. 7 Mt of steel and small quantities of chromium, manganese and iron were added to stocks. Of the 4 Mt of demolished and 0.1 Mt short-lived steel, 2.4 Mt was recovered as scrap, of which 0.5 Mt were exported. Another 0.2 Mt were reused. Finally, 1.1 Mt of steel and 4.9 Mt of iron as well as 0.5 Mt of chromium and manganese were landfilled. The export domination is visible as 40 % of mined material is exported, 52 % remains in the country as extractive waste and only 8 % is used to supply local markets.

3.4. Recycling and reuse including informal activities

Given the high level of informal recycling and reuse flows in South Africa, we used available data for formal cycling flows and estimated the informal flows (see SI). We detected 4 Mt of end-of-life steel of which 2 Mt were recycled and 0.1 Mt were reused. Concrete had a very low recycling and reuse rate. Of 9 Mt of wood-based products about 2 Mt were recycled (mainly paper) and 0.5 Mt reused. Of 0.8 Mt of clay bricks we estimate that 0.1 Mt were reused (14 %), a strong case for informal cycling flows. While lead played quantitatively a minor role, it is a case of very high recycling rates. Of the 0.05 Mt of end-of-life lead more than 90 % were recycled. With the aluminium end-of-life waste of 0.2 Mt the situation was similar. Finally, a formal reuse case is container glass. Of the 2.8 Mt of used container glass about 1.4 Mt were reused and about 0.5 Mt recycled.

Altogether we found the reuse and recycling for the end-of-life waste of metals steel, copper, lead and aluminium were relatively satisfactory; in total it was a combined reuse and recycling rate of the respective end-of-life waste of 71 %. The situation was similarly good for container glass (67 %), wood (42 %) and clay bricks (90 %). Plastic exhibits relatively low recycling rates (about 24 %), and concrete recycling is very low as well.

4. Discussion

The Domestic material consumption (DMC) is a headline indicator for resource use, included in monitoring of the SDGs (Eisenmenger et al., 2020). We find that South Africa's DMC amounts to 731 Mt or 12.9 t/cap, which is 2.2 % higher and thus in line with reported data in the UNEP-IRP Material Flow Database as used for the SDG indicators (all data for 2017) (UN-IRP, 2022). Interestingly, the per capita DMC of South Africa is rather close to the 13.9 t/cap of the European Union (Eurostat, 2022); however this comparison shows a closer look is needed to grasp the different nature of the South African biophysical economy and to understand the specific option space for change.

South Africa can clearly be called an extractive economy in contrast to the EU27, according to the two conditions put forward by Schaffartzik and Pichler (2017): extractive economies must be net exporters and domestic extraction must be more than 50 % of domestic material inputs, i.e. the sum of extraction and imports. South Africa's exports of 170 Mt far exceed the imports of 32 Mt and the economy extracts 96 % of its inputs. This extractivism shapes the biophysical economy to a large extent, as, for example, 30 % of all processed material is extractive waste that has no or only very limited potential uses. This in turn has far-reaching implications for implementing CE strategies, which essentially strive to firstly narrow and secondly slow down material flows, before then ultimately closing cycles for the remaining outflows.

Against this backdrop, we discuss the low societal stock additions for service provision in South Africa, explore the factors that limit further loop closing, and finally open up the option space for far-reaching circularity strategies and their potential benefits and trade-offs for South African society.

4.1. Low material stock building and low service provisioning

Societal material stocks of buildings, infrastructures, machinery, vehicles, household appliances or electronic devices are crucial factors for the provisioning of services to society (Carmona et al., 2017; Kalt et al., 2019; Lin et al., 2017). Resources such as crude oil or metal ores are in themselves barely useful, but need to be processed into societal material stocks, which then provide services such as comfortable living space, efficient transport and mobility, decent diets or good communication or entertainment options. This provisioning of services is an important factor for human well-being (Graedel and Cao, 2010; Haberl et al., 2017) and the literature suggests that at an intermediate amount of economy-wide stocks and flows, contributions to wellbeing saturate (Fisch-Romito, 2021; Haberl et al., 2019; Virág et al., 2022). Thus, the extent of material an economy spends on building and maintaining stocks allows discussing a society's ability to provide services for the economy and inhabitants.

We compare net additions to stocks (NAS) to other studies following the same methodology. One study is on the EU28, where 5.0 t/cap were calculated for the year 2014 (Mayer et al., 2019). Another one investigated China and established an estimate of 6.2 t/cap for 1995 and 18.0 t/cap for 2015 (Wang et al., 2020). Compared to the NAS of 2.0 t/cap in South Africa, it reveals a big difference. Another comparison based on a different methodology shows a similar picture (see SI1).

The detected per capita stock building flows are very low, especially since a share of these serve the extraction and processing of materials for exports (metals and coal exports are 3.0 t/cap). Thus, the low stock add can hardly provide and maintain the stock levels required for service provisioning and consequently well-being for all. Indeed, this very low level of stocks only seem to be feasible given that in South Africa's highly unequal society, 75 % of the population has a consumption share in terms of expenditure of only 25 % (World Bank Group, 2018). Only this allows for the remaining 25 % of the population access to service-providing stocks similar to those in high income countries.

4.2. Restraining factors for closing loops

Here, we only focus on closing loops; the discussion on narrowing and slowing down flows follows in Section 4.3. Out of 917 Mt of processed materials, 4 Mt are reused and 12 Mt are recycled, which results in an *input socioeconomic cycling rate* (ISC_r) of 2 %. From studies using the same methodology, we know that the global ISC_r was 10 % in 2015 (Haas et al., 2020), in China it was 5.8 % for 2015 (Wang et al., 2020) and in the EU27 9.6 % for 2014 (Mayer et al., 2019). Japan, based on a slightly different methodology, reports a cyclical use rate at inlet of 15.5 % for 2015, an analogous indicator to ISC_r (Japanese Ministry of the Environment, 2018).

For a better understanding we disaggregate the PM of 917 Mt into its major fates: 170 Mt are exports, 183 Mt are emissions, of which 111 Mt are from fossil fuels and 66 Mt water vapour (36 Mt of which stem from fossil fuels). These flows can neither be reused nor recycled; excluding carbon capture and storage, which is a) not done at scale and b) not understood as recycling (Bringezu, 2014; Mac Dowell et al., 2017), although carbon capture for utilization may play a role in the future. Furthermore, there are 31 Mt of dissipative uses, such as fertilizer, which are flows deliberately deposited in nature and therefore not available for socioeconomic cycling (see discussion on ecological cycling below). Another group of flows are extractive wastes which are 50 Mt from coal, 172 Mt from metal ore mining and 26 Mt from industrial minerals. These wastes remain in well to poorly managed tailings storage facilities, which under present technological conditions have no further use. In the future though options exist, where for example Stander et al. (2022) evaluated making soil amendment material from a fraction of coal discards. However, for the South African mining sector across the diverse range of ores which often contains many different metals, in our observation, inter-sectoral collaborations have already contributed to a relatively efficient use of extracted resources. Examples include the transfer of 0,5 Mt of pig iron from the titanium sands smelter to the steel industry, 4 Mt of chromite concentrate from PGM processing to ferrochrome smelters (documented in: Dlamini and von Blottnitz, 2023) or the production of dense media from magnetite byproducts of phosphate rock mining, for coal processing. However, these all make up for less than 5 % of the mining sector processed waste. The only sector that could take up such processed waste (or associated unused extraction) at scale is construction. Such transfers do occur, e.g. for road-building, but are limited by suitability of materials and geographic distance between mining sources and construction demand centres. Finally, there are 113 Mt of net additions to stocks, which cannot be cycled since they are in use.

This results in the remaining 107 Mt of PM, which, if reused and recycled could boost the ISC_r to 12 %, compared to the actual 1.7 % (16 Mt). This figure is a theoretical one, since unavoidable processing losses, additional infrastructure and additional energy use would need to be considered. For metals, only 3 Mt of 9 Mt of metal EoL waste are cycled, though the non-recycled portion is associated with mining and metallurgical operations rather than post-consumer waste. Regarding non-metallic minerals, EoL waste is 21 Mt, where 2.8 Mt are reused (mainly container glass and bricks) and 3.3 are recycled (mainly concrete and asphalt); thus improvements are possible.

A lack of ecological cycling is a major concern for South Africa, whose land use system is characterized by increasing intensification based on technological improvements and biomass trade (Niedertscheider et al., 2012). The potentially renewable biomass in PM amounts to 141 Mt, or 15 % of total PM. Based on the expert judgement developed in this research, only 36 Mt, or 4 % of total PM, are sustainably cycled via ecosystems. Major issues are unsustainable grazing practices which result in degrading grasslands, as well as high chemical fertilizer use which interferes massively with closed N and P cycles by producing unsustainable crops and crop residues. While crop production, including residues and grazed biomass, could contribute roughly 120 Mt to ecological cycling, we only count 20 Mt as ecologically sustainable.

While the main limitations for loop closing of socioeconomic and ecological cycles might have a common paradigmatic root cause, namely an extractivist mode of development, they have different characteristics and therefore require different strategies for improvement. Socioeconomic cycling would mainly benefit from international engagement in circularity that requires far less extraction with linear flow characteristics and a domestic effort to phase out fossil fuels. Improved ecological cycling would need an extensive implementation of sustainable farming and land use practices across South African agriculture and forestry.

4.3. Option space for a transformation towards a low-carbon CE

We close this discussion section identifying potentials for circularity strategies to jointly address environmental and social challenges in a highly unequal society.

The first and obvious entry point is closing loops. Domestic recycling already works well in South Africa for some metals (e.g. lead, copper, iron, aluminium) and partially for plastics. These efforts could be further improved to become learning models for other loop-closing initiatives, creating small business opportunities (e.g. through implementation of the extended producer responsibility regulations (Department of Environment, Forestry and Fisheries 2021) at community level or in industry via industrial symbiosis. Learning can focus on the link between circularity strategies and creating decent jobs and promoting entrepreneurship. South Africa has an abnormally high poverty and the highest unemployment rate globally as well as a relatively small informal sector (Shah, 2022). Addressing these calls for income opportunities in both the formal and the informal sector which in turn can improve product design; take-back and reprocessing could be strengthened, which could foster more circular products and supply chains at the expense of linear production-consumption modes, as findings into supplier-buyer innovation has shown (Franco, 2017).

Slowing down materials within the economy, which essentially means extending lifetimes of products and materials, is a more important but also more challenging priority amongst CE strategies. Good examples in South Africa are the reuse of bricks by the informal sector and the reuse of container glass in the formal sector (working via a deposit scheme). Furthermore, well-managed nationwide reuse corners and repair services might fruitfully extend life times of products and provide much needed employment and entrepreneurial opportunities (ZEOS, 2022). Such societal 'co-benefits' of slower material cycles could also be used to make the CE more appealing and accessible to a wider public.

This leads us to the CE's top priority of narrowing flows, which is a particular challenge in a country with rampant poverty and stock levels that can hardly provide sufficient services for all. First of all, an extractive economy is highly dependant on exports. And, sooner or later, metal ore and coal mining activities might face sales problems in global markets due to international policies on climate, sustainability and/or circularity, or because of resource depletion, as has already happened in the once dominant gold industry. These developments will increasingly limit the gains of the present economic orientation, which is an inherently linear resource use pattern. Thus, instead of waiting for the situation to worsen, planned phasing down of linear export-orientated activities can be an option to narrow flows since this could substantially reduce the 30 % of South African PM which is extractive waste. At the same time, it offers the opportunity to slow down flows by reusing and refurbishing legacy stocks of the extractive sector to improve services to communities in need of infrastructure, housing and durable consumer goods, thus stimulating alternative businesses. International examples for a redistribution and refurbishment of building components are promising, although context-specific (Arora et al., 2019). The South African design sector is well-positioned and could contribute towards providing decent jobs and to replace unhealthy waste picking (Yu et al., 2020). Further, developing agriculture and forestry into sustainable sectors that close ecological cycles and improve product quality might also imply a higher labour demand, while curbing land degradation and resource depletion (e.g. phosphorus deposits).

Overall, a pro-active strategy is a grand challenge, but could enable the country to seize the opportunities a CE potentially offers: new businesses in the manufacturing and service sector and a sustainable more labour-intensive agriculture and forestry which all provide decent jobs for all skill levels directed at a stronger domestic economy with lower environmental impacts.

5. Conclusion

Herein we have presented the first economy-wide circularity assessment of the South African biophysical economy, contributing to the evidence base for a just and necessary transition to a low-carbon and more circular economy. The presence of informal economic activities and the dominance of mineral extraction required several methodological extensions to the existing method. Through a series of expert workshops, results, procedures, and capacities were co-produced, contributing to broadening the national discussion on sustainable development across sectors and fields.

Overall, the findings are sobering, because of the extremely low levels of circularity due to the prevalent extractive export-orientated mode of economic activity. Annual net additions to the material stocks of buildings, infrastructure and machinery to the domestic economy for service-provisioning are much smaller than required to meet the needs of the population. We claim this as a structural implication of extractivism. Future studies would do well to examine the material and economic implications of both CE strategies and the energy transition in the importing economies of the Global North onto the Global South, especially in the context of historical and global as well as domestic justice.

Changes will need to be deep and will require time. It is safe to say, as Kirchherr et al. (2017, p.228) put it for the EU, that the CE is not "a 'quick win', but a major long-term undertaking". In the South African context, it is tempting to say, it is another long walk, this time not for freedom from oppression (Mandela, 2008), but for economic freedom for those still left behind by the inherited extractive and linear economy.

CRediT authorship contribution statement

Willi Haas: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft. **Doris Virág:** Methodology, Data curation, Formal analysis, Visualization, Writing – review & editing. **Dominik Wiedenhofer:** Conceptualization, Writing – review & editing, Project administration, Funding acquisition. **Harro von Blottnitz:** Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft.

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Data availability

Data will be made available on request.

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Supplementary materials

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