TRADE & INDUSTRIAL POLICY STRATEGIES

MITIGATION OPTIONS FOR SOUTH AFRICA'S PETROCHEMICAL VALUE CHAIN

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Trade & Industrial Policy Strategies (TIPS) is a research organisation that facilitates policy development and dialogue across three focus areas: trade and industrial policy, inequality and economic inclusion, and sustainable growth

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ABBREVIATIONS

Bio-PE	Bio-based polyethylene
CAIA	Chemical & Allied Industries' Association
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CDM	Clean Development Mechanism
CPH	Combined Heat and Power
CSIR	Council for Scientific and Industrial Research
CFL	Compact Fluorescent Lamp
CTL	Coal-to-Liquids
DEFF	Department of Environment, Forestry and Fisheries
DHC	District Heating and Cooling
DSI	Department of Science and Innovation
DST	Department of Science and Technology
dtic (the)	Department of Trade, Industry and Competition (formerly Department of Trade and Industry)
EnMS	Energy Management Systems
ESO	Energy Systems Optimisation
EU	European Union
FCC	Fluid Catalytic Cracking
GHG	Greenhouse Gas
GTL	Gas-to-Liquids
HFC	Hydrogen Fuel Cell
HVCs	High-Value Chemicals
HySA	Hydrogen South Africa
IDZ	Industrial Development Zone
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
LED	Light Emitting Diode
LPG	Liquefied Petroleum Gas
MACC	Marginal Abatement Cost Curves
MEAs	Membrane Electrode Assemblies
NAFTA	North American Free Trade Agreement
NCPC-SA	National Cleaner Production Centre South Africa
NERSA	National Energy Regulator of South Africa
NGLs	Natural Gas Liquids
ORC	Organic Rankine Cycle
OSAR	Osho SA Recycling

SEA	Strategic Environmental Assessment
PBT	Polybutylene Terephthalatetics
PET	Polyethylene Terephthalate
PGMs	Platinum Group Minerals
PHA	Polyhydroxyalkanoates
PI	Process intensification
PLA	Polylactic Acid
PV	Photovoltaic
REDISA	Recycling and Economic Development Initiative of South Africa
REIPPP	Renewable Energy Independent Power Producer Procurement
ROMPCO	Republic of Mozambique Pipeline Investments Company
SAASTA	South African Agency for Science and Technology Advancement Steering Committee
SACCCS	South African Centre for Carbon Capture & Storage
SANRAL	South African National Roads Agency
SEIAS	Socio Economic Impact Assessment System
RTS	Reference Technology Scenario
NACAG	Nitric Acid Climate Action Group
VOC	Volatile Organic Compound
VSDs	Variable Speed Drives
WMB	Waste Management Bureau
WtE	Waste-to-Energy
Bbl	barrel per day
CO_2	carbon dioxide
GJ	gigajoules
Km	kilometre
Kt	kilotons
$MtCO_2e$	million metric tonnes of carbon dioxide equivalents
Mtpa	million ton per annum
MW	megawatt
N_2O	nitrous oxide
NO_x	nitrogen oxide
SO_x	sulfur oxides
tCO2e	tonnes of carbon dioxide equivalent
TJ	terajoules

1. INTRODUCTION

The petrochemical industry in South Africa is unique with strong linkages into numerous downstream chemical and end-user markets domestically and internationally. The products that stem from the industry are vital as they enable the production of essential goods, such as clothing, medicine, housing and transportation. In addition, the sector provides industrial consumers with plastics, rubber and numerous other industrial products. Without the petrochemical industry, the economy in its current form could not feasibly operate. However, both globally and in South Africa, the petrochemical industry is highly reliant on fossil fuel inputs such as coal, oil and natural gas. With the climate crisis being prioritised globally, much focus has been placed on highly emitting sectors such as the petrochemical industry.

Growing concerns around climate change are forcing the petrochemical industry to revise its energy use for the future and assess its process routes. A further constraint is the industry's vulnerability to climate policies and variable fossil fuels prices, as it is highly dependent on these for energy and as a chemical feed stock. In the modern petrochemical industry, about half of the operating costs are due to feedstock inputs for energy and raw materials. Complex integration with fossil fuels makes the petrochemical industry uniquely challenged in the climate change landscape, and it is vital to understand the nuances of this industry from a climate perspective if climate-compatible policies are to be developed.

South Africa's unique and high dependence on coal feedstock creates a significant problem from a transition point of view, as coal is the highest emitter of carbon dioxide (CO_2) when combusted, compared to other fossil fuels. Substantial investments in coal have placed the economy on an unsustainable development pathway. Increasingly, global climate and trade policy seek to penalise countries and value chains that are carbon intensive. If South Africa does not speed up efforts to decarbonise the petrochemical value chain, the country faces real risks in the future around foreign investments, trade and development.

This paper seeks to add to the discourse on climate change mitigation in the petrochemical industry in South Africa, through a broad evaluation of the mitigation interventions available. For the purposes of the analysis, the scope is confined to the base and performance chemicals that are produced from the petrochemicals complex and does not include liquid fuels.

Section 2 presents an overview of the petrochemical value chain in South Africa and the climate challenges within the value chain.

Section 3 considers the current available mitigation measures in terms of their technological development, barriers and rollout in South Africa. The interventions include energy efficiency measures, which cover combined heat and power, carbon capture, and nitrogen oxide ($NO_{x)}$ mitigation technologies. Feedstock substitution options are also considered, which relate to increasing the use of natural gas, biomaterials and green hydrogen. Circular economy interventions which relate to the recycling of plastic and rubber are also discussed.

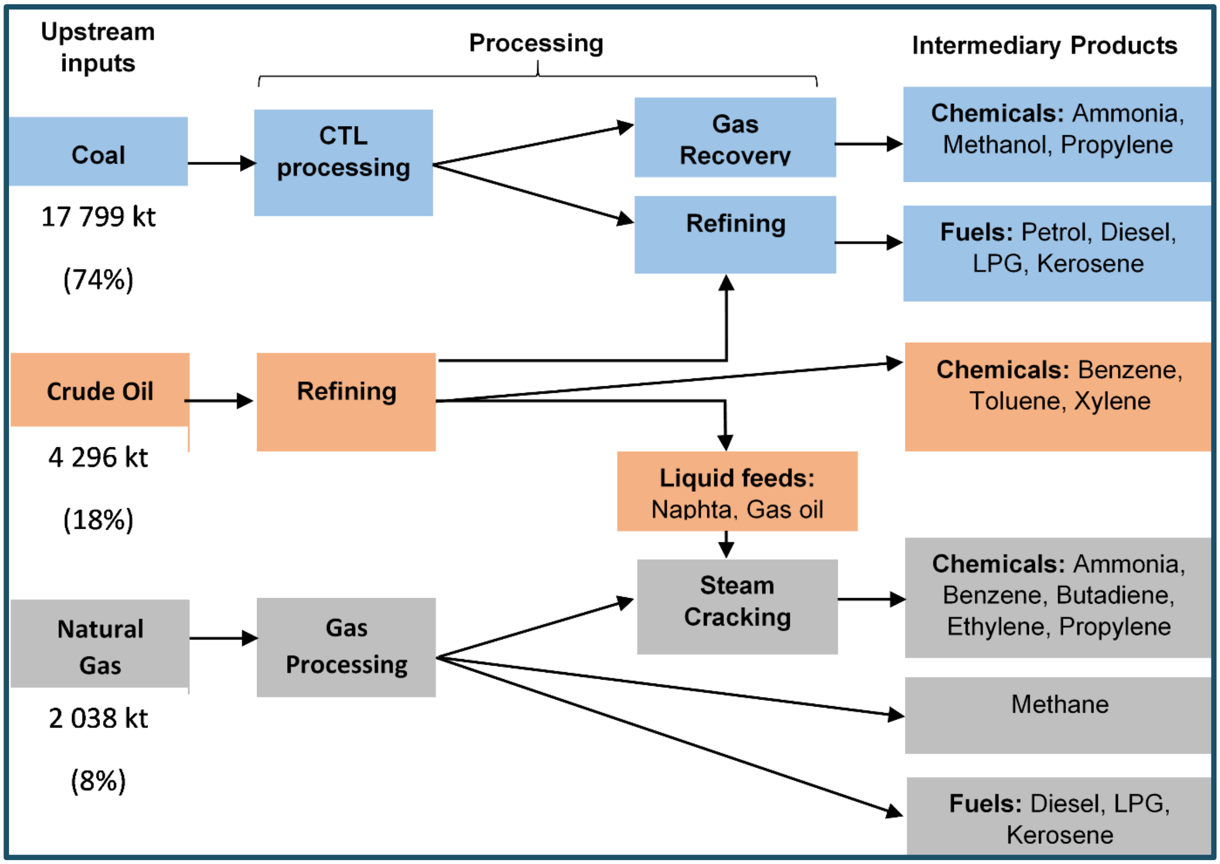
The benefits, risks and implementation requirements to various stakeholders are then explored in Section 4 for various mitigation pathways.

Section 5 concludes.

2. OVERVIEW OF THE VALUE CHAIN AND CLIMATE ISSUES

The petrochemicals value chain consists of three primary stages: (i) primary inputs/feedstock: (ii) the processing of these inputs into intermediary products; and (iii) the final processing of intermediaries into end-products. The petrochemicals industry produces a vast array of end-products with diverse uses. In the upstream, for example, Sasol, produces over 200 chemicals (Sasol, n.d.-a).

Figure 1. Petrochemical processing routes based on Sasol's feedstock use



Source: TIPS, based on (Sasol, 2018), (Sasol, 2020), (Mangena, 2012), and (Academic Room, 2013).
Notes: 1. Material use is indicated below each feedstock in both kilotons and percentage of fossil fuel inputs on the basis of average consumption over the period 2017 to 2020. 2. Percentages indicated are based only on fossil fuel material use and exclude nitrogen, oxygen and other marginal chemical and feedstock inputs.

2.1 Feedstock inputs

Hydrocarbons are required for petrochemical production and these hydrocarbons are naturally present in compounds such as coal, natural gas and crude oil. Three principal feedstock materials feature in South Africa, with coal dominating the feedstock mix.

Coal

Historically, the evolution of South Africa's petrochemicals industry was spurred on by the country's mining activities and its natural endowment of coal reserves (Majozi and Veldhuizen, 2015). This historical endowment of coal, combined with international sanctions during apartheid era, led to the petrochemicals sector being principally dependent on coal-to-liquids (CTL) as a technology to produce petrochemicals. Out of that legacy emerged the Sasol Secunda plant, which is the largest CTL plant in the world, and is a unique feature of the international petrochemicals landscape. Currently, 25%[1] of South Africa's liquid fuels is developed through coal gasification (SAPIA, 2019). Sasol is vertically integrated through its Sasol Mining operations, which owns five mines in Secunda and a mine near Sasolburg (Sasol, 2017a). These mines provide the coal feedstock to Sasol plants to produce petrochemicals.

Oil

Oil is a relatively easily handled liquid and an alternate feedstock with which fuels and chemicals can be produced (Bennett and Page, 2017). Firms in the upstream petrochemical market such as Sasol and Engen import and refine crude oil in addition to producing petrochemical products. The lion's share (86%) of crude oil is imported from three countries – Saudi Arabia (36%), Nigeria (31%), and Angola (19%).

Natural gas

The third type of feedstock used to produce petrochemicals is natural gas. Natural gas contains pure natural gas (methane), natural gas liquids (NGLs) and impurities including CO_2 and water (World Bank, 2009). A growing source of petrochemical production globally, natural gas is valued for its lower greenhouse gas (GHG) emissions compared to crude oil and coal (Bennett and Page, 2017). A barrier to the use of natural gas, however, is the cost of transport, thus firms which have used natural gas as an input have generally sourced natural gas from sources close to the production site. In South Africa, prior to 2004, all of the natural gas was sourced from the Mossel Bay fields, and the gas was principally used to produce liquid fuels by PetroSA in Mossel Bay (Energy Research Centre, 2017). In 2004, Sasol began importing natural gas from Mozambique and this accounts for most of natural gas sources in South Africa, and the only source of imports currently (the dti, 2017; Energy Research Centre, 2017).

There has been interest in investments into additional gas importation infrastructure over the past decade such that South Africa can tap into international gas supply markets, however substantial investments into importation and pipeline infrastructure have yet to materialise. Ports such as Coega and Richard's Bay have been identified as potential import destinations.

For domestic gas reserves, two new gas discoveries hold potential for domestic gas extraction. The Brulpadda gas discovery was announced by Total SA in February 2019, holding a potential one billion barrels of gas, 275 km south of Mossel Bay (Wasserman, 2019; Total, 2019). More recently, the Luiperd gas discovery was announced by Total in the same geographic region, and has been widely reported and celebrated in the local upstream oil and gas industry (Total, 2020).

2.2 Upstream processing

Production in the petrochemical upstream is mainly controlled by Sasol in South Africa. Sasol has become a vertically-integrated energy and chemicals company that procures fossil-fuel-based energy feedstock inputs and processes these into liquid fuels and a vast array of chemicals, which feed into downstream industries such as plastics, fertilisers and explosives. As indicated, the focus of the analysis is placed on

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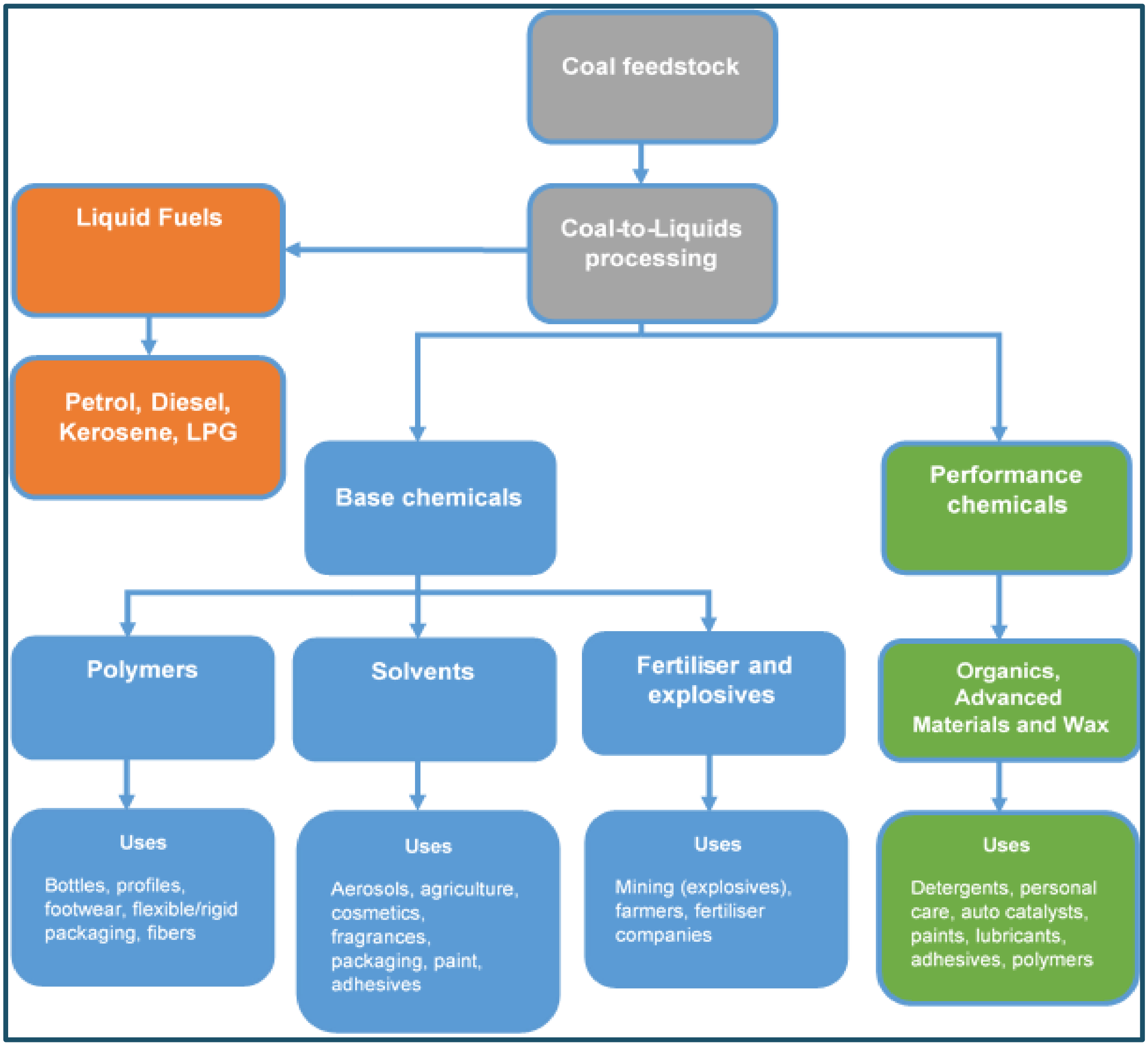
[1] Based on production capacity barrel per day (bbl/day) of Sasol refining (150 000 bbl/day) as a proportion of total refining capacity in South Africa (718 000 bbl/day) for the period 2016-2019.

base and performance chemicals; however for completeness the liquid fuels product stream is also indicated in Figure 2. Sasol's coal processing activities are concentrated in Secunda in Mpumalanga.

Figure 2. Petrochemicals products from CTL processing



Source: TIPS, based on Sasol, 2019a, n.d., n.d.

Sasol pioneered CTL technology in the mid-20th century in South Africa, producing liquid fuels through the patented Fischer-Tropsch process. Unlike oil and natural gas, solid coal has to be converted through a process known as gasification prior to chemical manufacture (Bennett and Page, 2017). This gasification converts carbon materials into syngas, which is then converted into liquid and wax products that can be further converted into synthetic fuels. Over time, Sasol has diversified its product offering to include by-products from the refining process, including the production of feedstocks for synthetic rubber, fertiliser, and secondary chemicals (Majozi and Veldhuizen, 2015). To date, Sasol is the only petrochemicals firm that uses the CTL technology in South Africa.

Petrochemical products can be largely broken down into two broad groups – liquid fuel products and chemicals, as depicted in Figure 2. These products are then further processed to produce a variety of end products.

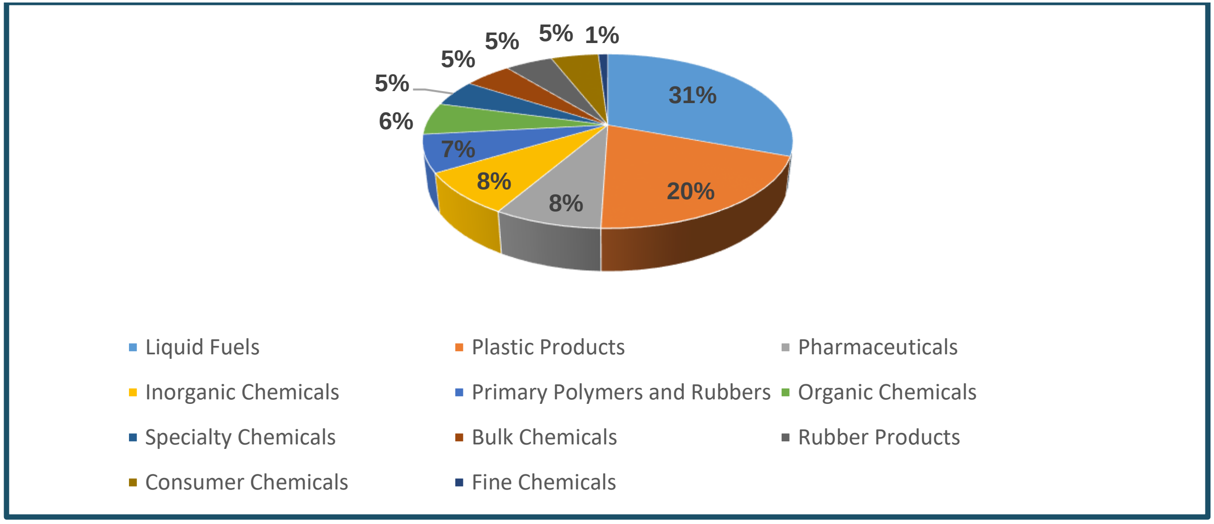
Fuels have traditionally been the primary product of petrochemical processing. The main fuel products are petrol, diesel, kerosene and liquefied petroleum gas (LPG). Fuels are mainly used in transportation, power generation and heating (World Bank, 2009). Major South African firms involved in the production of liquid fuels include Astron Energy, Engen Refinery (Enref), Natref (Sasol Oil joint venture with Total SA), SAPREF (joint venture with Shell Refining SA and BP Southern Africa), PetroSA and Sasol Synfuels.

Chemicals are the other main product of the petrochemical process. These chemicals consist of four groups – ammonia, aromatics, olefins and methanol (Bennett and Page, 2017). Ammonia is used in the production of explosives and fertilisers. Aromatics refer to chemical products that are acquired through the catalytic reforming of naphtha, and are used to manufacture products such as solvents, adhesives and detergents (SEDA, 2013). These products include benzene, toluene, and xylene. Olefins refer to chemical products that are produced through processes such as the steam cracking of ethane and propane, and are used to manufacture products such as plastics, resins, elastomers and lubricants (SEDA, 2013). Finally, methanol is used as a principal additive in biofuels.

From the stock of base chemicals produced in the petrochemical process, a vast array of downstream products are produced through further refining. These include intermediate chemicals (such as ammonia, waxes, solvents, phenols, tars, plastics, and rubbers) and speciality chemicals (agro-chemicals, biochemicals, food-, fuel- and plastics-additives).

Sasol distinguishes production of chemicals into base and performance chemicals. Base chemicals refer to chemicals that are produced in larger volumes and serve as primary inputs into other industries. These include chemicals such as ethylene, propylene and polypropylene. Sasol's base chemicals are categorised into polymers, solvents, fertilisers and explosives. Performance chemicals are those that tend to be high value and have specific uses. Sasol distinguishes performance chemicals into organics, advanced materials and waxes. Examples of products in this category include surfactants and paraffin wax.

Figure 3. Breakdown of chemicals sectors in South Africa



Source: Author's adaptation from (Majozi and Veldhuizen, 2015)

Figure 3 depicts South Africa’s chemical industry broken up into the main end-products. Over 50% of the chemicals produced are liquid fuels and plastic products. Approximately 30% is devoted to the production of pharmaceuticals, inorganic chemicals, primary polymers and rubbers, and organic chemicals. The remaining 21% is split in roughly equal proportions among speciality chemicals, bulk chemicals, rubber products, and consumer chemicals, with a small portion of fine chemicals. The following section describes some of the important sectors in terms of their supply chains.

2.3 Downstream Intermediary and final products

While the petrochemical upstream (through Sasol) produces a number of diverse chemical products, the chief products from the petrochemical industry serve as precursors into polymers (plastic production), fertilisers and explosives production.

Polymers (plastic) products

Plastic products, which account for 20% of the chemicals market, use petrochemical products as inputs. An example of an essential input into the chemicals industry is propylene, a byproduct of the petroleum processing, for which there is no substitute (Competition Tribunal, 2014a). For example, traditional crude oil refiners like Engen do not produce propylene for consumers, and the synthetic fuels produced by Sasol allow for propylene production to be feasible. In traditional crude oil refineries, it is more profitable to recycle feedstock propylene into the fuel pool which is used to produce fuel (CAC, 2015). In the production of synfuels by Sasol, however, the recycling of feedstock propylene into the fuel pool is less profitable than purifying the feedstock propylene into purified propylene and subsequently polypropylene, which is an input into the plastic industry (CAC, 2015).

Sasol is the only significant producer of purified feedstock propylene in South Africa, while SAPREF produces a marginal quantity (Competition Tribunal, 2014b). Sasol is dominant in the production of purified propylene occupying over 90% of the market (Competition Tribunal, 2014b). The purified propylene is used as an input in the production of polypropylene. Due to the nature of its vertical integration, Sasol produces purified propylene for itself and sells purified propylene to one other competitor in the polypropylene market, Safripol (Competition Tribunal, 2014b). In the market for polypropylene, Sasol serves about 80% of the market, while Safripol supplies 20% of the market[2] (CAC, 2015). Downstream purchasers of polypropylene include plastic manufacturers such as Addis, SB Plastics, and SA Leisure.

Fertilisers and explosives

The fertiliser industry is another significant downstream consumer of petrochemical products. Fertilisers are produced according to the key nutrient – nitrogen, phosphorous, and potassium (DAFF, 2016). The primary producers of inputs for the fertiliser industry include Sasol, Omnia, and AECI (Grain SA, 2011). Specifically, Sasol produces ammonia, nitric acid, phosphoric acid, sulphur and sulphuric acid (Grain SA, 2011). Omnia produces phosphoric acid and nitric acid, while AECI produces nitric acid only (Grain SA, 2011). The most consumed type of fertiliser is the nitrogen-based, accounting for about 70% of

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[2] Based on Sasol capacity of 528 000 tonnes per year and Safripol capacity of 120 000 tonnes per year.

fertiliser consumption in South Africa in 2015[3] (DAFF, 2016). The primary input into nitrogen fertiliser, ammonia, is produced locally exclusively by Sasol[4] (Grimbeek et al., 2017). Other ammonia suppliers, such as Omnia, Foskor and Kynoch, procure imported ammonia through a jointly-owned Richards Bay ammonia import facility with Sasol (Grimbeek et al., 2017). Sasol's production of ammonia is in equal proportions from its natural gas and CTL processes.

Downstream, ammonia is combined with nitric acid to produce ammonium nitrate by firms such as Sasol, Omnia and AECI (Grimbeek et al., 2017). Sasol is fully vertically integrated throughout the value chain, acting as the supplier of a key input (ammonia) and a competitor. Ammonium nitrate is then sold to downstream producers of fertilisers and explosives. Sasol occupies most of the market with about 40% of the ammonium nitrate market. The remainder of the market is shared by Omnia and AECI (Grimbeek et al., 2017). Once ammonium nitrate is produced, it is then sold to blenders and traders, such as Nutri-Flo and Profert, which blend the ammonium nitrate derivatives to the correct ratio of nitrogen, phosphorus, potash, and micro nutrients for consumers (Grimbeek et al., 2017).

2.4 Carbon intensity of the value chain

Petrochemicals production is by definition a carbon-intensive activity due to the nature of the production process. South Africa relies heavily on coal resources for petrochemical production, and a key source of emissions are upstream through the combustion of coal with Sasol's CTL processes. On the spectrum of available energy sources, coal is the highest emitter of CO_2 when combusted. This emission intensity is exacerbated by the fact that 86% of electricity generated in South Africa is based on coal power generation (Stats SA, 2018). The combination of these emissions sources makes the petrochemical value chain, and the upstream specifically (through Sasol), among the top emitters of CO_2 in South Africa. Based on the 2015 national energy balance, the petrochemical industry consumes approximately 11% of all energy consumed in South Africa by industry.

For the purposes of this analysis, emphasis is placed on the value chain producing the intermediary petrochemical products, in the upstream of the overall petrochemical value chain. Focus is placed on this level of the value chain as this is the point at which a substantial proportion of emissions occur in South Africa. Sasol alone produced between 50 and 60 million metric tonnes of carbon dioxide equivalents ($MtCO_2e$) in 2017, dwarfing the emissions produced by the downstream sectors in plastics, fertilisers and explosives.

Figure 4 indicates the levels of emissions by selected major firms upstream and downstream within the petrochemical value chain over time, distinguished by Scope 1 and Scope 2 emissions.

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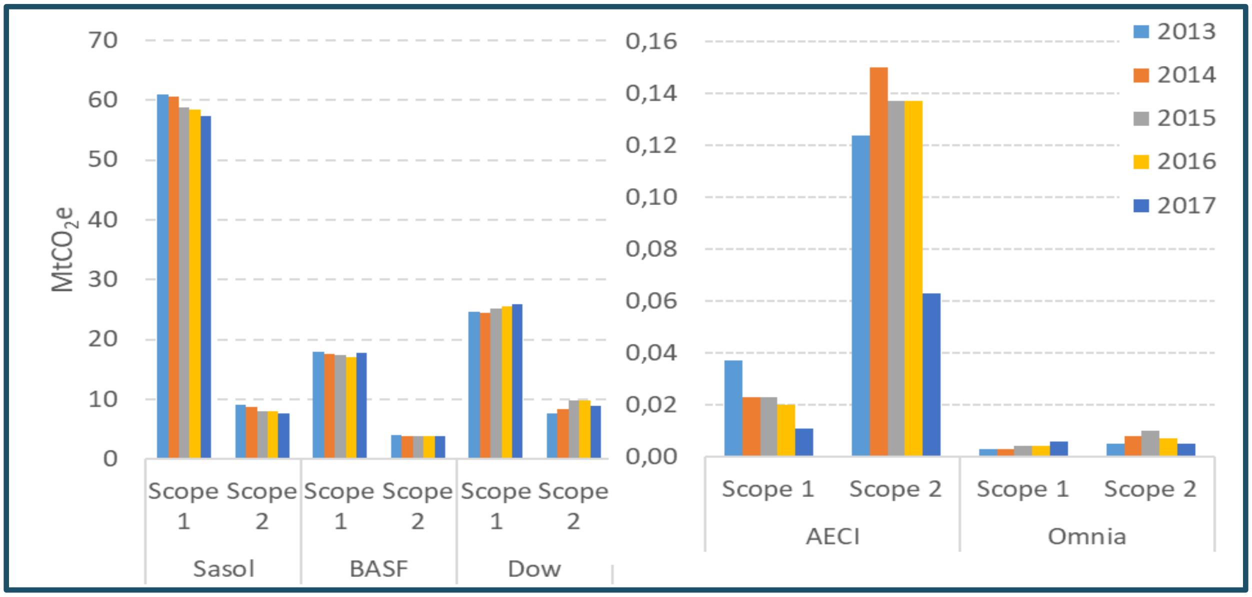
[3] Based on 2015 consumption of nitrogen, phosphorous, and potassium consumption of 400 000 tonnes, 100 000 tonnes, and 75 000 tonnes respectively.

[4] There are indications that Omnia will begin to produce ammonia, however this is expected to be purely for internal consumption. See Grimbeek et al., 2017, p.2,

Figure 4. Emissions data for selected large petrochemical firms



Source: TIPS, based on company annual reports and Carbon Disclosure Project reports. *Notes*: 1. Sasol's Scope 1 South Africa CTL emissions account for about 97% of Sasol's total scope 1 global emissions. See (Sasol, 2019b). 2. Sasol's Scope 2 South African emissions account for 94% of Sasol's total global emissions. See (Sasol, 2019b). 3. BASF and Dow do not separate scope 1 and 2 emissions for South African production. 4. AECI South African Scope 1 and Scope 2 emissions account for 93% and 81% of total emissions respectively. 5. Omnia Scope 1 and Scope 2 emissions account for 99% and 54% of total global emissions respectively.

Examining Figure 4, Sasol's Scope 1 and Scope 2 GHG emissions account for majority of the value chain's emissions based on the data analysed. The emissions of domestic producers such as AECI and Omnia are represented on the graph on the right as the emissions are substantially smaller as compared to those of Sasol. Further, the Scope 1 and Scope 2 emissions for international firms such as BASF and Dow include production in other countries as those firms do not disentangle emissions data for South Africa. Sasol's Scope 1 emissions dominate the emissions of the value chain, exceeding 50 $MtCO_2e$ per year and dwarfing the emissions of other major downstream producers.

While Sasol has reported making progress in reducing emissions over time, it still dominates in emissions in the value chain. The efforts by Sasol to mitigate carbon emissions have also been widely criticised as lacking in ambition given the size and impact of emissions (Just Share, 2020). Criticism has centred around the Sasol board's refusal to consider mitigation solutions initiated by shareholders, and the strong reliance of the decarbonisation pathway on access and exploitation of natural gas reserves by 2030 which have yet to be proven. With respect to the mitigation pathway, criticism has also focused on the 2030 emissions target as not aligning with the goals of the Paris agreement. The inclusion of Scope 3 emissions in the reporting of total emissions has also been critiqued, when Scope 3 emissions are included selectively.

With Scope 2 emissions for South African-based chemical producers, producers are mainly affected by the lack of diversity in the country's electricity mix, where coal dominates. To effectively transition the value chain towards one which emits a lower volume of CO_2, attention will have to be undoubtedly focused on reducing Sasol's emissions undoubtedly. When necessary, downstream products and sectors will be referred to in the following sections.

3. MITIGATION OPPORTUNITIES IN PETROCHEMICALS

A number of options are available to mitigate emissions in the petrochemical value chain and transition the value chain towards one that has a greater sustainability focus and reduced emissions. There is no single intervention that will transition the entire industry and a package of interventions (at different stages of development) will be required. The mitigation mechanisms that apply to the production and downstream activities related to base and performance chemicals are distinguished in three groups, based on where they fit in the value chain and the stage of processing.

Feedstock substitution is considered first. This relates to mitigation options that involve switching from carbon-intensive feedstock options like coal to options with a lower emissions profile such as natural gas, biomass, and hydrogen. The next group of interventions considered relate to options within the production process, or *process solutions*. Options include improving energy efficiency, combined heat and power technologies, carbon capture technologies, and NO_x mitigation. The final group of mitigation options considered are *end-of-pipe/circular economy solutions,* which concern petrochemical products post-consumption. Here, the recycling of key products from the industry (plastics and rubber) are considered.

3.1 Feedstock substitution

Substitute natural gas for coal

Compared to coal, the use of natural gas for energy is associated with lower CO_2 emissions when burned. Diverting from the use of coal towards natural gas offers a potentially cleaner petrochemical value chain and is one potential strategy of mitigating emissions.

Currently, natural gas accounts for about 3% of the total energy supply (DMRE, n.d.) and is principally supplied to South Africa via imported gas from Mozambique. According to the National Energy Balance,[5] about 80% of natural gas in South Africa is sourced from Mozambican imports, while the remaining 20% is sourced from domestic production. Imported gas is sourced by Sasol from the Pande and Temane gas fields in Mozambique and is transported via the Republic of Mozambique Pipeline Investments Company (ROMPCO) pipeline. Sasol is part owner of the ROMPCO pipeline, which is an 865 km pipeline running from the gas fields in Mozambique to Sasol Secunda's Gas-to-Liquids (GTL) plant. The pipeline transports about 240 million gigajoules (GJ) per annum from Mozambique to Secunda. About 50% of this supply is utilised in Sasol's GTL process, while the remainder is sold to domestic consumers of natural gas in Free State, Gauteng, Mpumalanga and KwaZulu-Natal (DoE, 2018). Current domestic sources of natural gas production are limited and based in offshore gas fields in Mossel Bay. PetroSA has the extraction rights to these fields, which provides the feedstock for the PetroSA GTL plant in Mossel Bay. The field is almost entirely extracted and the PetroSA GTL plant operates below capacity.

There has been significant interest in domestic extraction from other sources for greater internal energy security, however commercially viable sources have yet to be found, representing a domestic supply barrier to ramping up supply. To date, activities have largely centred around exploration activities. Three

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[5] Based on domestic production and imported data (in terajoules – TJ) sourced from the National Energy Balance for 2015-2017. See DMRE, n.d.

exploration rights have been granted for the exploration of shale gas in the Karoo shale basin. The permit holders are permitted to conduct exploration activities; however, no fracking activities have been permitted. The available gas resources are yet to be proven, and the geo-environmental impacts of fracking have yet to be assessed (Githahu, 2019). In addition, feasibility studies have been funded for the development of a coalbed methane resource in the Waterberg Coalfield, in Limpopo (USTDA, 2019). PetroSA has also been investigating new gas potential in the existing block that it has extraction rights for in Mossel Bay, however if no reserves are found, production of natural gas in the existing field will decline to zero from 2030 onwards (DoE, 2018; USAID, 2018). More recently, in 2019 and 2020, Total has discovered gas resources in the Brulpadda and Luiperd fields South of Mossel Bay (Total, 2019; 2020). While the find has been touted as promising, the quantity of reserves have yet to be proven and Total is still investigating the commercial viability of extracting the gas (TimesLIVE, 2019). Other gas opportunities are also being explored in the Orange basin, Bredasdorp, Pletmos, Gamtoos, Algoa, Southern Outeniqua, Durban, and Zululand (DoE, 2018). Since these efforts are still at the exploration stage, domestic sources have yet to be proven, so increasing the gas intensity in the short to medium term will have to rely on imported sources of gas if gas is to become a greater contributor to the energy mix.

Another major barrier to the scaling up of gas in South Africa is the lack of infrastructure to transport gas to consumers. The gas network consists mostly of four parts – the ROMPCO pipeline from Mozambique to Secunda; Transnet's Lilly pipeline from Secunda to Richards Bay and Durban, feeding methane-rich gas; a pipeline network from Secunda to Sasolburg and industries in Gauteng and Mpumalanga; and a subsea pipeline from the southern offshore gas fields to the PetroSA GTL plant in Mossel Bay (DBSA, 2016) (see Figure 17 in Appendix). Resources are currently being devoted to constructing a more extensive gas network in South Africa. In 2014, the Operation Phakisa Offshore Oil and Gas Lab identified the need, among other interventions, to plan for additional gas transmission pipelines to transition to a lower carbon economy (CSIR, 2018). This is aligned with the 2019 Integrated Resource Plan that calls for 3 000 megawatt (MW) of additional gas-to-power generation from gas from 2024 onwards. As a result of the Lab, the Council for Scientific and Industrial Research (CSIR) was commissioned to undertake a Strategic Environmental Assessment (SEA) for a Phased Gas Pipeline Network and for the expansion of the electricity grid infrastructure. With plans for investment still at early stages, it is unlikely that any substantial additions to the gas transport infrastructure will take place in the short to medium term (less than a decade).

Ultimately, for gas supply to substitute for coal supply to the petrochemical industry would require gas supply to increase from a low base of about 88 319 TJ natural gas contribution to liquefaction, to a total of 949 495 TJ to replace the total coal energy intensity of the petrochemical upstream[6]. In other words, liquefaction energy requirements currently consist of 91% coal and 9% natural gas. For natural gas to entirely replace coal would require substantial investment in gas transmission and storage infrastructure as well as a dramatic increase in natural gas supply. While South Africa is progressing in exploration activities for domestic gas sources and plans are underway to invest into gas transmission infrastructure, increasing gas intensity to replace coal is not a feasible in the short to medium term. The evolution of investments in new supply sources (domestic or international), combined with the development of transmission infrastructure, renders this option viable in a timeframe beyond, say, a decade.

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[6] Based on the energy inputs into liquefaction from the 2017 National Energy Balance. See DMRE, n.d.

Bio-based production

Biomass offers an alternative source of feedstock for chemical production, which could potentially offset fossil fuel feedstocks in chemical production. Biomaterials have already been incorporated in numerous manufacturing industries such as the automotive, chemical, energy, pharmaceutical and plastics sectors. The concept of a biorefinery has been put forward to replace conventional methods of chemical and composite manufacturing and to stimulate local bio-based industries. A biorefinery involves the processing of biomass sources into products which include value-added chemicals, fuels, and agricultural products (Bennett and Page, 2017). Biomass has been gaining traction in recent years as a viable sustainable alternative to oil- and coal-based feedstocks and energy production.

The quality and properties of the products from biomass gasification depend on the feedstock material, among other properties such as the gasifying agent, feedstock dimensions, reactor temperature, pressure and design, and the presence of a catalyst (Sikarwar et al., 2016). Biomass gasification can be used to produce syngas, heat, power, biofuels, fertiliser and bio-char. Of particular utility is syngas, which can be further processed through the Fischer-Tropsch process into methanol and other chemical feedstocks. Syngas is a blend of carbon monoxide and hydrogen and is a precursor to fuels and chemicals. Syngas can be readily converted to methanol, which in turn can be transformed to gasoline. Employing the Fischer Tropsch process, gasoline, diesel and other chemicals can be manufactured. Hydrogen can also be produced from syngas, which can then be used in fuel cells and industrial production processes. Synthetic natural gas can also be produced from syngas, which in turn can be used as turbine fuel. Finally syngas can be used as a fuel for the production of electricity.

Biomass feedstocks have the advantage of being easily storable and transportable, and typically are abundantly naturally available (Sikarwar et al., 2016). The gasifier is typically designed to generate a given product; however, the feedstock material is an important parameter to specify in the design process.

Renewable organic inputs are used as feedstocks and include starches, natural fibres and waste to produce plastics and platform chemicals (Quarshie and Carruthers, 2014). These feedstocks are favoured due to lower energy requirements during production processes. Furthermore, bio-based feedstocks are considered carbon neutral owing to processes whereby CO_2 is captured from the atmosphere and locked into the biomass, until end-of-life when CO_2 is released back into the atmosphere at a lower rate compared to non-renewable feedstocks (Bennett and Page, 2017, p. 389).

Further, life-cycle assessments have indicated that aside from environmental and economic efficiency gains, biorefineries contribute to local social development and transformation through the creation of jobs and support for small-scale farmers (Farzad et al., 2017).

Table 1: Feedstock options for biorefineries

RAW FEEDSTOCK		PROCESSED FEEDSTOCK	
Agriculture	Maize	**Solid**	Bagasse
	Wheat		Woody biomass
	Sugarcane		Pulp and paper
	Sorghum		Food waste
	Fruit and vegetables		Municipal solid waste
	Soya		Abattoir
	Sunflower		Agricultural residue
	Canola		Confectionery
	Agave	**Liquid**	Vinasse
	Flax		Confectionery
	Jute		Molasses
	Hemp		Brewery/Winery
	Cassava		Fertiliser
Aquatic	Seaweed		Food waste
	Algae		Abattoir
			Municipal wastewater

Source: Author's compilation based on Harrison et al., 2017; Quarshie and Carruthers, 2014; Sikarwar et al., 2016.

While a promising climate-compatible option for feedstock substitution, growth and cultivation of bio-based feedstocks requires land and water resources, which presents challenges for widescale rollout of raw feedstock in resource-stressed countries such as South Africa, this can be overcome through the use of waste feedstocks that can be beneficiated from the pre-existing forestry agriculture and sugar producing sectors.

Another barrier relates to the trajectory of technological development. Currently, technology in biomass gasification requires lower temperature filtration and scrubbing, which limits the products and applications produced, ultimately reducing the profitability of biomass-based production. Another process barrier relates to the formation of tar, which is inevitable with biomass feedstock and represents a serious operational problem that impacts on product quality, yields and process efficiency. If effective and costly tar separation processes are not implemented, the gas quality and yields reduce, rendering the product unfit for applications where high levels of purity are required. There are a number of process innovations which seek to attend to these challenges, and these are at various levels of development. At the current level of technological development, however, they are still presented with challenges that relate to product diversity (products that can be produced), capital and energy costs, complexity and, in certain instances, the need for downstream gas transmission systems.[7]

Despite these challenges, the market for bio-based plastics has been growing globally, particularly within the automotive, packaging, electronics, fibres, furniture and toy manufacturing spaces.

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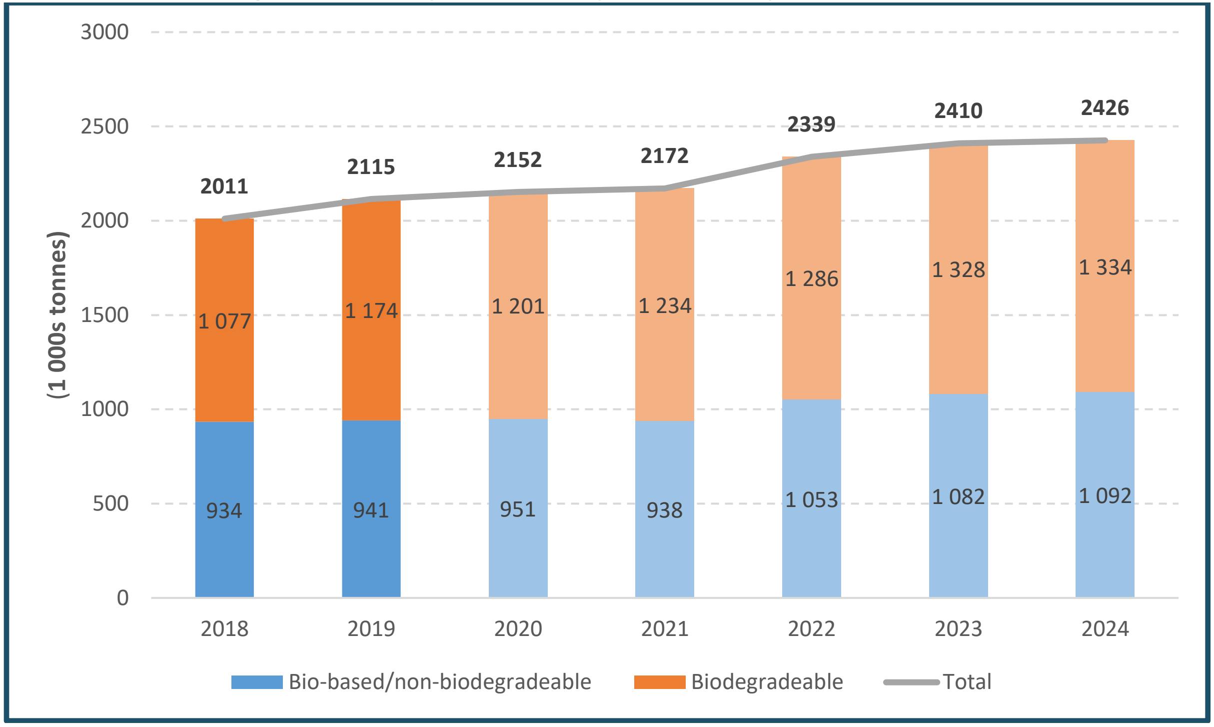
[7] See Section 2.2, Table 3 of Sikarwar et al., 2016) for a full review.

Figure 5. Global production capacities of bioplastics until 2024



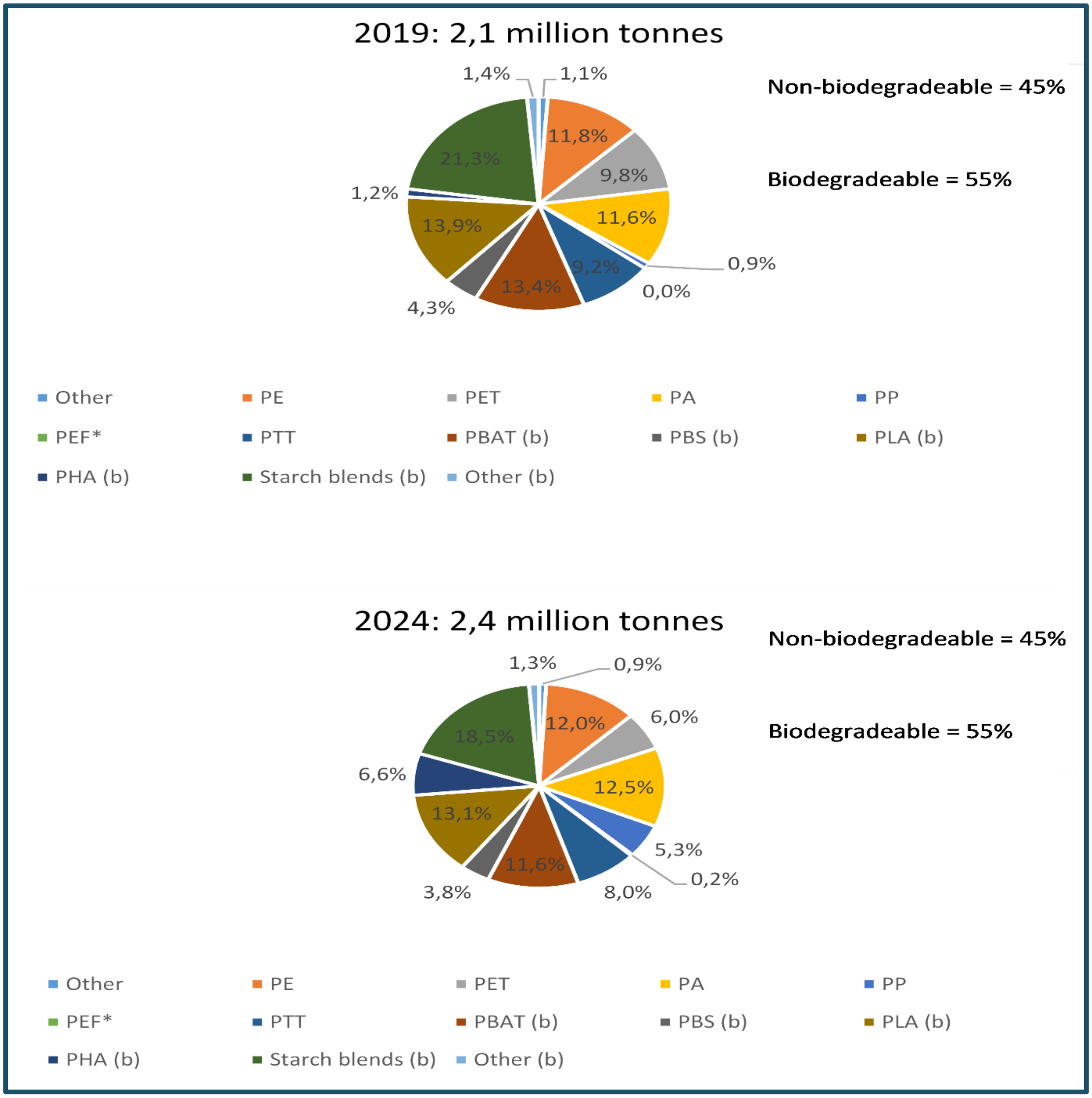
Source: Author, based on European Bioplastics, 2019*. Note*: Quantities beyond 2019 are projections.

Bioplastics currently account for about 1% of total global plastic production. Continual increases in demand for bioplastics, and the emergence of new technology, methods and products are expected to increase production capacity from approximately 2.1 million tonnes in 2019 to a projected 2.4 million tonnes in 2024 (European Bioplastics, 2019). Other estimates indicate that the global biodegradable plastic market is projected to move from US$3 billion to more than US$6 billion in 2025 (Narancic et al., 2020). The market is anticipated to be driven by rising demand for biodegradable polymers from emerging economies such as India, Brazil, and China. Bioplastics alternatives are set to substitute conventional plastics, and production capacity is expected to diversify in the medium term (approximately five to 10 years).

Currently, starch blends have the highest share in the biodegradable plastics production, as evidenced in Figure 6. Growth in bioplastics is expected to occur via increased demand for polyhydroxyalkanoates (PHA) and polylactic acid (PLA), for their diverse applicability in packaging, fibres, textiles and medical applications.

PHA and PLA currently have a market share of 1.2% and 13.9% of the bioplastic market respectively. PHA is anticipated to see a 6.3 times increase in global production from 25 320 tonnes 2019 to 159 700 tonnes by 2024 (Narancic et al., 2020). In addition, PLA is expected to see an 8% increase production from 293 290 tonnes in 2019 to 317 000 in 2024.

Figure 6. Bioplastic product mix in 2019 and 2024



Source: Author, based on European Bioplastics, 2019. Note: PEF is expected to be commercially available from 2023.

Renewable alternatives in the automotive sector also hold potential as a significant factor for growth in bioplastics. Bio-based polymers are cited as advantageous in the automotive space due to their resource efficient and lightweight properties that enable reductions in levels of CO_2 and energy requirements. Furthermore, when compared to polybutylene terephthalate (PBT) plastics, biopolymers are easier to process, provide better stiffness and rigidity, as well as higher thermal shock resistance (European Bioplastics, 2015). As such, leading vehicles manufacturers, Toyota for example, have been incorporating bioplastics (bio-based polyesters, bio-based polyethylene terephthalate (PET), and PLA-blends) into their manufacturing processes, setting targets to replace 20% of petroleum-based plastics with bioplastics by 2015.

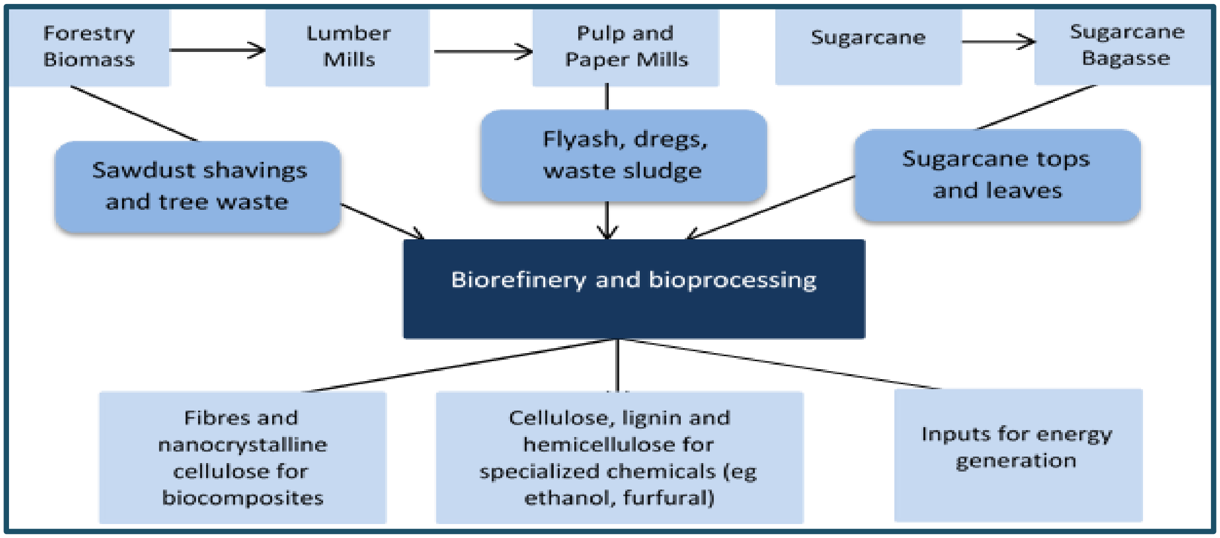
A number of other private firms have been incorporating bio-based products into their production. Fiat manufacturers, in conjunction with DuPont, have also shifted to bio-based solutions, replacing petroleum-based oils with castor oil long-chain polyamides in over one million vehicles, indicating efforts to increase this number in years to come (European Bioplastics, 2015). Mitsubishi Chemical, together with Faurecia, have also entered the bioplastic space producing products for vehicle interiors such as trimmings, door panels and air ducts to name a few. Toy firm Lego have also indicated plans to replace all fossil-based plastics with bio-based alternatives by 2030 (Bennett and Page, 2017).

With packaging, in 2015 Coca-Cola produced the world's first bio-based PET PlantBottle™, comprised solely from recyclable plant materials, such as starch from corn, sugarcane and bagasse, amounting to annual emissions savings of 315 000 metric tonnes of CO_2 since the launch of the 30% PET bottle in 2009 (Coca Cola, n.d.). UK-based firm Skipping Rocks Lab has launched edible water pouches, made from seaweed and brown algae membranes, in attempts to curb the use of tradition plastics in the wake of country commitments to transition away from fossil based products (Beanland, 2018). More companies are following, producing plant-based edible packaging products ranging from straws, cups, spoons and even plates, perhaps signaling glances into a future free of plastic (Beanland, 2018).

In South Africa, favourable climatic conditions coupled with a well-positioned forestry and the agricultural sector enables the country to seize opportunities to harvest suitable feedstock residues required for a potential circular bioeconomy and a competitive biomaterial industry (Harrison et al., 2017). South Africa generates 26 million tonnes of second-generation waste residues from agricultural and forestry waste residues. Similarly, the abundant supply of sugarcane by-products, namely bagasse, could potentially stimulate a local biomaterials industry through biorefinery technologies. Biorefineries technologies have now been integrated where a single facility/industry produces raw materials for biocomposite production and raw materials for high-value chemicals (HVCs), which then becomes feedstock for other value chains.

As biorefineries offer a potential avenue for the cleaner production of chemicals and fuels globally, South Africa has been exploring options to develop several biorefinery facilities. Added benefits are that biorefineries can be implemented into existing plants in South Africa. Figure 7 provides a simplified representation of the feedstock and products emanating from forestry and sugar biorefineries.

Figure 6. Forestry and sugarcane biorefinery processes and products



Source: Author's composition based on Federal Government of Germany, 2012; Sithole, 2017.

The Department of Science and Innovation (DSI) has identified five biorefinery opportunities for South Africa based on the following inputs and areas: forestry, sugar, algae, non-food crop plant oils and microbial biorefineries based in rural areas. Initiatives are also underway making use of agricultural and livestock waste in South Africa. The CSIR has launched a new newly developed Biorefinery Industry Development Facility housed at the CSIR in Durban. The facility is overseeing pilot projects using pulp and paper waste as well as chicken feathers from the poultry sector, to extract materials for high-value chemicals and fibres for biocomposites. It has been identified that only 40% of a tree is used to produce paper and pulp at mills, while the remainder is cast aside as waste. The biorefinery technologies aim to maximise potential value by using 90% of a tree to produce HVCs, and such an initiative is viewed as a sustainable strategy to revive the forestry industry in the country aiding competitiveness and contributing to employment generation within the sector. Starch extracted from plant oilseeds as well as cellulose from woody biomass, provides high-value biocomposite materials for the production of biolubricants, biopolymers, fine chemicals, platform chemicals, and biofuels that could be used to provide energy and electricity for production processes (Harrison et al., 2017).

Box 1: Company initiatives related to biomaterial production in South Africa

Biomaterial production is still at an early stage in South Africa with a limited number of firms engaging in the space. Data on market size and the distribution of volumes by product and sector are not available. Despite this, a few firms are trying to increase products and volumes of bio-based products. The main firms involved in the production of biomaterials and bio-based products are outlined below. While biomaterials production is still at an early stage in South Africa, a number of large and well-networked firms are involved in the production space. Given that these firms are important suppliers to downstream industries, they possess key leverage to influence the input choices of downstream markets and orient products towards greater biomaterials and bioplastic content.

Sappi Global, through the Sappi Biotech unit, is involved in developing and commercialising bio-based products. Given its access to forestry feedstocks (eucalyptus and pine in South Africa), the biomaterials are wood-based. Specifically, the bio-based products that SAPPI is involved in are nanocellulose, lignin, Sappi Symbio (plastics and composites), and hemicellulose sugars (Sappi, n.d.-b). In South Africa, SAPPI key initiatives in biomaterials include:

- The production of lignin from the Tugela Mill in South Africa since 2012, with a view to expand the lignin product range applications. These products can be used in biodegradable plastic products, in the production of cement, and in water treatment among others (Sappi, n.d.-b).
- Sappi has commissioned a sugar extraction demonstration plant at Ngodwana Mill in Mpumalanga. The process will extract hemicellulose sugars and lignin from Sappi's existing pulp. The key processes will include beneficiation to higher value organic acids, glycols and sugar alcohols which are utilised in numerous consumer products.

Safripol produces key input polymers into the downstream domestic plastic manufacturing market, competing with Sasol for the production of polymers. In addition, Safripol is the only producer of traditional fossil fuel polyethylene in the country. Given the changing landscape and move away from fossil fuels, Safripol has recently embarked on a strategic redirection towards increased sustainability in production. Currently, Safripol is the only producer of Bio-PET in the country, which feeds into downstream products, such as the Valpre Plant Bottle which contains 30% Bio-PET. The input polymer is currently imported into the country, however Safripol is investigating domestic production at its manufacturing facilities. Bio-PET is seen as an easy transition as it forms part of "drop-in" bioplastics that can be produced without technical disruption to existing infrastructure, polymerisation processes and value chains. To extend sustainable production, Safripol is further investigating the production of bio-based polyethylene (Bio-PE) from sugar cane, given the trade deficit in ethyhlene in South Africa.

LignoTech is a joint venture between Sappi and Borregaard AS of Norway, which has a lignin extraction plant in KwaZulu-Natal that was opened in 1999. The plant beneficiates the effluent stream from Sappi's Saiccor Mill to produce binding and dispersing agents that are used in agricultural and industrial applications. The plant has been regarded as a success, with expansions in 2003, 2008 and in 2017. The products are sold in the domestic market as well as exported to countries in Africa, Asia-Pacific, the Middle East and South America (Forestry, 2019).

OptimusBio manufactures biodegradable and biologically-active products for water treatment and industrial markets. The feedstock is based on indigenous bacteria. OptimusBio was formed as a business from the CSIR, and the technology is licensed from the CSIR. The products have applications in personal care, domestic cleaning, automotives and water and sanitation.

KwaZulu-Natal-based agro-processing company RCL Foods is involved in the production of a succinate monomer.

The community of firms working directly on biomaterials is small. A far larger and more developed set of firms operate in composites, plastics, and chemicals. Biomaterial development would certainly benefit from their active involvement in the industry. Sasol is the key player. While experts report Sasol is undertaking work on biomaterials, little information on these projects is publicly available. Sasol does have some experience in biomaterials, through a distribution agreement between the company's Chinese joint venture Wesco, and Australian bioplastics firm Cardia Bioplastics, but its biomaterials operation otherwise remains confidential.

Approved business plans have ensured that research into biocomposites produced from aquatic feedstock such as algae and seaweed, is already underway in South Africa. In contrast to maize, wheat and sugar, aquatic feedstocks can been grown under dry weather conditions on arid land using limited amounts of water, seawater and wastewater, proving promising for resource stressed regions of the country (Montmasson-Clair et al., 2017). Aside from the environmental benefits, cultivation of aquatic feedstock in secluded areas of South Africa offers opportunities for social and economic benefits, in terms of job creation and community development. Expansion and commercialisation of biorefineries in South Africa requires continued research and development as well as ongoing engagement with the waste economy. While notable projects and research and development are underway, utility-scale chemical production has yet to be proven in South Africa from a technical and commercially viable point of view.

Green hydrogen

The hydrogen economy offers another potential pathway to a sustainable future for the petrochemicals value chain. Hydrogen has two chemical properties which make it attractive for sustainable development – a high-energy density[8] and a source of clean combustion (Dou et al., 2017). While hydrogen is currently

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[8] Energy density refers to the amount of energy contained in a given volume or mass, and hydrogen contains a greater concentration of energy per unit mass when compared to fossil fuels and other sources of energy. For example, the energy contained in a kilogram of hydrogen gas is roughly equal to the energy in 2.8 kg of gasoline (United States DOE, n.d.).

produced predominantly through fossil fuels, the process of electrolysis offers a sustainable route as a substitute for hydrogen production from fossil fuels.

Electrolysis refers broadly to a process that utilises electrical energy to drive a chemical reaction that does not happen naturally (Chang and Goldsby, 2016). Electrolysis splits water into hydrogen and oxygen, with electricity and water as the principal inputs. Green hydrogen production refers to the generation of hydrogen and downstream hydrogen-based products through electrolysis, where the electricity input is provided through renewable energy-based electricity generation. Based on the cost trajectory of solar photovoltaic (PV) and wind energy, these renewable technologies are seen as ideal generation options for combination with electrolysis. When hydrogen is combusted it is associated with lower air pollution and CO_2 emissions compared to fossil fuels (Dou et al., 2017). The only waste produced from pure hydrogen is water, which results from the bonding of hydrogen and oxygen atoms (NPEP, 2017). There is increasing international interest and investment directed towards hydrogen as an energy carrier and its application in the production of energy and a variety of important chemical products. Green hydrogen offers an opportunity to decarbonise the production of chemicals, since traditional fossil fuel feedstocks such as coal and natural gas are avoided.

Green hydrogen can be used to substitute for hydrogen in industrial applications that previously required hydrogen from fossil fuels, and has increasingly found new potential for new industrial and commercial purposes.

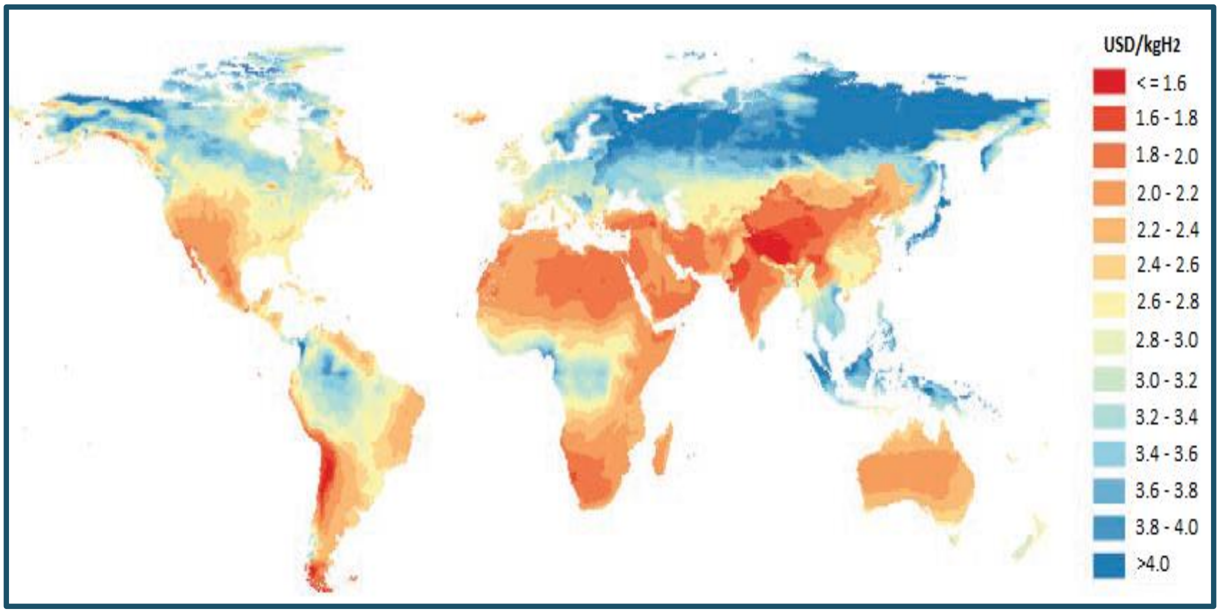
With current industrial applications, 74% of global hydrogen production is devoted to ammonia and methanol production (38%), oil refining (33%), and iron and steel production (3%) (IEA, 2019). In all of these applications green hydrogen can be phased into production and substitute for fossil fuel production over time. Ammonia is used to produce fertilisers and explosives and represents a key input into those downstream industries. Methanol is also an important input chemical used in the production of polymers. In oil refining, hydrogen has applications in the refining of oil where it is used to obtain high-grade petrol, and in the removal of sulfur compounds that are harmful to cars (Zohuri, 2019). Finally, in iron and steel production, hydrogen is used in the direct reduction of iron route for steel production.

New applications for green hydrogen are found in transport, buildings and power generation. In transport, hydrogen offers a low-carbon option in fuel cell electric vehicles when compared to oil and natural gas fuels, with zero tail pipe emissions. Hydrogen-based fuels also allow for low-carbon transport in difficult industries to decarbonise, such as aviation (in the form of synthetic jet fuel) and for shipping (as ammonia) (IEA, 2019). Green hydrogen can be used to provide heating to buildings through blending hydrogen with natural gas in existing heating networks or using hydrogen directly to produce heat within buildings. While hydrogen use in power generation is low at present, there is also potential for hydrogen and hydrogen-based products to sustainably generate electricity. Green hydrogen assists with the energy storage problem currently associated with intermittent renewable energy-based technologies that depend on climate conditions, such as solar PV and wind generation. During periods when electricity supply exceeds demand, excess electricity supply can be used to drive hydrogen production. This hydrogen can be stored or used to produce hydrogen-based energy carriers such as ammonia or synthetic methane. This stock of hydrogen and hydrogen-based carriers can then be used in hydrogen-fired gas turbines and combined-cycle gas turbines to generate electricity during periods when renewables do not produce electricity due to climate constraints such as daylight hours and wind conditions. The co-firing of ammonia with coal can also reduce the carbon intensity of existing conventional coal power plants.

As new pathways for hydrogen are developing and evolving, a number of barriers have surfaced in the green hydrogen value chain. Green hydrogen production is associated with high capital costs, particularly for newer membrane-based systems. These systems require high-cost catalysts made of platinum or iridium, and membrane materials. Given that electricity is a key input into green hydrogen production, the availability of low-cost, low-carbon electricity is also essential. This requires the price of renewable energy-based generation to be low in these systems, and for green hydrogen production to be proximal to regions with excellent resource conditions. In systems where hydrogen consumption is distant from production, the cost of transmission and distribution can be up to three times the price of production depending on the distance (IEA, 2019). In addition, for very long distances, hydrogen requires conversion processes such as compression and liquefaction, which places additional costs on the system. Green hydrogen production is also associated with high water consumption, consuming approximately double the water consumption of hydrogen production from natural gas (IEA, 2019). This constrains its use with freshwater in water-stressed regions. The use of desalinated seawater has been offered as a solution in coastal regions, however, desalination is associated with high electricity consumption and can lead to corrosion damage.

South Africa has three chief advantages in the production of hydrogen and value-added downstream products. South Africa has ideal weather conditions for solar and wind generation. High solar and wind availability factors increase the utilisation factors of the hydrogen electrolysers, ultimately lowering the cost of clean hydrogen production and make investments attractive to investors (Polity, 2019).

Figure 7. Hydrogen production costs by geography (with wind and solar generation)



Source: IEA, 2019.

According to the CSIR, South Africa has excellent conditions for wind and solar energy, which can be generated and then stored using hydrogen as a medium. South Africa's combined solar and wind power provide a hydrogen production capacity factor of almost 100% during daylight hours (Creamer, 2019). In the evening, wind generation can be harnessed to produce hydrogen at a capacity factor of about 30%, which exceeds the international norm of about 22% (Creamer, 2019).

Hydrogen can be combined with CO_2 to produce synthetic hydrocarbons such as methane, diesel, or jet fuel. South Africa has a unique capability in this regard with the patented Fischer-Tropsch process owned by Sasol (IEA, 2019). PetroSA also incorporates Fischer-Tropsch technology under licence from Sasol (PetroSA, n.d.). The process is proven commercially through Sasol's largest CTL plant, the largest in the world, in Secunda and PetroSA's GTL operations. In the production of synthetic diesel or kerosene, the Fischer-Tropsch process is used to convert carbon monoxide (derived from CO_2) into raw liquid fuels and synthetic diesel or kerosene. The technical expertise and skills which have developed around the Sasol and PetroSA operations provide South Africa with an edge in the production of liquid fuels based on the hydrogen route.

Finally, South Africa is the largest producer of platinum group minerals (PGMs) in the world, accounting for approximately 71% of global supply (Frost, 2019). PGMs serve as a key component of electrolysers in hydrogen production and as catalysts in fuel cells. Access to this key resource in the hydrogen economy thus places South Africa at an advantage to beneficiate its PGM resources and move down the value chain in the production of electrolysers and fuel cells, which face anticipated and rising demand. South Africa also has close proximity to platinum supplies, which can reduce the costs of transport and the other costs associated with importation of key materials.

Interest in developing the hydrogen economy in South Africa is high in both the public and private sectors. In 2008, the then-Department of Science and Technology (DST) launched a 15-year Hydrogen and Fuel Cell Technologies Research, Development, and Innovation strategy to guide the development of the hydrogen economy. Hydrogen South Africa (HySA), which consists of three competence centres, came out of this initiative. HySA's overall aim is develop the hydrogen economy with a distinct focus on drawing in PGMs into the technology, given South Africa's resource endowment of PGMs. The three competence centres each have a differing focus – HySA Infrastructure, HySA Systems and HySA Catalysis (SAASTA, n.d.). HySA Infrastructure is a collection of resources from North West University and the CSIR, and focuses on developing hydrogen production technologies, distribution, and storage. HySA Infrastructure has also been successfully operating a solar-to-hydrogen system since 2013 (Creamer, 2019). HySA Systems is based at the University of the Western Cape and focuses on the development of high temperature membrane electrode assemblies (MEAs), hydrogen purifiers, solid state hydrogen storage and compressors (metal hydrides), batteries, and other electrical devices. HySA Systems is also responsible for technology validation and system integration involving end-users. HySA Catalysis is a collaboration between the University of Cape Town and Mintek and focuses on the development of fuel cell catalysts, low temperature MEAs and fuel processors. In 2018, HySA indicated its intention to begin looking into manufacturing capability around hydrogen technologies to grow the domestic hydrogen fuel cell market (SAASTA, n.d.). HySA is currently conducting a study to determine the costs to transport hydrogen by land and sea, including shipping to Japan (Polity, 2019). Further, it is investigating the time period within which it is feasible for South Africa to competitively export hydrogen to Japan, a potential high-demand hydrogen export partner. An off-take agreement with Japan will be required to make the necessary investments into infrastructure. The ultimate goal of the HySA strategy is to enable South Africa to supply 25% of global platinum group metal-based catalyst demand for the hydrogen and fuel cell industry by 2020 (NPEP, 2017).

The DSI also networks with international experts on the hydrogen economy to understand the potential role that South Africa can play in the global hydrogen economy and develop the domestic industrial capabilities to feed into these markets. The then-DST and the South African Agency for Science and

Technology Advancement (SAASTA) hosted the 30th International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) Steering Committee Meetings in Pretoria in December 2018. IPHE encourages global collaborations, accelerate progress and widespread penetration of Hydrogen Fuel Cell (HFC) technologies across sectors. The partnership has a clear focus on energy security, improved resilience, emissions reduction and economic prosperity. Members of the partnership collectively invest approximately US$1 billion a year in HFCs. The event also included site visits by global experts to Mintek, the Minerals Council of South Africa, Impala Platinum Refineries, Poelano High School, HySA Infrastructure Centre of Competence, North West University and Mponeng Mine (SAASTA, n.d.).

South Africa has an opportunity to create new hydrogen-based chemical value chains while it has an opportunity to penetrate the market. While the potential avenues for hydrogen production continue to be investigated in South Africa, a number of areas offer potential opportunities to catalyse the domestic hydrogen economy. Given the existing Fischer-Tropsch capabilities within Sasol, South Africa has a head start over other countries with superior wind and solar PV resources, in that these countries have to engage in greenfield investments, while Sasol can modify its existing processes to intake green hydrogen into its petrochemical processes to produce hydrogen and hydrogen-based chemicals. To overcome the water-intensity of electrolysis, the CSIR has advocated the coupling of renewable energy with desalination and the use of the desalinated water to feed into the electrolyser, which then produces hydrogen from water as an energy storage medium (Polity, 2019). In inland areas, brackish water from mining activities can be desalinated and used to produce hydrogen. This system also has the advantage of water supply to municipalities during water stressed times. A dual supply model can be utilized where water is used to run the electrolyser and to produce potable water. By building capital expenditure and labour costs into the hydrogen supply expense, municipalities only have to pay energy costs for desalinated water which may make water supply costs cheaper for potable uses. Hydrogen export costs can also be mitigated by situating hydrogen production facilities close to major ports, reducing the transmission/transport costs. The Port of Ncqura in the Coega Industrial Development Zone (IDZ) has been identified as a potential port for exported hydrogen due to its proximity with renewable energy-based electricity generation. Combined with the fact that the Eastern Cape province is susceptible to water shortages, this allows the potential facility to divert from hydrogen production to potable water production should water supply from conventional sources be limited. To meet demand for hydrogen exports it may be required for some electrolysis infrastructure to be exclusively devoted to hydrogen production. In cases of excess supply, clean electricity can be fed back into the grid based on the appropriate regulatory framework being in place.

3.2 Process solutions

Improving energy efficiency gains

Energy efficiency is typically regarded as a low-hanging fruit and an easily implementable intervention to mitigate emissions. Efficiency gains refer to the positive benefits accrued from incorporating efficient technologies in the production process. Efficient technologies in this context refer to existing or new technologies that can be applied in petrochemical processes to improve their performance, from an energy efficiency and GHG emissions perspective (Boulamanti and Moya, 2017). Efficiency gains assist firms to reduce their exposure to variable fossil fuel prices and the burden of regulatory impacts (Bennett and Page, 2017).

Efficiency gains are considered to be the intervention responsible for the largest reductions in GHG emissions. The IEA estimates that energy efficiency alone can contribute to 78% of world carbon emissions savings by 2020[9] (IEA, 2017). Implementing the best available technology practices in core chemical production processing can result in a 14% to 21% energy savings a year (Bennett and Page, 2017). The petrochemical industry is complex and diverse, containing a large number of energy efficiency interventions which can be product/process specific. The interventions discussed in this report are the major cross-cutting interventions which can be implemented in the sector. Two particular interventions – Combined Heat and Power (CHP) and Carbon Capture and Storage (CCS) – are dealt with separately due to the specialised nature, and specific issues around these interventions.

The petrochemical industry has historically improved its efficiency in terms of energy and resource consumption in the face of external shocks. The oil crisis in the 1970s saw the petrochemical industry respond with efficiency-enhancing measures.[10] In the current global setting, new plants consume lower quantities of energy, and are more efficient as compared to the past (Bennett and Page, 2017).

There are a myriad of potential energy efficiency interventions that the industry can adopt (see Table 13 in the Appendix).

With respect to energy efficiency programmes, South Africa has instituted a number of policies aimed at improving energy efficiency. First among these policies are the Section 12i and 12L tax incentives (McNicoll et al., 2017). The 12i tax incentive, managed by the Department of Trade, Industry and Competition (the dtic) offers financial support for energy efficiency greenfield investments and plant expansion in commercial enterprises. The scheme targets investments in manufacturing sectors, such as chemicals, and plastics. The 12L tax incentive for energy savings has been implemented by the Department of Mineral Resources and Energy since December 2013, allowing businesses to claim a deduction against taxable income equivalent to the monetary value of proven energy efficiency savings. The scheme was further enhanced in 2015 with an increase in the deduction from R0.45 to R0.95 (US$0.04 to US$0.07) for every kilowatt-hour saved (McNicoll et al., 2017).

In addition, Eskom has run a number of energy efficiency demand side management programmes since the late 1990s, that provide financial and technical support to electricity consumers. The Efficient Lighting Initiative was a three-year US$10 million (R79.5 million) programme co-funded by the International Finance Corporation, Global Environment Facility and Eskom that ran from 1999 to 2003, aimed at accelerating the diffusion of energy-efficient lighting technologies in South Africa (McNicoll et al., 2017). From 2008 to 2013, Eskom extended support programmes for demand-side management initiatives. In 2015, Eskom restarted two programmes to rollout light emitting diode (LED) and compact fluorescent lamp (CFL) equipment, as well as to support energy efficiency projects through energy service/savings companies for industrial, commercial and residential customers. Further, an environmental levy on electric filament lamps, payable by manufacturers, was introduced in 2009 and progressively increased to

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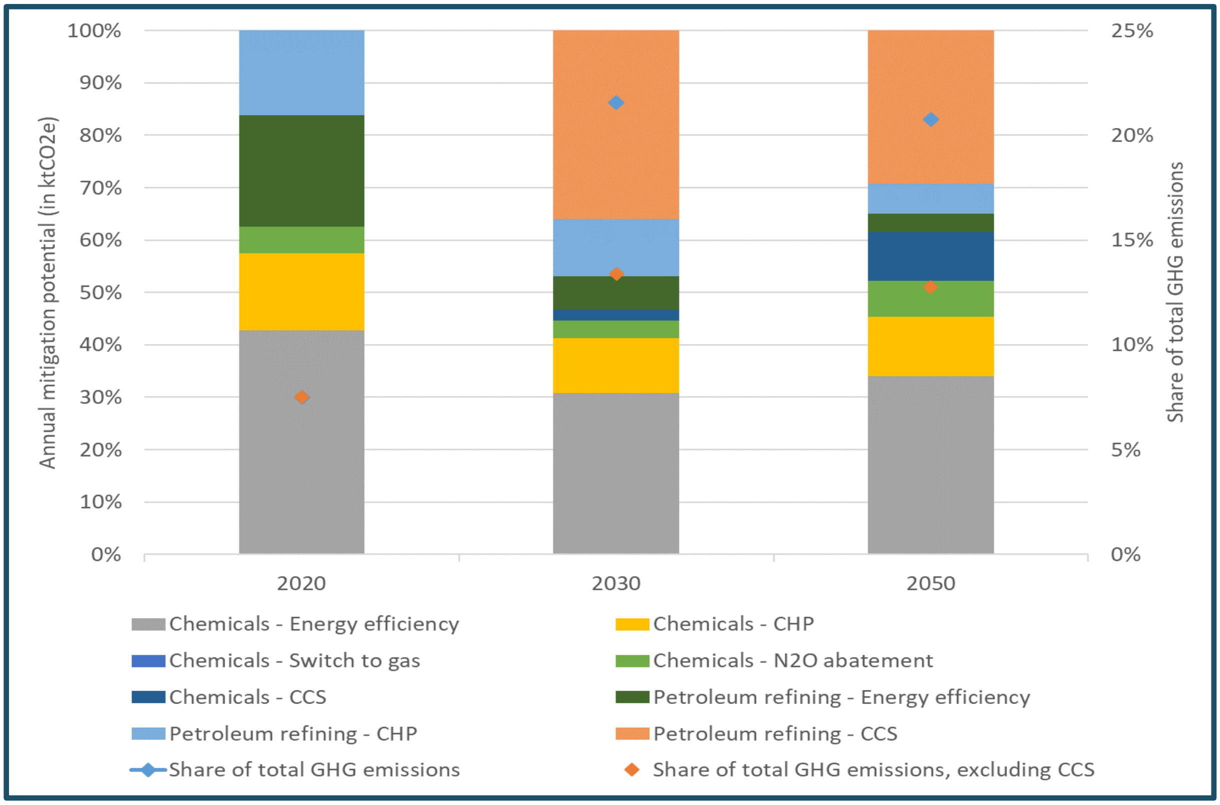
[9] This is under the 2°C Scenario (2DS) relative to the Reference Technology Scenario (RTS). The 2°C Scenario envisions an energy system pathway and a CO_2 emissions trajectory with at least a 50% chance of containing the average global temperature increase to 2°C by the year 2100 (IEA, 2017). The RTS takes into account today's commitments by countries to limit emissions and improve energy efficiency resulting in an average temperature increase of 2.7°C by 2100 (IEA, 2017).

[10] Prior to the crisis, naphtha crackers, for example, used 38 GJ of energy per ton of ethylene produced; after the advent of the crisis process redesigns reduced energy consumption by about 50% (Bennett and Page, 2017, p. 409)

R6 per bulb by April 2016. Jointly with support programmes, regulations and information measures have been used extensively to improve energy efficiency performance in South Africa.

With a focus on petrochemicals, in 2014, the Department of Environmental Affairs (now the Department of Environment, Forestry and Fisheries – DEFF) reviewed energy efficiency interventions in the petroleum sector[11] based on their emissions-savings and costs. Figure 9 represents the Marginal Abatement Cost Curves (MACC) for energy efficiency interventions in the petrochemical and petroleum refining sectors by the years 2020, 2030 and 2050, respectively.

Figure 8. Mitigation potential for petrochemicals and petroleum refining — 2020, 2030, 2050



Source: TIPS, based on DEA and GIZ, 2014, p. 38. Note: See Figures 18, 19 and 20 in the Appendix for individual year MACC curves for 2020, 2030 and 2040.

Based on the MACC analysis[12], the lowest marginal abatement costs originate from energy efficiency interventions, which include the installation of advanced energy management and monitoring systems; improvement of existing steam generating boiler efficiencies; improvement of process heater efficiencies; improved process control; and energy efficient utility systems. In addition, improved heat exchanger efficiencies present a negative marginal abatement cost in the 2050 scenario. Overall, cost-effective and feasible interventions, with a negative marginal abatement cost, account for about 50% of GHG emissions

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[11] While these curves relate to the petroleum refining sector, there is overlap between these interventions and those specific to the petrochemical sector. This is owing to the fact that petrochemical production is inextricably linked to petroleum refining. Thus, these curves are indicative of the possible interventions in the petrochemical sector.

[12] For individual MACC curves by year and detailed intervention please see the appendix.

abated in 2020. This picture changes for the 2030 and 2050 scenarios, when these options account for less than 25% of GHG emissions abated.

It is assumed in DEFF's analysis that after 2030, options like CHP and CCS will become a widescale reality. Based on the current evolution of these technologies, the widescale availability of these technologies in 2030 and 2050 appears highly improbable, however. Nevertheless, these costlier options offer differing GHG emissions abated at different costs. Efficient energy production for chemicals (including CHP) contributes less than 15% to GHG emissions abatement while costing less than R500/tCO2e in both scenarios. In 2030 and 2050, CCS offers the highest contribution to GHG emissions abatement, however, the costs are overwhelmingly substantial. In both scenarios, CCS on existing and new refineries contributes in the range of 68% to 76% to GHG emissions abatement, while costing in the region of R3 000/tCO2e for CCS on both existing and new refineries. More detail on CHP and CCS are included in the respective sections below.

Of the range of energy efficiency interventions presented in the MACC analysis (with the exclusion of CHP and CCS which are discussed later), most interventions have already been instituted in South Africa to a significant degree. Given the level of existing penetration, Table 2 indicates the extent to which these energy efficiency measures can be implemented further in South Africa.

Table 2. Implementation and scope of energy efficiency measures in South Africa

INTERVENTION	EXTENT OF IMPLEMENTATION IN SOUTH AFRICA	SCOPE FOR FURTHER IMPLEMENTATION
Waste heat boiler and expander applied to flue gas from the Fluid Catalytic Cracking (FCC) regenerator	This efficiency is widespread in the sector.	Limited opportunity for further development.
Waste heat recovery and utilisation	This efficiency is widespread in the sector.	There is scope for improvement. Space and configuration constraints are key barriers to greater levels of waste heat availability.
Improve steam generating boiler efficiency	This efficiency is widespread in the sector.	Scope of 3%-4% further improvement.
Improve process heater efficiency	This efficiency is widespread in the sector.	Scope of less than 5% further improvement. Retrofitting existing refineries is a key barrier.
Energy monitoring and management systems	This efficiency is widespread in the sector.	There is scope for improvement.
Improved process control	This efficiency is widespread in the sector.	There is scope for improvement.
Energy-efficient utility systems	This efficiency is widespread in the sector.	There is scope for improvement.
Improved heat exchanger efficiencies	This efficiency is widespread in the sector.	There is scope for improvement.
Improved electric motor system controls and variable speed drives VSDs	This efficiency is widespread in the sector.	There is scope for improvement.
Minimise flaring and utilise flare gas as fuel	Not widely implemented.	Potential for improvement.

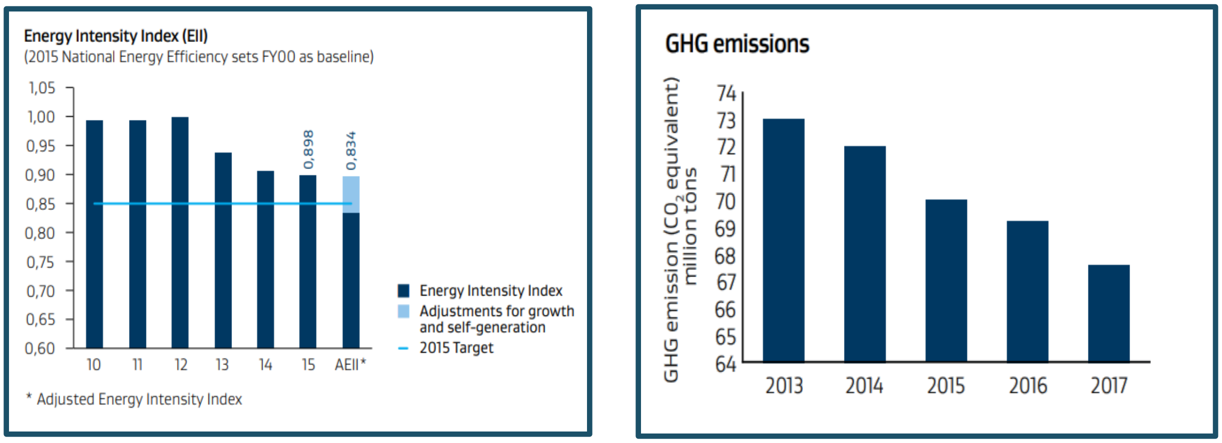
Source: DEA and GIZ, 2014, pp.21-22.

The only intervention which has seen limited roll out in South Africa relates to minimising flaring and utilising flare gas as fuel. Energy monitoring and management systems, improved process control, energy-efficient utility systems, improved heat exchanger efficiencies, and improved electric motor system controls and VSDs, all have been instituted widely but have room for improvement. Waste heat boiler and expander applied to flue gas from the FCC regenerator, waste heat recovery and utilisation, improving steam generating boiler efficiency, and improving process heater efficiency, all have limited scope for further improvement.

Energy efficiency efforts in the country have been driven by firms and industry bodies. In 1994 the Chemical & Allied Industries' Association (CAIA) of South Africa launched the Responsible Care (global level intervention) initiative to improve environmental, health and safety performances, build communication networks on energy efficient practices, and contribute to sustainable development for the chemicals sector. Since 1994, 150 chemical companies are signatories to the Responsible Care initiative. The National Cleaner Production Centre South Africa (NCPC-SA) has embarked on industrial energy efficiency interventions for the chemicals and businesses since 2010 in attempts to create energy management systems (EnMS) and energy systems optimisation (ESO) for the reduction of CO_2 emissions that enable energy and cost savings (CAIA, 2017). In addition to EnMS and ESO measures, energy efficiency demonstrations and awareness campaigns have been conducted to aid industrial energy efficiency at a corporate and sector level. Furthermore, partially subsidised skills development initiatives have been created to assist employees (engineers, energy managers and maintenance staff for example) with implementing EnMS and ESO measures at a firm level, through practical and theoretical training (CAIA, 2017). Interested firms are also able to enrol as demonstration plants for the purposes of practical knowledge sharing on implemented energy efficiencies measures.

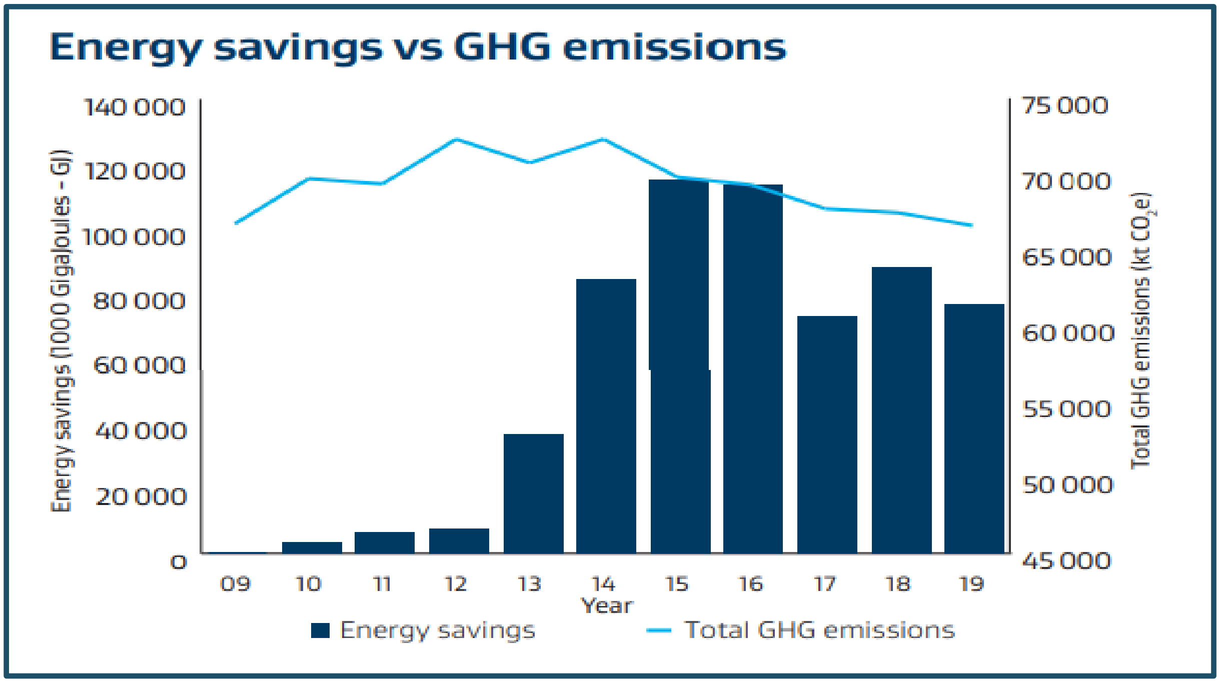
With private firm initiatives, Sasol is voluntarily participating in the carbon budget process and has considered a budget limit of 302 $MtCO_2e$ for the period of 2016 to 2020. In 2016, 55 $MtCO_2e$ of the budget was emitted. Sasol has also set energy efficiency targets in line with the South African Energy Efficiency Accord and as such has developed technologies making use of ultra-high purity calcined alumina products that contribute to energy efficiency.

Figure 9. Sasol energy efficiency and GHG emissions over time



Sources: Sasol, 2017a; Sasol, 2017b

Figure 10. Sasol Energy efficiency, 2009-2019



Source: Sasol, 2019*c.*

Sasol has engaged in processes to decrease their volatile organic compound (VOC) emissions with a R3.4 billion emissions abatement project that has seen emissions of VOC decrease from 46.2 kilotons (kt) in 2016 to 41 kt in 2017. NOx and sulfur oxides (SOx) emissions also decreased for the financial year from 156kt to 152kt, and 223 kt to 202 kt, respectively. Reduction of SOx emissions have been attributed to the better quality of coal. As part of its reporting on climate change activities, the company reported GHG emissions declining by 16% since the early 2000s due to energy efficiency investments made. While Sasol has engaged in a substantial decline in emissions, it still persists as one of the largest emitters in the country and has been subject to the criticisms indicated in Section 2.4.

Combined heat and power

CHP, also known as cogeneration, refers to the productive use of otherwise wasted energy from industrial processes and generation (IEA, 2014). Cogeneration is the use of a single energy source to produce more than one type of energy (Goth, 2014). Due to heat being a low-value product, rather than producing it exclusively, it can be recovered from other processes that generate excess heat, and put to productive use (Bennett and Page, 2017). CHP enables the simultaneous generation of productive heat and electricity, and has positive energy efficiency benefits for the conversion process, which ultimately reduces emissions (IEA, 2014). This efficiency manifests through the recovery of heat produced during electricity generation and other industrial activities, such as petrochemical production (IEA, 2014).

Globally, it is estimated that conventional thermal plants convert only 36% of energy into useful outputs, while CHP units convert between 58% and 90% of energy into useful outputs (IEA, 2014). This application can provide tremendous value in the petrochemical process, where petrochemical plants have a high demand for power and high temperature steam (heat) in applications, such as steam cracking (Bennett and Page, 2017). From a climate perspective, this allows heat and electricity users to use electricity and heat produced through cogeneration rather than relying on heat and electricity directly produced from fossil fuels, reducing GHG emissions.

Interrelated with cogeneration systems are district heating and cooling (DHC) technologies[13], which join energy users through a piping network to energy sources such as CHP; industrial waste heat and renewable energy sources such as biomass; and geothermal and natural sources of heating and cooling (IEA, 2013). DHC channels unused energy from industrial processes to end-users such as residential and commercial buildings, allowing these users to meet their heating and cooling needs (IEA, 2014). DHC networks can be linked to proximal carbon-free energy sources, such as solar thermal heat and waste heat recovered from industrial processes. Further, natural sources, such as lakes, seas and rivers, can also be used to meet cooling needs. It is estimated that DHC networks based on these carbon-free and natural energy sources can attain energy efficiencies in multiples of five to ten times compared to traditional electricity-driven equipment (IEA, 2014).

CHP interventions can be located within industrial applications and firm operations, where energy-intensive industrial sectors such as chemicals, refining, pulp and paper, and food and beverage typically have high process-heat requirements and considerable electricity needs, which can benefit from cogeneration technologies. In this context, however, barriers to increased implementation include high energy prices, insufficient regulatory conditions and high capital costs (IEA, 2014). CHP interventions can also be located in DHC systems when heat is channelled to end-users for applications such as space heating and hot water. In these systems, cooling needs can be met from natural sources like rivers and the sea. In these systems, barriers to further uptake include the same barriers as within firm operations but have additional complexities surrounding the alignment of technologies and urban planning strategies, a sustainable demand for offtake heating/cooling, and the need for consumers to be close to heating and cooling producers (NERSA, 2011).

South African industry has not fully tapped into CHP and there remains potential for its application, particularly in industries such as petrochemicals. It is estimated that the total potential capacity for cogeneration in South Africa ranges between 3 000 MW and 4 000 MW, of which in excess of 2 000 MW can be supplied by mineral smelters and chemical plants (Goth, 2014). While the National Energy Regulator of South Africa (NERSA), has mandated rules[14] for cogeneration, the uptake of CHP systems has tended to be small-scale, localised to plants to provide electricity and heat to the plant itself (Goth, 2014).

Sasol has been involved in CHP in the petrochemicals sector.[15] Sasol constructed two cogeneration turbine generators, which produce electricity from waste steam at its Secunda CTL operations. The project provides 200 MW of power and process steam to Sasol's Synfuels operations (WSP, 2017). Sasol has also constructed a R1.9 billion 140 MW CHP facility in 2012 at its Sasolburg operations which generates power from natural gas feedstock.

A large gap in the South African context is the supply of power and heat between different firms and users. CHP requires that users be located close to each other such that these projects are viable. Mismatches in

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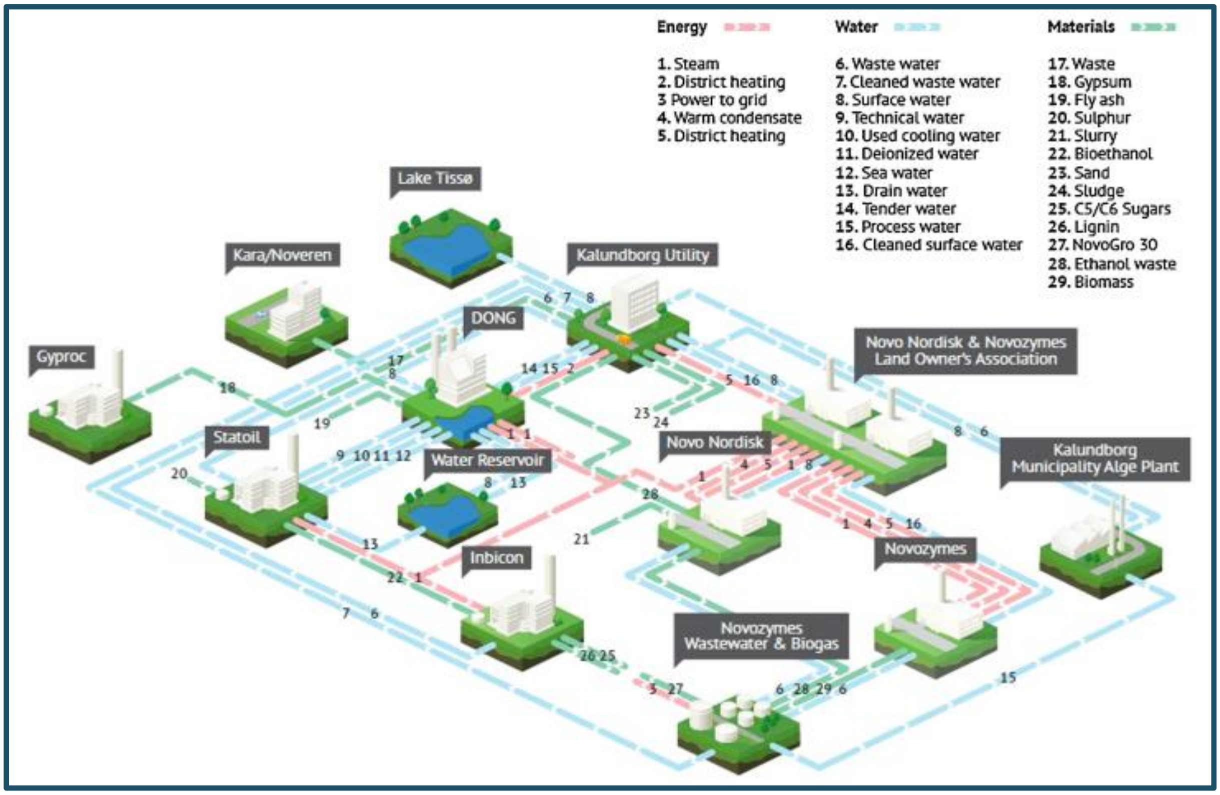
[13] When cogeneration is combined with cooling, this is also termed trigeneration, and when CHP is combined with cooling and CO_2 recovery, this is known as quadgeneration.

[14] See (NERSA, 2011)

[15] These examples refer exclusively to the petrochemicals sector. A myriad of other sectors have also instituted cogeneration in their processes. For information on these, see DoE, 2016, p.7; Meyer, 2008.

heat and power requirements also require many consumers of heat and electricity for CHP projects to be viable (Von Blottnitz, 2017). Increased distances between users mean increasing heat and electricity losses and increasing capital costs. International experience indicates that industrial symbioses is required for inter-firm CHP applications to work. Such is the case in Denmark, where the largest power producer Ørsted's CHP operations provide heat to the Kalundborg Utility, which then distributes it to citizens and companies (Kalundborg Symbiosis, 2018). This typically occurs within industrial parks or regions where large producers of heat supply other firms that require heat and electricity, usually in the form of steam or hot water. To date there are no examples of industrial symbioses and CHP in petrochemicals in South Africa, with such applications being concentrated within intra-firm divisions such as the Sasol's Secunda operations.

Figure 11. Denmark's Kalundborg cluster with CHP technology



Source: Gulipac, 2016.

While research has indicated that planned, co-located CHP symbioses are difficult to establish, clusters of firms such as the Special Economic Zones and IDZs have been identified as key initial points for this technology (Von Blottnitz, 2017). Specifically, research on the Richard's Bay IDZ has indicated potential for cogeneration coupled with a prospective Independent Power Producers powerplant. A two gigawatt electricity power plant has been planned for the Richard's Bay IDZ and, if cogeneration is coupled with this plant, it has the potential to generate at least 600 MW of heat for industrial users (Von Blottnitz, 2017). This would be able to provide heat for at least 60 commercial scale breweries, for example (Von Blottnitz, 2017). Further, initial research has indicated the potential for exchanges of heat and fuels in the Richard's Bay IDZ reducing the fuel usage, CO_2 emissions, and water use by the plant (Von Blottnitz, 2017).

Beyond the clusters identified, the widescale rolling out of CHP technologies is unlikely to materialise in the short to medium term due to the barriers identified. The need for proximal suppliers and consumers combined with the high costs of the technology mean that the technology can be implemented only in limited settings and locations.

Carbon capture and storage and Carbon capture and utilisation

Carbon capture refers to technologies which collect CO_2 emissions that would otherwise be released into the environment. CCS specifically refers to collecting CO_2 and channelling these emissions to less environmentally-harmful storage mediums (Bennett and Page, 2017). Carbon capture and utilisation (CCU) is complementary to CCS and includes technologies that allow captured CO_2 to be used as an input into industries that require CO_2 as a feedstock.

CCS is regarded as a potential future mitigation technology, due to its potential to reduce CO_2 emissions more than is feasible from current mitigation technologies (Boulamanti and Moya, 2017). The CCS technology involves trapping CO_2 produced in industrial processes and transporting it to a suitable storage medium. CCS has a number of technological configurations, and these configurations depend on the context. While CCS is typically discussed in the context of decarbonising the power sector, it has applications in the petrochemicals industry where the production of hydrogen, methanol and ammonia produce significant amounts of CO_2 (Bennett and Page, 2017).

Figure 12: CCS technology options

Point of collection	Transport	Storage
Pre-combustion	Pipeline	Depleted reservoirs
Post-combustion	Shipping	Saline aquifers
Oxy-fuel combustion	Trucks	Coal seams

Source: TIPS based on Bennett and Page, 2017 and SACCCS, n.d.-a.

As indicated in Figure 13, a number of technological options at each stage of CO_2 capture exist for the implementation of CCS. CO_2 can be captured prior to combustion, increasing the efficiency of the process, and CO_2 can also be captured post-combustion by retrofitting plants (Bennett and Page, 2017). Various transport options exist, in addition, when captured CO_2 can be transported via pipelines and/or via ships to the final point of storage. Captured CO_2 can be stored in a number of geographical mediums including aquifers, depleted fossil-fuel reservoirs, or under ground (Bennett and Page, 2017).

CCS activities generally consist of three categories – geological storage, enhanced oil/gas recovery, and mineral carbonisation. Geological storage refers to collecting CO_2 from sources at industrial installations, compressing it, transporting it and injecting it into geological formations, such as depleted oil and gas reservoirs; deep saline aquifers and coal bed formations; or beneath the ocean (Haerens, 2017). Enhanced oil/gas recovery involves pumping CO_2 into an already-tapped oil or gas field to liberate more oil or gas (Haerens, 2017). The technology underpinning enhanced gas recovery is not fully commercially developed, while enhanced oil recovery is a mature process (Haerens, 2017). The goal of enhanced oil recovery is to maximise the extraction of oil and not the storage of CO^2, and the process is costlier than new oil extraction, thus not many oil companies find enhanced oil recovery to be profitable (Haerens, 2017). Finally, mineral carbonisation involves reacting CO_2 with metal oxides to permanently store carbon in a solid product and, once stored in this form, CO_2 virtually cannot escape (Haerens, 2017).

In the petrochemical industry, CCS can be applied in the production processes of the following chemicals: ammonia and urea, hydrogen, methanol, ethylene oxide and polymers (Boulamanti and Moya, 2017). Internationally, many large multinational chemical companies such as BASF, Bayer, and Total have been identified as moving towards utilisation of captured CO_2 as raw material. Despite some potential, the complete chain of CCS has been implemented only on a limited scale internationally (SACCCS, n.d.-b). Only 17 commercially viable CCS projects exist internationally, of which six relate to the production of chemicals (see Table 14 in the Appendix). In addition to these large projects, pilot-scale projects are in operation in North America, South America, Europe, Asia and Australia (SACCCS, n.d.-b).

While CCS is touted as a promising technology to help large industries in curbing CO_2 emissions, international experience has identified barriers that accompany the technology. The primary barrier to implementation has been the extraordinary capital costs required to set up the full CCS system from capture to storage. Plants to capture CO_2 alone can reach billions of dollars, excluding the costs of transport and storage (Bennett and Page, 2017). This implies a lack of competitiveness with other carbon mitigation investments in the petrochemical value chain, with limited financial compensation (EC, 2018). Further, the risks associated with pipeline construction, identification of storage, and the monitoring of storage deter investment in CCS technologies (Bennett and Page, 2017). The risks associated with CCS technology render these projects highly risky from an investor perspective. For example, in the European Union (EU), €1 billion was allocated in 2009 to six projects throughout the Member States through the European Energy Programme for Recovery programme. By October 2013, three of the six projects had failed due to permitting, legislation and financing issues (EC, 2018).

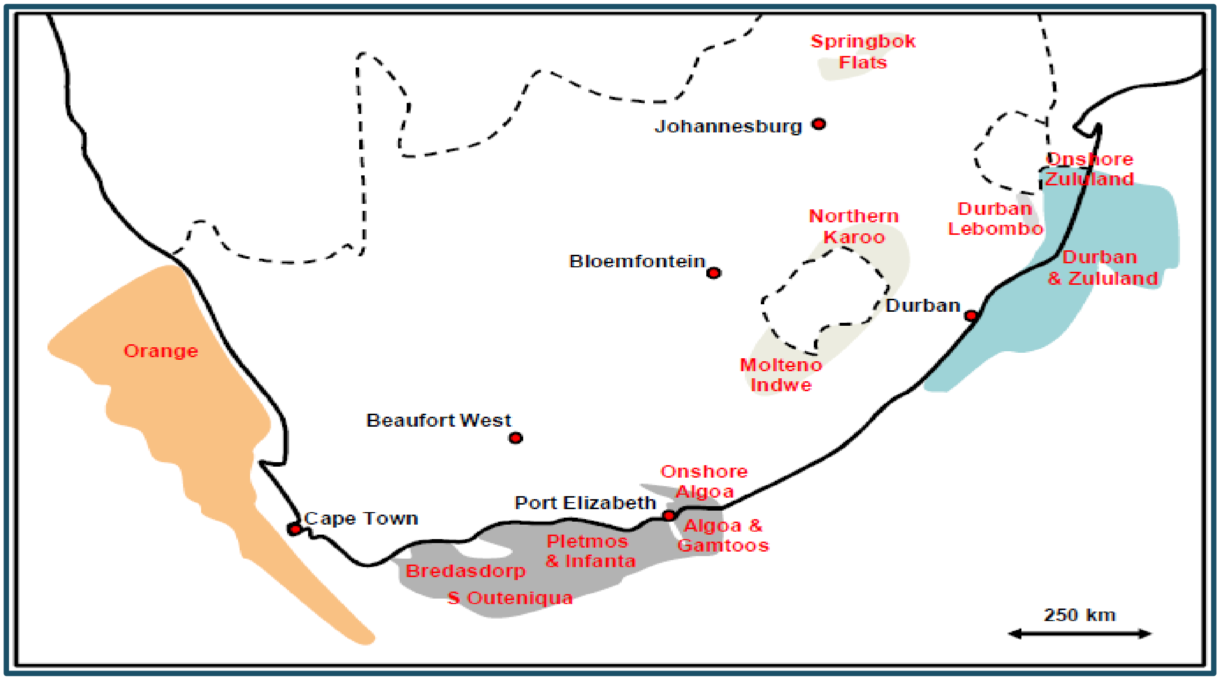
In South Africa, CCS developments have been spearheaded by the South African Centre for Carbon Capture & Storage (SACCCS), a body created within the South African National Energy Development Institute (SANEDI) in 2009 and mandated to pursue the development of CCS in South Africa.

CCS does feature in government plans through its inclusion in (SACCCS, n.d.-c):

- Long-term mitigation scenarios previously developed by the then-Department of Environmental Affairs and Tourism;
- South Africa's eight Near-term Priority Flagship Programmes of the National Climate Change Response White Paper;
- South African CCS Road Map endorsed by Cabinet in May 2013; and
- National Development Plan 2030.

The development of CCS in South Africa is still in its early stages, however, no commercially-operational CCS activities are in place along the full chain of CCS activities (World Bank, 2016). While certain elements of the CCS chain are already operational in South Africa through industrial CO_2 capture and small-scale CO_2 transport, fully-operational CCS projects have not been implemented (World Bank, 2016). Funding from the World Bank has assisted South Africa in developing CCS technology, with the bank provided US$1.35 million in 2009 for a first phase for developing a regulatory framework, conducting a techno-economic review, building capacity, and developing a national and local public engagement plan (World Bank, 2016). In addition, the World Bank has approved US$23 million for a five-year second phase, which involves the development of a pilot CO_2 storage project in either KwaZulu-Natal or the Eastern Cape (Kilian, 2015; World Bank, 2016).

Figure 13: Locations of potential CCS storage basins in South Africa (in red)



Source: World Bank, 2013, p.78.

Looking at potential storage locations in the country, sedimentary basins cover most of the land surface in South Africa but most of these basins are unsuitable for CO_2 storage (World Bank, 2013). The potential basins are indicated in Figure 14 and amount to 12 basins in the country. Basins occur along the coast of the country along with some inland basins. The onshore basins have been found to have negligible storage capacity and the offshore basins have been estimated to have lower than expected storage capacities (World Bank, 2013). Only two of the 12 basins have been identified as having substantial capacities – the Orange basin (6 588 Mt — 9 000 Mt) and the Durban and Zululand basins (0 Mt – 7 850 Mt)[16] (World Bank, 2013).

South African industry has acknowledged the potential for CCS through some activities in preparation for the technology. For example, Eskom included the potential for CCS through its design of the Kusile Power Station by requiring that the plant be "Carbon Capture Ready" (MacColl, 2015). Other firms have taken a more proactive approach towards CCS technologies. Sasol, for example, has conducted pre-feasibility studies throughout the world and sponsors workshops on CCS, monitoring developments in the technology (SASOL, 2015). Sasol is also a founding member of SACCCS and has contributed funds to CCS research and exploration. In 2009 Sasol contributed R2 million to the SACCCS and co-sponsored the development of a South African Carbon Dioxide Storage Atlas to identify potential sites for the geological storage of CO_2.

While notable efforts and funding have been directed to CCS technology, with the lack of a global price on carbon a general business case for CCS has yet to be proven globally and locally. The viability of CCS

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[16] The range has been estimated for probabilities between 50% and 90%.

will in the future depend on factors such as the price of carbon, emissions regulations and technology progression of CCS technology and cost competitiveness. Many international projects remain in the category of research or pilot scale, and those that extend to commercial scale receive substantial government subsidisation to remain viable. Given the high capital expenditure required, there is a risk that investments in CCS can create path dependency on the technology warranting further investments and placing a sizeable cost constraint on the national fiscus. As the technology evolves, CCS may very well be implemented in the long term. Its footprint in South Africa will be limited to regions where storage options are available, however.

CCU is a much newer development in carbon storage than CCS. Instead of storing CO_2, it is used as a raw material and transformed into value-added products and services. CCU is regarded as contributing to reduced emissions directly and indirectly. The direct effect is through utilising the CO_2 that would have been released into the atmosphere. The indirect effect is through product substitution of emission-intensive products (Haerens, 2017).

The CO_2 emissions reduction potential of CCU, however, depends on the market potential of CO_2-based products. Examples of industrial use of CO_2 include the production of urea, pigments, methanol, salicylic acid and propylene carbonate. Since CO_2 is a relatively non-reactive, the current industrial uses of CO_2 are highly energy intensive, requiring high levels of energy to collect and convert CO_2. This presents an emissions conundrum if energy is dependent on fossil fuels (Haerens, 2017, p.22). CCU can, in certain circumstances, attract additional carbon emissions when compared to CCS, as the CO_2 present in the products produced through CCU are eventually emitted into the air. The time at which this happens is sensitive to the type of product and can range from days or weeks (liquid fuels), years (polymers), or decades to centuries (cement) (Haerens, 2017).

CCU processes that accommodate CO_2 as a feedstock span four categories: direct utilisation, CO_2-to-fuel, CO_2-to-chemicals, and CO_2-to-materials via mineral carbonisation (Haerens, 2017, p.22). Direct utilisation concerns the use of CO_2 in its pure form in applications such as the carbonation of beverages, preservation of foods, coffee decaffeination, increasing plant growth rates, and refrigeration (Haerens, 2017, p.25). Direct utilisation requires high purity CO_2 which is generally produced in processes such as ammonia production and this market is small (Haerens, 2017, p.25). CO_2-to-fuel concerns converting CO_2 to a fuel source either through chemical or biological means. CO_2-to-chemicals involves converting CO_2 through chemical or biological means into a plethora of valuable chemicals such as methanol, ethanol, urea and polymers (Haerens, 2017, p.31). CO_2-to-materials via mineral carbonisation overlaps with mineral carbonisation, presented above under CCS.

CCU is still an infant technology only gaining traction in recent years. While much has been written on the technology from a technical perspective, not much research has been done on CO_2 reduction potential, potential profitability of CCU, and the quantification of the potential net benefits (Haerens, 2017, p.33).

Despite having promising potential, CCU faces substantial barriers from technological and economic points of view. From a technical perspective, a complete life cycle CO_2 mitigation has to be proven for the CCU to ultimately mitigate CO_2 emissions, and the experience to date indicates a limited ability of CCUs to accomplish this (Haerens, 2017). From an economic point of view, the offtake CO_2 price has to be sufficient to warrant a firm to invest into CCU technology. In the case of certain products, such as sodium carbonate and methanol, the ultimate price of these products will have to be in multiples of current prices, for the CCU investment to be feasible (Haerens, 2017).

CCU is a much newer technology than CCS and its full-scale implementation remains to be proven. There are still numerous uncertainties related to the feasibility, downstream markets and potential climate mitigation that need to be answered before investments in the technology can be made. CCS will see the light of day sooner as a technology than CCU, despite the low likelihood of CCS being implemented in South Africa in the near future.

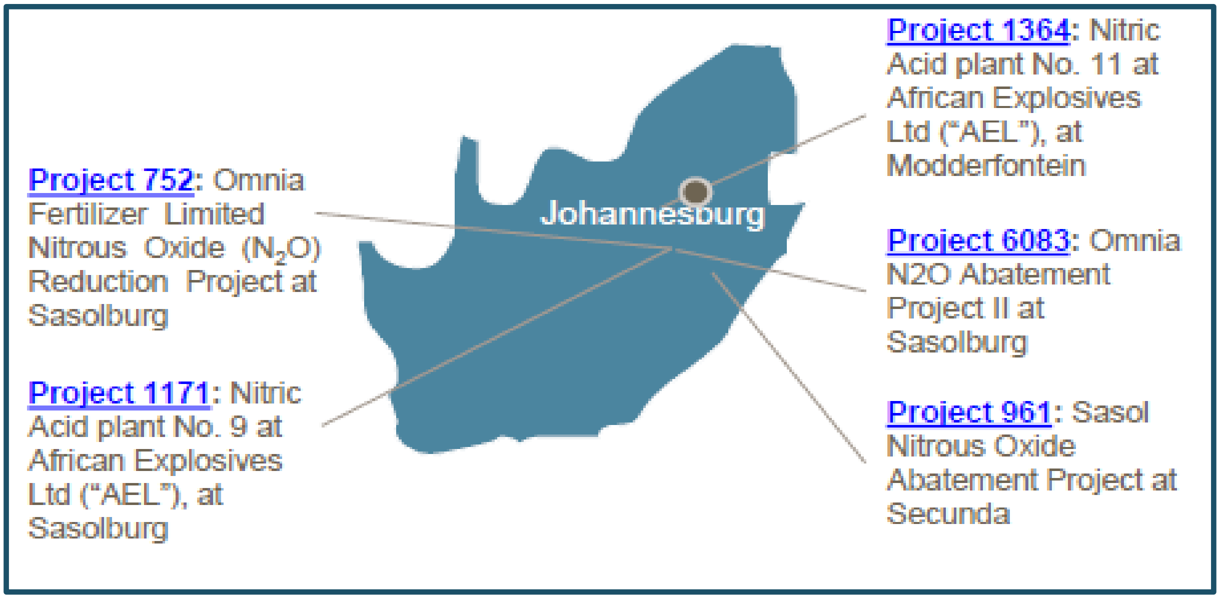
NOx mitigation

Nitric acid is a precursor feedstock that is produced in the petrochemical upstream and used chiefly in the production of nitrogen-based fertilisers. As a result of fertiliser production, NO_x gases are produced and emitted, primarily nitrous oxide (N_2O). These gases are irritants that can causes adverse health outcomes. NO_x gases in sufficient concentration can form smog, acid rain, fine particles and ground level ozone (US EPA, 1999). NO_x gases are a type of pollutant considered in the analysis as they are typically pertinent to the discussion surrounding the sustainable transition of the petrochemical industry.

In terms of its potency, NO_x gases are 265 more potent than CO_2 emissions (GIZ, n.d.). Currently, the annual emissions from nitric acid production in the country equate to 3.2 $MtCO_2e$, and account for approximately 0.7% of total emissions. In terms of mitigation of NO_x gases in the petrochemical value chain, the technology is regarded as technically easy, comparably cheap to other mitigation options and is a proven technology (NACAG and GIZ, 2018).

There are six major nitric acid plants in South Africa, concentrated in Secunda (Sasol), Sasolburg (Omnia and AECI) and Modderfontein (AECI). The Nitric Acid Climate Action Group was launched in 2015 by the German Ministry for Environment to drive N_2O abatement globally. South Africa was identified as a country deserving of assistance in installing N_2O abatement technologies.

Figure 14: N_2O mitigation projects



Source: NACAG et al., 2018.

Engagements with the Nitric Acid Climate Action Group (NACAG), German development agency GIZ and fertiliser companies have revealed that NO_x technologies were installed through the United Nations Framework Convention on Climate Change Clean Development Mechanism (CDM). All nitric acid plants in South Africa were registered for the CDM and, since the beginning of the programme, about 10 million Certified Emission Reductions were generated (NACAG et al., 2018). After the funding ceased, N_2O abatement technologies have largely been discontinued in South Africa due to the costs of these projects. The NACAG financial assistance applies only to projects that were not supported by the CDM, and most plants do not qualify for further financial assistance from NACAG. Fertiliser firms, absent any financial assistance or incentives, regard new NO_x mitigation investments as unfeasible due to those resources being better devoted to cost-saving efficiency investments. Other barriers to investment also include the carbon tax which, as it currently stands, does not provide a sufficient disincentive for emissions.

Based on the current sentiment towards NO_x emissions, and the lack of financing for ex-CDM funded capacity, substantial resources will have to be provided to firms as an incentive. Given that the current levels of NO_x emissions are lower compared to carbon emissions, and that greater wins can be devoted to other investments such as energy efficiency, there is a clear lack of prioritisation of NO_x mitigation among firms.

3.3 End-of-pipe/circular economy solutions

Waste management and recycling

Waste management[17] and recycling interventions offer complementary options to reduce the environmental impact of petrochemicals. Waste management includes the use of landfills and incineration, recycling, and other forms of waste-to-energy (WtE) methods of disposal. Traditionally, waste has been stored in landfills or “waste dumps”, where waste material is collected and stored, after being processed. The use of landfills is associated with serious environmental challenges such as local pollution of resources, and land-use restrictions (WEF, 2017). From an emissions perspective, landfills are one of the largest emitters of methane, which is a potent greenhouse gas (WEF, 2017). Interventions which divert waste away from landfills thus reduce the environmental harm which landfills cause. In South Africa, landfills are quickly approaching exhaustion, and other methods of disposal are urgent on the waste management agenda. There are currently 876 landfill sites in the country receiving municipal waste and these are rapidly approaching capacity, with new land to extend landfill sites or construct new ones constrained (IWMSA, 2017).

Industry in South Africa has working to tackle the climate impact of landfills. For example, the plastics industry in 2014 committed to reduce plastic waste to landfill to a minimum through the Zero Plastics to Landfill by 2030 vision. As the name of the vision indicates, the plastics industry targets to eliminate all plastic from the country’s landfill sites by 2030 (Plastics SA, 2014). Until recently, while the institution was still in operation, the Recycling and Economic Development Initiative of South Africa (REDISA) also funded research with various tertiary institutions in the country in finding new treatment processes for rubber recycling.

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[17] Waste management concerns how petrochemical products are handled at the end of their lives such that their environmental impact is managed (Bennett and Page, 2017, p.413).

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One method of landfill diversion is through retaining resources for as long as possible through the processes of recycling, repair and reuse. Recycling[18] refers to the recovery process where waste materials are reprocessed into products either to meet their original purpose or other purposes (Shehu, 2017, p.30). In the case of the petrochemicals industry, the key downstream products are plastics and rubber products, which can be recycled and reused to extend their lives. Recycling both conserves energy resources and reduces carbon emissions. Conservation of energy resources results from the reuse of petrochemical products that otherwise would have been manufactured. Reductions in emissions occur as the energy demand of plastic and rubber manufacture, and hence and carbon emissions, declines through the use of recycled products (Bennett and Page, 2017, p. 414).

In South Africa, waste is collected by municipalities (households) or private sector contractors (commercial and industry) (GreenCape, 2017, pp.12,15). While municipalities are mandated to implement alternative waste management processes (such as recycling) to divert waste from landfills, the focus has been on collection and landfilling infrastructure (GreenCape, 2017, p.15). Most municipal investment has been devoted to waste collection and landfilling. This contrasts with private investment, which has invested considerably in landfilling and alternative waste treatment, such as recycling (GreenCape, 2017).

The following sections consider plastic and rubber recycling separately as the market dynamics impacting these recycling markets differ markedly.

Plastic recycling

Globally, approximately 335 million tons of plastic were produced in 2016, of which South Africa contributed about 0.5%[19] (Plastics SA, 2017a; PlasticsEurope, 2017). The production of plastics is concentrated in the northern hemisphere, and the largest plastic producing nations are China (29%), the EU (19%), and North American Free Trade Agreement (NAFTA) countries (18%) (PlasticsEurope, 2017). The sources of plastic waste in South Africa originate from consumer and industrial waste. Post-consumer waste overwhelmingly dominates and accounts for 75% of all waste collected. This is followed by ex-factory[20] waste (12%), post-industrial waste (10%), and toll and in-house waste[21] (3%). On a geographic basis, consumer waste drives the largest sources of plastics and are concentrated in the most populous provinces of South Africa – Western Cape, Gauteng, and KwaZulu-Natal.

The vast number of plastics products, which are produced as downstream products from the petrochemical industry, have different applications (see Table 15 in the Appendix). Four products – polyethylene, polypropylene, polyethylene and PET - accounted for 70% of the plastics produced in tonnage terms in 2016. In the manufacture of new plastic goods, the country is still heavily dependent on virgin plastics, however. For example, in 2016, 82% of plastics produced in South Africa were produced

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[18] For simplicity, recycling here encapsulates all recovery processes including re-use and repair.

[19] Based on input polymer tonnages of 1.518 million tons of virgin polymer (Plastics SA, 2017a, p.2) and world plastic production of 335 million tons (PlasticsEurope, 2017, p.16)

[20] This refers to waste emanating from the factory producing the plastics.

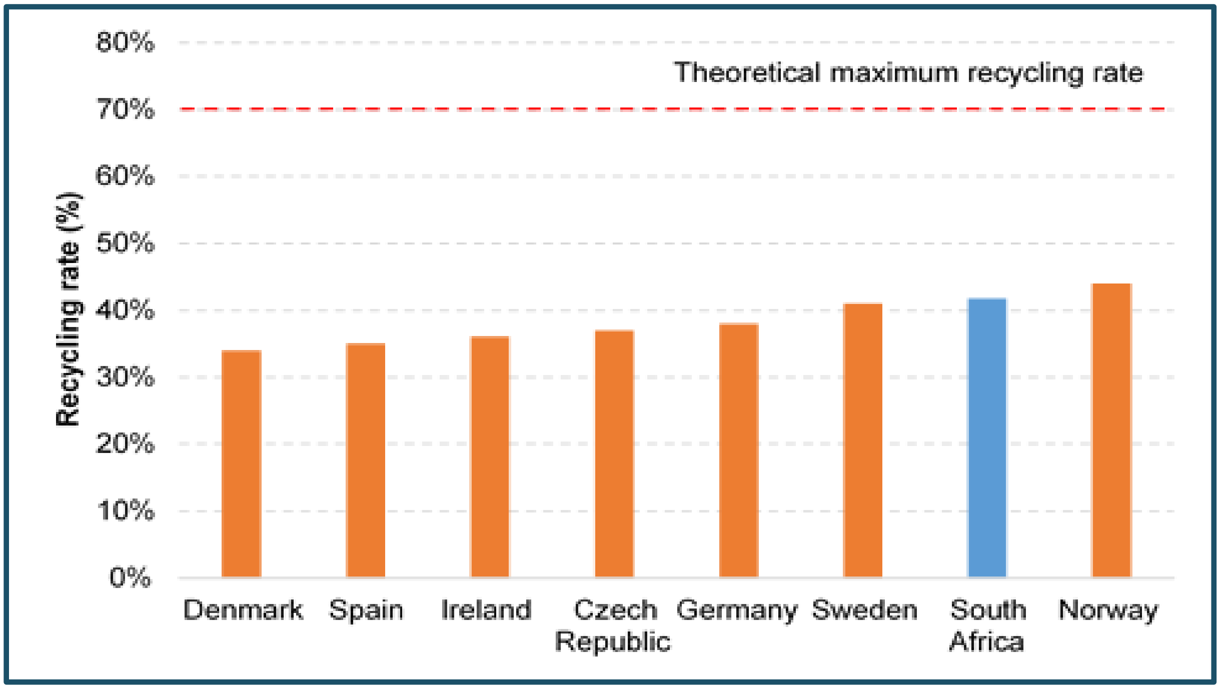
[21] This includes waste that is reused in-house.

from virgin materials, with plastic manufacturers only absorbing 17.2% of recycled plastic inputs[22] (GreenCape, 2018, p.47).

Two types of recycling technologies are prevalent in the world today – mechanical and chemical recycling. Mechanical recycling refers to processes that recover plastic waste through mechanical processes such as grinding, washing, separating, drying, regranulating and compounding, producing recycled products that can substitute for virgin plastics (PRE, 2016a). Chemical recycling refers to processes which chemically degrade plastic waste allowing it to be reused for polymerisation into new plastics for the production of other chemicals or as an alternative fuel (PRE, 2016b). The latter is generally applied to non-recyclable plastics and contaminated waste. In South Africa, mechanical recycling is the predominant technology that is used as other commercial facilities for alternative plastics recycling are limited (Cloete, 2017; Plastics SA, 2017b).

According to the local industry, South Africa fares favourably compared to other countries in terms of the plastic mechanical recycling rate[23]. The figure below depicts the plastic mechanical recycling rates in South Africa as compared to the rest of the world.

Figure 16: Plastic recycle rates for selected countries



Source: Author's adaptation from GreenCape, 2017, p.2, 2016, p.21; PlasticsEurope, 2017, p.33, 2015, p.7.
Notes: 1. Theoretical maximum rate of 70% is based on the fact that approximately 30% of plastics cannot be recycled in South Africa due to factors like contamination or a mixture of different plastics, combined with consultation with stakeholders on an approximate maximum recycling rate. This maximum rate is an average and varies based on the specific polymer concerned. See GreenCape, 2017, p.27. 2.The figure includes only mechanical plastic recycling and no other methods of plastic waste treatment, such as incineration and waste-to-energy operations.

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[22] The remaining recycled plastic is exported.

[23] The recycling rate can be defined as: Recycling rate = Annual total waste recycled/ Annual total waste generation. See Hotta, et al., 2013, p.2.

Recyclate material are used as inputs into a number of markets in South Africa. Recyclate refers to the raw material that is sent to a waste processing facility to be used in the formation of new products. The major users of recyclate plastic inputs in South Africa are the packaging, clothing and footwear, agricultural and furniture sectors as indicated in Table 3.

There has been recent debate around the accuracy of South Africa's methodology of estimating the recycling rate. The plastic recycling rate reported by Plastics SA refers to an "input recycling rate", which measures the collected waste rather than the produced recycled granulate from this waste (Von Blottnitz et al., n.d.). Further, the measurement has been criticised as an overestimate due to the fact that imported packaging is not accounted for in the estimation. Another potential view on the extent to which plastics are recycled is based on the average recycled content of plastics products made in South Africa, which accounted for 17% in 2017 (Von Blottnitz et al., n.d.). Despite this disparity in recycling statistics, South Africa is still regarded to fare relatively well at plastics recycling, but has the potential to increase recovery (Von Blottnitz et al., n.d.).

Table 3. Major downstream users of plastic recyclate

PRODUCTS	MARKETS FOR RECYCLED PLASTICS	PERCENTAGE OF RECYCLATE USED TO MANUFACTURE PRODUCT
PE-LD/LLD and PE-HD	*Flexible packaging:* Refuse and carrier bag manufacturers	20%
PVC	*Clothing and footwear manufacturers:* fibre applications and flexible PVC for shoe soles and gumboots	18%
PE-HD/PP/rPET	*Recycled rigid packaging:* drums and buckets; thermoformed sheet applications	15%
PE-LD/LLD	*Agricultural sector:* irrigation pipes *Furniture sector:* injection moulded chairs and tables, picture frames	10%
Others	N/A	37%

Source: Author's adaptation of Plastics SA, 2017c, p.2. *Note:* PE-LD (low-density polyethylene); PE-LLD (linear low-density polyethylene); PE-HD (high-density polyethylene); PVC (polyvinyl chloride); PP (polypropylene); rPET (recycled PET)

Most of the recyclate plastic material available in the country is consumed internally, with less than 10% of recyclate produced being exported in the period 2007 to 2017. The quantity of recylate produced in the country has been steadily increasing in line with the increase in the recycling rate. The small proportion of recyclate exported points to an opportunity for increased export of this input. The relative weakness of the South African Rand currently further favours the export of recyclate (Plastics SA, 2017c, p.2).

There is scope for the plastic recycling industry in South Africa to grow, given that only 41.8% of plastic waste is recycled, when up to 70% of plastic is recyclable[24] (GreenCape, 2017, p.27). The recycling market has seen growth recently, with recycled tonnages growing by 35% between 2011 and 2017 (Plastics SA, 2017d). The industry has also seen substantial investment in recycling and waste

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[24] This refers to the average recycling rate, however the recycling rates of individual plastic types may vary.

management solutions by the private sector (see Table 16 in appendix). Notably, a total of R1.1 billion was invested in 2016 in new and innovative technologies in the plastic recycling space by the private sector indicating the potential for future growth (GreenCape, 2017, p. 26).

While notable efforts have been made in increasing the recycling of plastic, barriers remain that preclude the substantial ramping up of the plastic recycling rate. Policy interventions can play a key role in moving the market to increase the recycling rate and reduce the climate impact of substandard waste management technologies, like landfills. The barriers to increased recycling consist of a mix of technological, political, and social factors, which are illustrated and discussed below.

When recyclable material is not separated at the source of disposal, the recyclable material gets contaminated with other waste, increasing the costs of separation at a waste dump (McKenzie, 2012). For example, the lack of a consistent incoming stream of recyclables is the single biggest challenge plastics recyclers face (Engineering News, 2016). In certain areas of the country, such as the Northern Province, where there is a consistent excess demand gap for plastic recyclables, up to 40% of recyclable materials are discarded due to contamination (Engineering News, 2016). Initiatives are in place that aim at promoting separation at the source. For example, Pickitup's Separation@Source programme encourages residential consumers to distinguish recyclable from un-recyclable material in different bins. A particular intervention which has been touted as optimal for South Africa by recent CSIR surveys is the "two-bag system" which requires consumers to separate waste into dry and wet bags, combined with a regular kerbside collection service (Brand South Africa, 2013). Collection mechanisms can also vary from "low-tech" inexpensive options like using a truck and trailer to high-tech options that include using separate vehicles for waste or split-compartment vehicles (Infrastructure News, 2016).

Non-recyclable materials: Some plastic materials by their very nature cannot be recycled for future use. These include products such as multi-laminated plastic foils, polystyrene food trays, and plastic carpeting that has been glued down to flooring. Further, as mentioned, some recyclable plastic products become mixed with other products or substances during their consumption which render them difficult to recycle. Instead of sending these products to a landfill, traditionally such materials would be incinerated. Incineration refers to burning of waste in the presence of oxygen and using the heat that is generated to convert water into steam, which is then used to drive a turbine and create electricity (Infrastructure News, 2017b). This is an old method of thermal waste treatment, which produces a number of harmful emissions that require treatment before being dispersed into the environment.

Newer climate-mitigation thermal options exist which use non-recyclable products as an energy source through processes such as pyrolysis and gasification and these are known as feedstock or chemical recycling (mentioned earlier). These processes are also referred to as "next generation" technologies, Advanced Thermal Technologies or Advance Conversion Technologies (REA, 2013, p.1; Syngas Products, 2018). These newer processes differ from traditional processes such as incineration, as oxygen is not present when combustion of waste occurs. During the traditional combustion process, waste is heated and reacts with oxygen creating combustion and ash. Due to the nature of the process, there is limited control in preventing the formation of harmful environmental emissions such as dioxins, furans, oxides of nitrogen and other oxides (Syngas Products, 2018). The newer processes heat waste with minimal or no oxygen, and these harmful products are not created (Syngas Products, 2018).

Such processes are used to recover energy and access the fuel value of discarded non-recyclable plastic products.

Pyrolysis involves heating organic waste to encourage decomposition to produce syngas and bio oil (Infrastructure News, 2017b). The nature of the pyrolysis process is that it yields a high calorific oil as an output, which can be used to produce valuable industrial chemicals replacing fuel and refined oil (Beyene et al., 2018). Gasification converts organic waste into syngas which is then used to generate electricity (Infrastructure News, 2017b), or to produce chemical feedstock such as methanol, ammonia, oxo-aldehydes, or for making fuels (VinylPlus, n.d.). Gasification is a process currently used by Sasol; however, at Sasol, the process uses coal as an input rather than non-recyclable waste (VinylPlus, n.d.). While incineration is a process used for some time in South Africa, newer processes such as pyrolysis are still in their infancy in the country. Pyrolysis is slowly gaining traction with trial plants for plastics and tyres running (Plastics SA, 2016).

Public awareness and education: Tying in with the “separation at source” barrier identified, it is vital for consumers of plastic products to separate waste prior to its collection as this increases the chances of plastic waste being recycled. Programmes targeted at educating consumers on the proper way to dispose of waste are important. Specifically, consumers need to be educated on how to separate waste, such as removing labels and cleaning out waste to prevent contamination (Engineering News, 2016). This is particularly an issue at the residential level, where only 3.3% of South Africa’s urban population regularly separates their waste and recycles (CSIR, 2015). Notable, efforts have taken place in certain regions of the country. For example, in the Saldanha Bay Municipality, a focused and concentrated public awareness and education programme which combined the dissemination of starter packs and leaflets with a two-bag system in 2017 saw nearly half of all households in the area participate in recycling efforts (Saldanha Bay Municipality, 2017). The project also tracked the type of waste that was collected by different households according to a number of variables including income. It was found that poorer households used a greater share of plastic products, while relatively wealthier households consumed a greater share of glass products. This observation is important when considering public awareness and education as, such interventions must be structured to have the widest reach across the socio-economic strata of the country.

Rubber recycling

Rubber recycling is largely synonymous with tyre recycling, as tyres are the overwhelmingly dominant form of rubber in use today. Tyres are sourced from vehicles of all types and present a significant environmental problem. It is estimated that there are about 1.7 billion tyres produced globally each year, and over a billion waste tyres generated every year (Smithers Rapra, n.d.). Approximately 25% of these tyres are destined for landfills at a global level, where they create substantial environmental problems (Smithers Rapra, n.d.).

Tyres are problematic in landfills for a variety of reasons. First, the rate at which waste tyres are generated means that a large volume of tyres are sent to landfill every year. Second, this is exacerbated by the fact that tyres contain a large volume of void space (75%) which means that a single tyre occupies a volume that other, more densely packed waste can occupy (Liu, et al., 1998). Third, as tyres are durable they last for long periods of time in landfills. Fourth, tires can trap methane gases, which can damage landfill liners and increase the probability of local surface and ground water pollution (Willard and Smith, 2008). Finally, tyre piles pose as breeding for vectors of disease, resulting in the spread of infectious diseases, particularly in illegal and unregulated dumps (EPA, 2010, p.1).

Other means of tyre disposal are thus necessary to mitigate against the harm that waste tyres can result in. Recycling plays a role when waste tyres are processed into other materials, meaning that less tyres go to landfill, and the environmental harm is mitigated against. Tyres are generally collected from garages, retail outlets, depots and vehicle dismantlers (Shulman, 2004, p.10). The process for recycling tyres generally consists of two steps – preparation and recycling. Preparation involves the pre-treatment of tyres to render them suitable for recycling and includes cleaning of debris and washing (Shulman, 2004, p.10). As with plastic recycling, both mechanical and chemical recycling is used in the case of tyres. Mechanical processes include crumbing and Kraftek, in which rubber is processed into goods. In the case of crumbing, tyres are shredded and converted into rubber crumb and used as an input in other industries. Kraftek pertains to the conversion of waste tyres into commodities for final consumption (Hartley, et al. 2016, p.2). The chemical recycling processes used for tyres overlap with those used for plastic and include incineration, pyrolysis and gasification. The technologies are identical, and there the explanation of these processes is not repeated.

In South Africa, the tyre recycling industry was set to soar, with promising prospects of growth and employment. However, recent developments in the industry have seen the sector stagnate, with uncertain prospects of the future, as is explained below. Industry body REDISA was created in 2013 to conduct a R500 million-a-year levy-collection tyre recycling programme. The business model worked by collecting a levy of R2.30 for every kilogram of tyre sold in South Africa and using these revenues to build 22 tyre recycling centres, which recycled tyres through reimbursing waste pickers who collected tyres (Kings, 2017). Among its accolades, REDISA boasted a business model that did not rely on the fiscus for its funding and was to be replicated for other waste streams. Thanks to REDISA's efforts, in 2015, 71 806 tonnes of waste tyres were recycled from 16 037 tonnes in 2013, and the tyre-recycling rate stood at 63% in 2015 (Hartley, et al., 2016, p. 2; GreenCape, 2017, p.25; PMG, 2018). Unfortunately, towards the end of 2017, REDISA was liquidated due to findings of corruption among its board members, leaving a gap in the tyre recycling industry in South Africa. The disruption in the sector has seen the recycling rate for tyres decline from 63% in 2015, to 55% in 2016, an subsequently to 49% in 2017 (PMG, 2018). The operations of REDISA have been handed over to the DEFF Waste Management Bureau (WMB) for the time being. Consequently, government has since gazetted legislation that shifted the collection mechanism from the levy (previously collected by REDISA) to an Extended Producer Responsibility tax, which is now paid directly to government from tyre producers (Parliament of South Africa, 2018, p.2).

Once tyres are spent, they are collected from micro-collectors, dealers, or other collection points. Waste tyres are then transported to processors or holding depots (PMG, 2018). REDISA serviced 3 000 dealers in the country, which the WMB subsequently inherited (PMG, 2018). The largest markets for waste tyres are depicted in Table 4. About half of waste tyres go to the reuse and cutting/shredding downstream markets.

Table 4. Markets for waste tyres in South Africa

MARKET	SHARE (%)
Reuse	25
Cutting/Shredding	23
Pyrolysis	18
Incineration	16
Other	18

Source: Hartley, et al., 2016, p.2.

Reuse includes converting waste tyres into playground material and retainer walls (PMG, 2018). Cutting or shredding of waste tyres produces finer particles of rubber which can substitute for coal in the production of cement in cement kilns, for example. Crumbing of waste tyres includes the production of rubberised asphalt for roads. Other uses of fine rubber particles are in athletic fields, artificial turf, carpet underlays children's playgrounds, and to make new tyres (ECSIP Consortium, 2013, p.62). Further, public works can benefit from the use of recycled rubber in the following applications: a foundation for roads and railways; using whole tyres for coastal protection; as insulation; and using shredded tyres as drainage layers in landfills (ECSIP Consortium, 2013, p.62). Pyrolysis, in the context of tyres, converts waste tyres into syngas and bio oil, much like in the case of plastics. All of these processes are highly capital and energy intensive with very specific market requirements (PMG, 2018). Besides the rubber which can be recovered from recycling tyres, steel can also be recovered to be reused as a substitute for virgin steel in steel-making activities or exported.

The ensuing climate of uncertainty has seen private sector players instituting their own tyre recycling efforts internally. Notably, the Mathe Group recently erected a R20 million recycling plant in KwaZulu-Natal, processing rubber into new products and exporting the steel recovered.

Table 5. Private sector investments in tyre recycling

FIRM	PROJECT COST	TECHNOLOGY	DESCRIPTION
Mathe Group	R 20 million	Crumbing	This plant was started in 2016 and is located in Hammarsdale, KwaZulu Natal. The plant is one of the largest plants of its kind in South Africa and processes truck tyres into products which are used in flooring, rubber crumb for sports fields using artificial grass, retreading of tyres, road resurfacing, and non-slip paint. Steel is removed from tyres and exported.
Osho SA Recycling (OSAR)	-	Pyrolysis	OSAR operates four pyrolysis reactors with a recycling capacity of 14 000 tons per annum. OSAR intends on further developing and expanding the facility to recycle up to 36 000 tons per annum of feedstock.

Source: Venter, 2018; OSAR, 2013.

Given the current developments in the tyre recycling industry in South Africa, notable barriers have been identified. These require attention for the industry to progress (PMG, 2018):

- A lack of capacity for collection, storage and processing by the WMB creates constraints on the Bureau's ability to service all the dealers. The DEFF is attempting to increase its storage capacity to relieve depots. Majority of depots are near or have reached full capacity, with exports of tyres being impermissible this creates a constraint on depots.
- Demand for waste tyres by processors is concentrated in KwaZulu-Natal, which accounts for the lion's share of demand. In absolute terms, however, demand for waste tyres is not substantial. Collections are chiefly concentrated in the Western Cape and Gauteng. The distance between collection points and processors implies high transportation costs for provinces with no processing capability.

- Tyre processors faces technological challenges dictated by the needs of their consumers. Consumer demand dictates the technologies that processors choose.
- Processing equipment and technology is highly capital and energy intensive.
- Natural rubber products provide a competitive constraint, which in some cases are cheaper that recycled products.
- The limitation on processing capabilities is further complicated by plants experiencing downtime and being unable to process waste tyres.
- Smaller companies have old equipment and, with substantial set-up costs for new technologies, are unable to compete with cheaper subsidised imported rubber products (Venter, 2018).

Given the analysis of the sector, a few key messages translate into the policy domain. The final downstream market to which product are destined determine the type of technology chosen by processors. While the WMB faces the daunting task of picking up the pieces of REDISA, ultimately, there needs to be a market for recycled goods if processors are to survive. The public sector has a notable role in stimulating demand for downstream products.

A good starting point would be to examine public sector procurement policies for infrastructure projects. Since recycled rubber can be used for a diverse array of final products, departments in charge of procurement for roads, public schools and government buildings can make mandatory that a certain portion of goods procured have recycled rubber in them. For example, in the construction of roads, recycled rubber can substitute for Styrene-Butadien-Styrene, a bitumen modifier (ECSIP Consortium, 2013, p.65). In the context of natural roads, South African National Roads Agency (SANRAL) can engage concessionaires to make mandatory that newly built roads and renovated roads substitute with recycled rubber asphalt. Further, municipal and provincial authorities can have the same policy for municipal and provincial roads. Another avenue for recycled rubber is the turf and carpet underlay applications. Through the Department of Basic Education, new and existing schools can make procurement of turf products containing recycled rubber products mandatory. Further, government buildings should procure carpet underlays which are manufactured from recycled rubber.

The use of recycled rubber in the production of new tyres is also a promising future area. The process of devulcanisation aims to break down spent rubber into a form which allows it to be mixed with virgin rubber in the production of new tyres. This forms a direct link between spent tyres and new tyres, reducing the fossil fuel intensity of producing new rubber. The technology still has some way to develop and is currently restrained by the impact that recycled rubber has on tyre quality. At present, only 1% to 5% of recycled rubber can be used to manufacture new tyres without reducing the quality of the tyres (Allen, 2018, p.1). In this regard, during the tenure of REDISA, the institution provided funding to Stellenbosch University and the Nelson Mandela Metropolitan University for research in new recycling methods including devulcanisation. With the demise of REDISA, it is unclear whether the WMB has the capacity and funding to champion the investigation of these new technologies; however funding in this arena could go far in creating domestic demand for recycled rubber in addition to reducing the carbon intensity of the tyre manufacturing value chain, should these technologies reach industrial scale.

Some portion of spent tyres can be restored to a fully functional tyre through rethreading. Retreading refers to replacing the surface of the tyre with new rubber tread, extending its life (ECSIP Consortium, 2013, p.72).

4. POTENTIAL PATHWAYS

Transitioning the petrochemical value chain to a low(er) carbon state will require a basket of mitigation technologies. No single technology can achieve this aim, given the current technological trajectory. It is widely acknowledged that the petrochemical value chain is a difficult value chain to transition given its current high reliance on fossil fuels as both an energy source and as a feedstock input. Further, the mitigation options considered are at different levels of technological development and availability. Based on these factors, this section considers possible staged pathways in which different mitigation technologies can be considered, taking into account the benefits, risks, and implementation requirements for each pathway. The pathways consider incremental additions of mitigation options and, when the intricacies of interventions have been discussed in a previous pathway, only the incremental intervention is discussed. In the analysis, short term refers to a period of two to five years, medium term refers to a period of five to 10 years, and long term refers to a period of 10 years or more.

Pathway 1: Maintain the status quo

The first pathway considered as a baseline is the status quo. A business-as-usual approach trades off short-term benefits for future costs. In this pathway, all stakeholders continue as usual with no strict climate change regulations in order to limit the regulatory/financial burden on the industry. Less regulatory burden leads to more a profitable industry in the short term, increasing growth and employment in the short term but generating material climate policy risks in the medium to long term.

Table 6. Socio Economic Impact Assessment System (SEIAS) for status quo

STAKEHOLDER	BENEFITS	RISKS	IMPLEMENTATION REQUIREMENTS
Upstream petrochemical (Sasol)	Business-as-usual with no greater resources required for climate-mitigation investments.	Short-term avoided costs result in long-term policy risk, which exposes the firm to drastic costs from a penalty and investment cost point of view, given high carbon reliance.	None.
Downstream petrochemical	Business-as-usual with no greater resources required for climate-mitigation investments.	Supply-side exposure and rising input costs for basic feedstock combined with direct penalties. This will necessitate business model restructuring and possible downsizing.	None.
Department of Environment, Forestry and Fisheries	No further regulatory, advisory, and policy capacity required.	Medium- to long-term environmental degradation as a result of carbon emissions	None.
Department of Trade, Industry and Competition	No further regulatory, advisory, and policy capacity required.	Short- to medium-term growth in industrial growth with substantial long-term growth and trade risks as a result of carbon intensity	None.
Vulnerable stakeholders	Short-term preservation of livelihoods linked to carbon-intensive activities based on egregious production processes (e.g. coal-based).	Once punitive legislation and climate change risks manifest, vulnerable stakeholders face worsened socio-economic conditions. These include job displacement, reduced incomes and entrenched poverty.	None.

This pathway preserves the current rate of growth, and profit rates for firms and shareholders, but takes a short-term view. It lacks any preparation for medium- to long-term risks. This positions the industry as a short-term "free-rider" in the climate change regime. It further fails to provide a platform or incentive for further mitigation and long-term competitiveness. These risks arise mainly in the form of government regulation to mitigate carbon emissions (increasing burden from carbon taxes and other regulations) and broader trade risks from evolving climate change policy in South Africa's principal trading partners such as the EU and the United States. Major response measures from trade partners could force closure and/or rapid climate action in the medium term. There is a higher risk of closure in the long term due to an inefficient and uncompetitive industry unable to internalise climate response measures from trade partners.

Pathway 2: Targeting *energy efficiency*

This pathway looks at targeting the feasible short- to medium-term energy efficiency options available to the petrochemical industry. Specifically this looks at investments in further energy efficiency measures - NO_x mitigation and CHP interventions. This requires the development of policies that incentivize these interventions.

Table 7. SEIAS for efficiency enhancements

STAKEHOLDER	BENEFITS	RISKS	IMPLEMENTATION REQUIREMENTS
Upstream petrochemical (Sasol)	Reduced carbon intensity and improved investor attractiveness. Reduced climate costs in terms of policy/legislation.	Investments do not deliver production/efficiency enhancements that are sufficient to meaningfully reduce carbon risks. In the case of CHP, internal uses or off-take capacity do not materialise and project is not profitable.	Divert resources towards investments in NO_x and CHP emissions at the cost of other efficiency-enhancing measures. Research and development (R&D) and feasibility studies, taking into account current technological lock-in and processes.
Downstream petrochemical	Reduced carbon intensity of feedstock chemicals. Reduced carbon intensity of production if downstream firms invest in NO_x mitigation or CHP.	Higher input costs from upstream mitigation investments. Higher production costs if downstream firms invest, reducing competitiveness. Investments do not deliver production/efficiency enhancements that are sufficient to meaningfully reduce carbon risks	Divert resources towards investments in NO_x and CHP emissions at the cost of other efficiency-enhancing measures. R&D and feasibility studies, taking into account current technological lock-in and processes.
Department of Environment,	Reduced carbon emissions and reduced	Projects fail or significant regulatory framework is	Ensure that investments are sufficiently

Forestry and Fisheries	environmental threat from carbon intensity of the industry.	not devised which leads to project failure.	incentivised within the current regulatory framework and, if, necessary, amend regulations to unlock blockages to investment.
Department of Trade, Industry and Competition	Greater competitiveness of domestic manufacturing industry.	Projects fail or significant policies or incentives are not devised which leads to project failure.	Ensure that investments are sufficiently incentivised with policies/incentives in the current regulatory framework. If necessary, mobilise resources to incentivise investments.
Vulnerable stakeholders	Preserved livelihoods in the short to medium term until the mitigation potential for energy efficiency is reached.	Energy efficiency initiatives alone do not adequately mitigate carbon emissions resulting in job losses in carbon-intensive production.	Encourage/lobby firms to increase energy efficiency and carbon mitigation technologies.

Further targeting of energy efficiency alone does provide some benefits from a climate mitigation point of view. Mitigation of carbon emissions will be across the value chain, and the extent of the mitigation will depend on the efficiency technologies chosen.

Risks manifest, based on the type of efficiency technology chosen. In the case of NO_x mitigation there is a risk that companies will cease mitigation once funding or incentives dry up, placing a constraint on the long-term effectiveness of the technology. In the case of CHP there is a strong likelihood of project failure if off-takers for heating and cooling are not secured, or if heating and cooling needs within a given CHP investor firm are not identified (for internal use). Given the capital intensity of newer efficiency technologies, there is strong likelihood that downstream firms will face higher input costs as a result of upstream investments, ultimately being passed on to domestic consumers, and impacting on the international competitiveness of downstream chemical firms.

This pathway targets limited climate change liability on firms. While energy efficiency investments are typically seen as low-hanging fruit, many interventions have already been taken up in local industry. Some interventions may attract substantial capital expenditure, such as large CHP projects. CHP projects of significant scale require off-take agreements, which necessitates firms agreeing with each other on quantum and cost of supply. These arrangements in turn would require the appropriate inter-firm regulatory frameworks. This pathway only targets energy efficiency and does not account for a feedstock substitution and a circular economy approach, and only considers process emissions at the level of the upstream and downstream. The long-term threat of insufficient carbon mitigation still remains due to the lack of mitigation on the feedstock side and on the post-consumption side.

Pathway 3: Energy efficiency combined with end-of-pipe solutions

This pathway consists of targeting all efficiency interventions combined with the end-of-pipe interventions identified in this analysis. Based on the plastic and recycling trends in South Africa, room remains for increasing the recycling rates of products as well as exploiting newer technologies. The end-of-pipe solutions include increasing the recycling rate combined with investments into research, and development and investments into new technology infrastructure.

Table 8. SEIAS for end-of-pipe solutions

STAKEHOLDER	BENEFITS	RISKS	IMPLEMENTATION REQUIREMENTS
Upstream petrochemical (Sasol)	None.	Reduced demand for polymer feedstock.	None.
Downstream petrochemical	Development of new capabilities in incorporate recyclate in products.	Reduced demand for virgin plastic goods. Investments do not offer commensurate returns.	Investment into new product lines/processing.
Department of Environment, Forestry and Fisheries	Reduced environmental impacts from waste, landfills and illegal dumping.	Technologies and policies are insufficient to change consumer behavior.	Research and enable national policy promoting end-of-pipe solutions. Firm policy stance on the use of landfills and setting of targets to avoid landfill usage. Ensure existing landfills operate according to strict environmental protocols.
Department of Trade, Industry and Competition	New manufacturing markets for the production of recyclable consumer goods. New industrial activities surrounding the processing of waste. Improved trade reputation of domestic firms.	Incentives do not drive the necessary investments. Technology lags prevent newer technologies from becoming commercially viable. Policies do not drive consumer change.	Formulate disposal and education policies to incentivise consumer change. Incentives to the manufacturing sector for use of recyclable/recycled materials in production. Investigate new downstream markets as consumers of recycled products.
Municipalities	Reduced waste to landfill and associated costs. Reduced pollution within municipalities.	Consumers do not change behaviour.	Devise and implement appropriate consumer education and awareness campaigns to incentivise separation-at-source including the education of waste pickers.
General consumer goods manufacturing	Improved brand image from using environmental-friendly packaging/products.	Products do not meet quality criteria of consumers.	Co-ordinate with recycling industry to test the use of recyclable materials in manufacturing.

Waste pickers	Improved co-ordination and separation of valuable recyclate. Improved livelihoods.	Waste pickers are marginalised by formal companies if this group is not prioritised in employment opportunities.	Willingness to benefit from education campaigns to increase recycling and modern waste treatment processes.
Vulnerable stakeholders	Reduced visible waste in neighbourhoods. Increased job opportunities in waste management.	Lack of appropriate awareness campaigns fail to empower stakeholders with knowledge of post-consumption behaviour and opportunities in the circular economy.	Vulnerable stakeholders are placed at the centre of policies related to increasing recycling and end-of-pipe solutions.

Increasing end-of-pipe solutions contribute to closing the loop in the circular economy and encourage carbon mitigation through recycling and reuse. New markets in the circular economy pertaining to plastic and rubber recycling would be formed as a result, increasing employment and the general capabilities in South African industry. This approach also channels waste away from landfills and the climate harm associated with this harmful form of waste disposal. The approach also encourages the development of new capabilities in newer technologies related to pyrolysis and gasification, in turn reducing pollution levels.

Risks arise from a number of avenues with this approach, however. Recycling of plastic and rubber waste would erode the demand for virgin plastics and rubber insofar as these inputs are used to produce products that traditionally require virgin materials. Examples include plastic bags, household goods and tyres. In this case, demand for polymer and rubber feedstocks would ultimately decline impacting the revenues and profitability of Sasol. Recycling hinges heavily on consumer behavior and the extent to which business and households engage in the separation of waste. Investments into recycling initiatives would require consumers to act in a way that provides a steady stream of input material for recycling initiatives to work, and recycling policies and plans would have to be designed in a way to adequately incentivise change.

There is room for both plastic and rubber recycling to increase in South Africa. A basket of policies would be required by various national departments such as DEFF and the dtic to link and co-ordinate various value chains. As identified in the analysis, separation-at-source is vital to increase recycling. Targeted education and awareness policies by municipalities combined with systems of refuse collection that make it easy for consumers to separate waste are required. Downstream markets for recyclate can be stimulated through co-ordination between consumer goods manufacturing and recyclers to ensure the investigation of opportunities for substitution of virgin packaging and products with recycled products. This will also ensure that the recycled products meet the quality and quantity requirements of consumer goods manufacturers.

For waste that cannot be recycled, technologies that are superior to landfills and incineration need to be investigated and deployed. Research and development combined with pilot projects can assist in the determination of commercial viability. There are numerous economic benefits from increasing policy focus on a circular economy. Increased industrial activities through more recyclers, and newer infrastructure, increase employment and develop new capabilities in the economy. This approach also reduces the future carbon emissions from archaic disposal methods such as landfills and, if planned appropriately, would result in reduced pollution in the country.

There are risks associated with this pathway, particularly related to newer waste management technologies such as pyrolysis and devulcanisation. Due to the technological trend of these technologies, there is a long way to go until these technologies can be proven at large scale. Further, newer technologies are highly capital intensive and would require state funding in the absence of private sector interest. Physical and chemical constraints may also impact on the ability of manufacturing firms to absorb recycled material to substitute virgin production. Finally, the implication of long-term decline of landfill use implies that employment in landfills will be expected to decline; however, newer opportunities would be anticipated in newer sustainable industries.

Pathway 4: Energy efficiency combined with increased natural gas intensity

This pathway involves devoting resources to energy efficiency and substituting existing coal-based chemical production with natural gas. Given that coal-based production is highly carbon-intensive, switching to natural gas would reduce the carbon profile of the chemicals value chain. This would involve scaling up existing gas supply in addition to investments into gas transmission and distribution infrastructure.

Table 9. SEIAS for natural gas substitution

STAKEHOLDER	BENEFITS	RISKS	IMPLEMENTATION REQUIREMENTS
Upstream petrochemical firms (Sasol)	Reduced carbon intensity of operations. Improved shareholder value and investor attractiveness.	Natural gas is still a fossil fuel and has associated carbon emissions. Inability to source new gas.	Sasol has to invest in or procure a new gas supply based on new indigenous sources or imported via pipeline or ship. Sasol has to invest in new processing plants/retrofit existing plants to use gas feedstock for chemical production.
Downstream petrochemical firms	Reduced carbon intensity of products.	Potentially higher prices for feedstocks.	None.
Department of Environment, Forestry and Fisheries	Reduced carbon emissions and environmental impact of chemical production.	Gas-based production still associated with carbon emissions	Set the correct environmental frameworks and legislation for gas-based production.
Department of Trade, Industry and Competition	Development of new gas-based and climate-friendly chemical production.	Increased imports in the short to medium term due to no domestic gas supply.	Provision of the correct incentives for investments into gas transport infrastructure and gas supply.
Transnet	Increased revenues from investment into new pipeline infrastructure.	Investments do not deliver adequate returns.	Mobilise resources for investment into new infrastructure.

			Source offtake agreements for gas supply.
Vulnerable stakeholders	Increased energy security for vulnerable households, communities and small businesses. Employment opportunities in the natural gas value chain.	Lack of buy-in from vulnerable stakeholders leads to political backlash. Development policies fail to account for vulnerable stakeholders and development places negative impacts on them. A shift in production away from coal-based regions reduces livelihoods in these regions.	Vulnerable stakeholders are placed at the centre of policies related to increasing gas intensity through labour absorption in the natural gas value chain.

If such a pathway is pursued and is successful, benefits from industrialisation and new employment would occur. This would further improve the trade perception of South Africa from a carbon-intensity point of view as natural gas is associated with a lower quantum of carbon emissions compared to coal-based chemical production.

There are risks associated with pursuing this strategy, however. The success of this strategy depends on sourcing natural gas in sufficient quantity to replace current and future coal supply. Domestic resources have not been proven and certain options, such as fracking in the Karoo, are associated with deleterious environmental impacts. Thus South Africa would have to procure natural gas via importation which leaves the industry exposed to international market price fluctuations. Also, a substantial amount of investment would be required to build the necessary gas import infrastructure and pipelines to transport gas to chemical producers.

This pathway requires the substitution of existing coal-based chemicals production with gas-based chemical production. This would involve either Sasol retrofitting existing coal-based production, investing in new capital and plants and/or new chemicals firms investing in gas-based chemical production. Based on the current setting, in the short to medium term (less than 10 years) this would have to be based on imported gas supply as domestic sources are still exploratory. Imported gas can be sourced via pipeline from neighboring countries such as Mozambique or imported via ship through ports (e.g. Coega). In the case of the latter, investments would have to be made into regasification infrastructure and pipelines to carry the gas from ports to the site of production. If gas is imported from Mozambique further extensions to the existing ROMPCO pipeline would be required, else if gas is imported from other countries new pipeline infrastructure and agreements will have to be negotiated.

Pathway 5: *Energy efficiency* combined with *full feedstock substitution* and *end-of-pipe solutions*

In this pathway, interventions target currently feasible energy efficiency, feedstock substitution and circular economy solutions. The additions considered in this pathway, which have not been considered before, are biomass and hydrogen feedstock substitution. This pathway aggressively targets carbon mitigation throughout the value chain.

Table 10. SEIAS for biomass

STAKEHOLDER	BENEFITS	RISKS	IMPLEMENTATION REQUIREMENTS
Upstream petrochemical firms (Sasol)	Increased capabilities through sustainable investments and improved investor image. Sustainable departure from carbon-intensive processes and business continuity.	Reduced demand for coal-based chemicals Increased competition and price pressure in the upstream provision of bio-based chemicals. A lack of consistent supply of biomass inputs at a competitive price.	Co-ordinate and plan investments into biomaterials-based feedstock processing. Modification of production processes through external procurement and/or retrofitting of existing operations.
Downstream petrochemical firms	Increased upstream competition and potentially lower prices.	Higher costs of bio-based chemicals.	Investigate the procurement of bio-based chemical feedstocks. Switch consumption to lower carbon feedstocks.
Department of Environment, Forestry and Fisheries	Lower carbon emissions from the chemical sector.	Potential environmental impacts from land usage for bio-based raw materials.	Feasibility of land usage for bio-based chemical production. Formulate regulations and frameworks for land usage. Formulate regulations and frameworks for bio-based chemical production.
Department of Trade, Industry and Competition	Increased industrialisation in new markets (bio-based chemicals). Improved trade competitiveness from lower carbon intensity.	Incentives do not materialise in commensurate returns.	Formulate policy and incentives to support bio-based chemical production including capital investment incentives and R&D funding.
Private bio-based chemical firms	Existing market demand for chemicals.	Bio-based chemicals do not meet the quality or quantity standards of consumers. Current technology does not provide feedstocks at a competitive price.	Harness existing funding sources and incentives to construct biorefineries and enter the chemical market. Source offtake agreements to warrant investment in plants.

		Competitive intensity from Sasol drives out new entrants.	Source proximal feedstock with the necessary properties at a competitive price. Calibrate plants appropriately for intended product profile.
Vulnerable stakeholders	Increased energy security for vulnerable households, communities and small businesses. Employment opportunities in the biomass value chain.	Lack of buy-in from vulnerable stakeholders leads to political backlash. Development policies fail to account for vulnerable stakeholders and development places negative impacts on them. A shift in production away from coal-based regions reduces livelihoods in these regions.	Vulnerable stakeholders are placed at the centre of policies related to increasing biomass intensity through labour absorption in the biomass value chain.

Table 11. SEIAS for hydrogen

STAKEHOLDER	BENEFITS	RISKS	IMPLEMENTATION REQUIREMENTS
Upstream petrochemical firms (Sasol)	Decarbonsation route that can preserve the firm from a decline in demand for coal-based production.	Increased competition from new hydrogen, methanol, and ammonia producers placing price pressure on these feedstocks.	Invest resources in pilot projects, infrastructure investments, research and development, and retrofitting of existing operations.
Downstream petrochemical firms	Potentially lower input prices of green hydrogen, methanol and ammonia. Lower carbon footprint of products increasing trade competitiveness.	Higher costs of green hydrogen and associated feedstocks (ammonia, methanol).	Redirect procurement towards green hydrogen and associated feedstocks (e.g. ammonia, methanol).
Department of Environment, Forestry and Fisheries	Lower carbon profile of the chemical industry. Indirect increased renewable generation through green-hydrogen electricity source.	Projects fail and the industry shifts back to previous carbon intensity.	Formulate regulations and frameworks to manage the environmental impacts of green hydrogen production.
Department of Mineral Resources and Energy	Energy security for the country along a sustainable pathway.	Development of the hydrogen economy does not provide the anticipated energy supply.	Enact policy to liberate greater renewable energy generation allied with green hydrogen production. Scale up Renewable Energy Independent Power Producer

			Procurement (REIPPP) ambitions to enhance renewable-based production. Foster the development of the renewable energy value chain.
Department of Trade, Industry and Competition	Increased industrialisation in new markets. Improved trade competitiveness of domestic chemicals industry.	Projects fail resulting in spent resources.	Formulate policy and incentives promoting green hydrogen. Incentivise research and development into green hydrogen and green chemicals production.
Private hydrogen producers	Increased market share and profits. Existing demand for chemicals.	Green hydrogen routes are not cost-competitive and feedstock prices are not competitive with existing production routes impacting demand for products.	Conduct feasibility studies on the setup of green hydrogen production. Mobilise funding and resources to build plants. Secure offtake agreements for green hydrogen and chemicals
Vulnerable stakeholders	Increased energy security for vulnerable households, communities and small businesses Employment opportunities in the hydrogen value chain.	Lack of buy-in from vulnerable stakeholders leads to political backlash. Development policies fail to account for vulnerable stakeholders and development places negative impacts on them. A shift in production away from coal-based regions reduces livelihoods in these regions.	Vulnerable stakeholders are placed at the centre of policies related to increasing hydrogen intensity through labour absorption in the hydrogen value chain.

Multiple benefits accrue from full feedstock substitution. Increasing the use of biomass feedstocks results in the development of a biomaterials value chain and increased capabilities, employment and resources for the country. Given that biomaterial-based petrochemical production draws on agricultural and food processing inputs, backward linkages to these value chains would form. In some cases this would involve the valorisation of waste, where the feedstock was previously regarded as a waste product, improving the sustainability and closing the circular loop of these value chains.

Green hydrogen presents a further opportunity to draw on some of these benefits, such as the development of sustainable production activities and increasing the capabilities, employment and resources in the economy. Given the wide array of uses for hydrogen, the development of the green hydrogen value chain can assist the country to decarbonise and transition high emissions value chains. These include the petrochemicals value chains, specifically those related to major, traditionally carbon-intensive input chemicals such as methanol and ammonia production, along with the iron and steel value chain and in oil refining. Further, green hydrogen can be channeled to newer sustainable industries related to transport (passenger cars, aviation, shipping), power generation, and to generate heat. The unlocking of green hydrogen as a feedstock can assist in developing these industries within the country.

In the case of Sasol, which is a large and established entity in the petrochemical value chain, biomaterials feedstock use, and the development of green hydrogen, offer sustainable and low-carbon business continuity routes, given its existing highly carbon-intensive profile. The development of the biomaterials and green hydrogen value chains also offer the opportunity to increase competition in the petrochemical upstream, with new biomaterials and green hydrogen producers placing a competitive constraint on Sasol, benefitting the downstream, and ultimately final consumers.

Full feedstock substitution is not without risks, however. Biomaterials-based petrochemical production requires arable land and water resources, combined with high capital investments. While land use constraints are partially overcome through the use of newer algae- and bacteria-based feedstocks, high capital costs still prevail as a constraint.

High capital intensity also applies to the case of green hydrogen, which requires investments into hydrogen production facilities that include the cost of electrolysers, which use platinum, and are electricity and water intensive. Dedicated renewable energy-based solar or wind production is also required and contributes to capital costs. Absent the appropriate support and carbon pricing and the identification of relevant niches, these high costs associated with biomaterials and green hydrogen development may increase the costs of inputs into downstream industries, impacting on their profitability and global competitiveness.

From an implementation perspective, there has to be a co-ordinated effort to develop the biomaterials and green hydrogen value chains. Absent co-ordination, investments may not occur or, if they do materialise, will be in an isolated manner and may not accrue the desired benefits. Sasol, which is dominant in the upstream, would have to investigate the integration of these feedstocks into its existing fossil fuel processes and examine the feasibility of substitution. This may have to be initiated on a pilot basis and scaled up over time. Competitor petrochemicals producers would have to also mobilise the resources to set up greenfield investments for entering into the petrochemicals value chain. This can take the form of supply into Sasol's existing processes or independent supply to the downstream chemicals market. From a state perspective, DEFF and the dtic have key roles to play in market formation and development. Alignment between the departments is crucial in the development of policies and plans that focus on promoting research and development among private stakeholders; generating and incentivising investments; co-ordinating suppliers and consumers; and developing export opportunities for the biomaterials and green hydrogen value chains.

Pathway 6: All solutions + carbon capture

In the final pathway, carbon capture technologies are included as a mitigation option. This includes CCS and CCU technologies.

Table 12. SEIAS for carbon capture

STAKEHOLDER	BENEFITS	RISKS	IMPLEMENTATION REQUIREMENTS
Upstream petrochemical firms (Sasol)	Reduced carbon intensity of production through captured carbon. Improved investor perception. Potential low-carbon business continuity route based on existing fossil fuel production.	Inability to generate return on investment. Substantially higher prices of products reduces revenues and international competitiveness. For CCU, insufficient demand for CO_2 consumers. Carbon capture is not technically feasible on certain elements of the carbon capture value chain (e.g. storage).	Mobilise resources for investment into carbon capture technologies in processes, assuming the availability of technology providers. Conduct feasibility studies into carbon capture implementation. Existence of carbon transportation industry via pipeline or transport (road/rail/ship). Existence of carbon storage options on site or externally. For CCU, offtake agreements for CO_2 product.
Downstream petrochemical firms	Reduced carbon intensity of final product. Improved investor perception. Potential low-carbon business continuity route based on existing fossil fuel production.	Substantially higher input prices which reflect upstream investments into carbon capture technologies. Inability to generate return on investment for downstream firms that invest in carbon capture. For CCU, insufficient demand for CO_2 consumers.	Mobilise resources for investment into carbon capture technologies in processes, assuming the availability of technology providers. Conduct feasibility studies into carbon capture implementation. Existence of carbon transportation industry via pipeline or transport (road/rail/ship). Existence of carbon storage options on site or externally. For CCU, offtake agreements for CO_2 product.
Department of Environment,	Reduced industrial carbon emissions	Projects do not deliver the carbon mitigation	Develop regulations and policies around carbon

Forestry and Fisheries		intended, and opportunity costs of resources devoted to carbon capture. Sizeable environmental costs as a result of carbon capture investments.	capture to mitigate negative environmental impacts
Department of Trade, Industry and Competition	Development of new industries and markets around carbon capture technologies. Development of export markets related to carbon capture technologies.	Projects do not deliver the carbon mitigation intended, and opportunity costs of resources, funds and incentives devoted to carbon capture.	Develop industrial policy measures to promote carbon capture technologies. Channel resources to R&D related to carbon capture.

The benefits of carbon capture technologies are that they would allow for the maximum carbon mitigation of the petrochemical value chain when combined with the other mitigation measures. Beyond carbon mitigation, the development of the carbon capture value chain would allow for some degree of retention of existing fossil fuel production, and the use of South Africa's existing coal resources that include mining activity. In addition, new markets surrounding the provision of carbon capture technologies, transport, and storage would be formed, in addition to potential export markets for the provision of these goods and services.

Given the current technology trajectory, however, carbon capture technologies do attract sizeable risks. Risks arise from the high capital costs required for the installation of carbon capture technologies in production processes; the costs of infrastructure development related to transport (in the case of greenfield pipeline construction); as well as the development of carbon storage (in the case of CCS). For investors to outlay this capital, a sufficient return on capital is required, which will have to be reflected in the prices of downstream chemical products produced and offtakers of CO_2, in the case of CCU. There is also the risk of wasted resources by the state through the development of policies and incentives to support the carbon capture value chain, should projects not materialise.

Compared to other technologies, the requirements for implementation are significant as carbon capture technologies are still limited in their commercial application. The upstream and downstream petrochemical value chain would have to mobilise resources to invest into the technologies and would require the entire value chain to be developed in some fashion before investments are made. That is, sufficient transport capacity will have to be available along with storage or offtake agreements. The limited storage options in South Africa do pose a significant challenge to CCS options and are a barrier to the development of the value chain. From a state perspective, resources would have to be devoted to formulating a cohesive development plan that generates the necessary investments and ensures that the market develops.

5. CONCLUSION

The petrochemical industry globally is a key contributor to GHG emissions and the current interventions to mitigate emissions are still at the early levels of technological development or penetration. In South Africa, the climate constraint placed on the economy by the domestic petrochemical industry is particularly problematic, given South Africa's heavy reliance on coal-based petrochemical production. This path dependency is incongruent with the sustainable transitions that are taking place throughout the world and places the economy at risk as the world moves to more sustainable methods of production.

This paper has evaluated a number of key interventions available to the domestic industry at various points in the petrochemicals value chain. What emerges from the analysis is that a number of options are available to the domestic value chain to transition towards a low(er) carbon state; however, these options vary in their cost, challenges, and existing developments in the country. The full decarbonisation of the petrochemical industry is not currently feasible even if all of the interventions presented are fully deployed. This could, however, evolve as newer technologies such as green hydrogen ramp up.

Policymakers looking to formulate a future pathway for a profitable and sustainable petrochemical industry have to evaluate these options carefully as many of them attract significant risk and hold the potential to waste limited resources if they are not pursued in a manner that co-ordinates the existing knowledge of these technologies with the key stakeholders and dynamics present in the value chain. Many interventions require co-ordination between producers and consumers and the state has a key role to play in this regard. Setting the policies and regulations, and formulating the correct incentives and disincentives, can go a long way in the creation of new low-carbon markets and value chains, particularly in cases where newer technologies have not reached price parity with traditional fossil fuel production.

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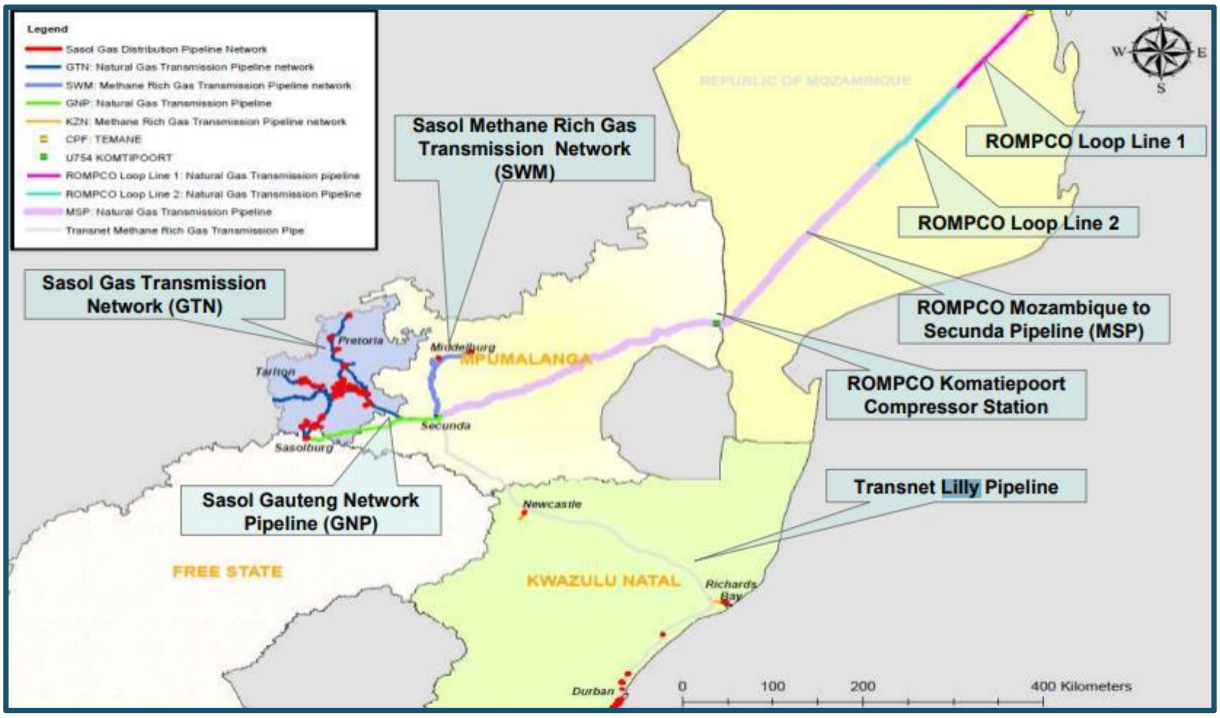
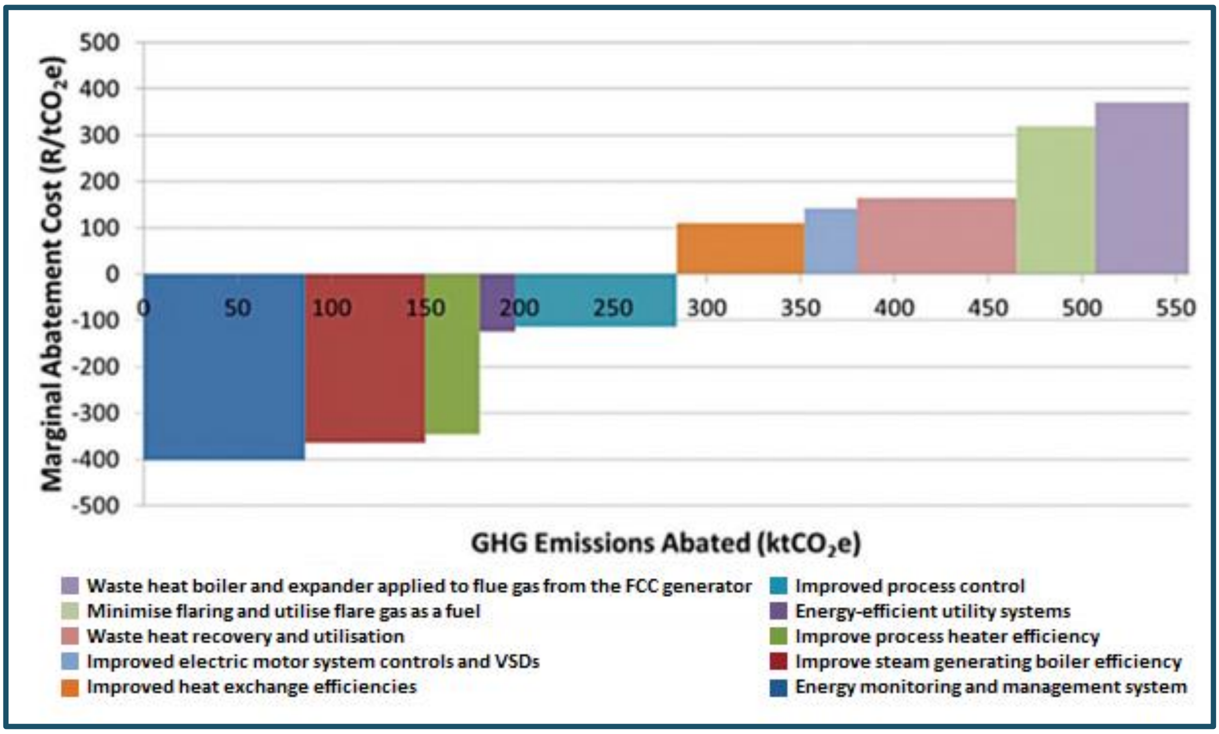
APPENDIX

Figure 17. Existing gas network in South Africa



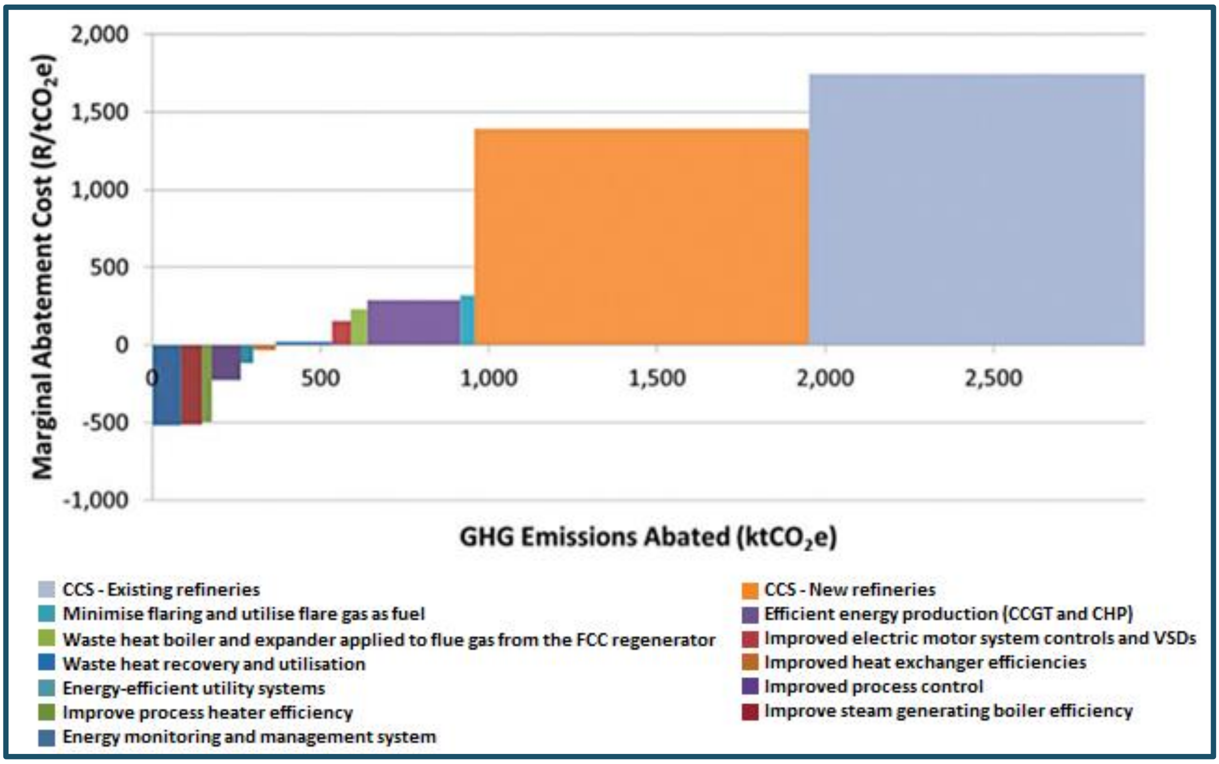
Source: CSIR, 2017.

Figure 18. MACC curve for petroleum refining – 2020



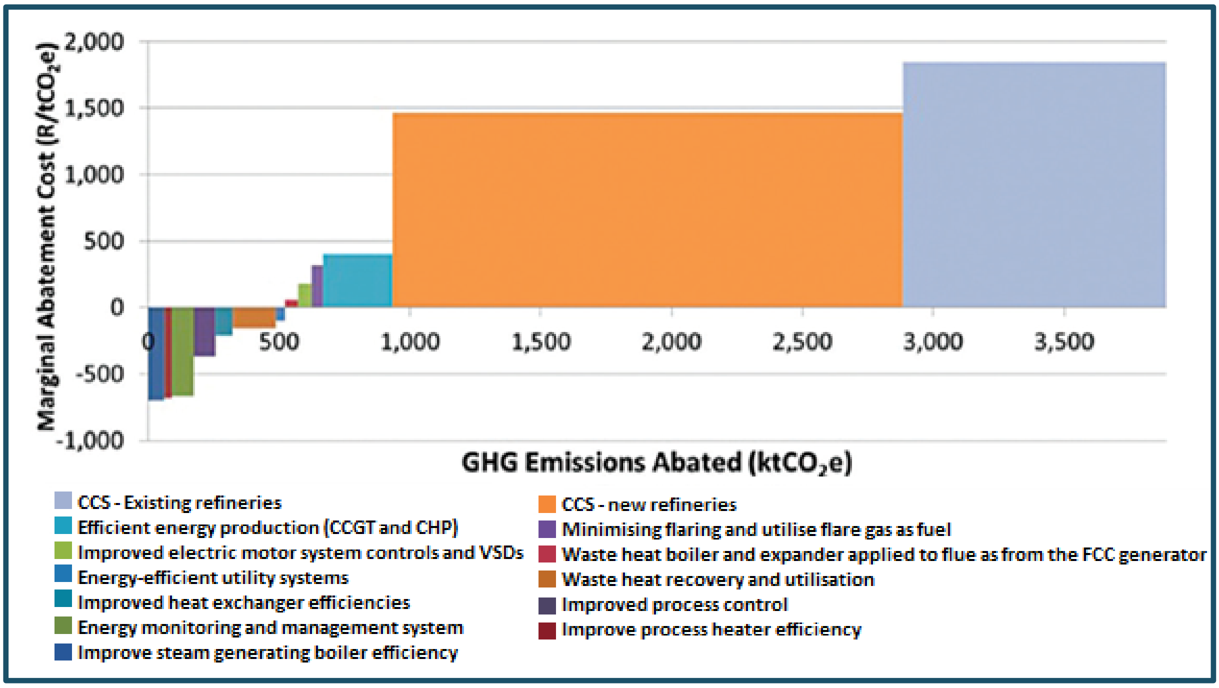
Source: DEA and GIZ, 2014, p.38.

Figure 19. MACC curve for petroleum refining - 2030



Source: DEA and GIZ, 2014, p.39.

Figure 20. MACC curve for petroleum refining – 2050



Source: DEA and GIZ, 2014.

Table 13. Potential energy efficiency measures

INTERVENTION	DESCRIPTION	EXAMPLES	APPLICATIONS IN SOUTH AFRICA	BARRIERS
Process intensification (PI) and other process improvements	Innovative principles in process and equipment design resulting in benefits in process and chain efficiency, capital and operating expenses, quality, wastes and process safety.	The development and use of catalysts can reduce energy intensity and carbon emissions by 50% and 1 000 $MtCO_2$ by 2050. (Bennett and Page, 2017, p. 412). In the production of ethylene, PI improvements have the potential to save up to three GJ of energy per ton of ethylene produced (Bennett and Page, 2017, p.411). Other examples include advanced distillation columns, high-temperature furnaces, novel reactors and gas turbine integration.	Improved process control. Minimise flaring and utilise flare gas as fuel.	High cost of retrofitting plants with PI technologies. Skills and knowledge in PI. Potential for benefit is greater for new plants and limited for existing plants.
Heat recovery and reuse	While heat recovery has been practiced historically, about 20%-50% of energy is lost as heat. The further optimisation of heat integration into processes may lower energy use. Heat recovery and reuse interventions can move beyond firm boundaries and firms can mutually benefit from each other.	Interventions include total site pinch analysis[25], heat pumps, heat-absorption and cooling[26], Organic Rankine Cycles (ORC)[27] and heat exchange between firms located in proximity to each other (concentration of chemical activities in mega-clusters). With respect to heat recovery and use, for example, the implementation of	Waste heat boiler and expander applied to flue gas from the FCC regenerator. Waste heat recovery and utilisation. Improved heat exchanger efficiencies.	Existing partial application of interventions preventing room for further improvements. High investment costs (e.g. ORC investments). Waste-to-electricity

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[25] Pinch analysis refers to the application of tools and algorithms based on thermodynamics methods that allow firms to enhance energy efficiency (MTU, n.d.). Total site pinch analysis allows for the analysis of the energy usage for an entire plant site which includes of many processes supported by a central utility system (MTU, n.d.).

[26] Heat-adsorption cooling refers to the conversion of waste heat into cooling (CEFIC, 2013, p.52). Certain petrochemical processes such as rubber and polymer production require cooling which can benefit from this process (CEFIC, 2013, p.52).

[27] ORC describes an energy extraction cycle where the fluids used are more efficient when used with heat at low temperature and for low power applications (Rycroft, 2016). The ORC benefits the energy intensity of processes, by recovering waste heat (Rycroft, 2016).

		total site pinch analysis in plants where no pinch analysis was done can result in fuel savings of 20-30%; and savings of approximately 5% in plants where previous pinch analysis was conducted (CEFIC, 2013, p. 52).		measures are still in development. Barriers to heat exchange between firms include risks in the security of supply of heat, economic viability, the lock-in of suppliers providing heat, and the distribution of costs and risks.
Efficient use of power	Electricity efficiency refers to the reduction of the amount of electricity used in a process.	Interventions include using energy-efficient motors, variable-speed drives[28], and optimisation of the entire system. For example, motors account for substantial consumption of electricity in petrochemicals –about 67%[29] (CEFIC, 2013, p.53). It is estimated that savings on electricity use of motor systems range between 17% and 30%, majority of which are profitable investments (CEFIC, 2013, p.52). Further, interventions in lighting can result in savings of 15-25% (IEA, 2009, p.20).	Improved electric motor system controls and VSDs.	Some investments in motors may not be profitable.
Energy management systems	An energy management system refers to computer-aided	Interventions include efficient boilers, offline or online supply-demand optimisation,	Improve steam generating boiler efficiency.	Existing efficient energy management

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[28] A variable speed drive can alter the speed of a motor by adjusting the power input (ABB, 2008). This contrasts with more inefficient motors that alter fuel or airflow without altering the speed (ABB, 2008).

[29] This estimation excludes electricity used for chemical processes.

	tools implemented to monitor, control, and optimize a process.	reduced flue gas quantity, flue gas heat recovery, regular maintenance, and better insulation. For example, efficient boilers can reduce fuel demand by 3%, while regular maintenance and better insulation can result in savings of 5% and 1.5% respectively (CEFIC, 2013, p 52).	Improve process heater efficiency. Waste heat boiler and expander applied to flue gas from the FCC regenerator. Energy monitoring and management systems. Improved process control. Energy-efficient utility systems.	systems may prevent further improvements.
New energy and resource management concepts	These refer to integrated demand-side management and decentralised energy and resources, and new business models and service concepts.	For example, more intensified, lower capital, but more flexible production units could allow greater distribution of process manufacturing closer to end-users and customers.	Not available.	None identified.

Source: Author's adaptation based on (Bennett and Page, 2017, pp.410-412; CEFIC, 2013, pp.49-59; and EC, 2015, pp.92-96)

Table 14. Large scale operational CCS projects in the chemicals industry

NAME	LOCATION	OPERATION DATE	INDUSTRY	CAPTURE CAPACITY (MTPA)	DESCRIPTION
Enid Fertilizer	United States	1982	Fertiliser production	0.7	The Koch Nitrogen Company produces nitrogen fertilisers producing a high-purity, high concentration CO_2 by-product. Processed CO_2 is transported to depleted oil fields in southern Oklahoma for enhanced oil recovery. The facility is located in Enid, Oklahoma.
Great Plains Synfuels Plant and Weyburn-Midale	Canada	2000	Synthetic natural gas	3.0	The Great Plains Synfuels Plant produces high purity CO_2 as part of its coal gasification process. The captured CO_2 is transported via pipeline to the Weyburn Oil Unit and the Midale Oil Unit in

					Saskatchewan, Canada, for use in enhanced oil recovery. About 35 million tonnes of CO_2 has been captured and transported to date. The plant is located in located in North Dakota.
Air Products Steam Methane Reformer	United States	2013	Hydrogen production	1.0	Air Products retrofitted its two methane reformers to isolate CO_2 from the process gas stream. CO_2 capture capacity is approximately one million tons per annum (mtpa) when both plants are fully operational. The captured CO_2 is transported to oil fields in Texas for enhanced oil recovery. More than three million tonnes of CO_2 has been captured since the facilities became operational in 2013. The plant is located in Port Arthur, Texas.
Coffeyville Gasification Plant	United States	2013	Fertiliser production	1.0	The Coffeyville Resources Nitrogen Fertilizers fertiliser plant has been retrofitted with CO_2 compression and dehydration facilities and since 2013 has delivered CO_2 to the North Burbank Oil Unit in Oklahoma for enhanced oil recovery. The plant is located in Coffeyville, Kansas.
Quest	Canada	2015	Hydrogen production	1.0	Quest retrofitted CO_2 capture facilities to three methane reformers at its existing plant. The captured $CO_2$is transported via pipeline to the storage site for dedicated geological storage. In

					July 2017, Quest announced it had captured and stored two million tonnes of CO_2. The plant is located in Alberta, Canada.
Illinois Industrial Carbon Capture and Storage	United States	2017	Ethanol production	1.0	Illinois Industrial CCS integrates new build compression and dehydration facilities to an existing corn-to-ethanol plant in Decatur, Illinois. Injection operations commenced in April 2017. The captured CO_2 is transported to a nearby injection well for dedicated geological storage.

Source: Global CCS Institute, 2018.

Table 15. Plastic products produced in South Africa

PLASTIC PRODUCT	PERCENTAGE	TONNAGE	USES
Low-density polyethylene (PE-LD), Polyethylene (PE-LLD)	22%	333 960	Bags and wire cables
Polypropylene (PP)	20%	303 600	Office/school folders, car bumpers, flowerpots
High-density polyethylene (PE-HD)	15%	227 700	Containers and caps
Polyethylene terephthalate (PET)	14%	212 520	Bottles
Polyvinyl chloride (PVC)	12%	182 160	Boots and windows
Polystyrene (PS/PS-E)	4%	60 720	Plastic cups, glasses frames, yoghurt containers
Polyurethane (PUR)	3%	45 540	Sponges, isolation
Others	10%	151,800	ABS bricks, fridges, Teflon pans
Total	**100%**	**1 518 000**	

Source: Author's adaptation of Plastics SA, 2017b.

Table 16. Recent investments in Recycling technology

FIRM	PROJECT COST	TECHNOLOGY	DESCRIPTION
MPact Polymers	R350 million	Recycling	Mpact Polymers opened a second PET bottle-to-bottle recycling plant in Germiston. The plant is capable of processing 21 000 tons of plastic waste, diverting this waste from landfills. Total landfill space savings are estimated at 180 000 cubic metres per annum.
New Horizons Energy	R400 million	WtE/Biogas	South Africa's first Municipal Solid Waste waste-to-energy plant was opened in 2017, in Athlone in the Western Cape. The plant produces biogas and is fueled on municipal and industrial waste. Output products include liquid carbon dioxide, organic fertiliser and compressed biomethane.
Averda	R250 million	Advanced landfill	Averda built the first landfill in South Africa to fully comply with the new Waste Classification and Management

			Regulations. The landfill is designed to mitigate against environment pollution including air and groundwater contamination, through the use of specialised containment barriers.
City of Cape Town/CFP Corporation/ Kanemiya joint venture, funded by the Japan International Cooperation Agency	R41 million	WtE/pyrolysis	The pilot plant at Kraaifontein produces cracked oil from unrecyclable plastic waste sourced from the municipality and commercial waste. Cracked oil can be used to produce electricity, and as a fuel for engines.
Reliance	R250 million	WtE	Reliance has recently received approval to construct a WtE plant in Paarl.
Ener-G Systems/ City of Johannesburg	R290 million	WtE/landfill gas utilisation	Ener-G Systems has developed landfill gas-to-power projects at five sites in the city.
City of Cape Town/Fountain Green Energy	Not available	WtE/landfill gas utilisation	A gas extraction and flaring facility was launched at Coastal Park landfill in Muizenberg in early 2018. The technology converts methane gas produced in the landfill by burning it into carbon dioxide and water and reducing its global warming impact, or by burned to produce electricity. Similar projects are expected to be launched in the City's other two landfill sites in Vissershok and Bellville South.

Sources: GreenCape, 2017, p.26; Infrastructure News, 2017a; Mpact, 2014; Bizcommunity, 2018; IWMSA, 2016, p. 2; SAAEA, 2017; Hyman, 2018; Burger, 2018.