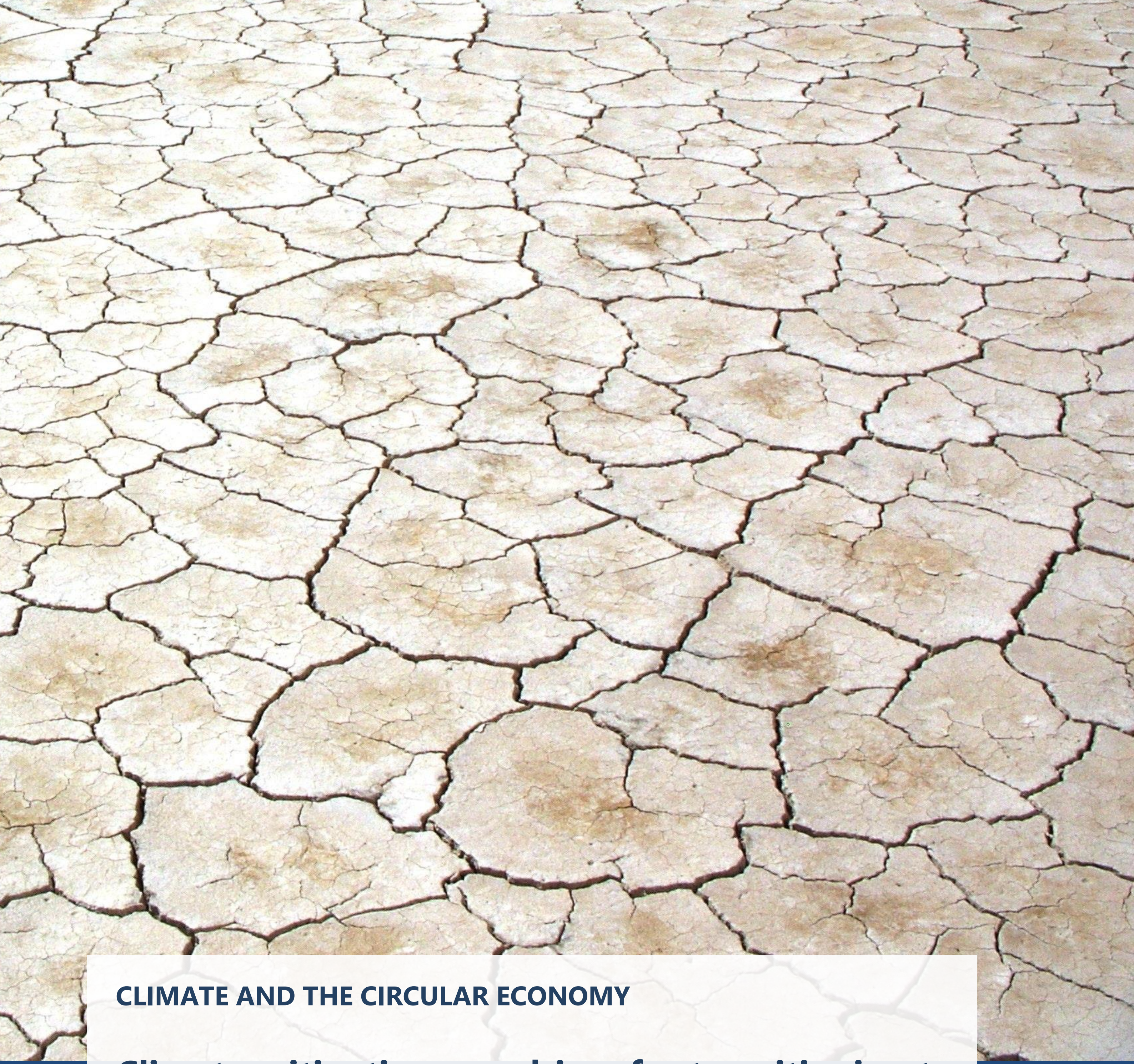

CLIMATE AND THE CIRCULAR ECONOMY

Climate mitigation as a driver for transitioning to a circular economy in South Africa

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EXECUTIVE SUMMARY

Over the last decade, a number of drivers for a circular economy transition have emerged, including the opportunity to reduce greenhouse gas (GHG) emissions. Internationally, studies have shown that adopting a circular approach to climate mitigation puts the world on track to meet climate targets. Countries have also begun to incorporate circularity into their Nationally Determined Contributions (NDCs) by broadening their climate pledges to include strategies to reduce emissions directly linked to the way resources are extracted, processed and consumed.

South Africa is reliant on the combustion of fossil fuels to meet its energy needs and recognises the need to shift to a low carbon economy. The country has made commitments towards reducing its GHG emissions through updates to its NDC which seeks to attain a low GHG emissions pathway that is aligned to its national circumstances and development challenges. There is little understanding at present on the potential to enhance the country's mitigation efforts through a circular economy approach. This report seeks to address this gap by providing the first attempt at quantifying the potential reduction in GHG emissions within various resource-intensive sectors of the South African economy through the adoption of circular economy principles. The sectors included in this study are energy, manufacturing, mining, mobility, agriculture, human settlements, and water. A desktop literature review of local and international circular economy interventions and their potential to address major sources of GHG emissions within the various sectors of the South African economy was undertaken. Interventions were aligned with the three principles of the circular economy to design out waste and pollution; to keep products and materials in use; and to regenerate natural systems.

To gauge GHG emissions reductions that are possible through circular economy interventions by 2050, existing emission reduction methods and potential technological advancements in the Business-as-usual (BAU) scenario were compared to the Circular Economy scenario. This approach enabled the quantification of emissions reductions achievable through current strategies and the potential reductions attainable with proposed technologies.

From the modelling, it was found that the total sector wide GHG emissions in the BAU scenario are 500.11 $MtCO_2e$ in 2050. Total GHG emissions in the circular economy scenario are 328.66 $MtCO_2e$. Ambitious circular economy interventions can reduce GHG emissions in 2050 by 34% from 500.11 $MtCO_2e$ to 382.66 $MtCO_2e$. Circular economy mitigation is mainly achieved through measures related to a combination of two principles, namely in designing out waste and pollution, and the regeneration of natural systems. The combination of these two principles result in total GHG emission reductions of - 161.54 $MtCO_2e$. GHG emission reductions for keeping products and materials in use amount to -9.91 $MtCO_2e$. The mitigation effects of circular economy measures are significant as shown in this study and highlights that climate mitigation is a driver for South Africa to transition to a more circular economy.

The energy sector has the largest emission reduction potential of -75.85 $MtCO_2e$. Sizable contributions to mitigation are achieved through ambitious changes to the use of energy resources in the manufacturing, mining and construction sectors (-44.51 $MtCO_2e$); mobility sector (- 34.58 $MtCO_2e$) and in the agriculture sector (-13.47 $MtCO_2e$). Included in the total emission reductions are 8.60 $MtCO_2e$ already aimed at reducing GHG emissions from the BAU 2019 to the BAU 2050.

This study represents the first attempt to quantify the climate change mitigation potential of the circular economy in South Africa. The evidence generated through this study aligns with findings from international research that there is merit in seeking to align climate change and circular economy policies and practices.

There are currently gaps in the knowledge of circular economy mitigation effects particularly those aligned with the principles of keeping products and materials in use, and regenerating natural systems. More specifically the mitigation effects of intensified embedded generation, green hydrogen, solid waste management in non-specified industries, and land restoration and rehabilitation, which are lesser known. A key limitation of this study is thus that not all emission sources could be accounted for in the modelling of GHG emissions as these emission sources have not been conceived as part of the circular economy before, or visa versa. The emissions reduction potential estimated in this study for the CE 2050 scenario, while being ambitious in terms of the levels of interventions, are not complete. As such, the mitigation potential of a circular economy transition, as outlined in this report, is considered to be a conservative estimation, given that detailed modelling for many circular economy interventions have not yet been conducted in South Africa.

Further research is needed to update and expand the definition of each circular economy sector to align these with the larger emission sources and sinks in the country and thus account for these GHG emissions. This would for example include carbon sequestration in the forestry sector, livestock emissions within the agriculture sector, hydrofluorocarbon usage for industrial processes, and fuel use in non-specified industries. These additional studies would provide a holistic perspective of the mitigation effects of circular economy measures towards the country reaching net zero carbon emissions by 2050.

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ACRONYMS

ACEA	African Circular Economy Alliance
AFOLU	Agriculture, Forestry and Other Land Use
BAU	Business-as-usual
CCUS	Carbon capture use and storage
CE	Circular economy
CH_4	Methane
CO_2	Carbon dioxide
CSIR	Council for Scientific and Industrial Research
CTL	Coal-to-liquid
DFFE	Department of Forestry, Fisheries and Environment
DSI	Department of Science and Innovation
GACERE	Global Alliance on Circular Economy and Resource Efficiency
GHG	Greenhouse gas
GRO	Global Resources Outlook
GTL	Gas-to-liquid
GWP	Global warming potential
IAP	Invasive alien plants
IEP	Integrated Energy Plan
IPAP	Industrial Policy Action Plan
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and Product Use
IRP	International Resources Panel
IRP	Integrated Resource Plan
N_2O	Nitrous oxide
NATMAP	National Transport Master Plan
NCPC	National Cleaner Production Centre
NDC	Nationally Determined Contribution
NDP	National Development Plan
NWMS	National Waste Management Strategy
WCEF	World Circular Economy Forum

1 Introduction

1.1 Climate as a driver for the circular economy

Over the last decade, a number of drivers for a circular economy transition have emerged. Early discussions focused on resource scarcity, resulting in a number of countries putting strategies in place to manage the risks associated with access to critical raw materials. The question of whether resource scarcity is a driver for South Africa to transition to a more circular economy, was answered by Khan *et al*. (2022), in which it was noted that South Africa has 18 critical / strategic minerals, five of which have less than 50 years of economically viable mining remaining, "*assuming no new major reserves are found, and demand, supply and hence economic value remains unchanged*". Furthermore, these critical minerals are mostly exported, with the result that South Africa has little access to, or control over, their circularity at end of product life.

The second global driver behind a circular economy transition has been the climate mitigation potential of adopting circular practices. The Global Resources Outlook (IRP, 2019) found that >50% of total global greenhouse gas (GHG) emissions, and >90% of biodiversity loss and water stress were the result of resource extraction and processing (Figure 1).

The Circularity Gap Report 2021 found that material handling and use accounted for the vast majority (70%) of GHGs emitted (Circle Economy, 2021). The recent Circularity Gap Report (Circle Economy, 2023) showed that driving circularity in just four global systems – food; manufacturing; built environment; and mobility & transport – could reduce global virgin material extraction by 34%; reverse the overshoot of planetary boundaries; and limit global temperature rise to within 2-degrees.

Decoupling economic development from resource consumption, therefore has the potential to address major environmental challenges facing our planet, including climate change. The climate mitigation potential has, as a result, become a major driver for a global circular economy transition. As noted by Nahman *et al*. (2021), "*The circular economy is recognized globally as an opportunity to reframe economic development and unlock new opportunities for growth and employment; while achieving global commitments relating to climate change and sustainable development, and reducing the negative impacts associated with both resource extraction and waste.*"

Without considering how we extract, use and dispose of resources, the global response to the climate crisis remains incomplete, and putting a circular economy in place puts the planet on the right track to achieving climate targets (Ellen MacArthur Foundation, 2021). The circular economy therefore provides a useful framework for looking at a country's economic system more holistically, to increase Nationally Determined Contribution (NDC) ambitions, and meet our current and future development needs (Soezer, 2019). Mapping out flows of materials and energy also allows us to develop an understanding of the transboundary nature of GHG footprints due to ever expanding international trade. The reduction of GHG emissions in one region often requires addressing root causes / sources in another region (Soezer, 2019).

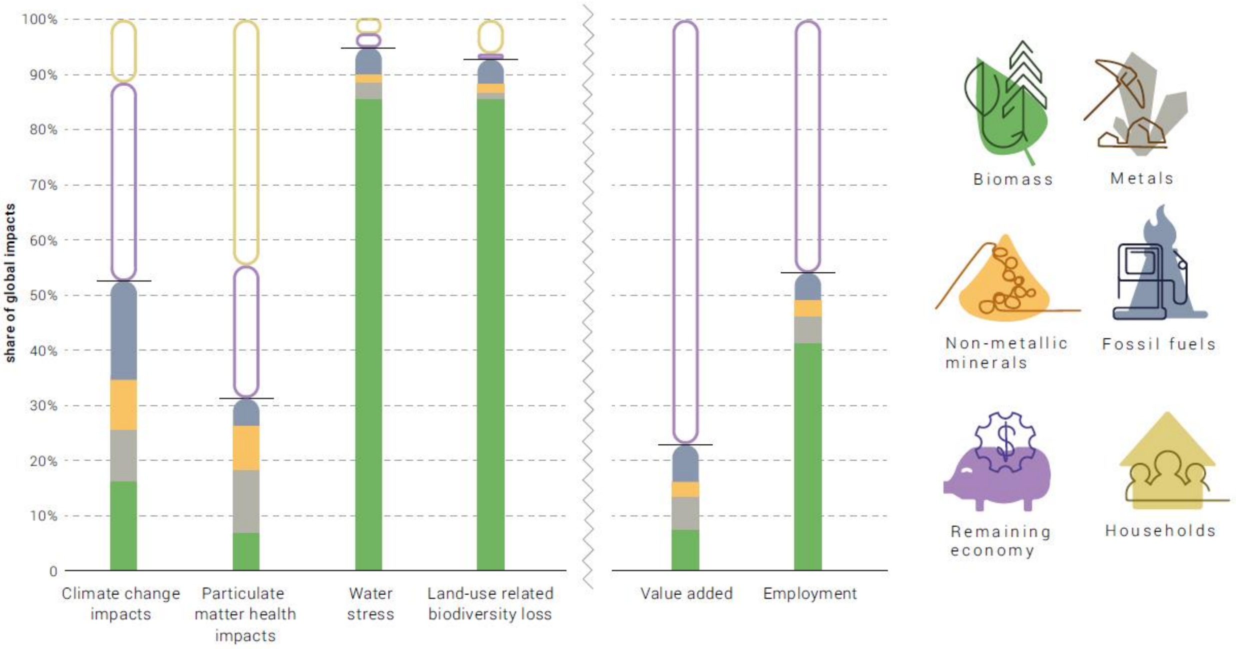


Figure 1. Global impacts split by resource type, remaining economy and households (IRP, 2019)

1.2 South Africa’s climate commitments

South Africa is currently, heavily reliant on the combustion of fossil fuels to meet its energy needs, but recognises the need to shift to a low carbon economy. The South African government has made commitments towards reducing its GHG emissions through updates to its NDC. The NDC seeks to attain a low GHG emissions pathway that is aligned to its national circumstances and development challenges (RSA, 2021). The decarbonisation of the economy in the 2020's is focussed on the electricity sector, whilst a deeper transition of the electricity sector together with a transition towards low emission vehicles in the transport sector, is envisaged for the 2030's. The emissions by 2026 and 2030 are expected to be in a range between 350 and 420 Mt CO_2e, down from 398 and 510 MtCO_2e in 2021 to 2025 (Table 1). The country has also developed a '*Just Transition Plan*' to ensure that the transition to a low carbon, climate resilient economy is achieved in a just way.

South Africa’s climate change vision is for “*an effective climate change response and the long-term, just transition to a climate-resilient and lower-carbon economy and society*” as articulated in the National Climate Change Response White Paper (DEA, 2011). A net zero carbon economy is the policy goal of South Africa’s Low Emission Development Strategy 2050.

Table 1. South Africa's GHG NDC targets (RSA; 2021)

Year	GHG emission limit (MtCO_2e)	
	Upper	Lower
2010	547	398
2011	550	398
2012	553	398
2013	556	398
2014	559	398
2015	562	398
2016	565	398
2017	568	398
2018	571	398
2019	574	398
2020	583	398
2021 - 2025	510	398
2026 - 2030	420	350
2050	0	0

1.3 The climate change mitigation potential for South Africa

Given the international findings on the opportunity a circular economy provides in mitigating climate change, and South Africa’s climate commitments, the aim of this study, is to answer the question, “*Can transitioning South Africa to a more circular economy, reduce national GHG emissions and assist in achieving national policy objectives of a net zero carbon economy by 2050?*”. This study therefore aims to evaluate the climate mitigation potential of circular economy interventions within various resource-intensive sectors of the economy.

This question is answered for South Africa through the following approach –

- Relate mitigation measures to circular economy principles, in each of the seven selected resource-intensive economic sectors with significant potential to reduce GHG emissions.
- Apply existing methods for modelling GHG emissions according to Department of Forestry, Fisheries and Environment (DFFE) Guidelines, with calculations documented using spreadsheet-based models. Scenarios will be developed from available activity data sources to project GHG emission reductions through mitigation actions related to the circular economy. This will help quantify the circular economy potential of reducing GHG emissions.

This report, reviews opportunities within and across economic sectors to enhance mitigation through the circular economy in South Africa; and through selected case studies, evaluates the benefits of circular approaches to mitigation.

1.4 The circular economy

The CSIR has, in previous publications, adopted the following definition of a circular economy –

A circular economy “*entails keeping materials and products in circulation for as long as possible through practices such as reuse of products, sharing of underused assets, repairing, recycling and remanufacturing*” (Nahman *et al*., 2021). It “*minimises the need for extraction of primary resources, while also reducing waste. It provides opportunities for improved resource efficiency and resource security, reduced energy and materials consumption, and reduced climate impacts; while offering new sources of economic growth and job creation. In short, it supports improved socio-economic development and well-being, while reducing associated environmental and human health impacts*.”

This definition, together with the three principles of a circular economy, have guided much of the CSIR’s research to date on this topic, including this study on the climate mitigation potential of a circular economy. The three circular economy principles (EMF, 2017) used to frame the climate discussion here, include:

- Designing out waste and pollution;
- Keeping products and materials in use; and
- Regenerating natural systems

The relevance of circular economy principles for the sectors outlined in this study (energy; manufacturing, mining; mobility; agriculture; human settlements; and water) are presented in Table 2.

Table 2. Examples of sectoral circular economy measures adapted from Godfrey *et al.*, 2021

Sector	Design out waste and pollution	Keep products and materials in use	Regenerate natural systems
Energy	• Energy efficiency (demand management) • Waste and emissions prevention • Reducing materials-use in manufacturing energy technologies • Increasing energy technology lifespans	• Waste gas and heat valorisation • Carbon capture use and storage (CCUS) • Repair and recycling of energy technologies (repurposing) • Waste-to-energy • Fly-ash to building materials	• Renewable energy • Green hydrogen
Manufacturing	• Redesign manufacturing processes and products to enhance resource efficiency, coupled with sharing economy	• Remanufacture, refurbish, repair and recycle materials and products across value chains	• Transition to green energy (solar, wind, hydrogen) and decouple resource utilisation
Mobility	• Shared, and multi-modal mobility • Increased use of zero-emission mobility • Encouraging remote and flexible working	• Scaling up vehicle remanufacturing • Recycling • Vehicle and infrastructure design for circularity	• Mobility systems based on renewable energy • Climate resilient transport infrastructure
Human Settlements	• Green, energy-efficient buildings, more compact cities • Pedestrian-friendly neighbourhoods	• Circular construction value chains • Circular organics • Waste management	• Urban agriculture • Renewable energy • Green roofs • Green open spaces
Agriculture	• Precision farming • Peri-urban and urban farming (Bringing food production and consumption closer) • The sharing economy	• Returning nutrients to the agricultural system • Biorefinery; value-add of waste products	• Crop rotation • Intercropping • Mixed farming • Reduced or zero till
Mining	• Redesign mining processes and value chains to be more resource efficient	• Reduce, reuse and recycle various waste streams, including end-of-life equipment	• Renewable energy • Restoring mining landscapes
Water	• Reducing water use and wastewater generation, improved water use efficiency, better water use practices	• Reuse and recycling of wastewater (return flows) • Reclamation and recovery of resources from water-based waste	• Improving water flow and quality through the restoration of land by controlling invasive alien plants (IAP) and rehabilitating and protecting wetlands and riparian systems

2 Climate mitigation potential of the circular economy

2.1 An International Perspective

There have been several global studies in recent years investigating the climate change mitigation potential of transitioning to a circular economy. Many of these studies propose that adopting a circular approach to climate change mitigation puts the world on track to meet climate targets (Ellen McArthur Foundation, 2021). Various approaches have been adopted in quantifying the climate mitigation potential of circular economy interventions in these international studies. However, a common thread that runs across these studies is a sectoral approach, where the key sectors that provide the greatest opportunities for GHG mitigation through circular economy interventions were identified at different geographic scales. These sectors differed depending on the priorities of the country or region. Key studies informing the current dialogue on the climate change mitigation potential of circular interventions are discussed here, followed by descriptions of case studies.

The Circularity Gap Report (Circle Economy, 2023) showed that the global economy is only 7.2% circular and that between the Paris COP21 and Glasgow COP26 more than half a trillion tons of virgin materials were consumed. Driving circularity in just four global systems – food; manufacturing; built environment; and mobility & transport could have significant climate benefits. The report states that transitioning to a circular economy could reverse the overshoot of planetary boundaries for climate change from 191% above the boundary to 46% above the boundary. This would be enough to limit global temperature rise to 2° Celsius. The report also acknowledged the need for different circular solutions across the globe, because each country has unique challenges and opportunities for circularity. As such, the report proposed circular solutions specific to each country profile, taking local contexts into account.

Hoogzaad *et al*. (2020) proposed key circular economy interventions to reduce GHG emissions in low- and middle-income countries and identified two key sectors – food and agriculture (shifting to healthy diets, regenerative crop production and agroforestry) and manufacturing (eco-innovation in industrial clusters and networks). Table 3 lists the circular economy interventions identified by Hoogzaad *et al*. (2020) in terms of GHG mitigation potential – with the highest GHG mitigation potential highlighted in red text.

In a 2021 position paper, the Ellen McArthur Foundation highlighted that while most efforts to tackle climate change have been focused on the switch to renewable energy, this leaves up to 45% of the remaining GHG emissions unaccounted for (EMF, 2021). Their study suggests that when applied to four key sectors related to industrial materials namely; cement, steel, plastic, and aluminium, circular economy strategies could reduce emissions by 40% in 2050. When applied to the food systems as well, such reductions could bring emissions from these areas 45% closer to their net-zero emission targets (EMF, 2021).

Table 3: Key interventions prioritised in terms of GHG mitigation potential (Hoogzaad *et al*., 2020).

Intervention	GHG mitigation potential between 2020 and 2050 (billion tonnes CO_2e)	
	Min	Max
Intervention 1. Improved livestock management	17	69
Intervention 2. Regenerative crop production and agroforestry	95	161
Intervention 3. Bioeconomy and bio-based materials	5.6	22.5
Intervention 4. Reducing food losses from harvest to processing	9	51
Intervention 5. Avoiding food waste at the retailer and consumer	5.7	32
Intervention 6. Closing the loop on urban organic residues and other organic waste	1.5	2.2
Intervention 7. Making the most of widely used materials focus on recycling of glass, paper, metals and plastics	5	6
Intervention 8. Making the renewable transition circular	The GHG potential of this intervention is undefined. However, the carbon footprint of producing renewable energy materials is still substantial (Hoogzaad, J.A. *et al,* 2020). Mitigating these emissions over the full lifecycle of the renewable energy generation and storage capacity is the scope of this intervention.	
Intervention 9. Eco-innovation in industrial clusters and informal networks	97	108
Intervention 10. Circular design in construction	24	57
Intervention 11. Non-motorised and shared transport	9.9	20
Intervention 12. Shifting to healthier and more sustainable diets	15	166

The World Resources Institute (WRI) (2022) further states that "*Circular economy strategies can complement decarbonisation measures to further reduce GHG emissions from material production, help lower emissions from operational energy use in the built environment and transport, and cut emissions from waste management*." According to the WRI, the built environment, transport, food systems and clean energy are the most relevant sectors for circular economy strategies to deliver climate change mitigation benefits. Van Veldhoven & Schmidt (2021) assert in a WRI opinion piece that while the path to circularity is not clear for all countries, a starting point would be to consider countries that have already incorporated circularity into their NDCs, including the European Union, the Netherlands and Chile. Understanding how the strategies to reduce emissions directly linked to the way materials are extracted, produced and consumed, allowed these nations to broaden their climate pledges (Veldhoven & Schmidt, 2021).

Considering case studies in the Global South where circular approaches to climate change mitigation have been applied, an Ellen MacArthur Foundation study (EMF, 2016) on the circular economy in India, showed that the adoption of circular interventions in three focus areas key to the economy and society – cities and construction, food and agriculture, and mobility and vehicle manufacturing – could significantly mitigate negative environmental externalities (Figure 2). This included a reduction in GHG emissions of 23% in 2030, and 44% in 2050 compared with the current development scenario, directly supporting the country in meeting its international climate commitments. The biggest potential for GHG emissions reduction was in mobility and vehicle manufacturing, with a potential 68% reduction in 2050.

The study by the Ellen MacArthur Foundation on the circular economy opportunities in China (EMF, 2018) showed that by applying circular economy principles across five high-impact areas comprised of three urban systems: the built environment, mobility, and nutrition, and two industrial systems (manufacturing): textiles and electronics, reductions in emissions of GHGs of 11% by 2030, and 23% by 2040, could be achieved (Figure 3). As with India, the biggest potential for GHG emissions reduction was in mobility, with a potential 37% reduction in 2040. And with a strong manufacturing economy, sizeable reductions were also possible in both the textiles (28%) and electronics (22%) sectors.

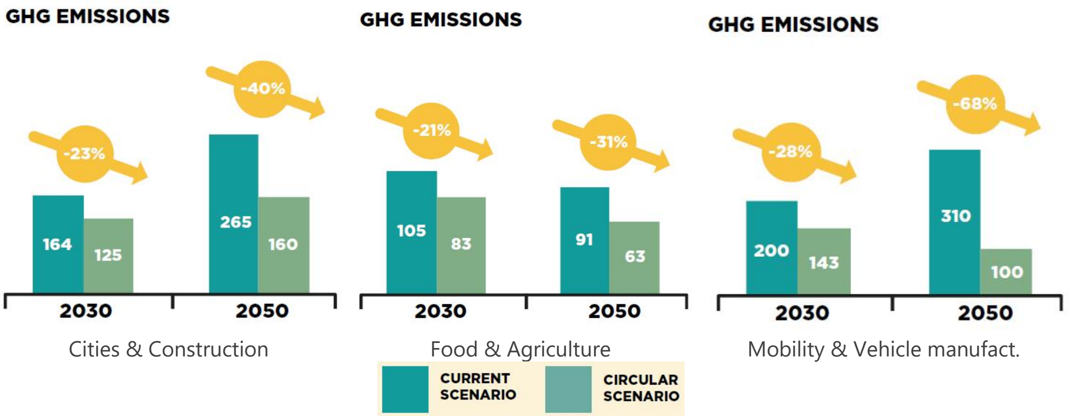
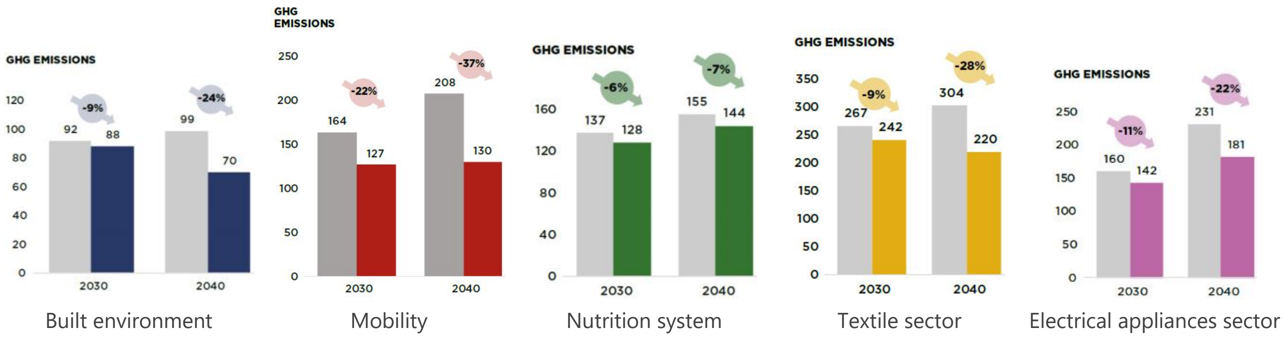


Figure 2. Mitigation potential of CE opportunities in India (EMF, 2016)



Built environment Mobility Nutrition system Textile sector Electrical appliances sector

Figure 3. Mitigation potential of the circular economy in China (EMF, 2018)

2.2 A South African perspective

Based on the definitions of the Circularity Gap Report (Circle Economy, 2023), South Africa would likely fall under the category of a "*Build country*". A country which lives within planetary boundaries but still needs to build an economic system that satisfies society's basic needs. While South Africa has not yet developed a national circular economy policy or strategy, there are a number of sectoral policies which pave the way for the adoption and scaling of circular economy initiatives in South Africa. These include the National Development Plan (NDP 2030), which calls for a transition to an environmentally sustainable, climate resilient, low-carbon and just society. This is supported in the energy sector by the National Climate Change Response White Paper (2014), and various flagship programmes including the Renewable Energy Programme; Energy Efficiency and Energy Demand Management Programme; and the Carbon Capture Storage and Use Programme. In addition, South Africa has made official global commitments to decarbonization through the Paris Agreement (2015) under the UNFCCC (Msimanga *et al*., 2021).

South Africa's Green Transport Strategy (DoT, 2018) aims to reduce the transport sector's GHG emissions, while the National Transport Master Plan (NATMAP) 2050 works towards an integrated, smart and efficient transport system, both of which provide an ideal launch pad for the adoption and scaling of circular economy interventions in the mobility sector (Mokoena *et al*., 2021).

The National Integrated Urban Development Framework (IUDF) (CoGTA, 2016) aims to steer urban growth towards a sustainable growth model of compact, connected and coordinated cities and towns, while the Comprehensive Plan for the Development of Sustainable Human Settlements (Breaking New Ground) (2004), encourages higher densities, mixed land use, integrating land use and public transport planning, and a more compact urban form to create more diverse and responsive environments and reduce travelling distances. The spirit of these policies and strategies supports the principles of a circular economy in developing and managing human settlements in South Africa (Cooper *et al*., 2021).

Within manufacturing, the Industrial Policy Action Plans and more recent Industry Master Plans recognise the sector opportunities in renewable energy, water conservation and waste reduction. Within the Steel Industry Master Plan, for example, the plan recognises climate resilience and greening of the industry as a key emerging opportunity, and calls for the sector to reach carbon neutrality by 2050 as a step towards mitigating cross-border carbon taxes, amongst others. The plan also recognises the potential of shifting to the production of green steel by 2050, and the potential of a local hydrogen economy (Fazluddin *et al*., 2021).

South Africa has a rich policy landscape applicable to the agriculture and agro-processsing sectors. The Agricultural Policy (1998) focusses on the conservation of agricultural resources. The White Paper on Science, Technology and Innovation (2019), the first policy document to specifically reference the circular economy, recognizes the circular economy as a new growth area for South Africa, with the need to modernize and strengthen productive sectors such as agriculture, manufacturing and mining (Okole *et al*., 2021).

The South African water sector is replete with policies, strategies and plans that embrace different aspects of the circular economy. Although these interventions are differently described, their intention and impact are the same as the circular economy. Relevant policies include the National Water Act (1998), the National Water Resources Strategy (2004 and 2013), Water Conservation and Demand Management Strategies (developed since 1999), a National Strategy for Water Re-Use (2011), the National Water and Sanitation Sector Masterplan (2018) and the National Water Security Framework for South Africa (2020) (Seetal *et al*., 2021)

The circular economy is one of the core features of South Africa's National Waste Management Strategy (NWMS 2020), through an approach which seeks to minimize the environmental impact of economic activity by reusing and recycling processed materials, to minimize the need to extract raw materials from the environment, and the need to dispose of waste. Moreover, as part of the NWMS Implementation Plan, one of the critical objectives is the identification of waste streams that have high potential for circularity and to develop a national circular economy action plan.

As part of transitioning to a circular economy, several waste-related initiatives have been undertaken in South Africa. Firstly, a market assessment and research on waste circularity in South Africa was instituted in line with the Africa Circular Economy Alliance (ACEA) Circular Economy Prioritization Framework. Secondly, the Chemicals and Waste Phakisa Initiative on Product Design and Waste Minimization – Packaging Guideline and Regulations was also initiated to accelerate the adoption of guidelines to increase collaboration between recyclers, designers, and brand owners. Thirdly, initiatives on product design and waste minimization through the recently gazetted Extended Producer Responsibility (EPR) regulations were planned for, to encourage and ensure the effective and efficient management of end-of-life products while enabling the implementation of circular economy initiatives. Lastly, there are NWMS interventions on construction and demolition waste that have been put in place, which include the development of a strategy for diversion of waste from landfills, development of construction waste value addition industries, and the need to stimulate supply and demand of construction and demolition waste.

As part of its transition to circularity, South Africa has been involved in circular economy dialogues and collaborations both regionally and internationally. South Africa is one of the founding members of ACEA and currently serves as a co-chair of this Alliance. In addition, South Africa is also a member of ACEA's centralized platform for knowledge-sharing and best practices identification, the creation of enabling legal and regulatory frameworks, which includes the building of partnerships for funding mobilisation and creation of circular economy projects in Africa. South Africa has also been involved in the World Circular Economy Forum (WCEF), which is a platform that brings together global forward thinkers and doers while presenting the leading role players and game-changers in the circular economy space. Lastly, South Africa is a member of the Global Alliance on Circular Economy and Resource Efficiency (GACERE). GACERE is an alliance of governments at the global level willing to work together on, and advocate for, a global, just circular economy transition and more sustainable management of natural resources at the political level and in multilateral fora.

It is clear that many supportive policies are already in place within each of the sectors, and that circular economy practices do exist within the country, but not yet at a scale to achieve meaningful impact (Nahman *et al*., 2021). The country has substantial potential for technological innovation for a circular economy as communicated in the White Paper on Science, Technology and Innovation (DST, 2019) and the DSI Medium Term Revised Strategic Plan (DSI, 2022). However, as noted by Nahman *et al*. (2021), the circular economy requires both a sectoral focus, and a broad systems approach, so as to piece these together into a systems view of the collective opportunity. This is particularly relevant both to the circular economy as well as climate change response strategies, where we run the risk of continued silo approaches to sector management.

What has not yet been quantified however, is the potential for GHG emissions reductions within, and across, various sectors of the South African economy, through the adoption of circular economy interventions. Which makes this study, the first of its kind for South Africa, and a very relevant study in setting and refining, South Africa's strategies towards a circular economy transition and climate mitigation.

3 Approach and Methodology

As noted under the objectives in Section 1, this study involved a two-pronged approach to quantifying the climate mitigation potential of a circular economy transition for South Africa. The first step involved a review of existing published literature, to identify activities with the largest contribution to South Africa's GHGs emissions and the relation between emission sources and circular economy sectors (Section 3.2 to 3.4) This was followed by a modelling exercise to quantify the climate mitigation potential of circular economy measures in South Africa (Chapter 4).

3.1 Literature review

The approach applied in this study encompassed a desktop literature review of local and international circular economy interventions; the linkages of the most disruptive interventions to implemented, planned and proposed climate change mitigation technologies and their GHG emission reduction effects for designing out waste and pollution; keeping products and materials in use; and regenerating natural systems. The resource-intensive economic sectors included in this study were energy; manufacturing, mining; mobility; agriculture; human settlements; and water.

The desktop study encompassed a review of:

- The circular economy measures adopted internationally and in South Africa.
- South Africa's emission sources and sinks, to determine a Business-as-usual (BAU) for direct GHG emissions.
- The mitigation potential of circular economy measures in 2050 in relation to the three circular economy principles.
- The costs and challenges to adopt circular economy measures in South Africa.
- The current implementation constraints and challenges for mitigation.
- The benefits of adopting circular economy measures.

The review of circular economy interventions was undertaken to assess the extent to which the subject has been considered in the context of climate change mitigation in South Africa. As part of the review, mini workshops were held with circular economy researchers and sector experts. These workshops helped to identify the circular economy interventions with the greatest opportunity for South Africa. The list of interventions was further refined to circular mitigation technologies by mapping circular economy interventions to the major GHG emission sources in the country (implemented, planned and proposed mitigation technologies). Based on information from existing studies; examples of circular mitigation technologies were selected aligned with the principles of designing out waste and pollution; keeping products and materials in use; and regenerating natural systems, to quantify the GHG emission reduction potential of the circular economy in the South African context.

3.2 GHG Emission Sectors

Anthropogenic emissions and removals refer to GHG emissions and removals recorded in national inventories, which arise from human activities. These national inventories encompass both onshore and offshore areas under the country's authority, accounting for the emissions and removals of GHGs.

A national GHG emissions inventory is a compilation of a country's key sources of direct GHG emissions as classified by the IPCC 2006 emission guidelines. Quantifying direct GHG emissions is crucial for holding entities accountable, targeting policies and measures, and promoting transparency and accountability in reporting on GHG emissions. An emissions inventory is thus critical to identifying key emission sectors and to providing a historical timeseries of GHG emissions. GHG emissions from electricity usage are not covered in national GHG inventories as these are indirect emissions and are already accounted for in inventories under the GHG emissions from electricity generation.

South Africa regularly updates its GHG emissions inventory, with the latest report, the 8th Greenhouse Gas Inventory Report, produced for the 2020 calendar year (DFFE, 2022). As emission categories used in the country's national inventory report are not analogous to circular economy sectors; additional calculations were performed, as part of this report, to summarise the sectoral shares to total GHG emissions which is shown in Section 3.4.

GHG emission and removal estimates are divided into main sectors as listed below (e.g., energy), which are groupings of related processes, sources, and sinks. Each sector comprises individual categories (e.g., transport) and sub-categories (e.g., cars)

- Energy
- Industrial Processes and Product Use (IPPU)
- Agriculture, Forestry and Other Land Use (AFOLU)
- Waste

The primary component of the Energy sector involves the emissions of GHGs resulting from the burning of fuels and the accidental release of gases. Emissions from fuel combustion encompass the intentional oxidation of materials within a device designed to generate heat or mechanical work, either for immediate use or for external processes. Mobile emissions encompass the combustion and evaporation of fuel in all transportation activities, excluding military transport, regardless of the specific sector. Fugitive emissions encompass both deliberate and unintended releases of gases that occur during the extraction, processing, storage, and transportation of fuel until its final utilization.

IPPU (Industrial Processes and Product Use) includes GHG emissions arising from industrial processes, the use of GHGs in various products, and the non-energy utilization of carbon derived from fossil fuels. The primary sources of emissions within this sector are the releases resulting from industrial processes that involve the chemical or physical transformation of materials. Furthermore, GHGs are frequently employed in the production of various products like refrigerators, foams, or aerosol cans.

The AFOLU sector includes GHG emissions and removals from agriculture as well as land, forestry, and other land use. The agriculture sector includes emissions from agricultural activities such as livestock production, rice cultivation, synthetic fertilizer application, manure management, and agricultural burning. Methane (CH_4) emissions from enteric fermentation in livestock and paddy rice fields, as well as nitrous oxide (N_2O) emissions from fertilizer use and manure management, are significant contributors. Emissions from deforestation, forest degradation, and the conversion of forests to other land uses are considered part of the AFOLU sector. Deforestation involves the permanent removal of forests, primarily for agriculture, infrastructure development, or urbanization. Forest degradation refers to the reduction in the quality of forests due to human activities. When forests are cleared or degraded, carbon stored in vegetation and soils is released as carbon dioxide (CO_2) emissions. Land use change refers to changes in land use patterns, such as conversion of forests to croplands, grasslands to urban areas, or wetlands to settlements. Land use change can lead to emissions if it involves the destruction of vegetation or the disturbance of carbon-rich soils, resulting in the release of stored carbon. Forest Management includes emissions resulting from forest management activities like timber harvesting, logging operations, and the decay or burning of harvested wood products. When trees are cut down and processed, carbon stored in the wood is released back into the atmosphere as CO_2. Emissions from soil management practices, such as ploughing, tilling, and application of organic or synthetic fertilizers, can contribute to the AFOLU sector. These activities can result in the release of CO_2 and N_2O from the soil. Peatlands are wetland ecosystems that contain large amounts of organic matter. When peatlands are drained for agriculture or other purposes, the organic matter decomposes and releases CO_2 into the atmosphere.

The waste sector encompasses both solid waste and wastewater management:

1. Landfills: One of the primary sources of emissions in the waste sector is landfill sites where solid waste is disposed of. Landfills produce significant amounts of CH_4 due to the decomposition of organic materials in an anaerobic (oxygen-limited) environment. Methane is a potent GHG with a much higher global warming potential than CO_2.
2. Wastewater Treatment: The treatment of wastewater can result in the release of GHG emissions. The processes involved in wastewater treatment, such as anaerobic decomposition of organic matter, can produce CH_4 and N_2O emissions.
3. Waste Incineration: Especially in municipal solid waste incinerators, can release CO_2 emissions. The burning of fossil fuel-derived plastics and other materials can contribute to CO_2 emissions.
4. Composting: Although composting is considered a more environmentally friendly waste management option, it can still produce emissions. The decomposition of organic matter during the composting process can release CH_4 and CO_2.
5. Waste Transport and Collection: The transport and collection of waste can contribute to emissions, primarily from the use of fossil fuel-powered vehicles. Fuel consumption and exhaust emissions during waste collection and transportation activities contribute to the sector's carbon footprint.

3.3 Alignment between GHG Emission Sectors and CE sectors

The linkages between GHG emission sectors and circular economy sectors are presented in Figure 4. The waste sector and more specifically solid waste management falls outside the designation of sectors in the circular economy which is discussed further in section 3.5.

The circular economy energy sector is about primary energy production and the manufacture of energy technologies (Msimanga *et al*., 2021). In relation to emission sources listed below; this includes the production of electricity and fuels including electricity generation; petroleum refining; manufacture of charcoal and other solid fuels and the manufacture of synthetic fuels including coal-to-liquid (CTL) and gas-to-liquid (GTL) fuels.

The manufacturing sector is about manufacturing processes and products (Fazluddin *et al*., 2021). In relation to GHG emission sources this includes energy use in manufacturing, excluding energy industries and industrial production processes and product use. Fuel combustion GHG emissions from manufacturing; mining and construction is reported together in the national GHG inventory report of 2020 (DFFE; 2022). As such for the purposes of this study; the mining and construction sectors are discussed together with the manufacturing sector. Fugitive GHG emissions from coal mining and handling are therefore also reported as part of manufacturing, mining and construction for the purposes of this study.

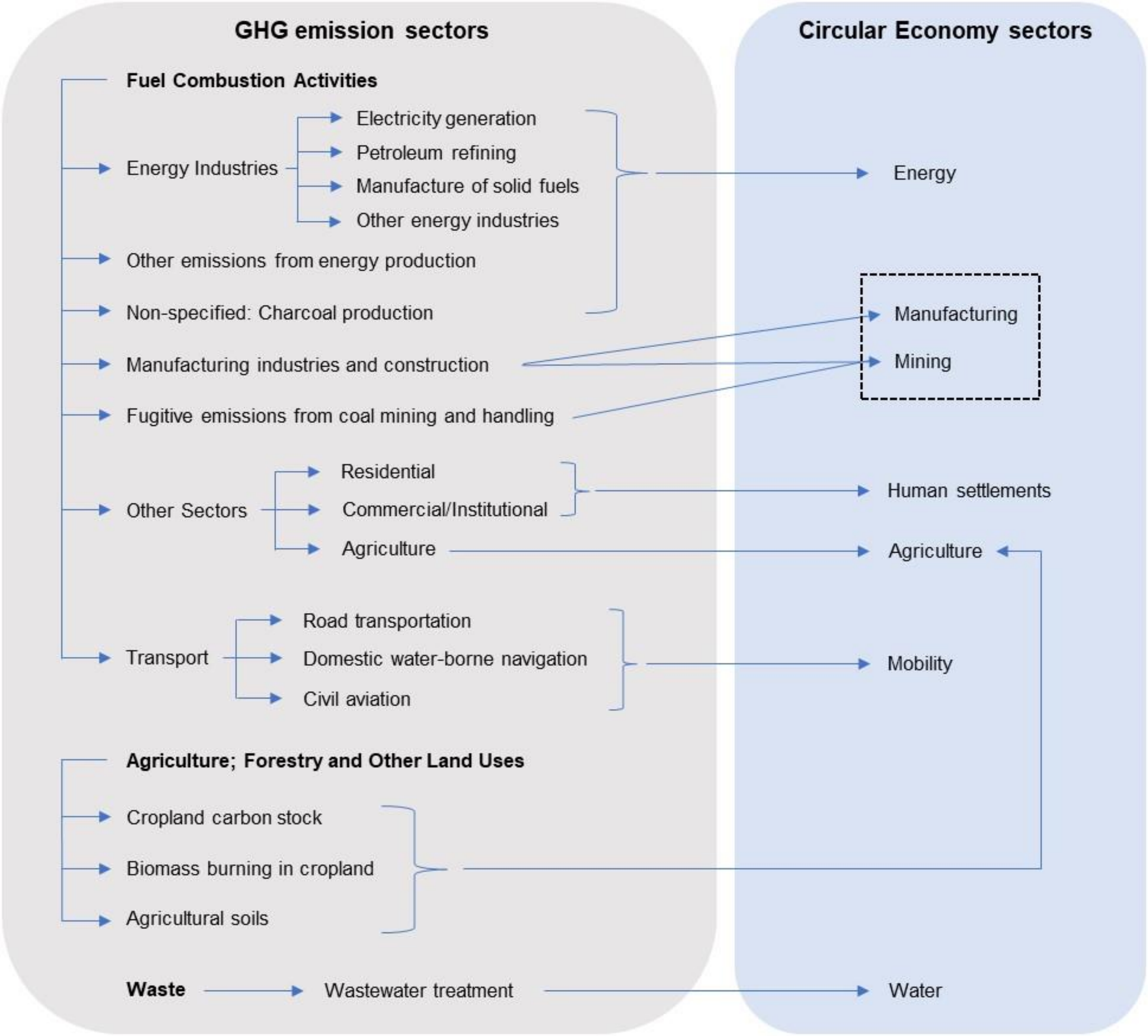


Figure 4. Linkages between GHG emission sectors and circular economy sectors

The circular economy human settlements sector is seen as "*cities, towns or villages – including the built environment (houses, engineering infrastructure etc.), the natural environment (vegetation, water bodies etc.), amenities (such as healthcare and recreation), and the residents (people)*" (Cooper *et al*., 2021). In relation to GHG emission sources this includes fuel combustion from residential and commercial/institutional sectors and carbon stock change in settlement land.

The circular economy mobility sector relates to the movement of goods and people; as well as transport operations and infrastructure (Mokoena *et al*., 2021). In relation to GHG emission sources, this includes mobile fuel combustion in road transportation; civil aviation; domestic shipping and pipeline transport. GHG emissions from international shipping; international aviation and bunkers are excluded from reporting in national inventories as these are outside the jurisdiction of the country.

The circular economy agriculture sector is about land use agricultural practices and the management of commercial crops for food (Okole *et al*., 2021). In relation to GHG emission sources this includes cropland carbon stock change; biomass burning in cropland and nitrous oxide (N_2O) emissions from agricultural soils. The future inclusion of livestock emissions is discussed in Chapter 6.

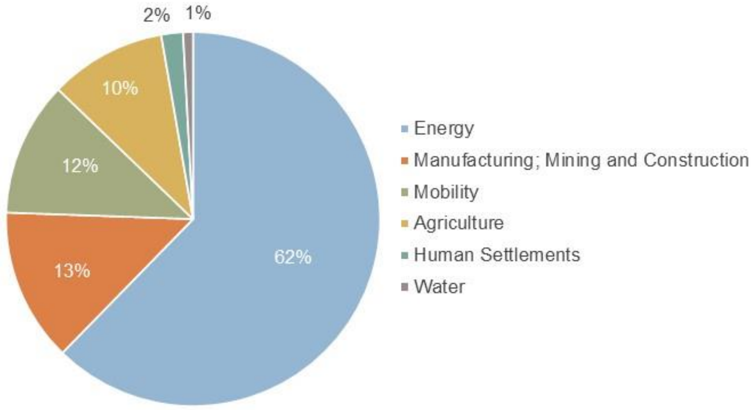
3.4 Current status of GHG emissions to setup the assessment boundaries of the GHG modelling in the study

In section 3.3; the alignment between circular economy and GHG emission sources were set out. In this section of the report; a description of GHG emission sources and their sectoral share is provided so as to indicate the importance of an emission source for circular economy mitigation in the sectors of energy; manufacturing, mining; mobility; agriculture; human settlements; and water. The relative contribution of emission sources in these sectors set outs the inclusion or exclusion of these sources from the assessment boundary of the study. The circular economy sectors GHG emissions for the year 2019 from DFFE (2022) are referred to as the base year which is used to determine sectoral emissions and shares.

As shown in Figure 5, total sector wide GHG emissions for South Africa in 2019, were 480.57 Million tonnes CO_2e ($MtCO_2e$). The energy sector accounts for 299.46 $MtCO_2e$ or 62% of the total GHG emissions. The energy sector is usually the most important sector in GHG emission inventories as the largest emissions come from coal fired power stations to generate electricity[1].

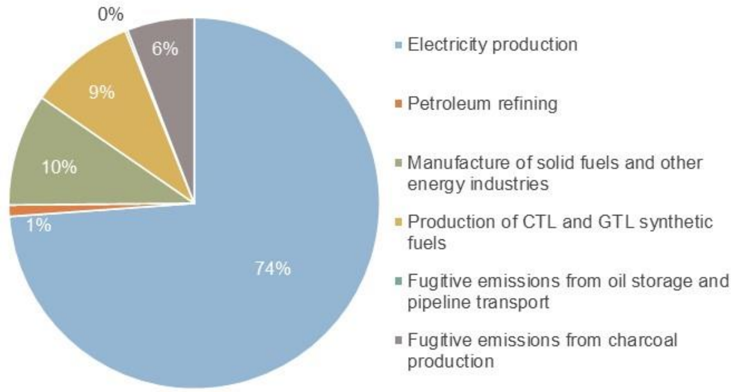
Figure 6 indicates that the GHG emissions from electricity production in coal fired power stations in South Africa amount to 221.20 $MtCO_2e$ which is 74% of the emissions in the energy sector. Petroleum refining and fugitive emissions from oil (fugitive emissions from oil are all the intentional and unintentional emissions from the processing, storage, and transport of oil to the point of final use) account for under 5% of the total emissions in the energy sector and thus are excluded from the assessment boundary of the study.

GHG emissions in the manufacturing, mining and construction sector contribute 63.66 $MtCO_2e$ or 13% of the total emissions. Emissions from the combustion of fuels in manufacturing, mining and construction industries are an important source that also includes combustion for the generation of electricity and heat for own use in these industries. Figure 7 shows that the GHG emissions of manufacturing, mining and construction stationary fuel combustion in South Africa amount to 33.76 $MtCO_2e$ which is 53% of the total emissions from the manufacturing, mining and construction sector. Industrial processes and product use (IPPU) in manufacturing industries are secondary emission sources in manufacturing which encompasses emissions resulting from industrial processes that chemically or physically transform materials and the use of GHGs in products. IPPU emissions account for 42% (27.04 $MtCO_2e$) of the total emissions from the manufacturing, mining, and construction sector. Fugitive emissions in coal mining are all the intentional and unintentional emissions from the extraction, processing, storage, and transport of coal to the point of final use. Accounting for 5% of the total emissions from the manufacturing, mining, and construction sector; the fugitive emissions in coal mining are minor emission sources and thus excluded from the assessment boundary of this study.



Sector	GHG emissions ($MtCO_2e$)
Energy	299.46
Manufacturing; Mining and Construction	63.66
Mobility	55.87
Agriculture	48.44
Human Settlements	9.01
Water	4.13
Total	**480.57**

Figure 5. Sector wide GHG emissions for South Africa (in 2019) ($MtCO_2e$) (DFFE, 2022)



Sector	GHG emissions ($MtCO_2e$)
Electricity production	221.20
Petroleum refining	2.97
Manufacture of solid fuels and other energy industries	29.28
Production of CTL and GTL synthetic fuels	27.85
Fugitive emissions from oil storage and pipeline transport	0.64
Fugitive emissions from charcoal production	17.52
Total	**299.46**

Figure 6. Energy sector GHG emissions for South Africa (in 2019) ($MtCO_2e$) (DFFE, 2022)

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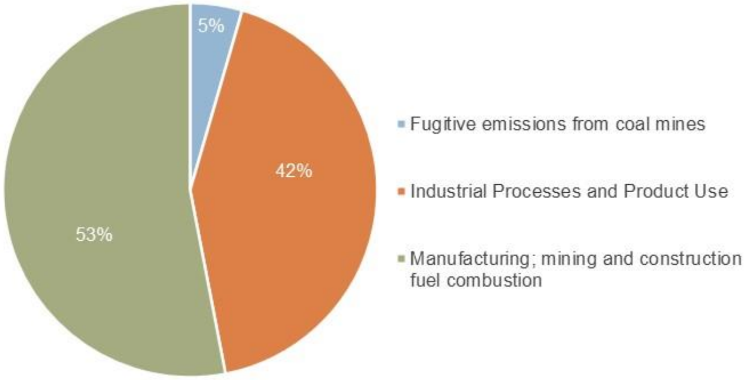
[1] Direct GHG emissions from electricity production come from the fuel combustion of fossil fuels such as coal, natural gas and diesel for the production of electricity. End use of electricity does not directly contribute to GHG emissions and therefore is not modelled in the study.

Figure 8 shows the sub-sectoral contributions from manufacturing, mining and construction to GHG emissions. The manufacturing sector accounts for 91% of fuel combustion GHG emissions and all of the GHG emissions from industrial processes and product use. Non specified industries which includes the manufacture of plastic and rubber products; manufacture of furniture and all other industries related to commercial products manufacturing, accounts for 46% of the fuel combustion emissions. The iron and steel sub-sector is the second largest contributor to GHG emissions from fuel combustion at 22%. Other manufacturing industries such as chemical and petrochemical; non-ferrous; metals and non-metallic minerals[2] account for 9%; 8% and 5% of GHG emissions from fuel combustion, respectively. The mining sector accounts for 9% of the fuel combustion emissions. The contribution of the construction sector to fuel combustion is negligible as it is less than 0% of total fuel combustion emissions. As such the construction sector is not included in the assessment boundary of the study as it accounts for under 5% of the emissions from fuel combustion GHG emissions.

Emissions in IPPU are chiefly from non-ferrous metals production (36%), chemicals and petrochemicals production (24%), non-metallic minerals (21%) and iron and steel production (19%). The IPPU emissions are not included in the assessment boundary of the study as there is not enough information known about the current state of IPPU mitigation to quantify a Business-as-usual (BAU) scenario. Additionally there is insufficient activity data available to model the effect of IPPU mitigation measures to reduce GHG emissions to quantify a circular economy (CE) scenario.



Sector	GHG emissions (MtCO$_2$e)
Fugitive emissions from coal mines	2.86
Industrial Processes and Product Use	27.04
Manufacturing; mining and construction fuel combustion	33.76
Total	**63.66**

Figure 7.	Manufacturing, mining & construction sector GHG emissions for South Africa (in 2019) (MtCO$_2$e) (DFFE, 2022)

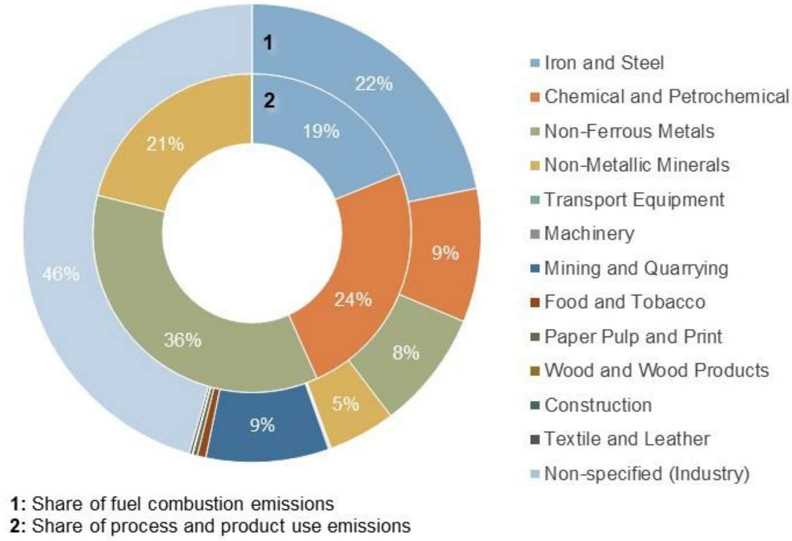


Figure 8.	Sectoral share of GHG emissions in manufacturing, mining and construction

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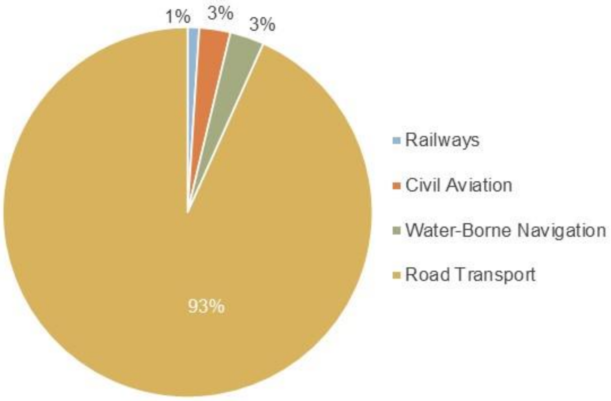
[2] Non-Metallic Minerals includes cement production, lime production and glass production.

The mobility sector accounts for 12% or 55.87 MtCO$_2$e of the total emissions. The road transport sector accounts for the bulk of emissions in mobility as shown in Figure 9 at 93% (52.11 MtCO$_2$e). Smaller contributions in mobility come from water-borne navigation or domestic shipping (1.67 MtCO$_2$e); civil aviation (1.52 MtCO$_2$e) and diesel usage in railways (0.56 MtCO$_2$e). As the emissions from domestic shipping; civil aviation and railways each contribute less than 5% of the mobility sector emissions; these emission sources are excluded from the assessment boundary of this study.

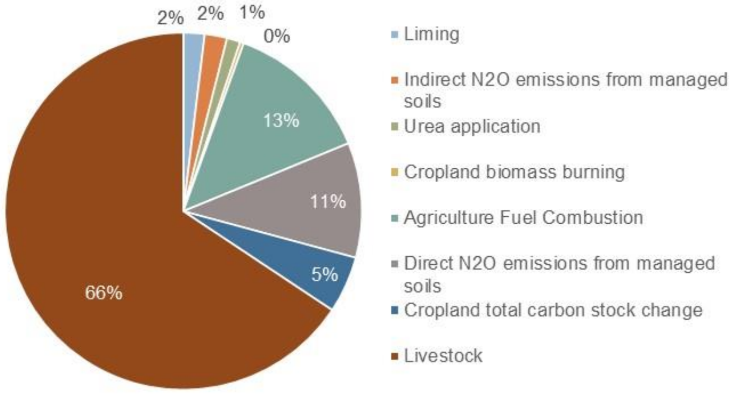
The agriculture sector includes emissions from fuel combustion; cropland carbon stock change; biomass burning in cropland; liming; urea application and N$_2$O emissions from agricultural soils.

- Carbon stock change refers to the overall net increase or decrease in the amount of carbon stored in agricultural land or across multiple carbon reservoirs over a specific period of time. It encompasses the cumulative change in carbon stocks within agricultural land and land use systems.
- Liming emissions are those from the use of limestone or calcium carbonate in agricultural soils to adjust soil pH and improve soil fertility.
- Urea application emissions are those from the application of urea as a type of nitrogen based fertilizer.
- N$_2$O emissions from agricultural soils include the direct and indirect N$_2$O emissions from managed soils. Indirect N$_2$O emissions from managed soils refer to the release of N$_2$O into the atmosphere as a result of human activities and management practices in agricultural or other soil-utilizing systems. These emissions occur indirectly through various processes involving nitrogen fertilizers, organic matter decomposition, and soil management techniques. Direct N$_2$O emissions from managed soils refer to the release of N$_2$O into the atmosphere as a direct result of human activities and management practices in agricultural or other soil-utilizing systems. These emissions occur due to specific processes associated with nitrogen transformations in the soil.



Sector	GHG emissions (MtCO2e)
Railways	0.56
Civil Aviation	1.52
Water-Borne Navigation	1.67
Road Transport	52.11
Total	**55.87**

Figure 9. Mobility sector GHG emissions for South Africa (in 2019) (MtCO$_2$e) (DFFE, 2022)



Sector	GHG emissions (MtCO$_2$e)
Liming	0.93
Indirect N$_2$O emissions from managed soils	0.98
Urea application	0.59
Cropland biomass burning	0.16
Agriculture Fuel Combustion	6.44
Direct N$_2$O emissions from managed soils	5.04
Cropland total carbon stock change	2.49
Livestock	31.81
Total	**48.44**

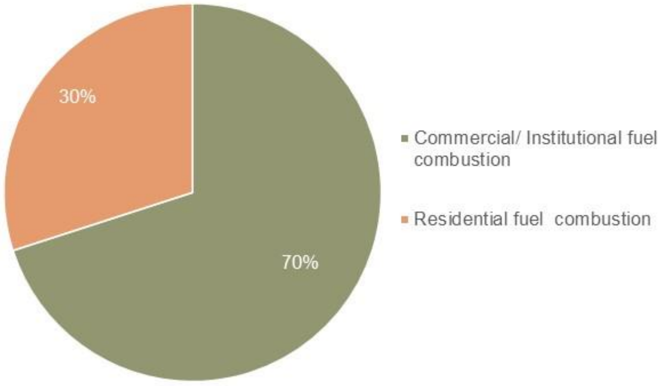
Figure 10. Agriculture sector GHG emissions for South Africa (in 2019) (MtCO$_2$e) (DFFE, 2022)

Total emissions from agriculture amount to 48.44 Mt CO_2e as shown in Figure 10 and contribute towards 10% of the total sector wide emissions.

- The largest emission source in agriculture is livestock that includes the emissions from enteric fermentation and manure management which is 31.81 $MtCO_2e$ (66% of agriculture emissions). Livestock emissions have been excluded from the assessment boundary of this study as it does not form part of the circular economy agriculture sector as it is conceived currently in the circular economy agriculture study of the CSIR (Okole *et al.*, 2021).
- Agriculture fuel combustion is a secondary emission source in agriculture with emissions amounting to 6.44 $MtCO_2e$ (13% of agriculture emissions).
- The emissions from carbon stock change in croplands amount to 2.49 $MtCO_2e$ (5% of agriculture emissions).
- Direct N_2O emissions from managed soils is a tertiary emission source in agriculture with emissions amounting to 5.04 $MtCO_2e$ (10% of agriculture emissions). These emissions are excluded from the assessment boundary of the study as it does not form part of the circular economy agriculture sector as it is conceived currently.

The emissions from the application of lime to agriculture soils amount to 0.93 $MtCO_2e$ (2% of agriculture emissions). Indirect N_2O emissions from managed soils amount to 0.98 $MtCO_2e$ (2% of agriculture emissions). There is also a smaller contribution from urea application which accounts for 0.59 $MtCO_2e$ or 1% of agriculture emissions. Also, biomass burning in cropland is a minor source of agriculture emissions that amounts to 0.16 $MtCO_2e$ (0.3% of agriculture emissions). Liming, Indirect N_2O emissions from managed soils; urea application and biomass burning in cropland emissions are minor sources of GHG emissions in agriculture with each one contributing less than 5% of the sectoral emissions, thus these emission sources are excluded from the assessment boundary of this study.

GHG emissions in the human settlement sector are from commercial/institutional and residential fuel usage otherwise known as building sector emissions which amount to 9.01 $MtCO_2e$ (2% of sector wide emissions). Commercial and institutional GHG emissions refer to the emissions associated with the operations and activities of commercial businesses and institutions. These emissions are generated in sectors such as offices, retail stores, hotels, hospitals, schools, government buildings, and other non-industrial facilities from the combustion of fossil fuels for heating or on-site power generation. Residential emissions result from the burning or combustion of fuels for heating, cooking, and other energy uses within residential households. These emissions typically arise from the use of fossil fuels, such as natural gas, oil, and coal, as well as from the combustion of biomass fuels, such as wood and charcoal. Commercial/Institutional emissions contribute to 6.31 $MtCO_2e$ to human settlement emissions (70%). Residential fuel combustion emissions contribute to 2.70 $MtCO_2e$ to human settlement emissions (30%). The emissions for human settlements are shown in Figure 11. Indirect emissions from electricity usage in human settlements is not included here as this is included in the GHG emissions from electricity production[3]. Direct emissions from transport in human settlements is not included here as this is accounted for in the mobility sector.



Sector	GHG emissions ($MtCO_2e$)
Commercial/ Institutional fuel combustion	6.31
Residential fuel combustion	2.70
Total	**9.01**

Figure 11. Human Settlement sector GHG emissions for South Africa (in 2019) ($MtCO_2e$) (DFFE, 2022)

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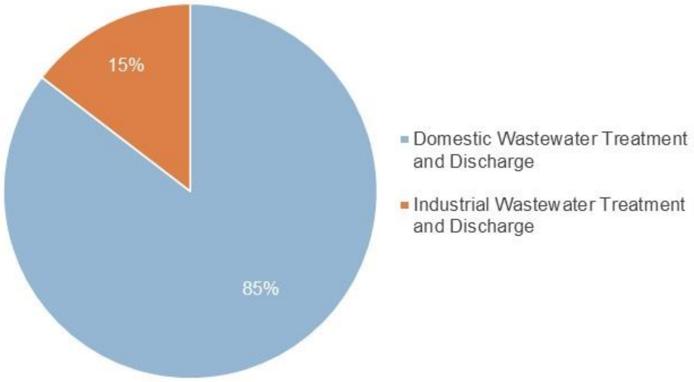
[3] GHG emissions from fossil fuel combustion in electricity production are the largest source of GHG emissions which are directly emitted to the atmosphere from the power plants where the electricity is produced. Electricity consumption at end use does not result in direct emissions to the atmosphere and is therefore not required to be reported as such for emissions inventories according to the DFFE Methodological Guidelines for the Quantification of GHG emissions.



Sector	GHG emissions ($MtCO_2e$)
Domestic Wastewater Treatment and Discharge	3.53
Industrial Wastewater Treatment and Discharge	0.60
Total	**4.13**

Figure 12. Water sector GHG emissions for South Africa (in 2019) ($MtCO_2e$) (DFFE, 2022)

Water sector emissions comprise those from domestic and industrial wastewater treatment. CO_2 emissions in wastewater treatment can occur through the aerobic decomposition of organic matter during biological treatment processes. Methane emissions from wastewater treatment primarily occur in anaerobic environments, such as anaerobic digesters or sludge treatment processes. N_2O emissions can occur during various stages of wastewater treatment, particularly during the biological nitrogen removal processes. The bulk of water sector emissions are from domestic wastewater treatment which contributes 3.53 $MtCO_2e$ (85%) to sectoral emissions. Industrial wastewater treatment contributes 0.60 $MtCO_2e$ (15%) to sectoral emissions. The emissions for the water sector are shown in Figure 12.

3.5 What about waste?

The Waste sector as defined as a GHG emission sector in the IPCC (2006) guidelines, was not identified as a specific circular economy sector in the CSIR reports. The reason for this, is that waste is a cross-cutting issue across all of the economic sectors, and is therefore dealt with within each sector. The difference between the waste sector defined in the circular economy and the waste sector as a key GHG emission sector lies in their respective scopes and objectives:

Waste Sector in the Circular Economy:
In the context of the circular economy, the waste sector refers to a component of the overall economic system that focuses on managing resources and materials in a way that promotes sustainability, resource efficiency, and waste reduction. The circular economy aims to move away from the traditional linear model of "*take, make, dispose*" to a circular model where resources are kept in use for as long as possible, and at the end of their life, they are recovered, regenerated, or recycled to create new value. The waste sector in the circular economy encompasses various activities, such as waste prevention, recycling, composting, energy recovery, and responsible waste management practices.

The primary goal of the waste sector within the circular economy is to minimize waste generation (design out waste), optimize resource use, and reduce the environmental impacts associated with waste generation and disposal. This includes reducing GHG emissions from waste management practices, as well as minimizing other environmental issues like pollution, habitat destruction, and resource depletion.

Waste Sector as a Key GHG Emission Sector:
On the other hand, when referring to the waste sector as a key GHG emission sector, the focus is specifically on the GHG emissions associated with waste management and disposal processes. The waste sector is recognized as a significant contributor to GHG emissions, mainly due to the decomposition of organic waste in landfills, which produces methane (CH_4), a potent GHG. Methane has a much higher global warming potential (GWP) than carbon dioxide (CO_2) over a shorter time frame, making it a significant concern in climate change mitigation efforts.

While the circular economy approach also addresses GHG emissions from the waste sector, it does so in the broader context of promoting sustainable resource management and waste reduction. The circular economy aims to tackle waste generation at its source and encourage the adoption of circular practices that reduce emissions by minimizing the need for raw material extraction, energy-intensive production, and disposal.

In summary, the waste sector in the circular economy encompasses a broader range of activities and objectives related to resource efficiency and waste reduction, while the waste sector as a key GHG emission sector focuses specifically on the GHG emissions associated with waste management and disposal. The circular economy approach is a comprehensive strategy that includes waste management as one of its components, recognizing the importance of addressing GHG emissions from the waste sector to achieve sustainability goals.

The following waste-related GHG emission sources in the circular economy are modelled in this study:

1. *Agriculture Sector:* In the agriculture sector, waste can include agricultural residues, crop leftovers, and animal manure. GHG emissions are from nitrous oxide (N_2O) emissions resulting from the decomposition of organic waste which is applied as a fertilizer to agricultural soils.
2. *Human Settlement Sector:* The human settlement sector involves waste generated by residential and commercial activities (for example food waste). GHG emissions in this sector are quantified by assessing the waste composition, the waste management practices in place (e.g., recycling, composting, landfilling), and the associated emissions from these activities. Emission factors specific to different waste treatment processes are used to estimate GHG emissions from landfills, incineration, and composting facilities. See below for further information about these activities.
3. *Energy Sector:* In the energy sector, waste can include various types of by-products and residues from energy production processes for example the usage of biomass and biodiesel for fuel. These emission sources are modelled in this study.
4. *Mining Sector:* The waste generated in the mining sector may include tailings, waste rock, and other by-products of extraction and processing activities. GHG emissions are quantified based on the waste characteristics and the chemical reactions that occur during waste decomposition or mineral processing. These emissions are quantified as part of solid waste disposal into landfills and further detail is provided below.
5. *Water Sector:* In the water sector, waste can include sewage sludge and other by-products from wastewater treatment processes. GHG emissions are quantified by measuring the CH_4 and N_2O emissions resulting from anaerobic decomposition in sewage treatment facilities. Methane is mainly emitted from wastewater treatment which is modelled in this study..
6. *Manufacturing Sector:* Waste generated in the manufacturing sector can vary widely depending on the industry. GHG emissions are quantified by assessing waste streams and their disposal methods. Recycling and waste-to-energy processes are considered, and emissions are calculated based on the specific waste treatment technologies used. Energy resource efficiency initiatives through the National Cleaner Production Centre of South Africa (NCPC-SA) have promoted uptake of some of these measures within the manufacturing sector since 2002. As such GHG emission reductions are already accounted for in the current National GHG inventory and included within the projection of GHG emissions to 2050 for planned and current policies.
7. *Mobility Sector*: The mobility sector can generate waste from various sources, including end-of-life vehicles, used tyres, and other automotive by-products. GHG emissions from waste in this sector are quantified by considering the disposal practices and the emissions associated with waste treatment or recycling processes. These emissions are quantified as part of solid waste disposal into landfills and further detail is provided below.

As per IPCC (2006) reporting requirements for the waste sector, the main GHG emission sources are the disposal of solid waste into landfill; incineration and open burning of solid waste; composting and wastewater treatment. In South Africa, the disposal of solid waste into landfills accounts for most of the waste sector GHG emissions at 79%. GHG emissions from wastewater treatment account for 19% of waste sector emissions. Composting and the incineration and open burning of solid waste account for less than 5% of the total GHG emissions in the waste sector and thus are minor emission sources which are excluded from the assessment boundary of the study.

Waste streams deposited into managed landfills in South Africa comprise waste from households, commercial businesses, institutions, and industry. Collectively the decomposition of the organic fraction of these waste streams in landfill result in the CH_4 emissions that are emitted. Quantifying the GHG emissions for each waste stream is complex unless the waste management practice and GHG emission profiles for each of these waste streams are known. Furthermore, GHG emission profiles of each waste stream must be known for managed; unmanaged; commercial and industrial landfills in South Africa. This gap in knowledge has already been identified as part of improving the National Waste Sector GHG emission inventory. Each circular economy sector generates a wide range of waste streams with varying compositions and characteristics. Different types of waste have different GHG emissions profiles. Thus the quantification of solid waste disposal into landfill for each circular economy sector is complicated and is a gap in the current knowledge about GHG emissions in the waste sector for South Africa which is an opportunity for much-needed further research. As such solid waste disposal into landfills is excluded from the assessment boundary of this study although it is acknowledged that solid waste disposal into landfills is an integral circular economy package of measures.

3.6 Scenario development and modelling methodology of emissions 2021 - 2050

Scenarios depict plausible future conditions encompassing distinct economic, social, and environmental attributes. They serve as valuable tools in the development of strategies and technologies for achieving net zero goals. By employing various scenarios, it becomes possible to assess current capabilities and determine the resources necessary for attaining maximum mitigation. To gauge GHG emissions by 2050, existing emission reduction methods and potential technological advancements are compared in two scenarios, a Business-as-usual (BAU) scenario and a Circular Economy (CE) scenario. This approach enables the quantification of emissions reductions achievable through current strategies and the potential reductions attainable with proposed technologies.

Business-as-usual (BAU) scenario: The Business-as-usual (BAU) scenario encompasses the events or conditions that are expected to unfold if the circular economy measures under examination are not put into effect. It is a linear projection of historical emissions which is assumed to represent the projection of current policy conditions.

Circular Economy (CE) scenario: The CE scenario represents the events or conditions most likely to occur in the presence of the circular economy measures being assessed. The CE scenario is the same as the BAU scenario except that it includes the circular economy measures being assessed. In the CE scenario where active attempts are made to reduce emissions, the amount of emissions will depend on when and how these actions occur, and how effective those actions are expected to be.

GHG emission reduction: Quantified decrease in GHG emissions between a BAU scenario and the modelled CE scenario in this study.

Mitigation actions: Activity or activities that alter the conditions of a BAU and which cause GHG emission reductions or GHG removal enhancements.

The information needed for analysing and predicting GHG emissions depends on the specific sectors being studied and the mitigation activities being considered. Available activity data from 2030 to 2050 were used to create a model that shows how emissions are expected to change over time in the BAU and CE Scenarios. GHG emissions are quantified as:

$$GHG\ Emission = Activity\ Data \times Emission\ Factor \times GWP$$

The GHG emission reduction of circular economy measures are quantified as follows:

> Total net change in GHG emissions resulting from circular economy measures (Million tonnes CO_2e - $MtCO_2e$) = Total net CE scenario emissions ($MtCO_2e$) – Total net BAU scenario emissions ($MtCO_2e$).[4]

For this study the 2030 to 2050 GHG emission reductions are calculated using outputs from the Global Energy and Climate Outlook 2022 (Keramidas *et al*., 2022); Net Zero Pathways Study (Marquard *et al*., 2022) and Mitigation Potential Analysis in the 2050 Pathways Calculator for South Africa. GHG emissions from the national GHG inventory provide values for historical emissions and its linear projection in the sectoral BAU scenarios.

The emission factors and global warming potential values (GWPs) used in the model were based on the DFFE Methodological Guidelines for the Quantification of GHG emissions A list of emission factors and GWPs referred to for this study are shown in Annexure A.

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[4] "Net" refers to the aggregation of emissions and removals. "Total" refers to the aggregation of emissions and removals across all sources and sinks included in the GHG assessment boundary.

4 Sectoral Circular Economy Mitigation Potential

4.1 Energy sector

Circular economy measures in the energy sector are described in Msimanga *et al.* (2021) and are indicated in Table 4.

For this study, the measures modelled in the energy sector in relation to the measures listed above includes:

- Waste and emissions prevention by reducing synthetic fuels production and switching to cleaner fuels such as hydrogen and bio-diesel.
- Increasing renewable energy sources in the electricity energy mix and reducing fossil fuel sources such as coal and natural gas.

4.1.1 Electricity Generation

From 2000 to 2014; emissions grew annually as more coal was consumed for electricity generation, and the electricity available for distribution also increased over this period. The decrease in GHG emissions in 2019 by 11.96 $MtCO_2e$ (Table 6) is attributed to less coal consumption in coal-fired power stations. Overall, it is noted that the total electricity available for distribution has fallen after 2014 as less coal is used as a fuel source. The year-on-year average percentage growth in emissions from 2000 to 2019 is 0.8%.

Under a BAU Scenario, we therefore assume that in the absence of policy to shift away from fossil fuels as an energy source, emissions continue to grow annually by 0.8% from 2019 to 2050. With increasing loadshedding and energy insecurity, the BAU scenario for the energy sector already includes some circular interventions, such as the adoption of renewables. Lower fuel combustion of coal for electricity generation causes the decrease in emissions from 2019 to 2030 as shown in Table 6. GHG emissions from 2030 to 2050 grow in the BAU scenario as there is increased fuel combustion of natural gas for electricity generation (Figure 13), while coal consumption also contributes to the emissions (Figure 14).

In the 2040 CE scenario, electricity generation from nuclear energy which is a cleaner fuel together with increased generation from renewable energy, helps to offset the emissions from the burning of fossil fuels. In the 2050 CE scenario, renewable energy sources become the dominant energy source for power generation in the electricity mix thereby contributing more to reducing emissions from electricity generation. The total GHG emissions in the BAU and CE scenarios for electricity generation are shown in Figure 15.

Table 4. Circular economy measures in the energy sector (Msimanga *et al.*, 2021)

Design out waste and pollution	Keep products and materials in use	Regenerate natural systems
• Energy efficiency (demand management) • Waste and emissions prevention • Reducing materials-use in manufacturing energy technologies • Increasing energy technology lifespans	• Waste gas and heat valorisation • Carbon Capture • Repair and recycling of energy technologies (repurposing) • Waste-to-energy • Fly-ash to building materials	• Renewable energy • Green hydrogen

Table 5. Historical emissions from electricity generation 2000 - 2019

Year	2000	2005	2010	2015	2019
Historical emissions from electricity generation ($MtCO_2e$)	186.08	209.99	234.78	226.33	212.19

Table 6. GHG emissions and emission reductions from 2019 to 2050 in the BAU and CE scenarios

Year	GHG emissions in the BAU Scenario ($MtCO_2e$)	Current Emission Reductions ($MtCO_2e$)	CE Emission Reductions ($MtCO_2e$)	GHG emissions in the CE Scenario ($MtCO_2e$)
2019	224.15	-11.96	0	212.19
2030	222.27	0	-12.29	209.98
2040	240.27	0	-35.67	204.60
2050	259.73	0	-42.62	217.11

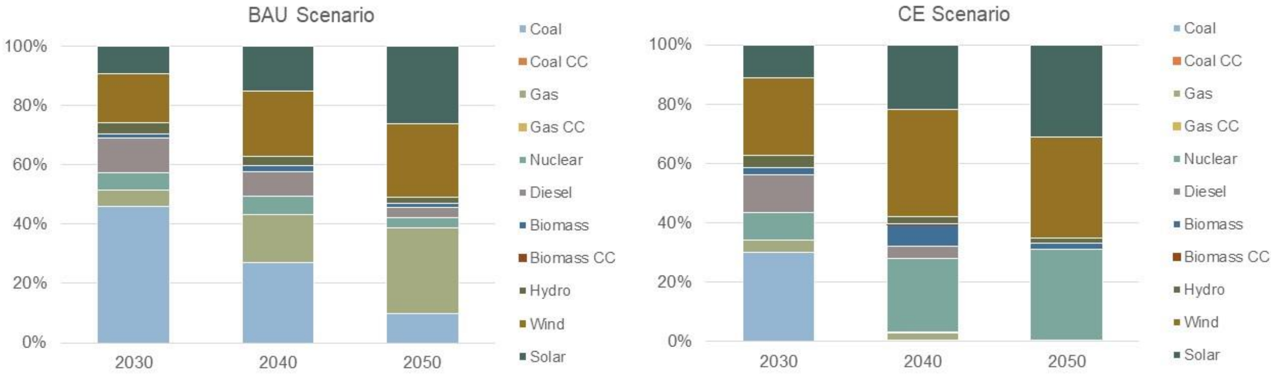


Figure 13. Share of energy sources to the electricity generation mix in the BAU and CE scenarios

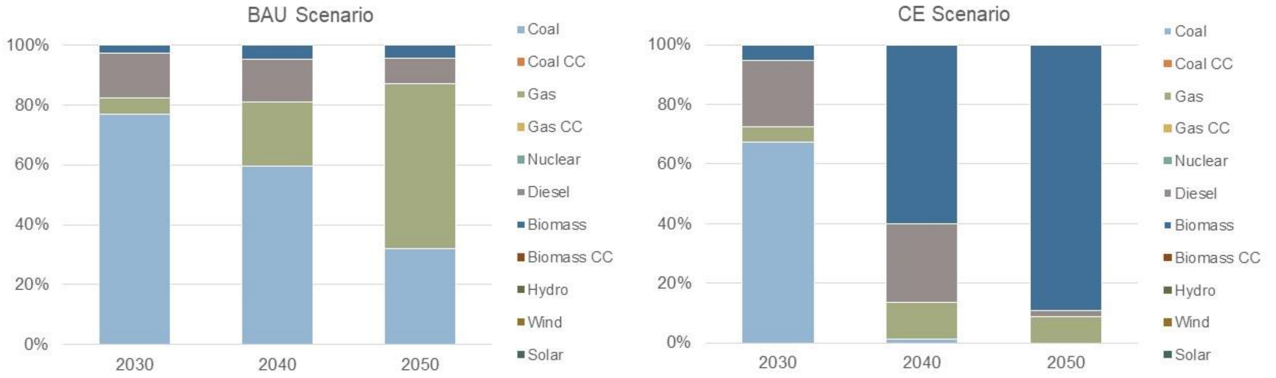


Figure 14. Share of energy sources to GHG emissions from electricity generation in the BAU and CE scenarios

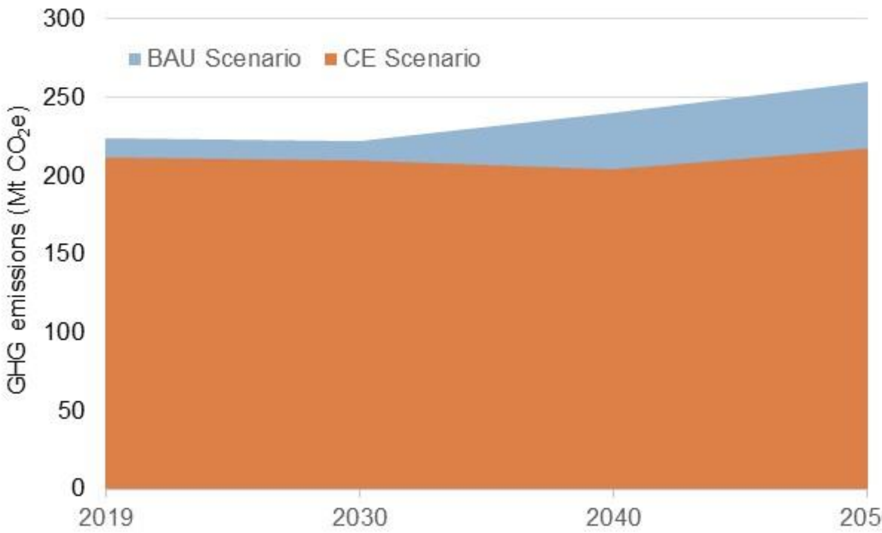


Figure 15. Total GHG emissions in the BAU and CE scenario from fuel combustion of energy resources used in the production of electricity

Table 7. Historical emissions from synthetic fuels production 2000 - 2019

Year	2000	2005	2010	2015	2019
Historical emissions from synthetic fuels production (MtCO$_2$e)	30.70	27.67	26.70	26.83	27.85

4.1.2 Synthetic Fuels

Fuel combustion emissions from synthetic fuels production decrease from 2000 to 2019 as the quantities of synthetic fuels produced fall. Overall from 2000 to 2019 (Table 7); there is an average year-on-year decrease in emissions of 0.4%.

In the BAU scenario, emissions decrease from 2019 to 2030 and remain almost the same until 2050 as the quantities of synthetic fuels produced decline. Current annual emission reductions due to a fuel switch from using coal to natural gas as feedstock amount to 7.91 $MtCO_2e$. Decommissioning of synthetic fuels production occurs in the CE scenario with 50% reduction of CTL fuel production by 2050 and the decommissioning of GTL fuel production to zero from 2035 onwards. By 2050; the remainder of emissions are from the production of CTL fuel. The emissions reduction in 2050 is mostly due to less coal consumed (Table 8) as the production of CTL fuels decline.

Table 8. Energy consumption of fuel sources used for fuel combustion in the production of synthetic fuels 2030 to 2050

Energy source	BAU Scenario energy consumption (PJ)			CE Scenario energy consumption (PJ)		
	2030	2040	2050	2030	2040	2050
Coal	301.23	290.75	290.75	156.25	103.71	66.87
Diesel	32.37	49.42	49.42	14.56	0.00	0.00

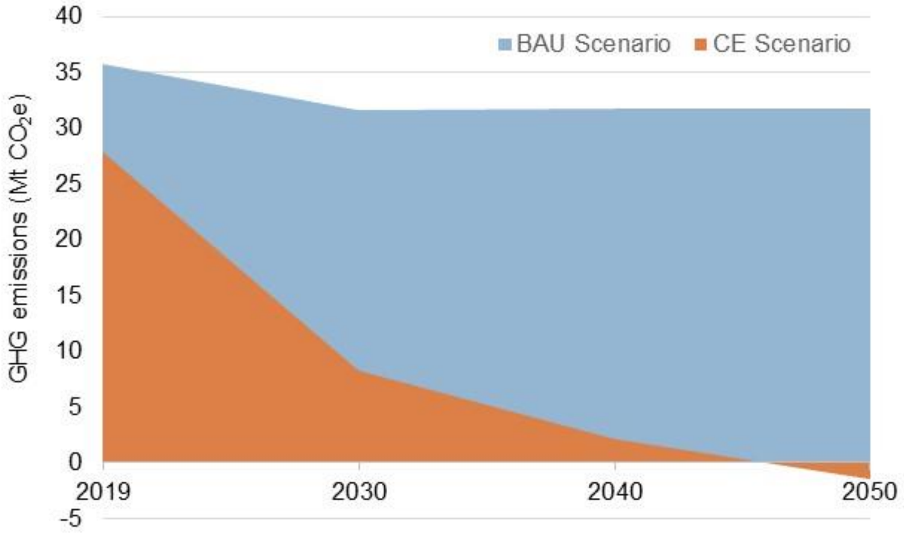


Figure 16. GHG emissions in the BAU and CE scenario from fuel combustion of coal and gas used in the production of CTL and GTL fuels

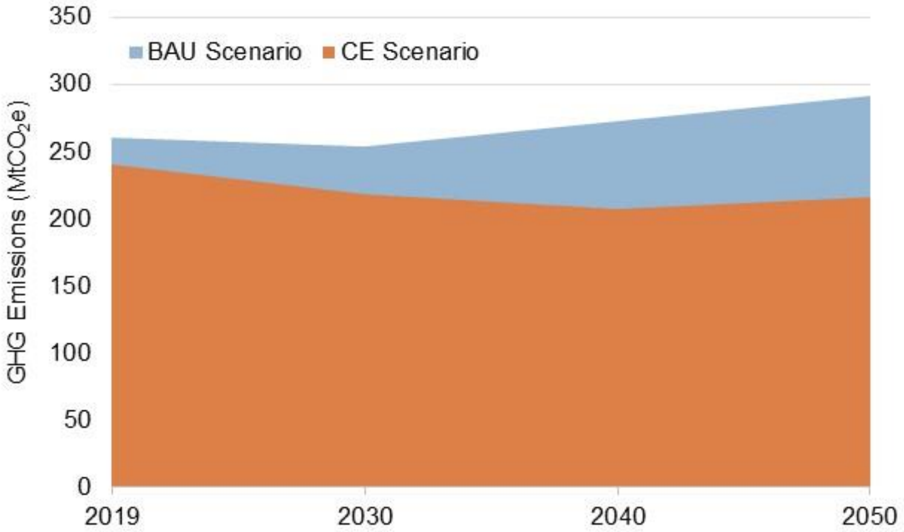


Figure 17. GHG emissions in the BAU and CE scenario for circular economy measures in the Energy sector

As shown in the CE scenario; as synthetic fuels production is scaled down from 2030 to 2050; the GHG emissions decline from 8.28 $MtCO_2e$ in 2030 to -1.44 $MtCO_2e$ in 2050 (Figure 16). The decline in synthetic fuels production is driven by changes in fuel demand in the mobility sector as there is a shift to electric and hydrogen fuelled vehicles.

4.1.3 Total GHG emissions in Energy

The total GHG emissions reduced in 2050 amount to 75.85 $MtCO_2e$ (Figure 17, 18) from a combination of mitigation measures related to designing out waste and pollution (reduction of coal and gas electricity generation capacity; phase out of synthetic fuels production) and the regeneration of natural systems (increase in the share of electricity generation from renewable energy sources and zero emission fuel alternatives to synthetic fuels). While the BAU scenario already includes some circular interventions for the energy sector (e.g., renewables), adopting more ambitious regenerative energy practices as outlined above creates an opportunity to reduce GHG emission levels to well below 2019 levels by 2050, though circular economy interventions (Figure 18).

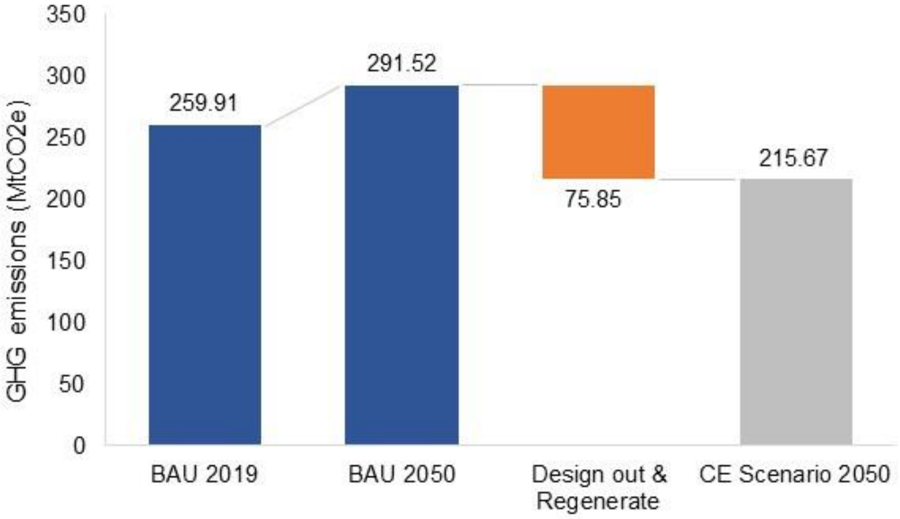


Figure 18. GHG emissions reductions in 2050 due to the effect of circular economy mitigation measures in the Energy Sector

Table 9. Circular economy measures in the manufacturing; mining and construction sector (Fazluddin *et al.*, 2021 and Khan *et al.*, 2021)

Design out waste and pollution	Keep products and materials in use	Regenerate natural systems
• Redesign manufacturing processes and products to enhance resource efficiency, coupled with sharing economy • Redesign mining processes and value chains to be more resource efficient • Waste and emissions prevention	• Remanufacture • Refurbish • Reduce, reuse and recycle various waste streams, including end-of-life equipment	• Transition to green energy (solar, wind, hydrogen) and decouple resource utilisation

Table 10. Historical emissions in manufacturing and mining 2000 - 2019

Year	2000	2005	2010	2015	2019
Historical emissions in manufacturing and mining ($MtCO_2e$)	28.93	30.08	37.51	34.64	33.76

4.2 Manufacturing; Mining and Construction Sector

Circular economy measures in the manufacturing and mining sector are presented in Fazluddin *et al.* (2021) and Khan *et al.* (2021) and are shown in Table 9.

In relation to the measures mentioned above; the following case is modelled in this study for the manufacturing and mining sector:

- Waste and emissions prevention linked to a transition to green energy associated with a fuel switch from fossil fuels in manufacturing and mining (coal and coking coal) to electricity (assuming net zero energy mix), gas, hydrogen and biomass.

The historical emission trends in manufacturing and mining from 2000 to 2019 (Table 10) can be attributed to changes in manufacturing productivity since the bulk of emissions are from that sector. GHG emissions in manufacturing and mining increase by 2% annually on average over the 2000 to 2019 period. Overall growth in manufacturing productivity over this period drives the increase in emissions in the sector.

It is assumed in the BAU scenario that emissions increase year-to-year by 2% based on historical emission trends. Current emission reductions (Table 11) are from the implementation of industrial energy efficiency measures which in 2019 amount to 0.49 $MtCO_2e$. It is assumed that the emission reduction benefits of 0.49 $MtCO_2e$ from industrial energy efficiency measures remain over the long-term. By 2050; additional emission reductions are due to a decline in the use of coal and coking coal in manufacturing as industries switch to hydrogen from 2040 onwards (Figure 19). In 2030; emission reductions are due to a lower amount of biomass consumed in manufacturing in the CE scenario in relation to the BAU (Figure 20). In 2040; emission reductions amount to zero; as coal and coking coal remain important fuel sources used in manufacturing. In 2050; the fuel switch to hydrogen is sufficient to offset the emissions from fuel combustion in the sector. Figure 21 shows the total GHG emissions in manufacturing and mining from 2019 to 2050 for the BAU and CE scenarios. The total GHG emissions reduced in 2050 amount to 44.51 $MtCO_2e$ (Figure 22). Adopting circular economy practices in manufacturing, mining and construction creates an opportunity to reduce GHG emission levels to well below 2019 levels by 2050 (Figure 22).

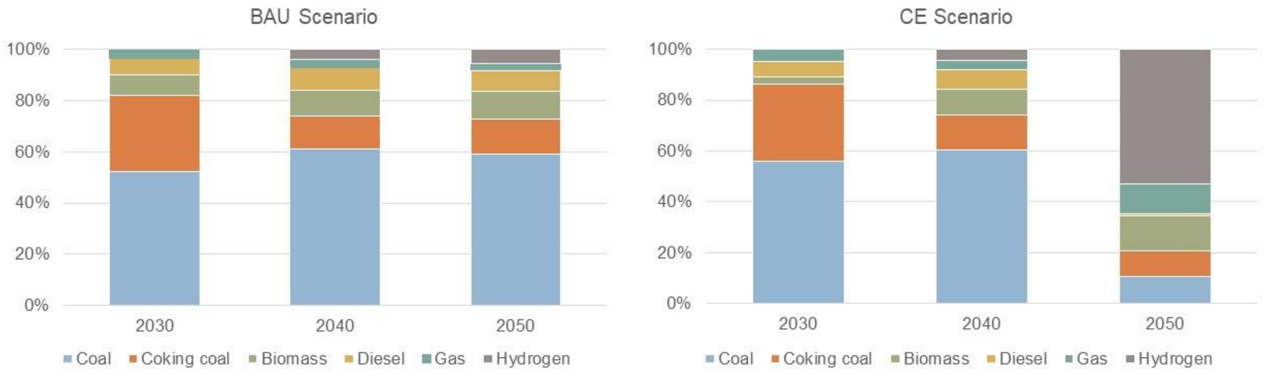


Figure 19. Share of energy sources to projected energy consumption in the BAU and CE scenarios in manufacturing and mining

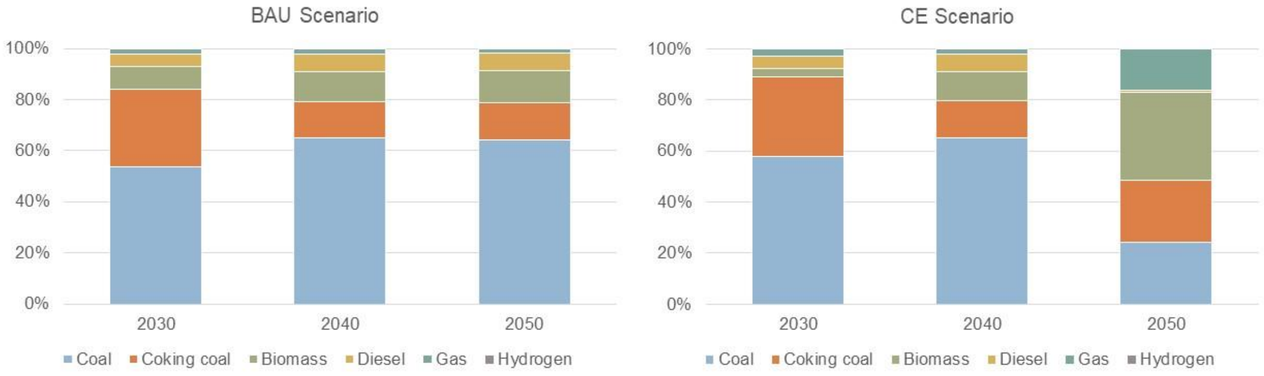


Figure 20. Share of energy sources to projected GHG emissions in the BAU and CE scenarios in manufacturing and mining

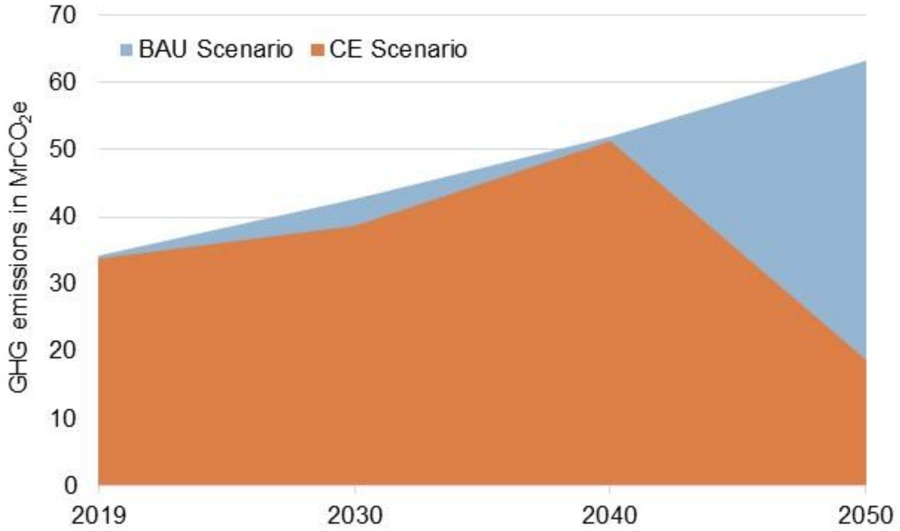


Figure 21. Total annual GHG emissions in the Manufacturing and Mining Sector for the BAU and CE scenarios

Table 11. GHG emissions and emission reductions from 2019 to 2050 in the BAU and CE scenarios in manufacturing and mining

Year	GHG emissions in the BAU Scenario (MtCO$_2$e)	Current Emission Reductions (MtCO$_2$e)	CE Emission Reductions (MtCO$_2$e)	GHG emissions in the CE Scenario (MtCO$_2$e)
2019	34.27	-0.49	0	33.78
2030	42.56	-0.49	-3.4	38.67
2040	51.87	-0.49	0	51.38
2050	63.26	-0.49	-44.02	18.75

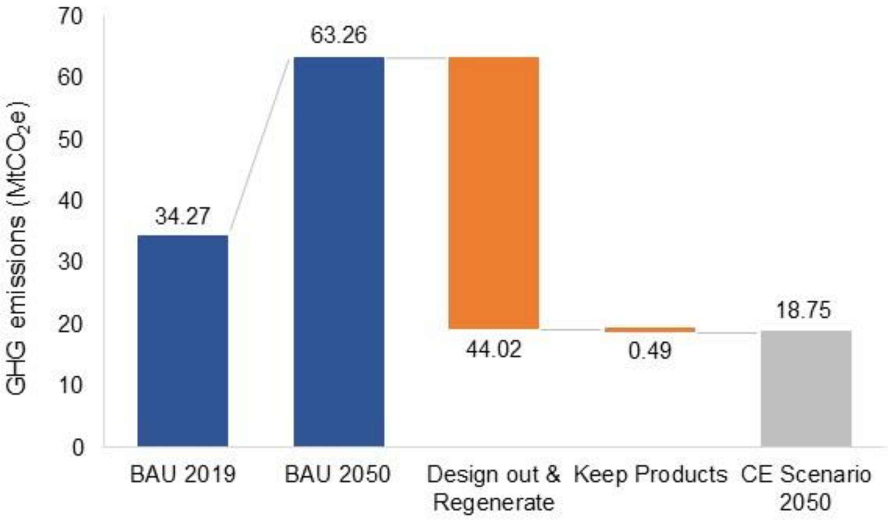


Figure 22. GHG emissions reductions in 2050 due to the effect of circular economy mitigation measures in the Manufacturing and Mining Sector

4.3 Mobility sector

Circular economy measures in the mobility sector are described in Mokoena *et al*. (2021) and are indicated in Table 12.

The measures modelled in the mobility sector for this study includes:

- Mobility systems based on hydrogen
- Increased use of zero emission mobility

The historical emission trends in transport from 2000 to 2019 (Table 13) can be attributed to the increasing number of vehicles on the road since the bulk of emissions in transport are from the road transport sector. GHG emissions in transport increase by 2% annually on average over the 2000 to 2019 period.

It is assumed in the BAU scenario that emissions increase year-to-year by 2% based on historical emission trends. In the BAU 2050 scenario; most of the transport emissions are from the use of diesel (Figure 24) in road transport. Current emission reductions are from the implementation of Bus Rapid Transport and Transnet Road-to-Rail Shift measures which in 2019 amount to 0.20 $MtCO_2e$. It is assumed that the emission reduction benefits of 0.20 $MtCO_2e$ from these measures remain over the long-term. By 2050; additional emission reductions are due to a decline in diesel vehicles from 2040 onwards in favour of electric and hydrogen powered vehicles (Figure 23). Figure 25 shows the total GHG emissions for mobility in the BAU and CE scenarios from 2019 to 2050.

Table 12. Circular economy measures in the mobility sector (Mokoena *et al*., 2021)

Design out waste and pollution	Keep products and materials in use	Regenerate natural systems
• Shared, and multi-modal mobility; • Increased use of zero-emission mobility; • Encouraging remote and flexible working	• Scaling up vehicle remanufacturing; • Recycling of parts from scrapped vehicles • Vehicle and infrastructure design for circularity	• Mobility systems based on renewable energy or hydrogen. • Climate resilient transport infrastructure

Table 13. Historical emissions in mobility 2000 - 2019

Year	2000	2005	2010	2015	2019
Historical emissions in mobility ($MtCO_2e$)	40.20	48.58	51.23	54.15	55.87

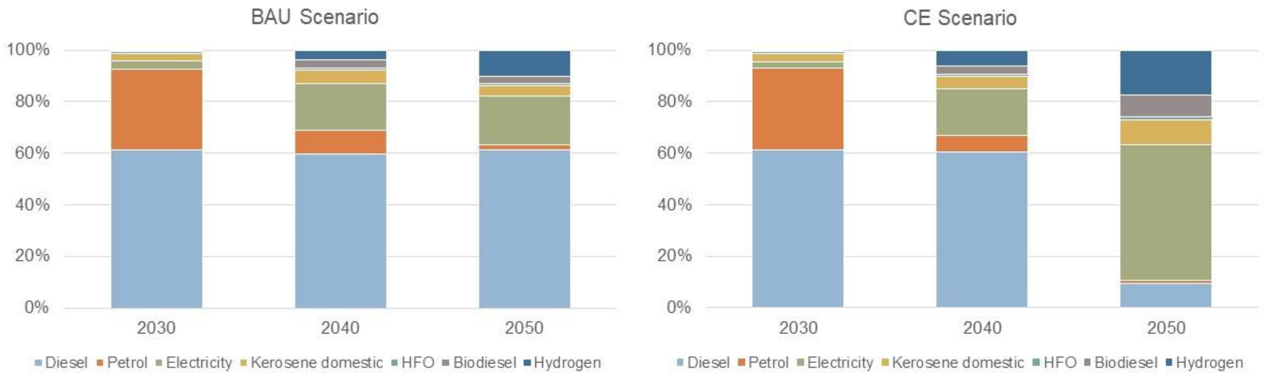


Figure 23. Share of energy sources to projected energy consumption in the BAU and CE scenarios in mobility

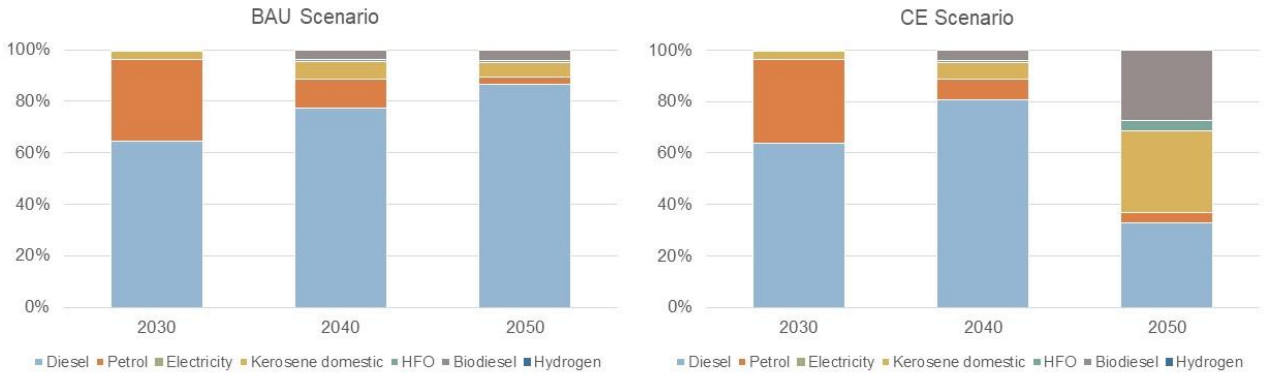


Figure 24. Share of energy sources to projected GHG emissions in the BAU and CE scenarios in mobility

Table 14. Freight transport distance in billion tonne kilometres (derived from Marquard *et al.*, 2022)

BAU Scenario	Year			CE scenario	Year		
Transport mode	2030	2040	2050	Transport mode	2030	2040	2050
Rail electricity	122	154	194	Rail electricity	122	162	178
Rail diesel	16	0	0	Rail diesel	20	0	0
Heavy electricity	10	28	38	Heavy electricity	10	28	40
Heavy diesel	212	238	292	Heavy diesel	218	210	56
Light electricity	0	0	24	Light electricity	0	0	30
Light petrol	4	2	0	Light petrol	4	0	0
Light diesel	16	20	12	Light diesel	18	26	0
Heavy hydrogen	0	0	0	Heavy hydrogen	0	0	230

Table 15. Private and passenger transport distance in billion passenger kilometres (derived from Marquard *et al.*, 2022)

BAU Scenario	Year			CE scenario	Year		
Transport mode	2030	2040	2050	Transport mode	2030	2040	2050
Car electricity	13	193	141	Car electricity	11	189	272
Car diesel	61	6	144	Car diesel	59	6	0
Car gasoline	91	22	0	Car gasoline	89	20	0
Motorcycle electricity	2	4	6	Motorcycle electricity	2	4	7
Bus diesel	22	4	0	Bus diesel	24	4	0
Minibus electricity	22	89	89	Minibus electricity	37	91	91
Minibus diesel	24	6	0	Minibus diesel	24	4	0
Minibus gasoline	59	7	0	Minibus gasoline	56	9	0
Rail electricity	9	9	9	Rail electricity	7	7	7

In the BAU scenario, there is no policy incentivisation for a shift from road freight to rail freight and private passenger transport to public transport. So, more road freight and private passenger transport is used instead of rail freight and public passenger transport as presented in Table 14 and Table 15. Rail freight transport is important in both the BAU and CE scenarios. The difference between freight transport in the BAU and CE scenarios is the shift from diesel to hydrogen.

Private transport is dominated by smaller diesel and petrol vehicles initially, with more electric vehicles joining the vehicle population after 2030. After 2040; there is a shift back to diesel for private transport, as diesel becomes a cheaper fuel. Passenger transport is important in both BAU and CE scenarios The effect of these shifts in the mobility sector on GHG emissions in the BAU scenario are shown in Table 16. Mitigation measures in the mobility sector are a combination of the increased use of zero-emission mobility (designing out waste and pollution) and freight mobility systems based on hydrogen (regeneration of natural systems). The total GHG emissions reduced in 2050 amount to 34.58 MtCO$_2$e (Figure 26). Adopting circular economy practices in mobility creates an opportunity to reduce GHG emission levels to below 2019 levels by 2050 (Figure 26).

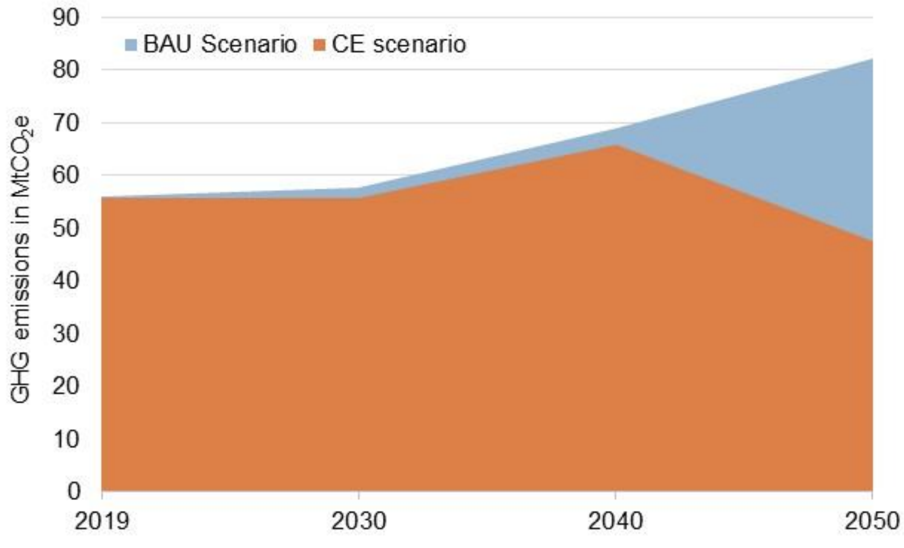


Figure 25. GHG emissions in the Mobility Sector for the BAU and CE scenarios

Table 16. GHG emissions and emission reductions from 2019 to 2050 in the BAU and CE scenarios in mobility

Year	GHG emissions in the BAU Scenario (MtCO$_2$e)	Current Emission Reductions (MtCO$_2$e)	CE Emission Reductions (MtCO$_2$e)	GHG emissions in the CE Scenario (MtCO$_2$e)
2019	56.07	-0.2	0	55.87
2030	57.74	-0.2	-1.86	55.68
2040	68.91	-0.2	-2.93	65.78
2050	82.23	-0.2	-34.38	47.65

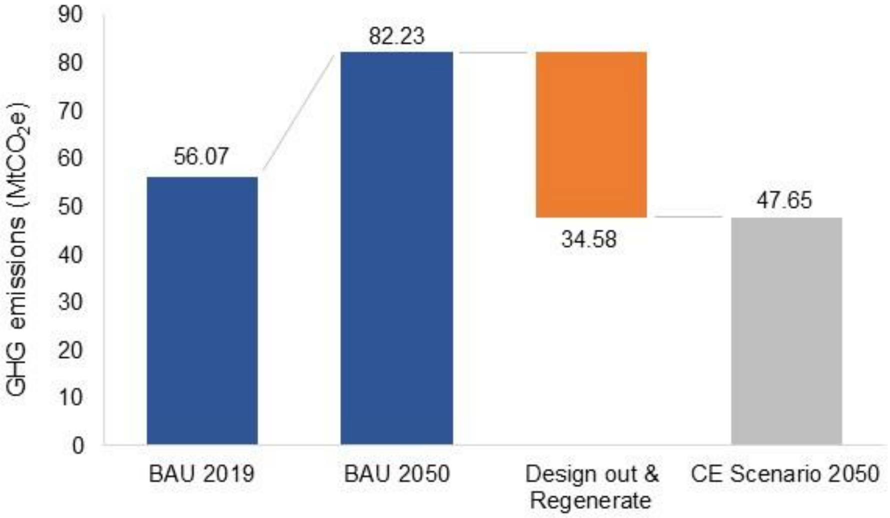


Figure 26. GHG emissions reductions in 2050 due to the effect of circular economy mitigation measures in the Mobility Sector

4.4 Agriculture sector

Circular economy measures in the agriculture sector are described in Okole *et al.* (2021) and are shown in Table 17. The following measures are modelled in this study –

- zero till, and
- shift to cleaner energy sources (electricity – net zero energy mix assumed)

4.4.1 Zero till

Historical emissions from agricultural land (Table 18) are primarily driven by biomass losses of carbon in organic matter in the soil and in the carbon stored in vegetation as organic matter. Forests and grasslands store more carbon in the soil and vegetation in relation to agricultural land as the harvesting of crops, tillage of land and burning of veld result in the removal of carbon in the soil and vegetation. Emissions from agricultural land grow as more forest and grassland is converted for agricultural use. GHG emissions from agricultural land have grown on average by 3% each year over the period 2000 to 2019.

It is assumed in the BAU scenario that emissions increase year-to-year by 3% based on historical emission trends. Current emission reductions (Table 19) are from the application of zero tillage to agricultural land. Zero tillage helps reduce the loss of carbon stored in agricultural soils. Based on the AFOLU Strategy (DEFF; 2020) it is assumed that the area under zero tillage is 14% of the annual crop area in 2018, growing at a rate of 7.5% per year with a mitigation potential factor of 0.2 tC/ha/yr. The annual crop area in 2018 is 11,126,022 ha (DEFF, 2020). Figure 27 shows the total GHG emissions in the BAU and CE scenarios for carbon stock change emissions in agriculture.

Table 17: Circular economy measures in the agriculture sector (Okole *et al.*, 2021)

Design out waste and pollution	Keep products and materials in use	Regenerate natural systems
• Precision farming; • Peri-urban and urban farming (urban agriculture)	• Returning nutrients to the agricultural system; • Biorefinery; • Value-add of waste products	• Crop rotation; • Intercropping; • Mixed farming, • Reduced or zero till • Cleaner energy sources (renewables, hydrogen)

4.4.2 Agriculture fuel combustion

Diesel is the main fuel used in agriculture. GHG emissions from fuel combustion in agriculture grow (Table 20) as more diesel is consumed for farming as more land area goes under cultivation each year.

In the BAU scenario, the emissions increase by 6% each year over the period 2019 to 2050 based on historical emission trends. Current emission reductions amount to zero (Table 21). Additional emission reductions are due to a switch from diesel to electricity as the main energy source. In the BAU scenario as shown in Figure 29; GHG emissions from agricultural fuel combustion grow unabated without any incentives for a switch to cleaner energy sources. In the CE scenario; GHG emissions are from biomass fuel use in 2050 with the decline in coal and oil fuel consumption (Figure 28). Figure 30 shows the total GHG emissions in the BAU and CE scenarios for fuel combustion in agriculture.

Table 18. Historical emissions from carbon stock change in agriculture 2000 - 2019

Year	**2000**	**2005**	**2010**	**2015**	**2019**
Historical emissions from carbon stock change in agriculture (MtCO$_2$e)	1.79	1.95	2.03	2.06	2.49

Table 19. GHG emissions and emission reductions from 2019 to 2050 in the BAU and CE scenarios from carbon stock change in agriculture

Year	GHG emissions in the BAU Scenario (MtCO$_2$e)	Current CE Emission Reductions (MtCO$_2$e)	Additional CE Emission Reductions (MtCO$_2$e)	GHG emissions in the CE Scenario (MtCO$_2$e)
2019	3.72	-1.23	0	2.49
2030	5.5	-2.72	0	2.78
2040	9.16	-5.61	0	3.55
2050	16.11	-11.56	0	4.55

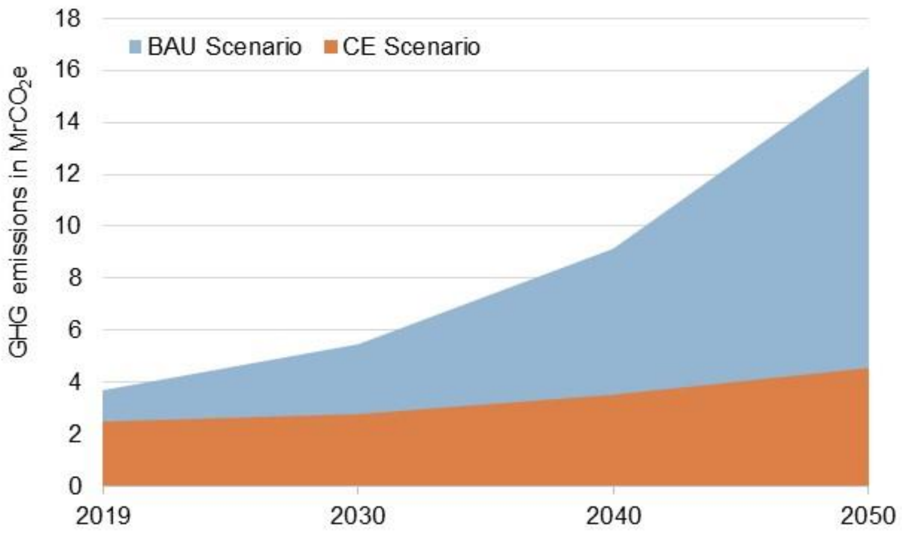


Figure 27. GHG emissions from carbon stock change in agriculture in the BAU and CE scenarios

Table 20. Historical emissions from agriculture fuel combustion 2000 - 2019

Year	**2000**	**2005**	**2010**	**2015**	**2019**
Historical emissions from fuel combustion in agriculture (MtCO$_2$e)	2.46	2.80	3.42	4.01	6.44

Table 21. GHG emissions and emission reductions from 2019 to 2050 in the BAU and CE scenarios from fuel combustion in agriculture

Year	GHG emissions in the BAU Scenario (MtCO$_2$e)	Current CE Emission Reductions (MtCO$_2$e)	Additional CE Emission Reductions (MtCO$_2$e)	GHG emissions in the CE Scenario (MtCO$_2$e)
2019	6.44	0	0	6.44
2030	10.48	0	-0.59	9.89
2040	18.52	0	-1.2	17.32
2050	32.75	0	-1.91	30.84

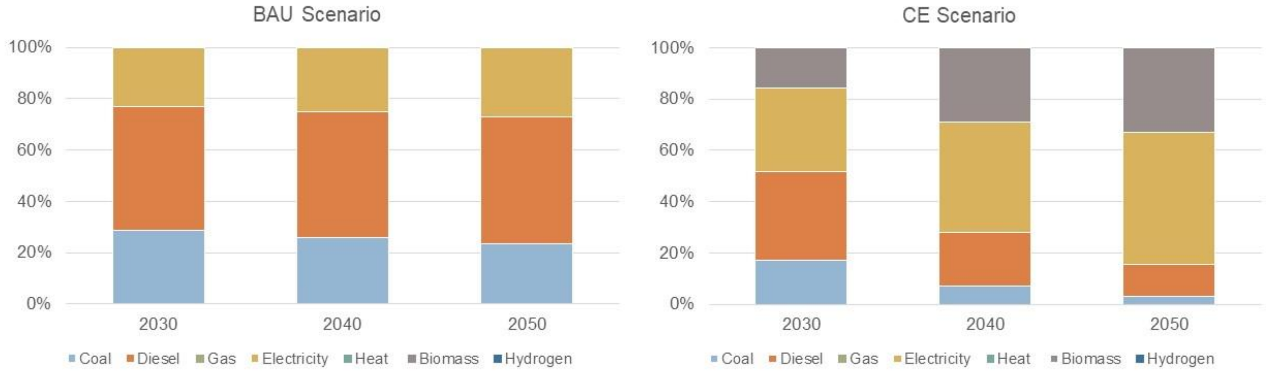


Figure 28. Energy consumption by source for agriculture fuel combustion in the BAU and CE scenarios

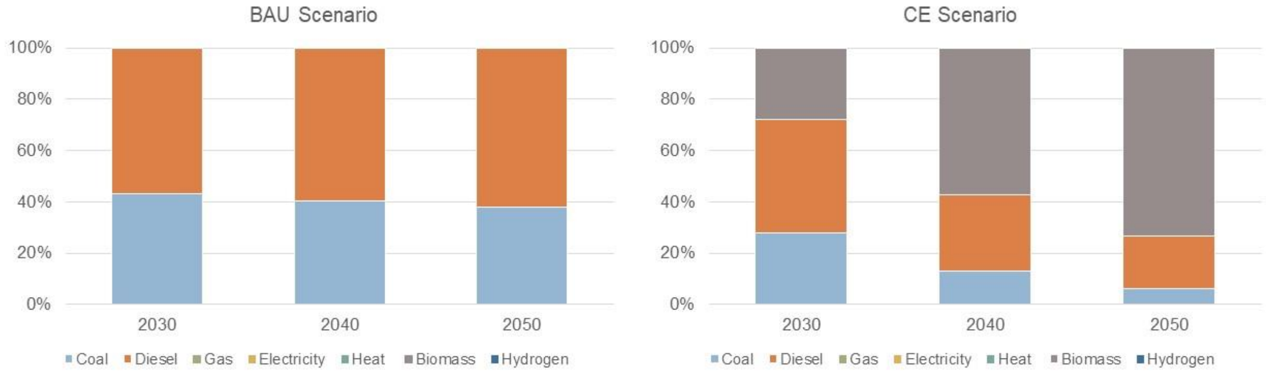


Figure 29. GHG emission by source for agriculture fuel combustion in the BAU and CE scenarios

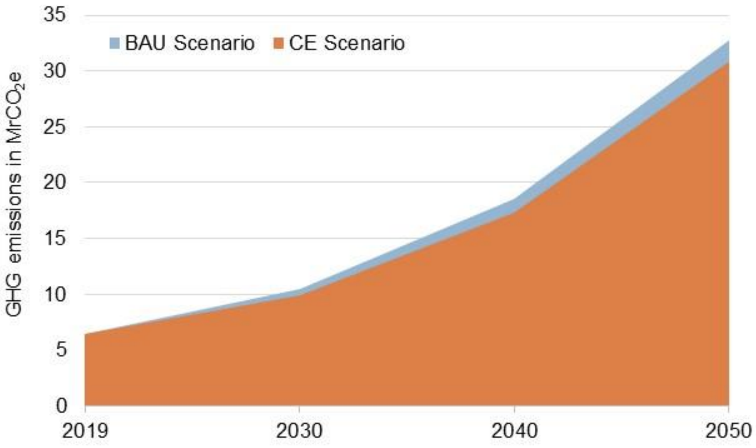


Figure 30. Total GHG emissions from fuel combustion in agriculture in the BAU and CE scenarios

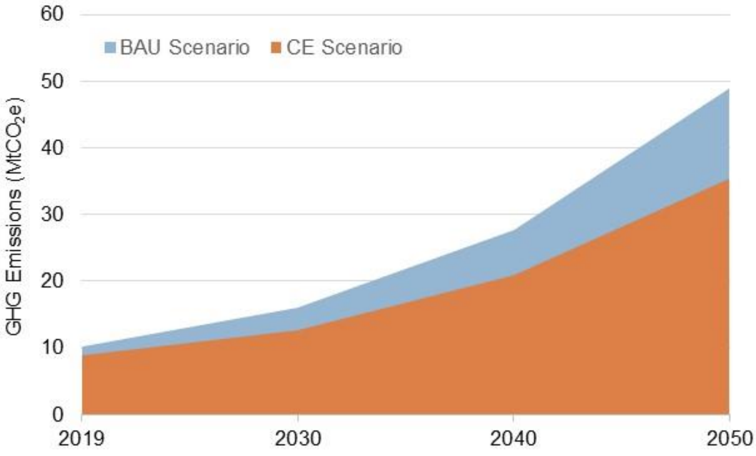


Figure 31. Total GHG emissions in the Agriculture sector in the BAU and CE scenarios

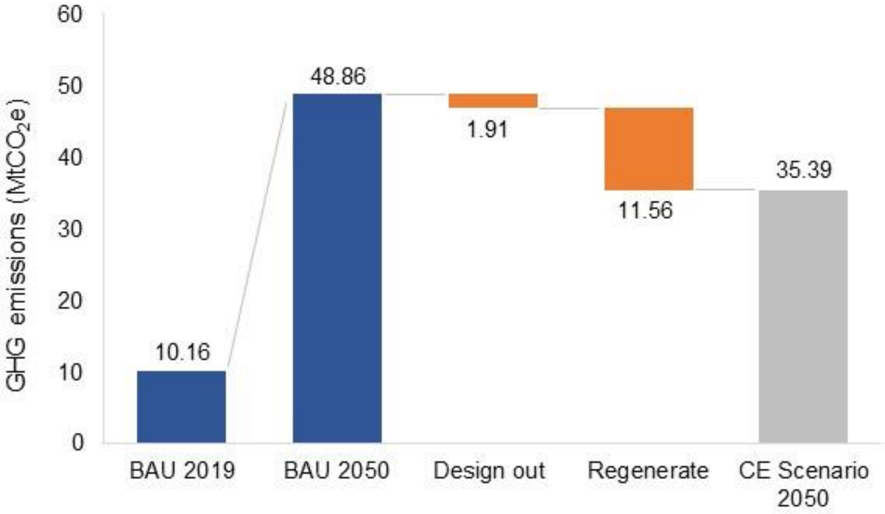


Figure 32. GHG emissions reductions in 2050 due to the effect of circular economy mitigation measures in the Agriculture Sector

4.4.3 Total GHG emissions in agriculture

Figure 31 shows the total GHG emissions in the BAU and CE scenarios in agriculture. Figure 32 shows the scenario emission reductions from zero till and fuel switch in agriculture in relation to the circular economy principles.

4.5 Human Settlements sector

Circular economy measures in the human settlements sector are described in Cooper *et al*. (2021) and are shown in Table 22.

The case modelled for the human settlement sector is linked to a fuel switch from coal to electricity consumption (assuming a net zero electricity energy mix by 2050). Wood, kerosene, coal, diesel and LPG are the main fuel sources consumed in settlements for fuel combustion. GHG emissions from fuel combustion in human settlements decline from 2000 to 2019 (Table 23) as more businesses and households switch to electricity. Overall there is a net 2% increase year-on-year in GHG over this period.

In the BAU scenario, the emissions increase by 2% each year over the period 2019 to 2050 based on historical emission trends. Current emission reductions amount to zero (Table 24). Additional emission reductions are due to a switch from the main fuel sources to electricity (Figure 33) as the main energy source.

GHG emissions in the BAU scenario (Figure 34) are mainly from coal consumption; although there is inclining trend in emissions in this scenario as some businesses and households do not switch to electricity. GHG emissions also increase in the CE scenario as the number of businesses and households that consume fossil fuels are greater than the number of businesses and households which switch to electricity.

As shown in Figure 36; GHG emissions are reduced by -1.04 MtCO$_2$e from 10.24 MtCO$_2$e in the BAU scenario to 9.20 MtCO$_2$e in the circular economy scenario through a combination of measures related to the design out of waste and pollution and the regeneration of natural systems – the direct result of a change in the mix of energy sources used in our human settlements. There is a greater drop in the BAU scenario from 2019 to 2050, as more households and business switch from using coal to electricity instead due to the impact of carbon pricing on the cost of fuels which makes electricity with a low carbon electricity energy mix cheaper than coal.

Table 22. Circular economy measures in the mobility sector (Cooper *et al*., 2021)

Design out waste and pollution	Keep products and materials in use	Regenerate natural systems
• Green, energy-efficient buildings, • More compact cities, • Pedestrian-friendly neighbourhoods • Waste and pollution prevention	• Circular organics • Waste management	• Urban agriculture • Renewable energy • Green roofs • Green open spaces

Table 23. Historical emissions from fuel combustion in human settlements 2000 - 2019

Year	2000	2005	2010	2015	2019
Historical emissions from fuel combustion in human settlements (MtCO$_2$e)	28.22	37.44	15.20	4.75	9.01

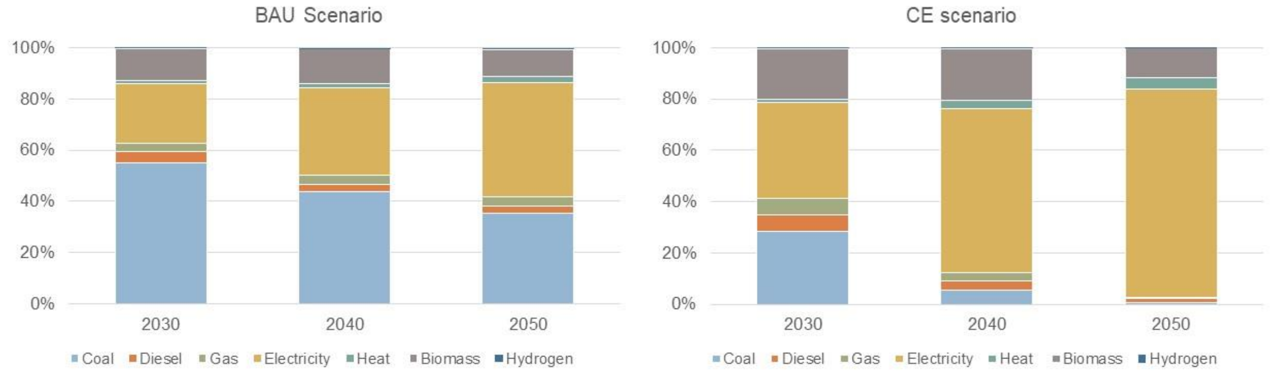


Figure 33. Share of energy consumption by source in the human settlements sector in the (a) BAU and (b) CE scenario

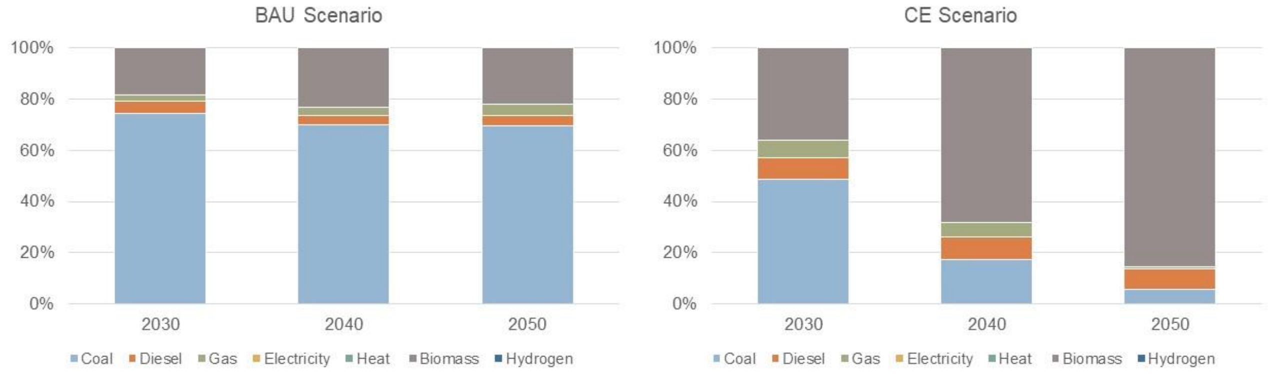


Figure 34. Share of projected GHG emissions by energy source in the human settlements sector for the (a) BAU and (b) CE scenarios

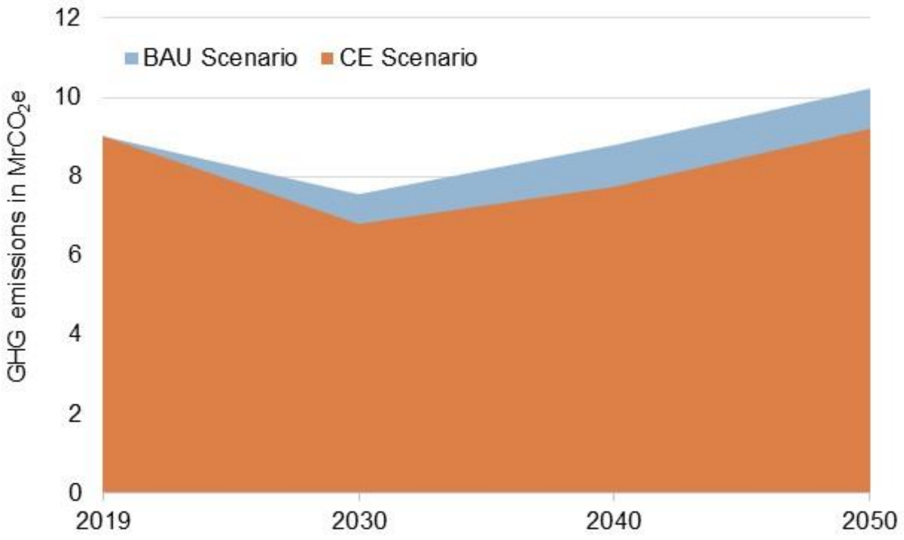


Figure 35. Total GHG emissions in the human settlements sector in the BAU and CE scenarios

Table 24. GHG emissions and emission reductions from 2019 to 2050 in the BAU and CE scenarios from fuel combustion in human settlements

Year	GHG emissions in the BAU Scenario (MtCO$_2$e)	Current CE Emission Reductions (MtCO$_2$e)	Additional CE Emission Reductions (MtCO$_2$e)	GHG emissions in the CE Scenario (MtCO$_2$e)
2019	9.01	0	0	9.01
2030	7.54	0	-0.75	6.79
2040	8.79	0	-1.05	7.74
2050	10.24	0	-1.04	9.20

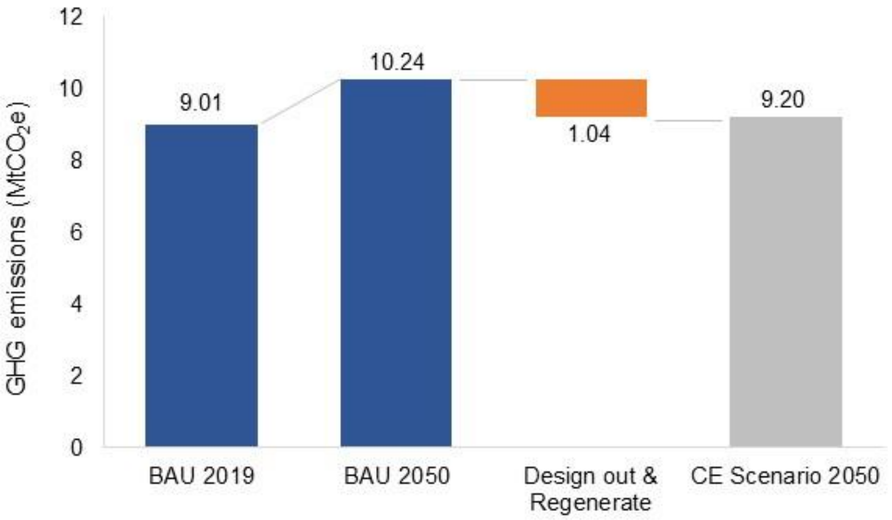


Figure 36. GHG emissions reductions in 2050 due to the effect of circular economy mitigation measures in the Human Settlements Sector

4.6 Water sector

Circular economy measures in the water sector are described in Seetal *et al*. (2021) and are shown in Table 25.

The recovery of methane (CH_4) emitted during wastewater treatment process and utilization for on-site power generation was selected as a case for modelling in the water sector. GHG emissions from wastewater treatment is the sole direct emission source in the water sector. Indirect emission reductions from energy efficiency measures in water management are not considered in this study as it does not reduce direct emissions from electricity generation in the energy sector. Furthermore, the contribution of indirect emission reductions from energy efficiency to mitigation will be much smaller in relation to the emissions reduction contribution from an electricity generation mix dominated by renewable energy sources.

GHG emissions from wastewater treatment are mainly due to CH_4 emissions from anaerobic digesters or sludge treatment processes during wastewater treatment. Historical GHG emissions from wastewater treatment (Table 26) are driven mainly by increases of the population with access to centralised sewage systems services. An increase in the population not serviced by centralised sewage systems will reduce GHG emissions from wastewater treatment.

In the BAU scenario, the emissions decrease by 0.4% each year over the period 2019 to 2050 based on historical emission trends since the population not serviced by centralised sewage systems are more numerous than those with access to centralised sewage treatment services. Current emission reductions amount to zero (Table 27). Additional emission reductions are from the capture and utilisation of CH_4 emitted during wastewater processes for onsite power generation.

GHG emissions in the BAU scenario decrease from 4.13 $MtCO_2e$ in 2019 to 4.00 $MtCO_2e$ in 2050 (Figure 37) as more wastewater is treated in systems which have lower CH_4 emissions, such as closed sewers. In the CE scenario, GHG emissions from wastewater treatment are further reduced due to the recovery and use of CH_4 emissions for on-site power generation.

As shown in Figure 38; GHG emissions are reduced by -2.00 $MtCO_2e$ from 4.00 $MtCO_2e$ in the BAU scenario to 2.00 $MtCO_2e$ in the CE scenario through measures related to keeping products and materials in use.

Table 25. Circular economy measures in the water sector (Seetal *et al*., 2021)

Design out waste and pollution	Keep products and materials in use	Regenerate natural systems
• Reducing water use and wastewater generation • Improved water use efficiency • Better water use practices	• Reuse and recycling of wastewater (return flows) • Reclamation and recovery of resources from water-based waste • Recovery of methane (CH_4) emitted during wastewater treatment process and utilization for on-site power generation	• Improving water flow and quality through the restoration of land by controlling invasive alien plants (IAP) and rehabilitating and protecting wetlands and riparian systems

Table 26. Historical emissions from fuel combustion in wastewater treatment 2000 - 2019

Year	2000	2005	2010	2015	2019
Historical emissions from wastewater treatment ($MtCO_2e$)	4.46	4.31	4.22	3.98	4.13

Table 27. GHG emissions and emission reductions from 2019 to 2050 in the BAU and CE scenarios from wastewater treatment

Year	GHG emissions in the BAU Scenario ($MtCO_2e$)	Current CE Emission Reductions ($MtCO_2e$)	Additional CE Emission Reductions ($MtCO_2e$)	GHG emissions in the CE Scenario ($MtCO_2e$)
2019	4.13	0	0	4.13
2030	4.30	0	-0.7	3.60
2040	4.15	0	-1.2	2.95
2050	4.00	0	-2.0	2.00

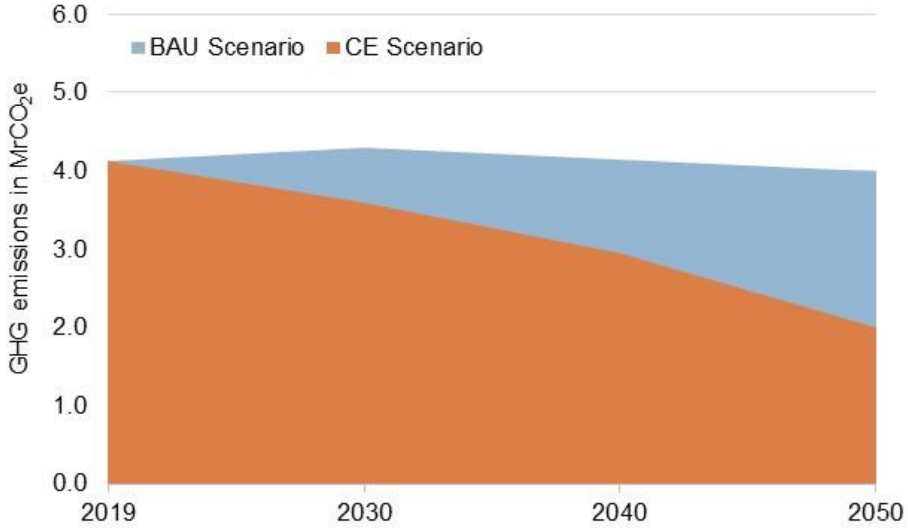


Figure 37. GHG emissions from wastewater treatment in the BAU and CE scenarios

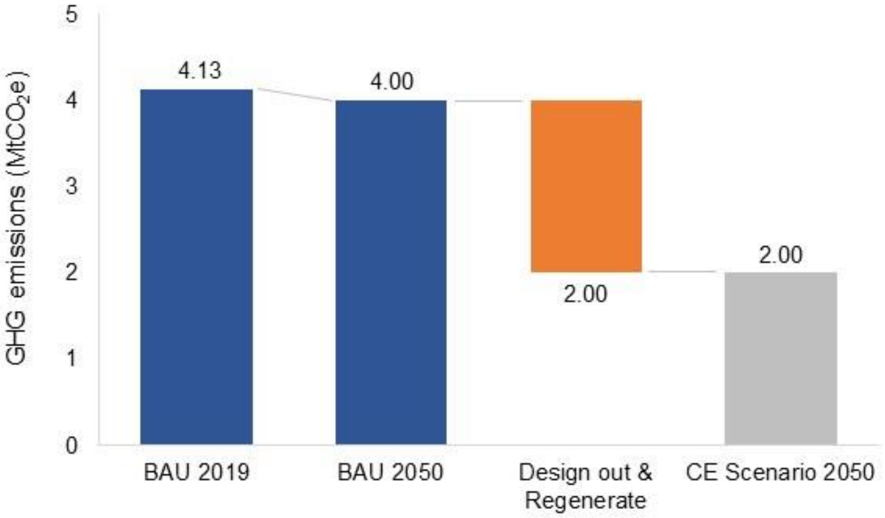


Figure 38. GHG emissions reductions in 2050 due to the effect of circular economy mitigation measures in the Water Sector

4.7 Summary of circular economy mitigation potential

Total sector wide GHG emissions under a BAU scenario are 500.11 $MtCO_2e$ in 2050. Total GHG emissions in the CE scenario are 328.66 $MtCO_2e$. Circular economy measures can reduce GHG emissions in 2050 by 34% from 500.11 $MtCO_2e$ to 328.66 $MtCO_2e$ (Figure 39). Circular economy mitigation is mainly achieved through measures related to a combination of two principles, namely in designing out waste and pollution, and the regeneration of natural systems (both of which are mostly associated with a change in energy generation). The combination of these two principles result in total GHG emission reductions of -161.54 $MtCO_2e$ (Figure 40). GHG emission reductions for keeping products and materials in use amount to -9.91 $MtCO_2e$. By 2050; 94% of mitigation achieved is from designing out waste and pollution and the regeneration of natural systems; while 6% is achieved from industrial energy efficiency and the capture and utilization of CH_4 from wastewater treatment related to keeping products in use.

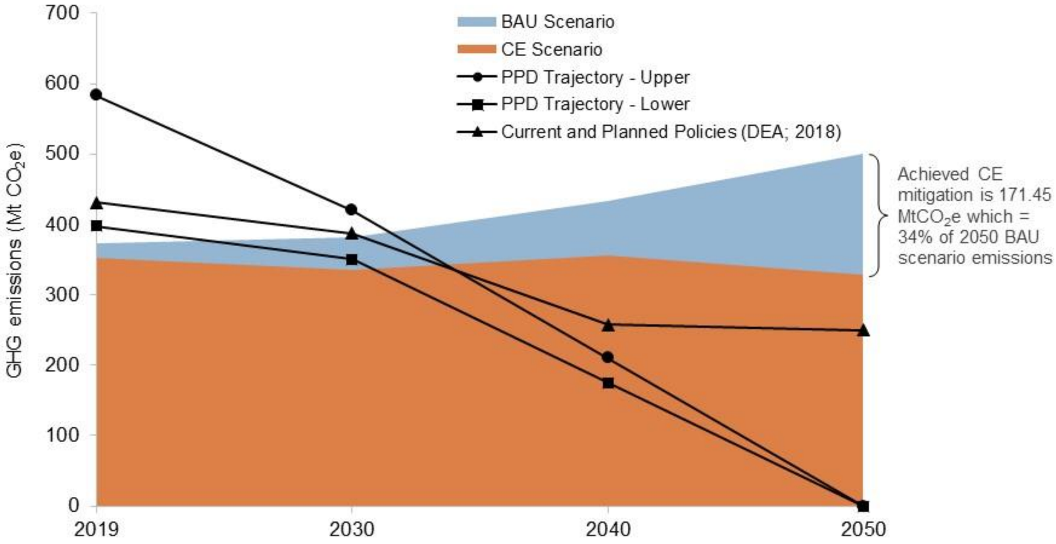


Figure 39. Modelled CE mitigation in relation to South Africa's NDC GHG emissions trajectory to 2050

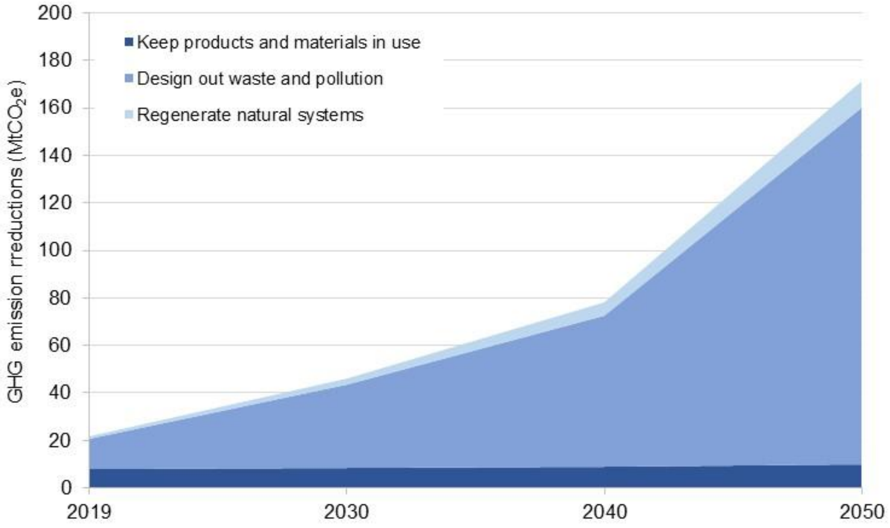


Figure 40. Projected GHG emission reduction pathways of the circular economy

5 Policy opportunities to achieve ambitious circular economy mitigation

5.1 In CE scenario 2050, 92% of the total emission reductions can be attributed to fuel combustion

The Integrated Energy Plan 2016 provides government's long-term policy expectations to 2050 for the final consumption of energy and the generation of electricity. The IRP 2019 (DoE; 2019) is government's medium-term outlook until 2030 for electricity generation and the energy sources required to supply demand. It is important that long-term goals for electricity generation and final consumption related to mitigation are ambitious to achieve the 33% reduction of fuel combustion emissions modelled in the CE scenario. Comparing the current IEP 2016 electricity assumptions to our CE scenario reveals the need for significantly higher shares of renewables and alternative fuels (e.g., hydrogen, biodiesel, biomass) in the updated IEP.

ENERGY SECTOR

Modelling assumption in the IEP 2016	Modelling assumption in this study for circular economy scenario
Coal remains an important energy source in 2050 for electricity generation	Coal consumption is almost eliminated by 2050 and is not an important energy source for electricity generation.
Share of renewables to the energy mix in 2050 is 60% in the "Green Shoots" Scenario	Renewable energy share is about 80% of the electricity energy mix in 2050.
The production of synthetic fuels rises due to increased production of GTL fuels, while CTL fuels maintain their current production levels.	By the year 2050, GTL fuel production will be completely phased out, and the production of CTL fuels will be reduced to only 50% of their current levels. Additionally, there will be a notable transition in the use of synthetic fuels, as cleaner alternatives like hydrogen and biodiesel become increasingly favoured for various applications.

MANUFACTURING AND MINING SECTOR

Modelling assumption in the IEP 2016	Modelling assumption in this study for circular economy scenario
According to the "green shoots" scenario of the IEP 2016, fossil fuel consumption is projected to increase by 5% compared to the fossil fuel consumption in the year 2020.	Hydrogen is modelled as an alternative fuel for the sector. This results in a significant reduction of fossil fuel consumption, which amounts to 69% compared to the levels seen in 2020.
Biomass is not used for fuel combustion in manufacturing or mining	Biomass is used for fuel combustion as an alternative fuel in manufacturing and mining

MOBILITY SECTOR

Modelling assumption in the IEP 2016	Modelling assumption in this study for circular economy scenario
Hydrogen is not a future alternative fuel source for freight and passenger transport.	Hydrogen fuel consumption increases from 0 PJ in 2019 to 73 PJ in 2050.
There is an increase in the consumption of diesel and a smaller decrease in the consumption of petrol	Diesel consumption undergoes a drastic 90% decline, while petrol consumption sees an even more significant reduction of 98% compared to the levels in 2020..
By 2050; there is a small number of electric vehicles on the road which results in a small increase in electricity demand.	Electricity consumption increases by 210 PJ from 2020 to 2050 as electric vehicles becomes the main mode of passenger transportation and a secondary mode of freight transportation.

HUMAN SETTLEMENTS SECTOR

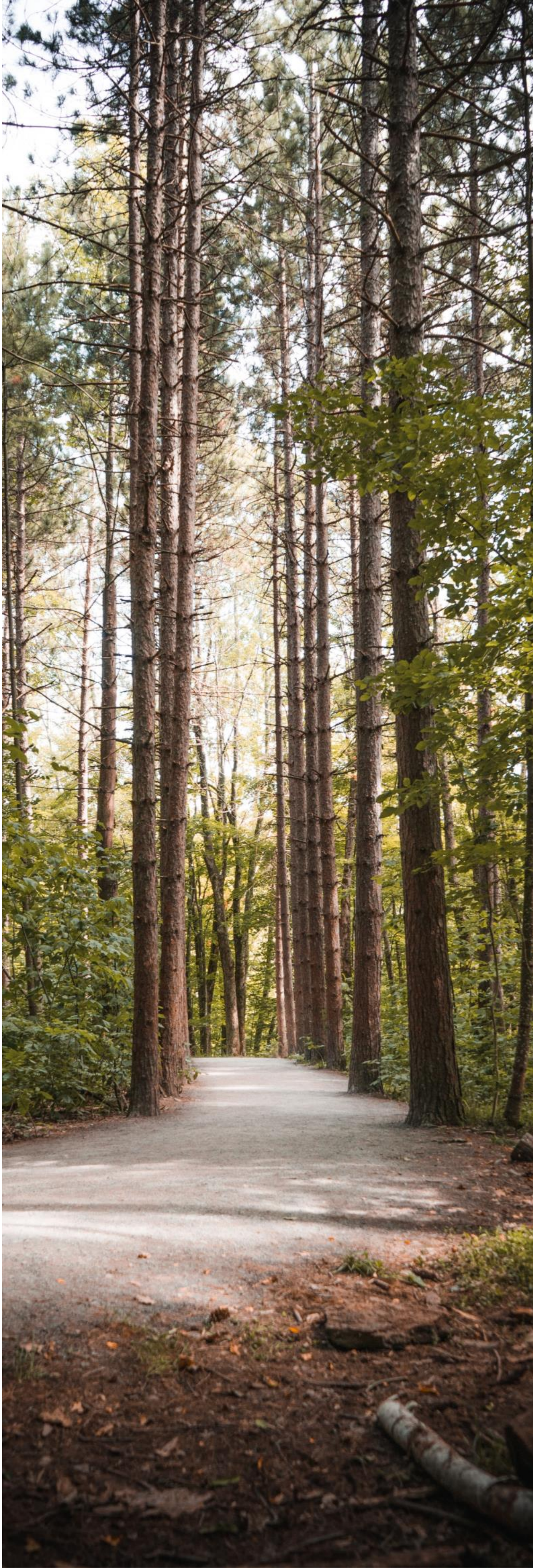
Modelling assumption in the IEP 2016	Modelling assumption in this study for circular economy scenario
The "green shoots" scenario models a 40% increase in coal usage compared to the levels of coal consumption in 2020.	Coal usage is reduced by 99% in 2050.
Electricity demand grows by 400 PJ by 2050 in the "green shoots" scenario	Electricity demand increases by 290 PJ by 2050

5.2 In CE scenario 2050, 7% of the total emission reductions can be attributed to cropland carbon stock change

South Africa ratified the United Nations Convention to Combat Desertification (UNCCD) in 1997. In 2018; the country established voluntary land degradation neutrality targets for 2030 (DEA; 2018c). Improvement of land productivity and soil organic carbon stocks[5] have been set for 6 million hectares of cropland. While the best practice for climate smart agricultural practices and technologies for South Africa have been reviewed and reported in policy (DFFE; 2020); the intensity of implementation per hectare of cropland has not been established. Updates to South Africa's agricultural policy requires inclusion of intensity targets per hectare for climate smart agricultural practices to achieve greater emission reductions. Furthermore, detailed mitigation potential assessments to 2050 of these practices and technologies are needed to inform target setting.

5.3 In CE scenario 2050; 1% of the total emissions reductions can be attributed to wastewater treatment.

The case for methane recovery and utilisation in wastewater to contribute climate change mitigation in the country has been made. Population growth and the increasing number of households with access to sanitation facilities connected to sewage systems will increase GHG emissions from wastewater treatment. As such, methane recovery and utilisation could play a meaningful role in the reduction of GHG emissions in the future. There needs to be clear policy targets established for the retrofitting of existing wastewater treatment plants and inclusion of this technology for planned wastewater treatment plants in future updates of water sector policy.



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[5] Soil organic carbon stocks refer to the amount of carbon stored in the organic matter present in the soil.

6 Conclusions

There is little understanding at present on the potential to enhance South Africa's climate mitigation efforts through the transition to a more circular economy, and the adoption of circular economy interventions across various resource-intensive sectors of the South African economy. This report seeks to address this knowledge gap by providing the first attempt at identifying some of the main opportunities to enhance climate change mitigation through circular economy interventions.

The circular economy sectors included in this study are energy; manufacturing, mining; mobility; agriculture; human settlements; and water. A desktop literature review of local and international circular economy interventions and their potential to address major sources of GHG emissions within the South African economy was undertaken. Interventions were aligned with the three principles of the circular economy to design out waste and pollution, to keep products and materials in use, and to regenerate natural systems.

To gauge GHG emissions reductions that are possible through circular economy interventions by 2050, existing emission reduction methods and potential technological advancements in the business-as-usual scenario were compared to a circular economy scenario. This approach enabled the quantification of emissions reductions achievable through current strategies and the potential reductions attainable with proposed technologies.

From the modelling, it was found that the total sector wide GHG emissions in the BAU scenario are 500.11 $MtCO_2e$ in 2050. Total GHG emissions in the circular economy scenario are 328.66 $MtCO_2e$. Circular economy measures can reduce GHG emissions in 2050 by 34% from 500.11 $MtCO_2e$ to 328.66 $MtCO_2e$. As the circular economy is defined currently in South Africa (Godfrey, 2019); mitigation is mainly achieved through an ambitious overhaul of South Africa's energy resources – reflected in the circular economy principles of designing out waste and pollution, and regenerating natural systems (Figure 41). The combination of these two principles result in total GHG emission reductions of -161.54 $MtCO_2e$. The mitigation effects of circular economy measures are significant as shown in this study and highlights that climate mitigation is a driver for South Africa to transition to a more circular economy.

The energy sector has the largest emission reduction potential of -75.85 $MtCO_2e$. Sizable contributions to mitigation are achieved through ambitious changes in the use of energy resources in the manufacturing, mining and construction sector (-44.51 $MtCO_2e$); mobility sector (-34.58 $MtCO_2e$) and in the agriculture sector (-13.47 $MtCO_2e$). Included in the total emission reductions are 8.60 $MtCO_2e$ already aimed at reducing GHG emissions from the BAU 2019 to the BAU 2050.

This study represents the first attempt to quantify the climate change mitigation potential of the circular economy in South Africa. The evidence generated through this study aligns with findings from international research that there is merit in seeking to align climate change and circular economy policies and practices.

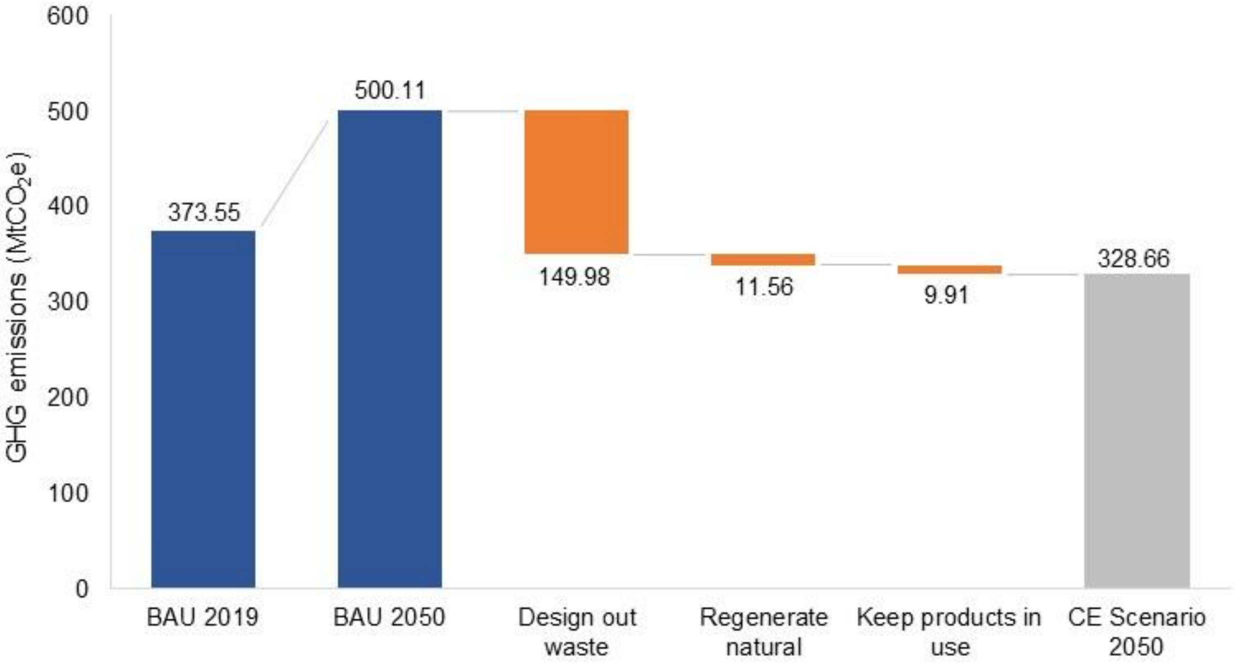

Figure 41. Reduction of GHG emissions in 2050 through circular economy principles (in $MtCO_2e$)

In the absence of a national circular economy strategy, there is currently little official guidance on what a circular economy future could look like for South Africa, and the level of ambition of that future. As such, the type of circular interventions and the magnitude of those interventions, adopted for the CE scenario, were informed by existing literature about South Africa's Just Energy Transition and Net Zero Pathway which largely focussed on the generation and usage of energy resources. Achieving the full potential of a circular economy transition would therefore need greater clarity on the specific circular interventions to be implemented in future, to allow for greater detail, and accuracy, in the climate mitigation potential modelling.

The study has also highlighted that there are currently gaps in the knowledge of circular economy mitigation effects particularly those aligned with the principles of keeping products and material in use, and regenerating natural systems. More specifically the mitigation effects of intensified embedded generation, green hydrogen, solid waste management in non-specified industries, and land restoration and rehabilitation, which are lesser known. It is also suspected that there are significant opportunities within embodied emissions – in the materials we use, how we build infrastructure, and in our urban design – creating more resilient, sustainable and liveable urban spaces. Due to limitations in data availability this lead to the consumption based emission accounting approach applied in this study. An embodied emissions accounting approach could not be applied as we do not know the full picture of the effect of emerging technologies on supply and use of products and materials in the country's economy. Albeit this supports the need for an in-depth economic modelling analysis of the embodied consumption of emerging technologies within the supply and use of products and materials (which was not part of the scope of this study).

A key limitation of this study is thus that not all emission sources could be accounted for in the modelling of GHG emissions as these emission sources have not been conceived as part of the circular economy before, or visa versa. The emissions reduction potential estimated in this study for the CE 2050 scenario, while being very ambitious in terms of the levels of interventions, are not complete. As such, the mitigation potential of a circular economy transition, as outlined in this report, is considered to be a conservative estimation, given that detailed modelling for many circular economy interventions have not yet been conducted in South Africa.

Further research is needed to update and expand the definition of each circular economy sector to align these with the larger emission sources and sinks in the country and thus account for these GHG emissions. This would for example include livestock emissions within the agriculture sector, fuel use in non-specified industries, carbon sequestration in the forestry sector, and hydrofluorocarbon usage for industrial processes,. These additional studies would provide a holistic perspective of the mitigation effects of circular economy measures towards the country reaching net zero carbon emissions by 2050.

Given the potential for a more circular South African economy to significantly reduce future GHG emissions, thereby contributing to national climate commitments and policy objectives, there may be an opportunity to tap into global climate funding to support South Africa's transition to a more circular, low-carbon economy, And with it, unlock much needed socio-economic opportunities for the country.

Findings from further research need to be integrated into updates to South Africa's sectoral policy particularly related to energy production and generation. Unpacking the opportunities to transition to cleaner energy sources in the medium- to long-term will help clarify how the country will achieve ambitious mitigation and in doing so decouple economic development from being chiefly reliant on natural resource exploitation.

Conceptually the circular economy approach requires further crafting for the South African development context and its diverse local economies; so that mitigation can become embedded at the grassroots level and made achievable for citizens to implement within all sectors of society.

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8 Glossary

Activity data	Data on the magnitude of a human activity resulting in emissions or removals taking place during a given period of time. Data on energy use, metal production, land areas, management systems, lime and fertilizer use**,** and waste arisings are examples of activity data.
Anaerobic	Conditions in which oxygen is not readily available. These conditions are important to produce methane emissions. Whenever organic material decomposes in anaerobic conditions (in landfills, flooded rice fields, etc.) methane is likely to be formed.
Carbon dioxide equivalent emission	The amount of carbon dioxide (CO_2) emission that would cause the same integrated radiative forcing or temperature change, over a given time horizon, as an emitted amount of a greenhouse gas (GHG) or a mixture of GHGs. There are a number of ways to compute such equivalent emissions and choose appropriate time horizons. Most typically, the CO_2-equivalent emission is obtained by multiplying the emission of a GHG by its global warming potential (GWP) for a 100-year time horizon.
Carbon sequestration	The process of storing carbon in a carbon pool.
Carbon stock change	Total carbon stock change refers to the overall net difference for carbon stored within a specific ecosystem or across multiple ecosystems over a given period. It represents the balance between carbon uptake and carbon release by natural processes and human activities.
Emission factor	A coefficient that quantifies the emissions or removals of a gas per unit activity. Emission factors are often based on a sample of measurement data, averaged to develop a representative rate of emission for a given activity level under a given set of operating conditions
Emissions	The release of greenhouse gases and/or their precursors into the atmosphere over a specified area and period of time
Fuel combustion	Intentional oxidation of materials within an apparatus that is designed to provide heat or mechanical work to a process, or for use away from the apparatus
Fugitive emissions from Energy Production	Fugitive emissions from synfuels and gas-to liquids/chemicals processes
Fugitive Emissions (oil and natural gas systems)	The intentional or unintentional release of greenhouse gases that occur during the exploration, processing, and delivery of fossil fuels to the point of final use. This excludes greenhouse gas emissions from fuel combustion to produce useful heat or power. It encompasses venting, flaring, and leaks
Global warming potential	Global Warming Potentials (GWP) are calculated as the ratio of the radiative forcing of one kilogramme greenhouse gas emitted to the atmosphere to that from one kilogramme CO_2 over a period of time (e.g., 100 years).
Manufacture of Solid Fuels	Fuel combustion for the production of coke, brown coal briquettes and patent fuel
Non-specified stationary fuel combustion	Fuel combustion for the production of charcoal
Non-energy products	Primary or secondary fossil fuels which are used directly for their physical or diluent properties. Examples are: lubricants, paraffin waxes, bitumen, and white spirits and mineral turpentine (as solvent).
Petroleum refining	Petroleum refining is an industrial process in which crude oil is transformed into products that include liquefied petroleum gas (LPG), petrol, diesel, kerosene, fuel oils and bitumen, amongst others.

Public Electricity Generation	Electricity generation involves the conversion of fossil fuels (coal, oil, gas etc.) into electrical energy.
Other Energy Industries	Combustion emissions arising from the energy-producing industries own (on-site) energy use not mentioned above or for which separate data are not available. This includes the emissions from own-energy use to produce charcoal, bagasse, saw dust, cotton stalks and carbonizing of biofuels as well as fuel used for coal mining, oil and gas extraction and the processing and upgrading of natural gas.
Other emissions from Energy Production	Fugitive emissions from synfuels including Coal-to-Liquid (CTL) and Gas-to-Liquid (GTL) Fuels
Sink	Any process, activity or mechanism which removes a greenhouse gas, an aerosol, or a precursor of a greenhouse gas from the atmosphere. Notation in the final stages of reporting is the negative (-) sign
Source	Any process or activity which releases a greenhouse gas, an aerosol or a precursor of a greenhouse gas into the atmosphere. (UNFCCC Article 1.9) Notation in the final stages of reporting is the positive (+) sign.

Appendix A Emission Factors and Global Warming Potentials

Default and Country Specific Emission factor list applied in the study[6]. Country specific emission factors were preferred as these are the most up to date.

Table A.1: Default Emission Factors and Net Calorific Values for Stationary Combustion – (solid, liquid and gaseous fuels)[1]

Fuel Type	**CO_2**	**CH_4**	**N_2O**	**Default calorific value**
	($kgCO_2$/TJ)	($kgCH_4$/TJ)	(kgN_2O/TJ)	(TJ/Tonne)
Anthracite	98,300	1	1.5	0.0267
Aviation Gasoline	70,000	3	0.6	0.0443
Acetylene	67,870	NA	NA	0.049818
Biodiesel	70,800	3	0.6	0.027
Biogasoline	70,800	3	0.6	0.027
Bitumen	80,700	3	0.6	0.0402
BLast Furnace Gas	260,000	1	0.1	0.00247
Brown Coal Briquettes	97,500	1	1.5	0.0207
Charcoal	112,000	200	4	0.0295
Coal Tar	80,700	1	1.5	0.028
Coke Oven Coke & Lignite Coke	107,000	1	1.5	0.0282
Coke Oven Gas	44,400	1	0.1	0.0387
Coking Coal	94,600	1	1.5	0.0282
Crude Oil	73,300	3	0.6	0.0438
Diesel	74,100	3	0.6	0.043
Ethane	61,600	1	0.1	0.0464
Gas Coke	107,000	1	0.1	0.0173
Gas Works Gas	44,400	1	0.1	0.0387
Industrial Wastes	143,000	30	4	NA
Jet Gasoline	70,000	3	0.6	0.0443
Jet Kerosene	71,500	3	0.6	0.0441
Landfill Gas	54,600	1	0.1	0.0504
Lignite	101,000	1	1.5	0.0119
Liquefied Petroleum Gases	63,100	1	0.1	0.0473
Lubricants	73,300	3	0.6	0.0402
Municipal Wastes (Biomass Fraction)	100,000	30	4	0.0116
Municipal Wastes (Non Biomass Fraction)	91,700	30	4	0.01
Naphtha	73,700	3	0.6	0.0445
Natural Gas	56,100	1	0.1	0.048
Natural Gas Liquids	64,200	3	0.6	0.041
Oil Shale & Tar Sands	107,000	1	1.5	0.0089
Orimulsion	77,000	3	0.6	0.0275
Other Biogas	54,600	1	0.1	0.0504
Other Bituminous Coal	94,600	1	1.5	0.0192
Other Kerosene	71,900	3	0.6	0.037
Other Liquid Biofuels	79,600	3	0.6	0.0274
Other Petroleum Products	73,300	3	0.6	0.0402
Other Primary Solid Biomass	100,000	30	4	0.0116
Oxygen Steel Furnace Gas	182,000	1	0.1	0.00706
Paraffin	71,900	3	0.6	0.0438
Paraffin Waxes	73,300	3	0.6	0.0402
Patent Fuel	97,500	1	1.5	0.0207
Peat	106,000	1	1.5	0.00976
Petrol	69,300	3	0.6	0.0443
Petroleum Coke	97,500	3	0.6	0.0325
Refinery Feedstock	73,300	3	0.6	0.043
Refinery Gas	57,600	1	0.1	0.0495
Residual Fuel Oil (Heavy Fuel Oil)	77,400	3	0.6	0.0404
Shale Oil	73,300	3	0.6	0.0381
Sludge Gas	54,600	1	0.1	0.0504
Sub-Bituminous Coal	96,100	1	1.5	0.0192

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[6] DFFE (2022). National Environmental Management: Air Quality Act (39/2004): Methodological Guidelines for Quantification of Greenhouse Gas Emissions. Government Gazette No 47257, Notice 2598. Pretoria, South Africa

Fuel Type	CO_2	CH_4	N_2O	Default calorific value
	(kgCO_2/TJ)	(kgCH_4/TJ)	(kgN_2O/TJ)	(TJ/Tonne)
Sulphite Lyes (Black Liquor)	95,300	3	2	0.0118
Waste Oils	73,300	30	4	0.0402
Waste Tyre	88,400	1	1,5	0.0325[52]
White Spirit & SBP	73,300	3	0.6	0.0402
Wood/Wood Waste	112,000	30	4	0.0156

Table A.2: Default emission factors and net calorific values for mobile combustion[1]

Fuel Type	CO_2	CH_4	N_2O	Default calorific value
	(kgCO_2/TJ)	**(kgCH_4/TJ)**	**(kgN_2O/TJ)**	**(TJ/Tonne)**
Aviation Gasoline	70,000	0.5	2	0.0443
Compressed Natural Gas	56,100	92	3	N/A
Diesel	74,100	4.15	28.6	0.0381
Diesel - (Ocean-Going Ships)	74,100	7	2	0.0381
Diesel -Offroad	74,100	3.9	3.9	0.0381
Diesel-Rail	74,100	4.15	28.6	0.0381
Jet Kerosene	71,500	0.5	2	0.0441
Kerosene	71,900	3	0.6	0.037
Liquefied Natural Gases	56,100	92	3	NA
Liquefied Petroleum Gas	63,100	62	0.2	0.0473
Lubricants	73,300	3	0.6	0.0402
Natural Gas	56,100	92	3	0.048
(Paraffin) Other Kerosene	71,900	3	0.6	0.0438
Other Petroleum Products	73,300	3	0.6	0.0402
Paraffin Waxes	73,300	3	0.6	0.0402
Petrol	69,300	3.5	5.7	0.0443
Petrol-Oxidation Catalyst	69,300	25	8	0.0443
Petrol-Uncontrolled	69,300	33	3.2	0.0443
Refinery Gas	57,600	1	0.1	0.0495
Residual Fuel Oil - (Heavy Fuel Oil)	77,400	7	2	0.0404
Sub-bituminous Coal – Rail	96,100	2	1.5	0.0192
White Spirit & SBP	73,300	3	0.6	0.0402
Biodiesel	70,800	4.15	28.6	0.027
Biogasoline	70,800	3.5	5.7	0.027

Table A.3: Country specific CO_2 emission factors for stationary and mobile combustion[1]

Fuel Type	CO_2
	(kgCO2/TJ)
Aviation Gasoline	65,752
Diesel	74,638
Heavy Fuel Oil	73,090
Jet Kerosene	73,463
LPG	64,852
Paraffin	64,640
Petrol	72,430
Refuse Derived Fuel	83,000
Sasol Methane Rich Gas (MRG)	54,888

Table A.4: Global warming potential (GWP) of greenhouse gases used in this report and taken from IPCC SAR (Source: IPCC, 1996)[7].

Greenhouse gas	Chemical formula	Second Assessment Report Global Warming Potential
Carbon dioxide	CO_2	1
Methane	CH_4	21
Nitrous oxide	N_2O	310

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[7] IPCC, 1996. Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Houghton, J.T.; Meira Filho, L.G.; Callander, B.A.; Harris, N.; Kattenberg, A.; Maskell, K., (eds.), Cambridge University Press.