



SOUTH AFRICA

FUEL FOR THE FUTURE

A BLUEPRINT FOR THE PRODUCTION OF
SUSTAINABLE AVIATION FUEL IN SOUTH AFRICA

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ABOUT THIS REPORT

This summary report is based on the technical report titled *Blueprint for sustainable aviation fuel (SAF) production potential in South Africa: A multicriteria analysis of South Africa's techno-economic potential for sustainable aviation fuel production and the socio-economic impacts*, available online at www.wwf.org.za/report/technical_blueprint_for_sustainable_aviation_fuel_in_sa

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ABBREVIATIONS AND ACRONYMS

1G	First generation
2G	Second generation
3G	Third generation
AtJ	Alcohol-to-jet
CCUS	Carbon capture and usage
CO	Carbon monoxide
CO ₂	Carbon dioxide
CORSIA	Carbon Offset and Reduction Scheme for International Aviation
DTIC	Department of Trade, Industry and Competition
EE	External renewable energy scenario
EU	European Union
FT	Fischer-Tropsch
FTE	Full-time equivalent
FT-SPK	Fischer-Tropsch – Synthetic Paraffinic Kerosene
FT-SPK/A	Fischer-Tropsch – Synthetic Paraffinic Kerosene plus Aromatics
GFT	Gasification, Fischer-Tropsch
GFT-R	Gasification, Fischer-Tropsch and refining
GHG	Greenhouse gas
GJ	Gigajoule
HEFA	Hydroprocessed Esters and Fatty Acids
IAPs	Invasive alien plants
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IH ₂	Integrated hydropyrolysis and hydroconversion
I-JEDI	International Jobs and Economic Development Impacts
MJ	Megajoule
Ml	Million litres
Mt	Million tonnes
PtL	Power-to-liquid
SAF	Sustainable aviation fuel
SS	Self-sufficiency scenario
StJ	Syncrude-to-jet
Syncrude	Synthetic crude
Syngas	Synthetic gas
WACC	Weighted average cost of capital



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KEY MESSAGES

Sustainable aviation fuel (SAF) is the main climate mitigation measure for the “hard-to-abate” aviation sector. Its production also has a number of environmental and socio-economic benefits.

A domestic SAF industry could be a pillar of South Africa’s low-carbon economy, playing a key role in the just transition process. This report lays out a blueprint for the production of SAF in South Africa, given the various alternatives available.

- South Africa has the immediate technical potential to produce 3,2 billion litres of SAF annually, following the strictest sustainability requirements. Introducing green hydrogen into the SAF manufacturing process can extend this potential to 4,5 billion litres per year.
- This is enough to replace the use of conventional jet-fuel domestically up to a maximum blending threshold of 1,2 billion litres per annum, while also providing 2–3,3 billion litres for export.
- The quickest and cheapest route to initial SAF quantities produced in South Africa is the first-generation (1G) alcohol-to-jet (AtJ) pathway based on sugarcane A-molasses as feedstock. Over 300 million litres of SAF could be produced annually following this pathway, at an internationally competitive price.
- Invasive alien plants (IAPs) and garden waste are potentially the largest available lignocellulosic feedstocks in the country. They could be converted to 1,8–3 billion litres of SAF annually using Fischer-Tropsch synthesis. This is also the most economic pathway to produce SAF from IAPs and garden waste.
- The Hydroprocessed Esters and Fatty Acids (HEFA) pathway could produce 1,1 billion litres of SAF per annum using plant oil extracted from Solaris seeds and create nearly 20 000 agricultural jobs.
- The AtJ pathway could produce an additional 80–116 million litres of SAF per annum in South Africa using third-generation (3G) ethanol produced from industrial off-gas.
- While all SAF is more expensive than conventional jet-fuel, some of the assessed pathways are already competitive with the current international SAF price and several more could become competitive if the cost of capital for the processing facilities and/or the feedstock cost could be lowered through policy support or concessional funding.
- A domestic SAF industry offers some major environmental, socio-economic and macro-economic benefits:
 - Implementation of biomass-dependent SAF pathways could provide significant impetus to address the longstanding concern around woody invasive alien species, realise jobs in the small and medium-sized enterprises sector, bolster government investment in removals and build national resilience to climate change by improving water availability in multiple catchment areas across South Africa.
 - A domestic SAF sector offers the opportunity to create over 100 000 direct green jobs along the SAF supply chain.
 - Feedstock production could provide employment to 20 000 farm workers and possibly even bigger numbers of IAP harvesters. It would also preserve at-risk jobs in sugarcane production.
 - The highest achievable localisation of all promising production pathways would provide 40 000 direct and 48 000 indirect jobs during the construction phase, and 46 500 direct and 3 600 indirect jobs over the 20-year operational period of SAF production plants.
 - In addition to this, the nationwide SAF supply chains could create nearly 7 500 truck-driver jobs and over 800 support jobs. About 3 800 of the truck-driver jobs are in coal-mining regions and have the potential to offset almost all coal-hauling jobs that might be lost in the energy transition, as well as preserve jobs in truck maintenance and refuelling.
 - Reducing jet-fuel imports by developing a domestic SAF industry can improve South Africa’s balance of trade by R118 billion (US\$7,9 billion) per annum. Full export of all SAF would further improve the balance of trade, generating about R159,5 billion (US\$10,6 billion) per annum from sales at the minimum sale price.

INTRODUCTION

The Paris Agreement commits the global community to pursuing efforts to limit global warming to an average temperature increase of 1,5 °C. To achieve this goal, rapid decarbonisation of all economic sectors is required, including those considered “hard-to-abate” such as aviation.



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THE GROWING DAMAGE OF AVIATION TO THE CLIMATE

The commercial aviation industry currently accounts for 2–3% of global carbon dioxide (CO₂) emissions (IATA, 2021a). If no mitigation measures are taken, CO₂ emissions from commercial aviation are expected to triple by 2050 due to a surge in both passenger and freight transport (ICCT, 2021). These emissions could by then account for over 22% of all anthropogenic CO₂ emissions (Cames et al., 2015).

Aviation also has non-CO₂ impacts in the form of particulate matter, water vapour and nitrogen oxides (NO_x) that are released into the atmosphere. These additional emissions can more than double the contribution of the aviation sector to the overall warming of the atmosphere (EASA, 2020).

At present, international aviation accounts for about 65% of global aviation emissions, whereas 35% comes from domestic aviation worldwide (ICAO, 2020a).



THE COMMERCIAL AVIATION INDUSTRY CURRENTLY ACCOUNTS FOR 2-3% OF GLOBAL CARBON DIOXIDE EMISSIONS

MITIGATION MEASURES TOWARDS AVIATION NET-ZERO BY 2050

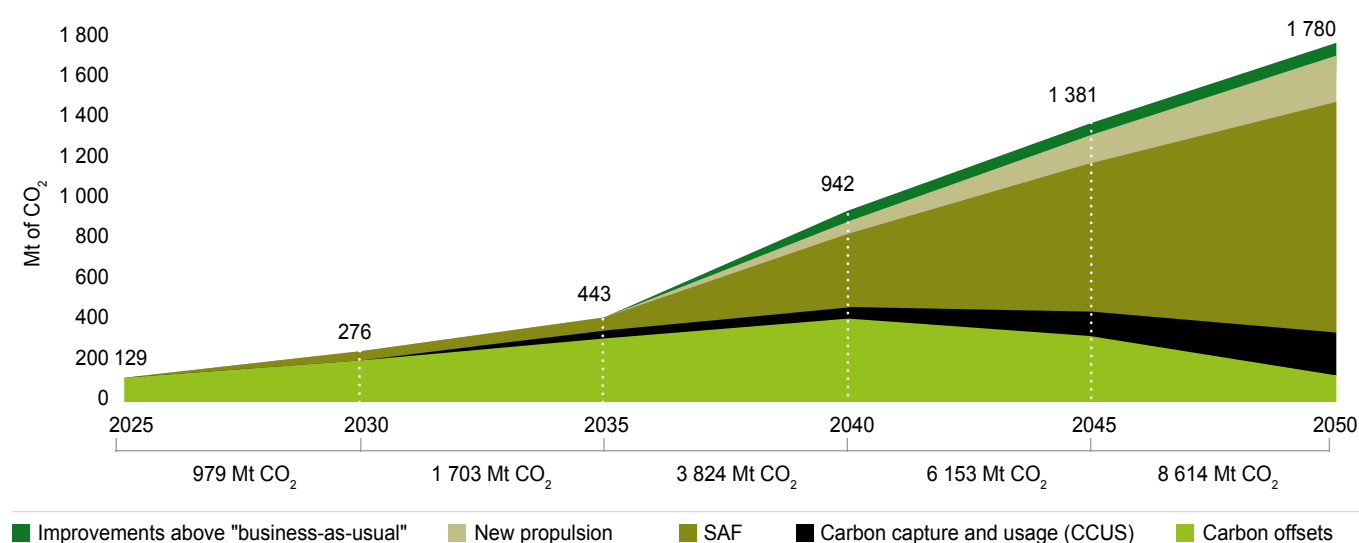


Figure 1: Contribution of different mitigation measures to aviation net-zero CO₂ emissions by 2050

CLIMATE MITIGATION IN AVIATION AND THE ROLE OF SUSTAINABLE AVIATION FUELS

Emissions from domestic aviation are covered by the Paris Agreement (UNFCCC, 2021), and their mitigation is included in countries' Nationally Determined Contributions (NDCs). Regulating emissions from international aviation, however, is the responsibility of the International Civil Aviation Organization (ICAO). In this regard the organisation has adopted two aspirational goals for the sector, namely a 2% annual fuel-efficiency improvement through 2050, and carbon-neutral growth from 2020 onwards (known as the CNG2020 goal) (ICAO, 2020a). These have been widely criticised as insufficient.

More recently, the International Air Transport Association (IATA), the trade association for the world's airlines representing about 290 airlines or 83% of total air traffic, approved a resolution for the global air transport industry to achieve net-zero carbon emissions by 2050 (IATA, 2021c). Both ICAO's and

IATA's more ambitious goals are based on a basket of measures. These include aircraft technology and operational improvements, with sustainable aviation fuels (SAF) providing the majority of in-sector climate mitigation. Credible offsetting schemes are expected to compensate for any residual emissions (Figure 1) (IATA, 2021b).

Achieving deep cuts in aviation emissions will require a dramatic ramp-up of SAF production. SAF currently accounts for less than 1% of global jet-fuel consumption (IATA, 2021d). Replacing just 2% of conventional jet-fuel with SAF by 2025 will require 7.9 billion litres per annum, while meeting 65% of jet-fuel demand with SAF by 2050 will require 449 billion litres per annum (IATA, 2021c).

Scaling up SAF production will entail a coordinated effort by all stakeholders in the value chain. At present, the price differential between SAF and conventional jet-fuel, as well as the option available to airlines to reduce their emissions with the relatively cheaper carbon offsets, has held back the pace of growth of SAF supply. Despite this, early movers in the sector

have reached offtake agreements for 20.1 billion litres over the course of the next 10 years (ICAO, 2022), providing the necessary learnings and track records for a selection of SAF production pathways that will allow them to scale up faster.

SUSTAINABLE AVIATION FUELS - THE BASICS

To date, nine SAF production routes have been certified under the relevant ASTM International (formerly known as the American Society for Testing and Materials) standards for aviation turbine fuel (ICAO, 2021), with several more having applied for certification (CAAFI, 2020). Their blending ratios with conventional jet-fuel range from 5–50%, depending on the production pathway.

It is important to note that not all alternative aviation fuels are created equal and they will only mitigate the industry's detrimental impact on the climate (and potentially deliver other social and environmental benefits) if they comply with rigorous sustainability criteria.



TO AVOID UNINTENDED NEGATIVE SOCIO-ENVIRONMENTAL IMPACTS, ALTERNATIVE FUELS SHOULD BE COMPREHENSIVELY SCREENED FOR SUSTAINABILITY RISKS

Without complying with sustainability criteria, some of these fuels run the risk of achieving only negligible reductions in greenhouse gas (GHG) emissions. Some fuels may even increase emissions, reduce food security from repurposing land dedicated to food production to feedstock production, accelerate deforestation and unsustainable soil and water usage, and infringe on the land-use rights of local communities, among other things.

To avoid such unintended negative socio-environmental impacts, alternative fuels, including those for aviation, should be comprehensively screened for sustainability risks. Those that meet the criteria of a robust sustainability standard should then be certified by a credible certification body, to earn the title “sustainable”. While a number of sustainability standards exist, the Roundtable on Sustainable Biomaterials is recognised as an industry gold standard that provides a robust, credible and practical framework to support the aviation industry in ensuring that their use of SAF safeguards and advances social and environmental sustainability (WWF, 2013).

The recent ambitious mitigation announcements by the world’s airlines, many of which service South African routes, as well as the steady increases in the price of

carbon offsets and the expansion of the suite of approved SAF production technologies and their maturation, will result in a sharp increase in SAF supply over the coming decades. South Africa is well positioned to take advantage of this momentum and build a domestic SAF sector based on a number of local competitive advantages. These include an excellent resource base and long-standing experience with some promising SAF production technologies.

Besides the need to start decarbonising its own aviation sector (domestic airlines are already subject to carbon tax and South Africa will have to start participating in the Carbon Offset and Reduction Scheme for International Aviation (CORSIA) at the latest from 2027), SAF also represents an important export opportunity. Both regulated (compliance) and voluntary markets for SAF already exist and are forecast to grow, making SAF one of the key opportunities in the global green economy.

This report describes the ways that SAF could be produced in South Africa in greenfield facilities. Previous analyses have explored the potential to produce SAF at existing refinery complexes in Secunda (Sasol) (Bole-Rentel et al., 2019) and Mossel Bay (PetroSA) (Bole-Rentel et al., 2021).



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WHAT ARE SUSTAINABLE AVIATION FUELS?

Sustainable aviation fuels (SAF) are low-carbon fuel alternatives for the aviation industry. These non-petroleum-based aviation fuels are generally produced from bio-based feedstocks such as energy crops, waste, residues and end-of-life products (in which case they may be synonymous with aviation biofuels or bio-jet-fuels), or fossil waste such as industrial off-gases like carbon monoxide (CO).

The SAF technologies approved to date are for “drop-in” fuels, meaning that they can be used in the same equipment and infrastructure (engines, pipelines, distribution networks, etc.) as conventional jet-fuel, without any modifications. They are chemically similar to conventional jet-fuel but are derived from alternative feedstocks rather than crude oil, coal or natural gas, and hence have the potential to reduce both the CO₂ and non-CO₂ emissions from aircraft (EASA, 2020). Alternative fuels – including SAF – are typically classified as first-, second- or third-generation fuels.

FIRST-GENERATION FUELS

First-generation (1G) alternative fuels are typically bio-based and are produced from sugar, starch or oilseed crops (e.g. sugarcane, maize (corn) and rapeseed) through well-established conversion processes such as fermentation or hydrogenation. Feedstocks for 1G biofuels are in most cases purposely grown and can be associated with (direct or indirect) land-use changes and concomitant carbon emissions, which can negate the climate benefit of replacing conventional fuel with biofuel.

SECOND-GENERATION FUELS

Second-generation (2G) alternative fuels are usually also bio-based; however, they are made from non-food crops or lignocellulosic biomass, including wastes. Jatropha, Solaris, miscanthus, agricultural residues and municipal solid waste, among others, are considered 2G feedstocks (Aro, 2016). Some of these are processed with the same technologies as 1G feedstocks (non-edible oilseeds), whereas others require more advanced technology to be converted into fuel, including gasification and Fischer-Tropsch synthesis. Purposely grown 2G crops might still cause land-use change and compete with food for suitable agricultural land, but waste-based feedstocks do not. Their removal may in some instances have additional benefits, although there are also risks associated with over-abstraction.

THIRD-GENERATION FUELS

Third-generation (3G) alternative fuels refer to fuels made from biological or non-biological substances, including algal biomass and CO-rich industrial waste gases. Algal biomass can be processed into biofuel using similar processes as for 1G oilseeds. Industrial off-gases can be fermented with the help of specially engineered microbes to produce ethanol, which can be further processed to SAF like any other ethanol. Similar to waste-based 2G biofuels, 3G fuels are typically considered to not pose high land-use change risk; 2G and 3G biofuels are also often referred to as advanced fuels.

E-FUELS OR POWERFUELS

Most recently, “electrofuels (e-fuels)” or “powerfuels” have been gaining prominence as an important decarbonisation solution in “hard-to-abate” sectors, including aviation. “Powerfuels” is an umbrella term for gaseous or liquid fuels and feedstocks produced from renewable electricity. It includes hydrogen, synthetic gas and synthetic liquid fuels used in aviation (also known as power-to-liquid or PtL). PtL is often positioned as offering superior sustainability benefits compared to 1G SAF. However, it is important to remember that renewable electricity produces only green hydrogen and that a source of carbon is still required to produce a hydrocarbon fuel that can be used as a drop-in fuel in existing infrastructure. Therefore, even PtL fuels need to be subjected to rigorous sustainability assessments, as their climate benefit is also closely linked to the type of carbon used for the production of the fuel.

APPROACH TO THE STUDY

SAF can be produced from a wide variety of feedstocks processed by a multitude of technologies. This study examines the potential of full supply chain implementation using feedstocks that could meet the sustainability criteria outlined by the Roundtable on Sustainable Biomaterials.



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FEEDSTOCK SELECTION

WWF has previously estimated the SAF production potential from sustainably grown energy crops in sub-Saharan Africa (Fischer et al., 2019). The analysis shows that the technical potential for purposely grown crops in South Africa is sizeable; however, only a fraction of those will be economical to produce. Thus, there is a clear need to better understand a more diversified feedstock base, including non-cultivated feedstocks that will become increasingly relevant with the growing adverse effects of climate change on agricultural output. To determine the most realistic pathways for the development of a SAF industry in South Africa in the next 5–10 years, the following feedstocks have been selected:

Solaris

Solaris is a nicotine-free tobacco variety specifically developed to maximise oilseed production. It has been successfully grown in South Africa and was the feedstock used in South African Airways' first SAF-powered flights in 2016 (Creamer Media, 2016).

A-molasses

A-molasses is a co-product of sugar production that could see its output readily scaled up at existing sugar mills. It can be used for production of first-generation (1G) ethanol. This would reduce South Africa's sugar output somewhat but is in line with the new Sugarcane Value Chain Masterplan (DTIC, 2020), which aims to diversify market opportunities for sugarcane products in view of the prolonged global sugar glut.

FEEDSTOCK SELECTION



SOLARIS



A-MOLASSES



LIGNOCELLULOSIC
WASTE



INDUSTRIAL
OFF-GASES

SAF SUPPLY CHAINS HAVE BEEN ASSESSED BASED ON SPATIAL AND TEMPORAL AVAILABILITY OF EACH OF THESE FEEDSTOCKS

Lignocellulosic waste

Invasive alien plants (IAPs)

The introduction of IAPs has led to the unhealthy conversion of landscapes from climate-adapted, species-rich indigenous vegetation to single-species stands of water-thirsty invasive trees. This threatens biodiversity, water security, the productive use of land and the ecological functioning of natural systems. Due to the extent of invasions and the need for their removal, IAPs are the largest source of sustainable carbon for the production of second-generation (2G) biofuels in South Africa, including SAF, with the caveat that their extraction should be followed immediately by land restoration to quickly restock the carbon in the landscape and maximise the GHG benefits of SAF produced from IAPs.

Garden waste

Garden waste removed from private and public green areas often takes up valuable landfill space instead of being utilised as a highly sustainable, easily exploitable source of lignocellulose, at least where its collection is centralised by municipal waste management services. It can be co-processed into SAF along with IAPs via various pathways.

Industrial off-gases

Industrial waste gases rich in carbon monoxide from South Africa's heavy industry can be used for carbon recycling and the production of third-generation (3G) ethanol, which can be further processed into SAF.

Potential feedstocks that are fully allocated elsewhere, such as used cooking oil or bagasse, or that

might be very far from large-scale commercial production, such as miscanthus or jatropha, have been excluded from the analysis. Sugarcane harvest residues also represent a potentially significant source of lignocellulosic biomass; however, their availability depends on the extent to which green harvesting can replace the current slash-and-burn method. The use of these feedstocks remains technically feasible in case of a change in market conditions, farming practices or successful large-scale agricultural trials.

SELECTION OF SAF PRODUCTION PROCESSES

Whereas there are several approved SAF production processes, in this study we focused on:

- Hydroprocessed Esters and Fatty Acids (HEFA)
- Alcohol (ethanol)-to-jet (AtJ)
- Fischer-Tropsch – Synthetic Paraffinic Kerosene (FT-SPK)
- Fischer-Tropsch – Synthetic Paraffinic Kerosene plus Aromatics (FT-SPK/A)
- Integrated hydropyrolysis and hydroconversion (IH₂).

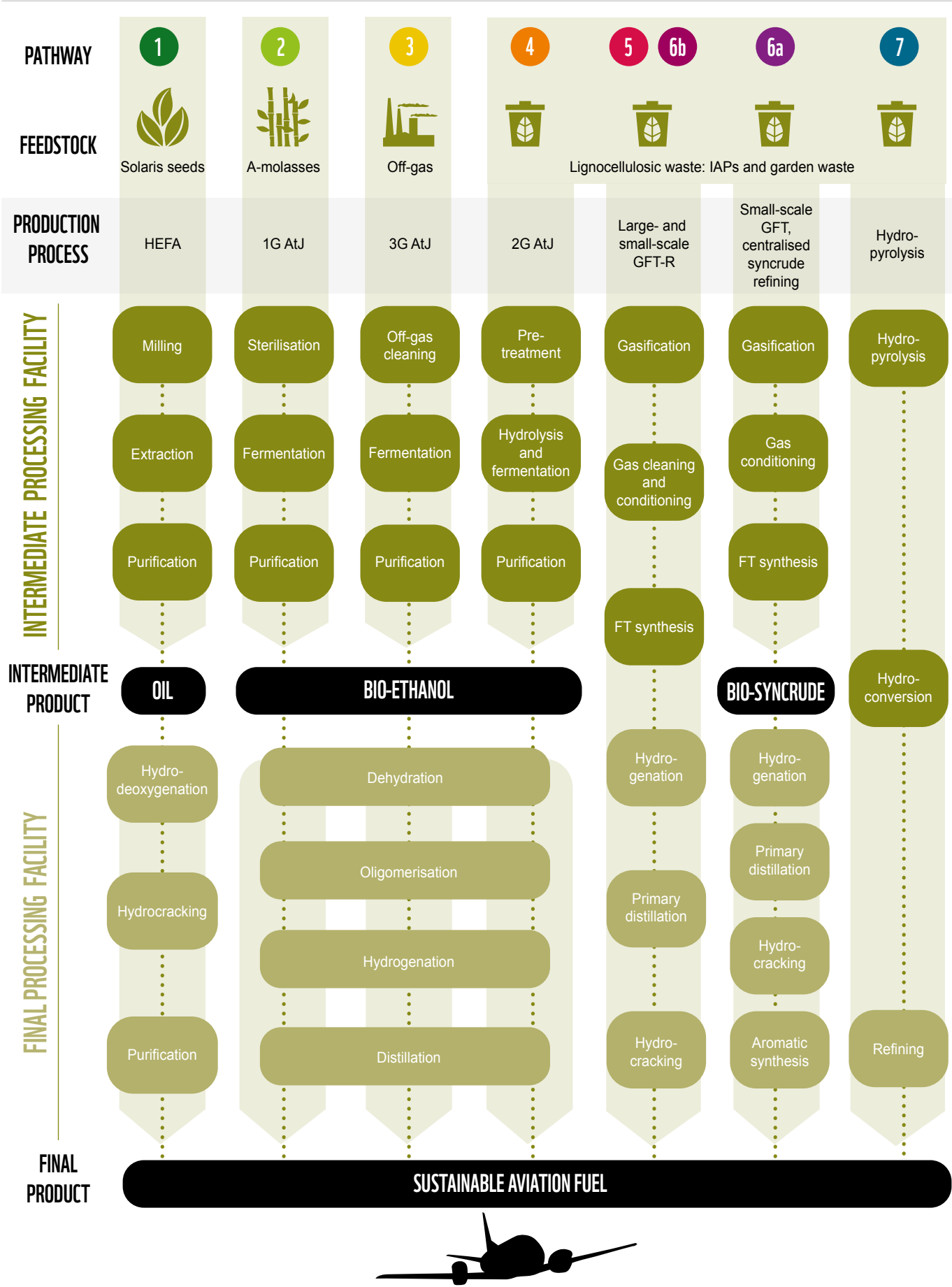
These are the most mature technologies for SAF production and, therefore, the choice of most of the SAF plants coming online in the near future.

In addition, South Africa has a competitive advantage with Fischer-Tropsch (FT) technology, which has been used to manufacture liquid fuels and chemicals in the country for decades.

Electrofuels (e-fuels) or power-to-liquid (PtL) technologies are also promising components for the production of SAF. At least initially, PtL-based SAF will still require a sustainable carbon source, so it is highly likely that early PtL facilities will be combining green hydrogen produced via electrolysis and bio-based carbon using one of the already certified SAF production pathways, such as HEFA or FT-SPK, until such time as direct air capture (DAC) becomes a commercial reality.

The processing steps of the various SAF production pathways are shown in Figure 2. A total of seven feedstock technology combinations were considered. It is worth noting that the processing of any feedstock to SAF often involves the production of an intermediate product at an intermediate facility, which must be further processed into SAF at a final facility. SAF can also be produced at an integrated facility where both intermediate processing and SAF production occur in a single facility. Pathways 1 to 4 all have intermediate and final facilities, while Pathway 5 and 7 have integrated facilities. Pathway 6 has been split into Pathway 6a, which has both an intermediate and a final facility, and Pathway 6b, which is an integrated facility. The main difference between Pathway 5 and Pathway 6b is production scale.

PROCESSING STEPS IN THE PRODUCTION OF SAF AND ITS INTERMEDIATE PRODUCT



TECHNO-ECONOMIC MODELLING

Processing models for the various pathways were developed and simulated in the ASPEN Plus® V10 process simulator, using classic chemical-engineering techniques. Two scenarios were considered for each pathway:

Self-sufficiency scenario (SS)

All thermal and electrical energy needed for process operation, as well as all hydrogen requirements for the SAF production, are derived from the feedstock.

External renewable energy scenario (EE)

The hydrogen requirements for the conversion of feedstock into SAF are supplemented with green hydrogen produced by a captive renewable energy system powering an electrolyses plant (and in the case of Pathway 3 (3G AtJ) also providing some external energy to the primary process).

Economic assessments based on the ASPEN Plus® simulation results were used to determine the processing costs for the different conversion technologies. The capital costs for process units, installation and balance of plant were calculated from

the internal stream data simulated in ASPEN Plus®, using an in-house tool developed by Stellenbosch University (Petersen et al., 2018). The input-output mass and energy data were used to estimate the variable operating costs, such as chemical and energy costs. Discounted cash flow analysis was undertaken to determine the processing costs or minimum product selling prices for the desired return on investment (ROI) at conversion facilities.

The facility sizes considered in this study are given in Table 1. The choice of facility sizes (input capacity) was based on international benchmarks for operational and planned commercial facilities (Head et al., 1995; SkyNRG, 2019; Brown et al., 2020; Lane, 2021). The 1G ethanol production scale was based on the material flows in a typically sized South African sugar mill, whereas 3G ethanol production varied depending on the amount of off-gas available at an industrial facility. These baseline capacities have been scaled up or down depending on feedstock availability in different localities to maximise feedstock utilisation within a reasonable range (0,5–4 of baseline values).

TABLE 1: BASELINE PRODUCTION SCALES FOR THE DIFFERENT FACILITIES

Facility	Pathway and facility type	Annual input capacity and units		Annual output capacity		
				Self-sufficiency scenario (SS)	External energy scenario (EE)	
Solaris oil extraction	1 Intermediate	124 000	tonnes of seeds	46 800 000	46 800 000	litres of vegetable oil
HEFA	1 Final	185 000 000	litres of oil	112 593 000	112 593 000	litres of SAF
1G ethanol	2 Intermediate	164 806	tonnes of A-molasses	82 000 000	82 000 000	litres of ethanol
3G ethanol	3 Intermediate	36 131	Nm ³ /h off-gas	41 300 000	55 000 000	litres of ethanol
2G ethanol	4 Intermediate			98 161 000	98 161 000	litres of ethanol
Small-scale GFT	6a Intermediate			65 062 000	110 453 000	litres of syncrude*
Small-scale GFT-R	6b Combined	304 000	tonnes of biomass	44 453 000	75 520 000	litres of SAF
Hydropyrolysis	7 Combined			27 200 000	– ¹	litres of SAF
Large-scale GFT-R	5 Combined	912 000	tonnes of biomass	133 358 000	226 860 000	litres of SAF
AtJ refinery	2 3 4 Final	304 000 000	litres of ethanol	81 925 000	86 948 000	litres of SAF
FT – centralised refinery	6a Final	287 000 000	litres of syncrude	231 324 000	231 324 000	litres of SAF

* Synthetic crude oil equivalent

¹ Not evaluated as literature data for IH² using green hydrogen and renewable energy was not available.

Table 2 shows the assumed feedstock costs and Table 3 the range of assumed costs for green hydrogen produced through electrolysis.

TABLE 2: FEEDSTOCK PRICES USED IN THIS ASSESSMENT

Feedstock	Price (US\$/tonne)	Description	Reference
Soybeans (Solaris seeds proxy)	366	5-year average	IndexMundi, 2021
Sugarcane A-molasses	140	5-year average	Selina Wamucii, 2020; Petersen et al., 2021
Sugarcane residues	16,34	Stellenbosch University estimate	Petersen et al., 2018
Invasive alien plants	107,38*	Private company estimates	–
Industrial off-gas	0	Assumed to be available for free	–

* Price includes cost of clearing, chipping and transport to central collection point

TABLE 3: ASSUMED GREEN ELECTRICITY AND HYDROGEN PRICE RANGE

	Minimum price	Maximum price	Reference
Renewable electricity	US\$0,03/kWh	US\$0,03/kWh	DMRE, 2021
Green hydrogen*	US\$2/kg	US\$4,4/kg	IHS Markit, 2021

* An average price of US\$3/kg was used to cost the supply chains for each pathway

SUPPLY CHAIN OPTIMISATION AND TRANSPORT COSTING

Bioenergy plants, including SAF production facilities, require huge amounts of feedstock. Because of this, biomass transport costs can be significant components of the final price of bio-based products. Thus, a rigorous feedstock-sourcing strategy was assumed, based on a centre-of-gravity study that optimised the locations of both intermediate and final facilities in relation to their feedstock source to minimise transport costs and the related GHG emissions. The SAF supply chains considered in this study are represented graphically in Figure 3.

Different vehicle options were considered for both the primary and the secondary transport legs. Rail was not considered in this assessment as previous research showed that rail was cheaper than road in only 12% of the towns where it was a possibility (Bole-Rentel et al., 2019). Of course, this should not preclude further investigation of using rail as much as possible for individual supply chains.

In Pathways 1 (HEFA), 4 (2G AtJ) and 6a (Small-scale GFT with centralised syncrude refining), there is primary transport of the raw feedstock to the intermediate facilities and then secondary transport of the intermediate product to the final SAF facility. For Pathways 2 (1G AtJ) and 3 (3G AtJ), there is no primary transport as the intermediate product (ethanol) is assumed to be generated at the feedstock location. For the GFT production pathways, the advantages of including an intermediate facility (Pathway 6a) were compared to the processing of biomass to SAF at a combined facility (Pathway 6b: Small-scale GFT-R). In addition, any potential advantages from using larger as opposed to smaller-scale facilities were also explored. Whereas larger

facilities benefit from economies of scale (Pathway 5: Large-scale GFT-R), it is likely that the biomass required to feed such a plant will have to be sourced across longer distances compared to smaller facilities (Pathway 6b), where biomass is sourced from shorter distances and thus benefits from cheaper transport costs.

The calculation of the total cost of SAF production varied based on the production pathway because the supply chain components of each network were different. However, in essence, total cost is a simple summation of feedstock costs, applicable transport costs and processing costs.

GREENHOUSE GAS ASSESSMENT

To play a decisive role in decarbonising aviation, SAF must meet robust sustainability criteria. A high-level assessment of sustainability risks associated with the different feedstocks considered for SAF production in South Africa had been undertaken in previous studies (Bole-Rentel et al., 2019, 2021). These assessments followed the sustainability principles of the Roundtable on Sustainable Biomaterials (RSB) (WWF, 2013).

In this study, we took a closer look at the compliance of the modelled SAF supply chains with GHG emission reduction requirements (based on life-cycle assessments). There are different requirements and different CO₂ savings calculation methods for different market segments. We assessed those for:

- The regulated European market, based on the requirements as set out in the European Union's Renewable Energy Directive (RED II)
- The regulated CORSIA scheme
- The global RSB Standard used in voluntary markets.

SUPPLY CHAIN DIAGRAMS FOR SAF PATHWAYS

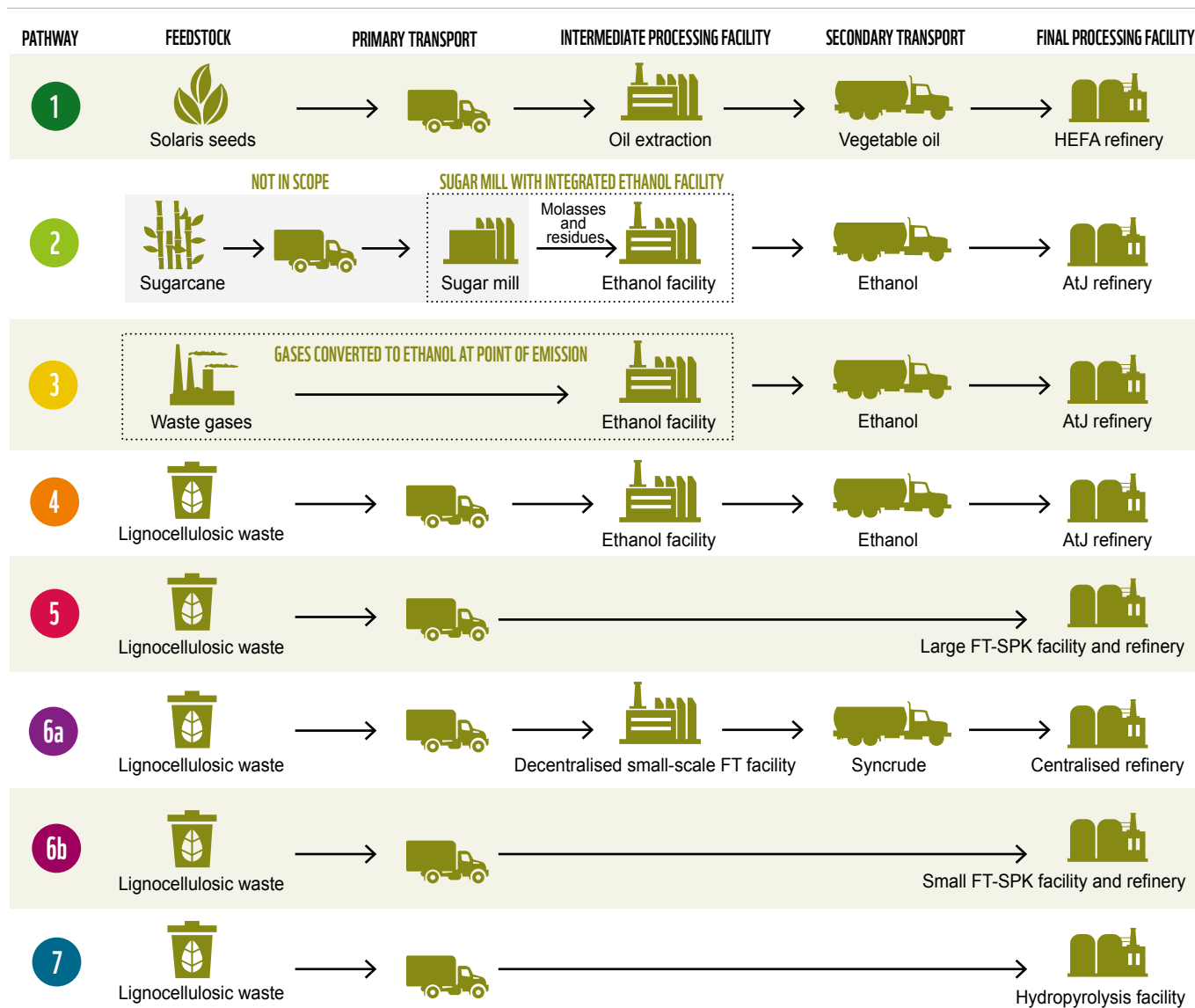


Figure 3: Network diagrams of the SAF supply chains considered

SOCIO-ECONOMIC IMPACTS

The circular and bio-based economy offers a number of socio-economic benefits. The impacts of a domestic SAF sector on critical developmental objectives in South Africa need to be better understood. These objectives include employment creation, trade balance improvement and GDP growth. The potential role of the sector in the just energy transition also needs to be better understood.

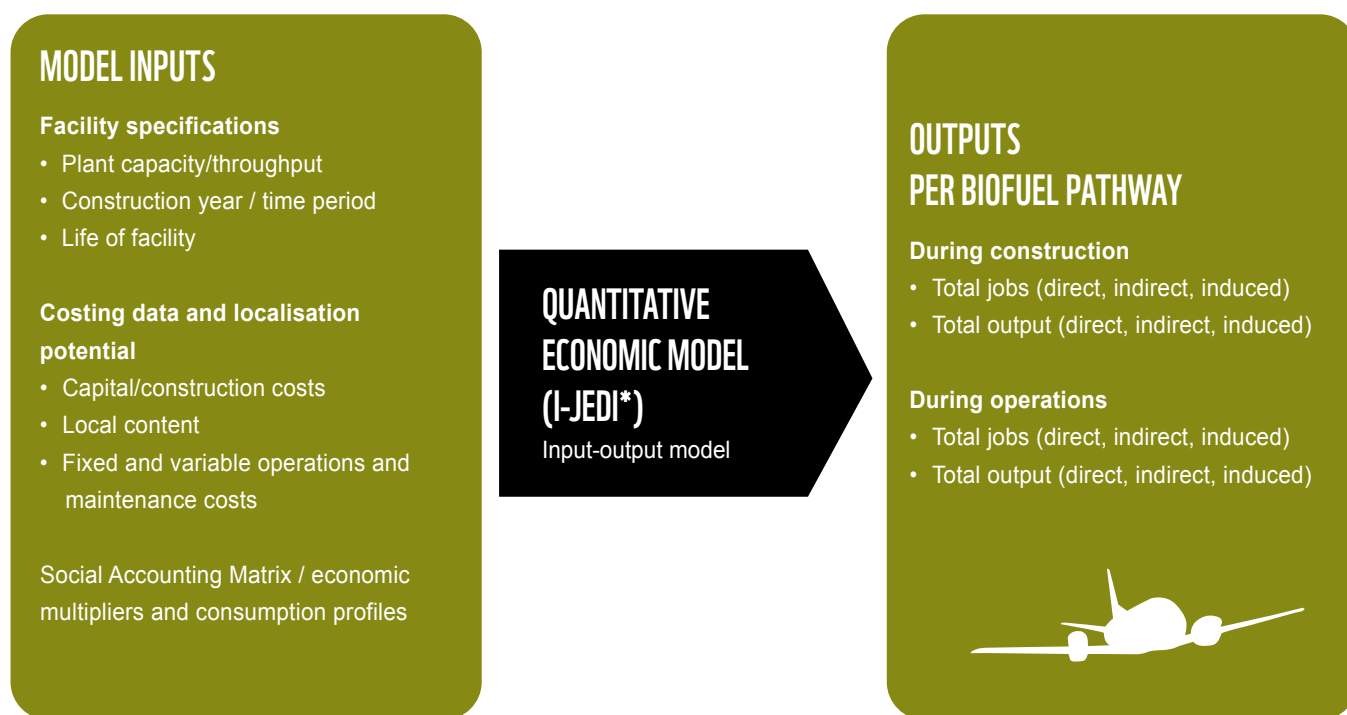
Job creation potential

The number of jobs that could be generated in a strong domestic SAF sector was estimated using the International Jobs and Economic Development Impacts (I-JEDI) model (Figure 4). The model works through economic input-output analysis, which uses a fully balanced model of the economy to estimate how the increased demand associated with the development of each supply chain impacts on other industries throughout the economy. The core of the model is therefore a social accounting matrix, developed through

analysis of national accounts to determine production, consumption and interlinkages between aggregated economic sectors. By assigning the proportion of local project expenditure for each pathway component to the relevant economic sectors, the model can determine the total upstream impacts of this expenditure, including all direct and indirect jobs linked to the expenditure. In order to localise the I-JEDI model, a 2019 social accounting matrix was constructed from data obtained from Quantec.²

Two different localisation scenarios were considered:

1. Installation as turnkey operations by international financiers
2. Maximised localisation in which all feasible installation features that could be manufactured locally were sourced through local suppliers.



Source: Calitz et al., 2022

Figure 4: I-JEDI* model structure, data inputs and product outputs for estimating the socio-economic impacts of SAF pathways

* International Jobs and Economic Development Impacts (I-JEDI) model

A separate, more detailed analysis than would be possible with the I-JEDI model was undertaken to assess the potential jobs associated with the transportation of feedstock and intermediate products. Special emphasis was placed on this segment of the labour market, based on an awareness that the energy transition will result in a reduction in coal use and thus a reduction in coal transportation jobs. Considering South Africa's large biomass feedstock base and parallels in coal- and biomass-hauling operations, coal transporters may be able to find alternate livelihoods by hauling sustainable biomass for emerging green industries, including SAF.

The number of alternate jobs for coal truckers built on the resource assessment and centre-of-gravity studies carried out to determine the location-specific biomass transport routes. The following steps were added:

1. Detailed route and volume analysis to determine the number of trucks (tanker, superlink and side-tipper) required to ensure continuity of supply for processing facilities.
2. Application of different shift and best-practice coordination regimes to determine the number of drivers and administrative staff required to fulfil the supply chain.
3. With the help of a geographic information system (GIS), an overlay of the number of biomass truck drivers and their associated home bases (assumed to be located around the intermediate facilities) was created with the current routes and numbers of coal-truck drivers to estimate job-transfer opportunities between the two (Chireshe and Bole-Rentel, 2022).

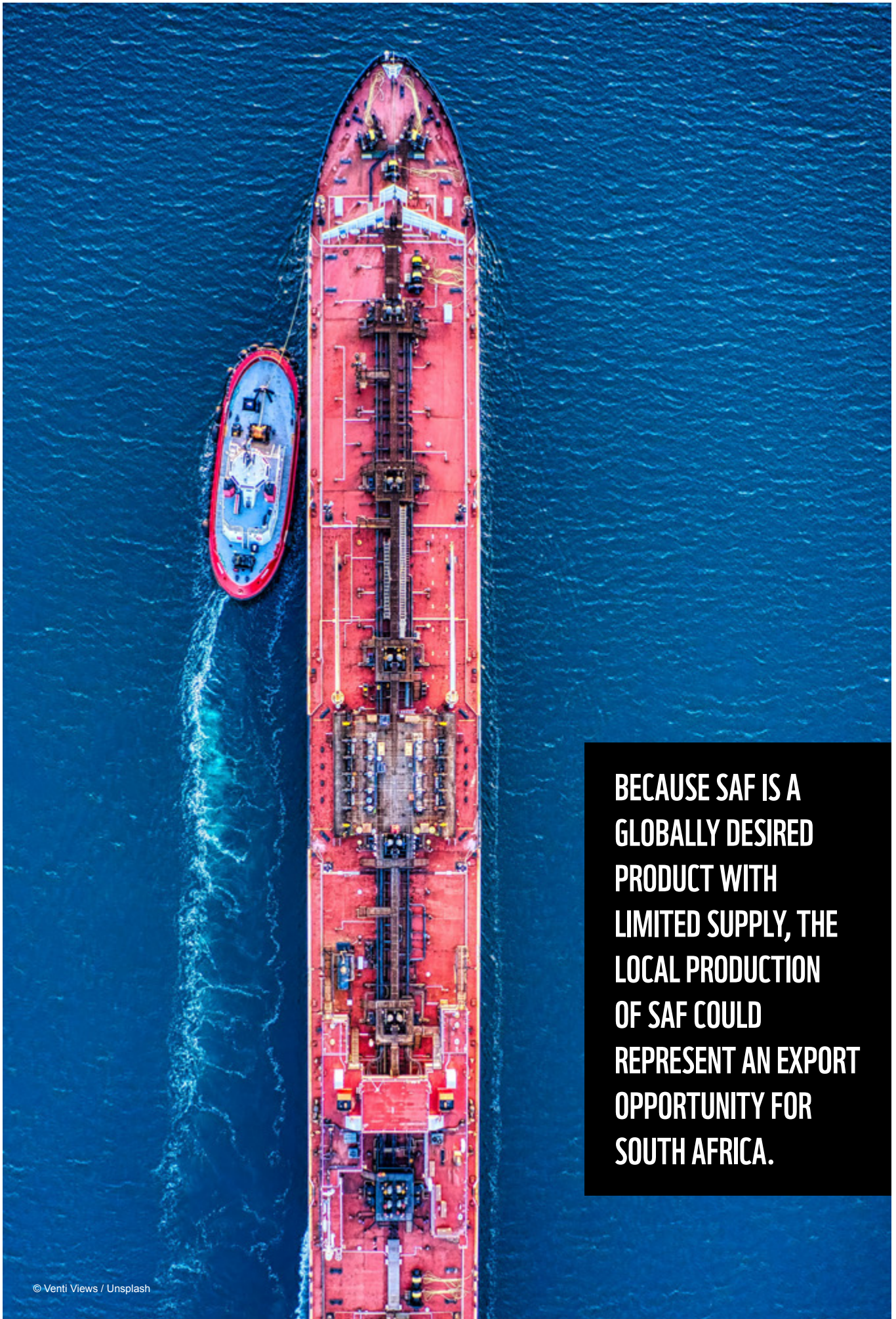
Macro-economic impacts

The magnitude of macro-economic impacts from developing domestic SAF production capabilities will depend on the extent to which such SAF is consumed domestically or is exported.

South Africa is currently a net importer of aviation fuel, with about 19% of total jet-fuel consumption covered by imports. Replacing aviation fuel imports with locally produced SAF would have a positive impact on South Africa's balance of trade.

At the same time, because SAF is a globally desired product with limited supply, the local production of SAF could represent an export opportunity for South Africa. Despite SAF prices being considerably higher than for conventional jet-fuel, there is a large international demand for low-carbon aviation fuels to meet industry targets for emissions reduction. Consequently, the sale of SAF has high export potential, with a concomitant reduction in the deficit on the balance of trade.

To determine the most favourable outcome on the balance of trade, we consider a range of scenarios for blending locally produced SAF and their impact on aviation fuel imports, with blending amounts ranging from 0% (all domestically produced SAF is exported) to over 25% (domestically produced SAF replaces all jet-fuel imports) of total aviation fuel consumed in the country. This provides an estimate of the potential reduction in fuel imports and/or export earnings per blending scenario and their impact on South Africa's balance of trade.



**BECAUSE SAF IS A
GLOBALLY DESIRED
PRODUCT WITH
LIMITED SUPPLY, THE
LOCAL PRODUCTION
OF SAF COULD
REPRESENT AN EXPORT
OPPORTUNITY FOR
SOUTH AFRICA.**

MAPPING THE SAF OPPORTUNITY IN SOUTH AFRICA

South Africa has the potential to manufacture as much as 4,5 billion litres per year of sustainable aviation fuels at globally competitive prices. The supply chains would benefit multiple communities and could provide an economically viable means for addressing invasive alien plant infestations.



AVAILABILITY OF FEEDSTOCK

Availability assessments for each feedstock revealed that a significant amount of purposely produced and/or waste biomass can be made available for the production of SAF (and other advanced fuels, chemicals and materials in South Africa), as summarised in Table 4. It is important to note that these estimates take into consideration sustainability principles that restrict the production of purposely produced feedstock (such as Solaris) to a level that would not affect food security or the environmental integrity of the SAF produced from it. Similarly, it takes accessibility into account, as is the case for cleared IAPs and garden waste.



AVAILABILITY ASSESSMENTS REVEALED THAT A SIGNIFICANT AMOUNT OF WASTE BIOMASS CAN BE MADE AVAILABLE FOR THE PRODUCTION OF SAF IN SOUTH AFRICA

TABLE 4: OVERVIEW OF FEEDSTOCK AVAILABILITY

Feedstock	Potential availability	Reference
 Solaris	5,2 million tonnes of seed per annum	Fischer et al., 2019
 A-molasses	165 000 tonnes per sugar mill per annum	Dogbe et al., 2020
 Industrial off-gas	3,34 million tonnes per annum	Own research based on off-gas producers' reports
 Cleared IAPs	215 million oven-dry tonnes on less-than-35% slopes	Stafford et al. (2021) (available on request)
 Garden waste	170 000 tonnes per annum at two municipal depots (Johannesburg and Eden)	Integrated Pollutant and Waste Information System (IPWIS)

By first designating as “no go” areas for biofuel production those land areas that are of high carbon stock, that need to be conserved and that are required for current or future food and feed production, energy crops can be restricted to what is termed “remaining land”. This is marginal, abandoned or other land without competing uses. Considering the relatively favourable agro-ecological conditions in particular areas of South Africa’s “remaining land” and the high productivity of Solaris, farmers could still produce approximately 5,2 million tonnes of Solaris seed per annum. This is enough to supply several SAF refineries based on the HEFA process.

There are 14 sugar mills in operation in South Africa that can vary the output of sugar and molasses in pursuit of the best economic outcome. Based on the assumption that the number of hectares under sugarcane cultivation remains the same (thus avoiding the direct land-use change emissions associated with land conversion), South African mills could produce a maximum of 165 000 tonnes of A-molasses annually, for further processing into

bio-ethanol. It is assumed that the ethanol facility would be co-located with the sugar mill.

The primary sources of industrial off-gas are closed-furnace operations of iron and steel and ferroalloy smelters where carbon (coke) is used to reduce (purify) the mineral ore, producing CO as a by-product. The quantities of off-gases available at some smelter sites were found from publicly available CO emissions reports. In the cases where direct CO emissions data could not be found, metal production quantities at each site, together with off-gas yield data available in literature, were used to estimate the off-gas potential. These two approaches added up to 3,34 million tonnes of CO per annum that could potentially produce 410 million litres of ethanol.

Invasive alien plants are recognised as being a substantial candidate resource for sustainable advanced fuel in South Africa, including SAF. Based on existing data, spatial analysis was used to estimate the distribution and amounts of IAP biomass across the country while awaiting the new national invasive alien plants survey

(NIAPS). The amount of IAP biomass available at less-than-35% slope (the accessibility limit for most forestry machinery) has been estimated to be 215 million oven-dry tonnes for South Africa as a whole.

The majority is located in KwaZulu-Natal (49,5 million tonnes), the Eastern Cape (39,5 million tonnes), Limpopo (34,6 million tonnes) and the Western Cape (24,4 million tonnes). It is also crucial to bear in mind that IAP biomass is considered a strictly non-renewable resource. This means the identified total biomass available must be apportioned over the lifetime of SAF production (assuming no other uses for IAPs), which means any given area can act as a sourcing area once only.

The results of the techno-economic assessment presented in the next section offer important insights into how the different SAF production technologies compare with one another on resource utilisation, fuel yield and processing cost.

TABLE 5: SELF-SUFFICIENCY SCENARIO (SS): FUEL YIELDS OF CONSIDERED FACILITIES

Intermediate processing facility – product yield from primary feedstock							
Pathway	1	2	3	4	5 6b	6a	7
Feedstock	 Oilseed (Solaris)	 A-molasses	 Industrial off-gas	 Lignocellulosic waste: IAPs and garden waste			
Intermediate process	Oil extraction	1G ethanol	3G ethanol	2G ethanol	Large-scale and small-scale GFT-R*	Small-scale GFT	Hydro-pyrolysis*
Product yield	£/tonne	376	497	114	322	214	
	GJ/tonne	13	12	3	8	8	
Final processing facility – product yield from intermediates							
Pathway	1	2	3	4	5 6b	6a	7
Final process	HEFA		Central AtJ			Central refinery (StJ)	
SAF (£/tonne)	662		341			897	
Gasoline (£/tonne)	219		263			210	
Diesel (£/tonne)	12		44				
Finished product from intermediate process (GJ/tonne)	33		24			41	
Overall yield from primary feedstock							
Pathway	1	2	3	4	5 6b	6a	7
SAF (£/tonne)	229	134	31	87	146	173	89
Gasoline (£/tonne)	76	103	24	67	11	41	0
Diesel (£/tonne)	4	17	4	11		0	0
Overall fuel yield (GJ/tonne)	11	9	2	6	6	8	3

* Integrated pathways, i.e. no separate intermediate and final facilities

TECHNO-ECONOMIC ASSESSMENT OF SAF PATHWAYS: TWO SCENARIOS

Most biorefineries, even if optimised for SAF output, will inevitably produce co-products such as renewable diesel and gasoline, which are also represented here.

Self-sufficiency scenario (SS)

Table 5 shows the fuel yields that could be achieved with the various processing options, for both the intermediate and final processes, where all energy and hydrogen requirements are met from the primary feedstock (biomass or industrial off-gas). The main observations on the overall processes are:

- Pathways 1 and 2 have the highest energy yield of finished fuels, namely 11 and 9 GJ/tonne, respectively, since they have the highest yields from primary feedstock.
- Pathway 1 (HEFA) has the highest yield of SAF at 229 £/tonne of oilseed, even though the final processing facility of Pathway 6a has the highest SAF selectivity.
- Pathway 6a has a higher SAF yield, namely 173 £/tonne from primary feedstock, than Pathway 2 (134 £/tonne), even though Pathway 6a had the lower fuel yield of 8 GJ/tonne. This is due to the non-selective characteristic of AtJ facilities, which causes Pathways 2 to 4 to have gasoline yields that are close to their SAF yields.
- The overall fuel yield of Pathway 4 (6 GJ/tonne) compares unfavourably with Pathway 6a (8 GJ/tonne); however, it is similar to that of Pathway 5 (6 GJ/tonne), even though Pathways 5 and 6a follow similar processing steps. This is because the final refining facility in Pathway 6a is specifically optimised to refine syncrude at a large scale

TABLE 6: EXTERNAL ENERGY SCENARIO (EE): FUEL YIELDS OF CONSIDERED FACILITIES

Intermediate processing facility						
Pathway	1	2	3	4	5	6a
Feedstock	 Oilseed (Solaris)	 A-molasses	 Industrial off-gas	 Lignocellulosic waste: IAPs and garden waste	 Lignocellulosic waste: IAPs and garden waste	 Lignocellulosic waste: IAPs and garden waste
Intermediate process	Oil extraction	1G ethanol	3G ethanol	2G ethanol	Large-scale GFT-R	Small-scale GFT
Product yield	£/tonne	376	497	179	322	363
	GJ/tonne	13	12	4	8	14
Final processing facility						
Pathway	1	2	3	4	5	6a
Final process	HEFA		Central AtJ			Central refinery (StJ)
SAF (£/tonne)	662		358			897
Gasoline (£/tonne)	438		276			210
Diesel (£/tonne)	12		46			
Finished product from intermediate process (GJ/tonne)	41		25			41
Overall yield from primary feedstock						
Pathway	1	2	3	4	5	6a
SAF (£/tonne)	229	141	51	91	245	293
Gasoline (£/tonne)	151	108	39	70	18	69
Diesel (£/tonne)	4	18	7	12		
Overall fuel yield (GJ/tonne)	14	10	4	6	10	13

and has additional advanced reaction units to convert liquefied petroleum gases (LPGs) to SAF.

- In terms of SAF yield from lignocellulosic material such as IAPs and garden waste, all GFT pathways offer higher SAF yields than converting the material to 2G ethanol and then to SAF via the AtJ process.
- From a resource-utilisation point of view, a small-scale GFT process, as has been modelled for Pathway 6a, is the preferred approach to convert lignocellulosic feedstock such as cleared IAPs and garden waste into SAF.

External energy scenario (EE)

Because sustainable biomass is a very scarce commodity, its use in the production of sustainable hydrocarbons should be prioritised for the supply of green carbon, while external renewable energy and green hydrogen may be used to meet process energy needs and hydrogen requirements. This would in essence “extend” the supply of biomass and the number of sustainable products that can be produced with it. Preliminary simulations carried out under this study show that some increases in the amount of SAF production, with associated decreases in the production cost, may be achieved by supplementing the primary biomass/

off-gas feedstocks with secondary energy sources, in particular renewable electricity and/or green hydrogen. Table 6 shows that introducing external green hydrogen under the EE scenario:

- Makes no difference to SAF yield in the HEFA pathway because the hydrogen requirement comes from reforming the gasoline co-product; therefore, introducing external green hydrogen will increase only the output of the gasoline co-product.
- Leads to a small increase in SAF yield across the AtJ pathways where under the self-sufficiency scenario about 5% of the ethanol is diverted to produce green hydrogen; therefore, when

SELF-SUFFICIENCY SCENARIO (SS): INTERMEDIATE AND FINAL PROCESSING COSTS

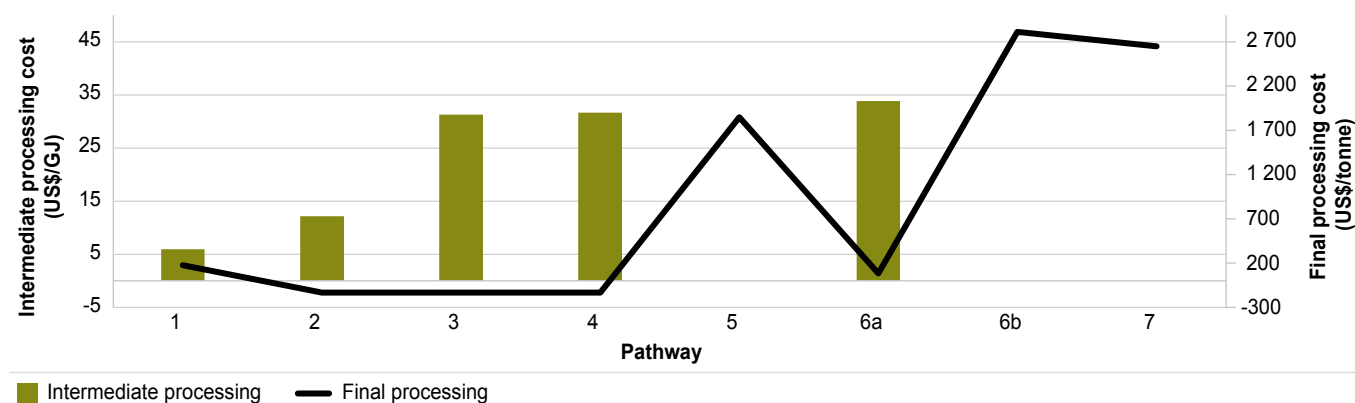


Figure 5: Intermediate and final processing costs of the different SAF production pathways under the self-sufficiency scenario

EXTERNAL ENERGY SCENARIO (EE): INTERMEDIATE AND FINAL PROCESSING COSTS

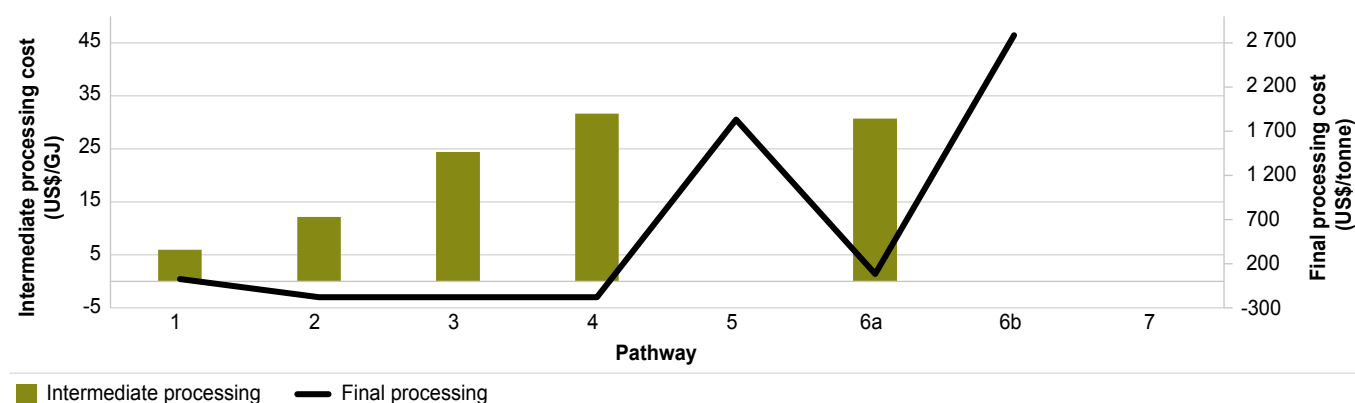


Figure 6: Intermediate and final processing costs of the different SAF production pathways under the external energy scenario

external green hydrogen is used, this additional ethanol becomes available to produce SAF.

- Leads to a very significant increase in SAF yield in the GFT pathways (65–69%). The gasification process steps in the GFT pathways would benefit from the external supply of hydrogen, which avoids the need for the water-gas shift reaction, thereby increasing the available carbon for synthesis and, in turn, the yield of syncrude and SAF per tonne of biomass processed.
- The overall fuel yield increases across all pathways, with the most dramatic increases in the GFT pathways, followed by the HEFA pathway.

Pathways 6b and 7 were excluded from this scenario as they were deemed the least likely to be developed based on the results obtained in the self-sufficiency scenario.

Figure 5 and Figures 6 show the intermediate and final processing costs of the different SAF pathways. With regard to intermediate processing costs, they show that:

- Those of Pathways 1 and 2 are relatively low, since both rely on relatively simple, well-established processes.

- More advanced technologies are linked to higher processing costs; syncrude production for Pathway 5 is expensive due to high capital costs, while ethanol production for Pathway 4 is relatively expensive due to the chemicals and hydrolysing enzymes needed. The relatively low ethanol yield raises the average processing costs for the self-sufficiency scenario (SS) of Pathway 3. This can be improved by introducing external electricity to meet process energy needs.

With regard to the final processing costs, Figure 5 shows that:

- The processing costs for Pathway 1 (HEFA) is US\$175/tonne SAF, and US\$84/tonne SAF for Pathway 6a (Small-scale GFT with centralised refining). The reason for these relatively low costs is that these processes had high selectivity towards SAF production.
- The AtJ facilities (Pathways 2, 3 and 4) reflected a negative processing cost of -US\$133/tonne SAF because this process produces a large amount of gasoline and diesel as co-products (see Table 5). These products can effectively generate enough revenue to pay back capital and non-feedstock operating costs and essentially cross-subsidise the SAF fraction of the output.



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SIX STRONG PATHWAYS TO SAF IN SOUTH AFRICA

This section presents the individual pathways that have been investigated in this study. The cost of SAF production per pathway was calculated as follows:

Cost of SAF production = Feedstock costs + processing costs + transport costs

Processing costs were estimated by the techno-economic modelling. Transport costs were estimated for the distances between feedstock source areas and the locations of intermediate and final processing facilities as determined by the centre-of-gravity analysis.

Pathways 6b and 7 were excluded from this overview as the least attractive SAF pathways based on the outcomes of the techno-economic assessment.³

³ They are included in the technical report.

NOTES

- The optimisation study excluded intermediate facilities situated in areas of insufficient resource density or too far away to supply a final facility. This results in less-than-100% utilisation of the potentially available feedstock resources.
- The intermediate facilities are grouped based on the corresponding final facilities that they supply.
- The direction of intermediate product supply is indicated by the flow maps also showing final facility locations.
- Overlapping markers indicate multiple facilities in the same region.
- Bubble size are correlated with plant capacities.
- The SAF facilities that could be built under each pathway are then ranked based on their SAF production cost.
- Total potential SAF production across all facilities has been aggregated starting from facilities producing the cheapest SAF to the more expensive ones, calculating the weighted average cost of SAF per litre along the way.

HEFA PROCESSING FROM SOLARIS SEEDS



Seeds from sustainably produced Solaris tobacco are collected and transported to an oil-extraction facility using superlink tautliners. From there, tankers transport the vegetable oil to a refinery where it is processed into SAF (and co-products) via the Hydroprocessed Esters and Fatty Acids (HEFA) process.

RESULTS OF OPTIMISATION ANALYSIS

Intermediate facilities: 27

Final facilities: 11

Solaris seed used: 92% (4,8 million tonnes per annum)

PRODUCTION COSTS AND VOLUMES

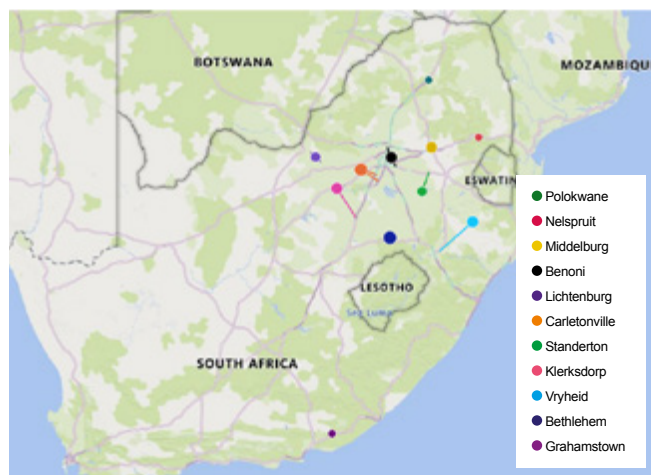
Cost component ranking:

1. Feedstock (> 60%)
2. Intermediate processing (25%)
3. Final processing (< 10%)

SAF OUTPUT AND PRODUCTION COST RANGES

	Max output across all facilities	Weighted average production cost across all facilities	Lowest cost facility	Highest cost facility
Self-sufficiency scenario (SS)	1 090 Mt/a	R36/ℓ	R34/ℓ	R50/ℓ
External energy scenario (EE)	1 090 Mt/a	R34/ℓ	R33/ℓ	R46/ℓ

FACILITY LOCATIONS



● Benoni ● Bethlehem ● Carletonville ● Grahamstown ● Klerksdorp ● Lichtenburg ● Middelburg ● Nelspruit

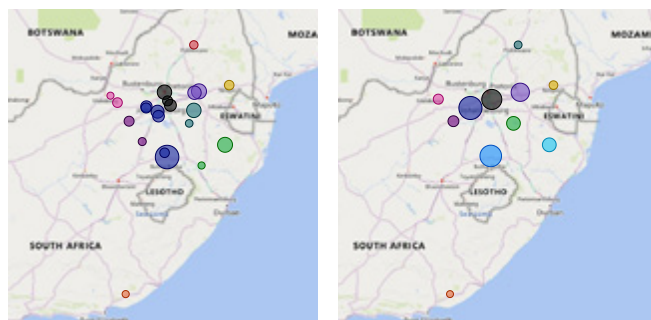


Figure 7: Pathway 1 – Flow map (above), intermediate facility (left) and final facility locations (right)

1 CUMULATIVE SAF POTENTIAL, AVERAGE AND MARGINAL PRODUCTION COSTS

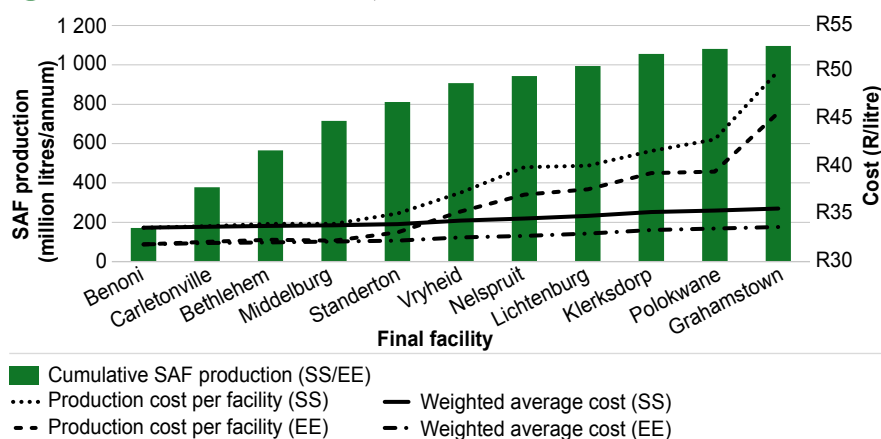
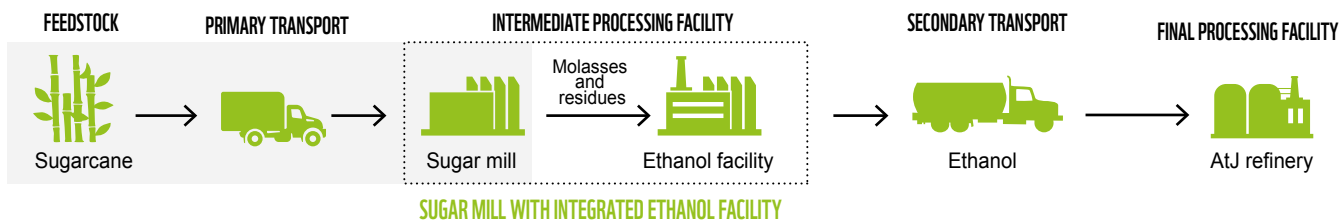


Figure 8: Pathway 1 – Cumulative SAF production potential, average and marginal production costs (per facility)

Although introducing external green hydrogen into the SAF facility does not increase the SAF yield, it does increase the production of the gasoline co-product. Greater revenue from the sale of the gasoline co-product could decrease the average SAF cost compared to the self-sufficiency scenario.

1G ALCOHOL-TO-JET



A-molasses, a co-product of sugar refining, is converted to 1G ethanol at existing sugar mills. The ethanol is then transported with tankers to independent alcohol-to-jet (AtJ) facilities where it is converted to SAF and co-products.

RESULTS OF OPTIMISATION ANALYSIS

Intermediate facilities: 14 (existing sugar mills)

Final facilities: 4

A-molasses used: 100% (2,3 Mt per annum)

PRODUCTION COSTS AND VOLUMES

Cost component ranking:

1. Feedstock (> 60%)
2. Intermediate processing (40%)

Final processing can be cross-subsidised by the sale of co-products.

SAF OUTPUT AND PRODUCTION COST RANGES

	Max output across all facilities	Weighted average production cost across all facilities	Lowest cost facility	Highest cost facility
Self-sufficiency scenario (SS)	309 Mt/a	R31/l	R30/l	R32/l
External energy scenario (EE)	328 Mt/a	R29/l	R28/l	R30/l

FACILITY LOCATIONS



● Gledhow ● Komatipoort ● Sezela ● Umfolozi

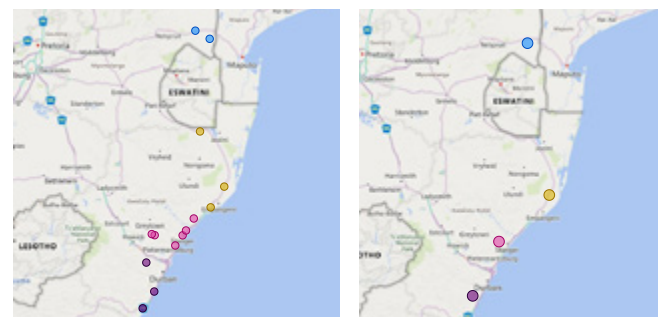


Figure 9: Pathway 2 – Flow map (above), intermediate facility (left) and final facility locations (right)

2 CUMULATIVE SAF POTENTIAL, AVERAGE AND MARGINAL PRODUCTION COSTS

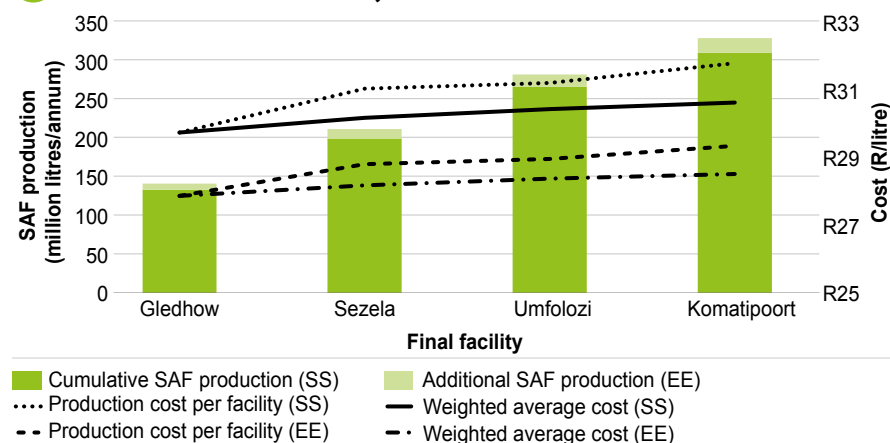
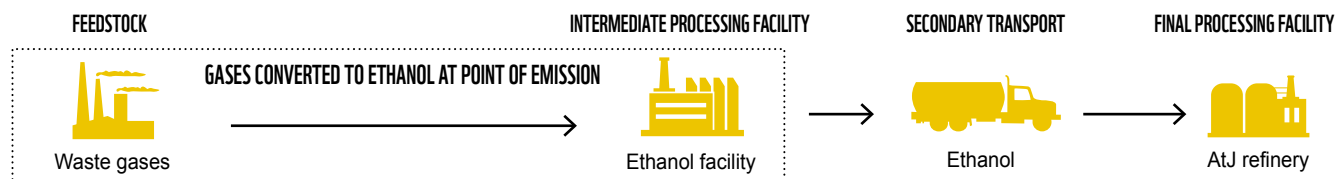


Figure 10: Pathway 2 – Cumulative SAF production potential, average and marginal production costs (per facility)

Introducing external green hydrogen to the SAF production process results in a higher SAF output (+ 6%).

3G ALCOHOL-TO-JET



Industrial off-gas from steel and ferroalloy industrial processes is captured to produce 3G ethanol at the same site. The ethanol is then transported by tankers to an AtJ facility, where it is processed into SAF and co-products.

RESULTS OF OPTIMISATION ANALYSIS

Intermediate facilities: 9 (out of 15 industrial sites producing off-gas)

Final facilities: 1

Waste gases utilised: 68% (2,26 million tonnes per annum)

PRODUCTION COSTS AND VOLUMES

Cost component ranking:

1. Intermediate processing (100%)

Final processing can be cross-subsidised by the sale of co-products.

SAF OUTPUT AND PRODUCTION COST RANGES

	Max output across all facilities	Weighted average production cost across all facilities
Self-sufficiency scenario (SS)	82 309 Mt/a	R51/ℓ
External energy scenario (EE)	116 309 Mt/a	R38/ℓ

FACILITY LOCATIONS

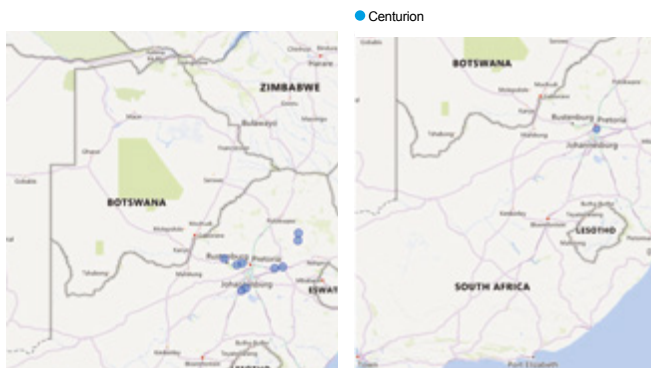
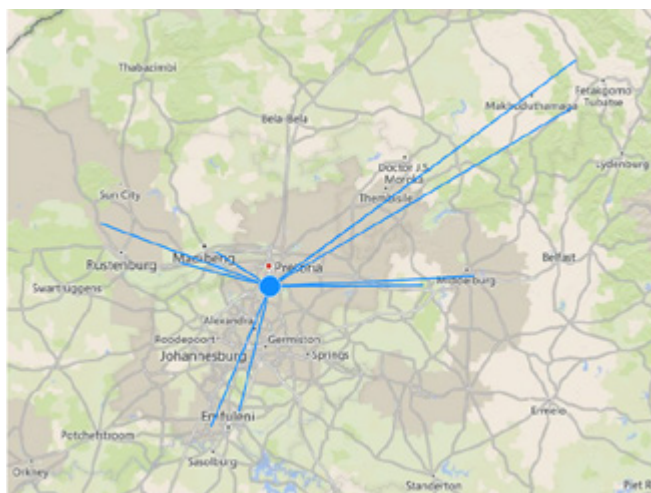
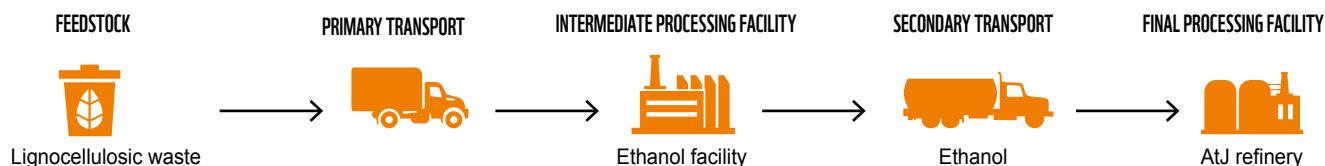


Figure 11: Pathway 3 – Flow map (above), intermediate facility (left) and final facility locations (right)

Pathway 3 shows the greatest variation between the self-sufficiency and the external energy scenarios.

2G ALCOHOL-TO-JET



Lignocellulosic biomass (IAPs and garden waste) can be used to produce advanced fuels through several processes. In this case, it is collected and chipped at the source and transported with side-tipper trucks to facilities where it is converted to 2G ethanol via the hydrolysis-fermentation route. The ethanol is then transported in tankers to AtJ refineries where it is converted to SAF and co-products.

RESULTS OF OPTIMISATION ANALYSIS

Intermediate facilities: 29

Final facilities: 10

IAPs utilised: 94% (202 million tonnes over a 20-year period, or 10,1 million tonnes per annum)

PRODUCTION COSTS AND VOLUMES

Cost component ranking:

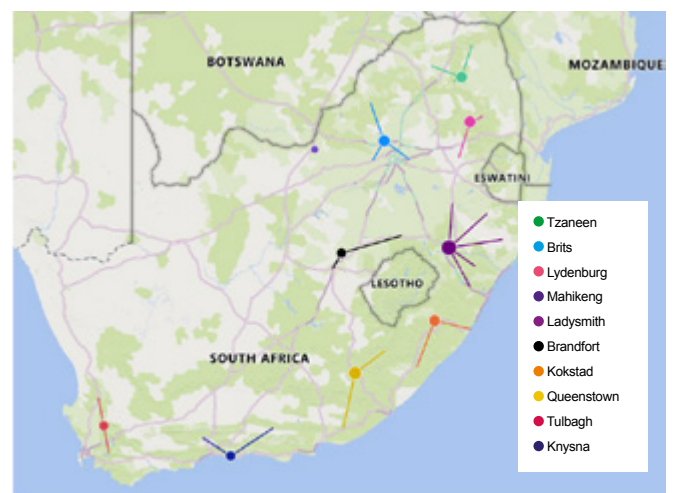
1. Intermediate processing (65%)
2. Feedstock (30%)
3. Primary transport (6%)

Final processing can be cross-subsidised by the sale of co-products.

SAF OUTPUT AND PRODUCTION COST RANGES

	Max output across all facilities	Weighted average production cost across all facilities	Lowest cost facility	Highest cost facility
Self-sufficiency scenario (SS)	900 Mt/a	R59/l	R55/l	R66/l
External energy scenario (EE)	935 Mt/a	R55/l	R52/l	R62/l

FACILITY LOCATIONS



● Brandfort ● Brits ● Knysna ● Kokstad ● Ladysmith ● Lydenburg ● Mahikeng ● Queenstown ● Tulbagh ● Tzaneen

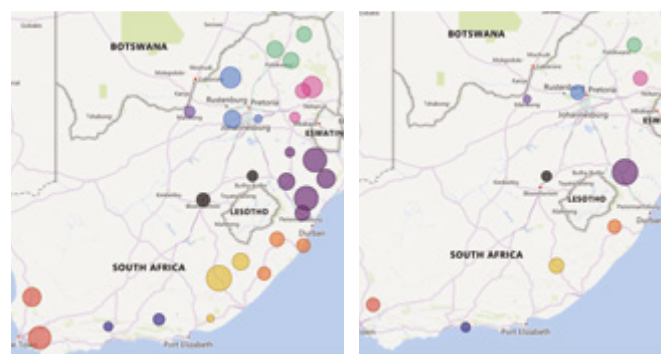


Figure 12: Pathway 4 – Flow map (above), intermediate facility (left) and final facility locations (right)

4 CUMULATIVE SAF POTENTIAL, AVERAGE AND MARGINAL PRODUCTION COSTS

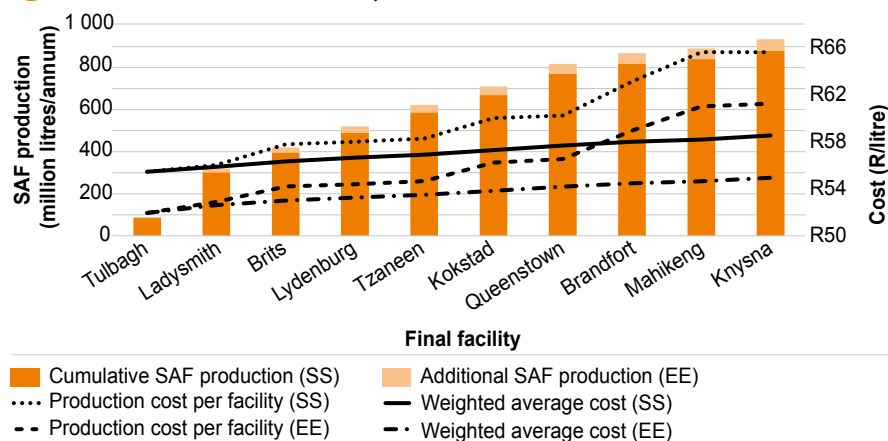


Figure 13: Pathway 4 – Cumulative SAF production potential, average and marginal production costs (per facility)

The relatively high cost of intermediate processing is due to the high cost of capital required for the hydrolysis-fermentation technology, and the relatively lower cost of feedstock (compared to Pathways 1 and 2).

LARGE-SCALE GASIFICATION, FISCHER-TROPSCH (GFT) AND INTEGRATED REFINING



The same lignocellulosic biomass as for Pathway 4 (IAPs and garden waste) is chipped and transported with side-tipper trucks to an integrated (combined) facility. It is then converted to SAF (and co-products) via the Fischer-Tropsch – Synthetic Paraffinic Kerosene (FT-SPK) pathway.

RESULTS OF OPTIMISATION ANALYSIS

Integrated (combined) facilities: 10

IAPs utilised: 97% (209 million tonnes of biomass over 20 years, or 10,5 million tonnes per annum)

PRODUCTION COSTS AND VOLUMES

Cost component ranking:

1. (Integrated/combined) processing (60%)
2. Feedstock (30%)
3. Transport (10%)

SAF OUTPUT AND PRODUCTION COST RANGES

	Max output across all facilities	Weighted average production cost across all facilities	Lowest cost facility	Highest cost facility
Self-sufficiency scenario (SS)	1 530 Mt/a	R35/ℓ	R32/ℓ	R43/ℓ
External energy scenario (EE)	2 610 Mt/a	R33/ℓ	R31/ℓ	R39/ℓ

FACILITY LOCATIONS

Brandfort Carletonville Knysna Ladysmith Nelspruit Polokwane Port Shepstone
Queenstown Tulbagh Ulundi

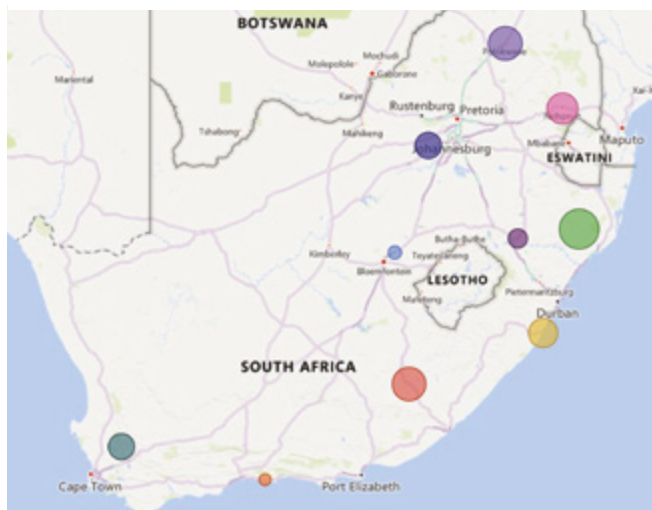


Figure 14: Pathway 5 – Combined facility locations

5 CUMULATIVE SAF POTENTIAL, AVERAGE AND MARGINAL PRODUCTION COSTS

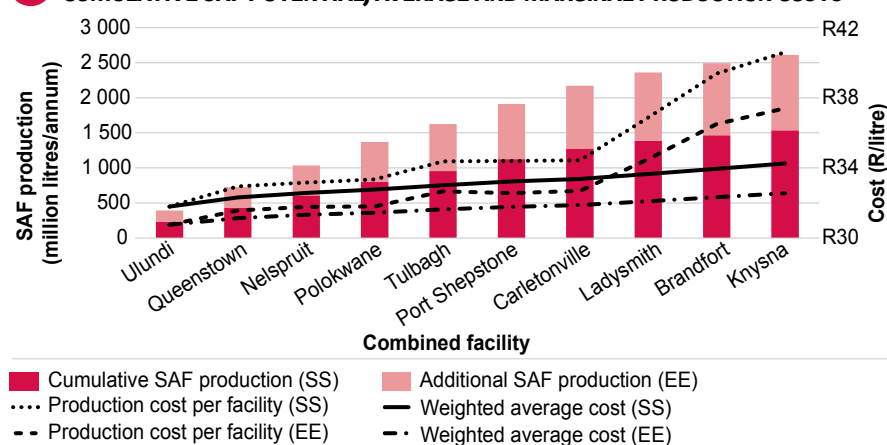
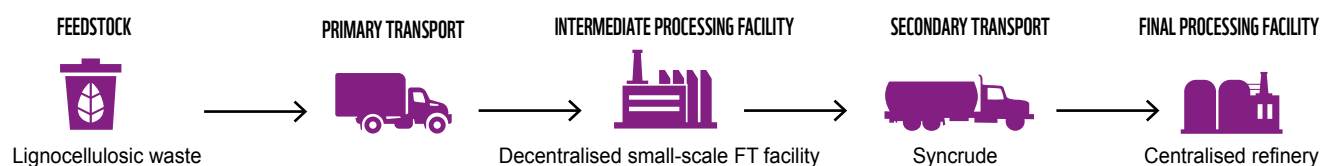


Figure 15: Pathway 5 – Cumulative SAF production potential, average and marginal production costs (per facility)

Introducing external green hydrogen increases the SAF yield considerably as it removes the requirement of the water-gas shift reactor. The role of this reactor is to deplete the carbon content of the syngas (synthetic gas) to provide hydrogen for the Fischer-Tropsch process. Using green hydrogen produced from renewable energy means that there is about 70% more carbon available to produce synerude and hence SAF.

SMALL-SCALE GASIFICATION, FISCHER-TROPSCH (GFT) AND CENTRALISED REFINERY



Pathway 6a is also based on lignocellulosic biomass (IAPs and garden waste). The biomass is transported in chipped form by side-tipper trucks to standalone gasification and Fischer-Tropsch facilities where it is processed into syncrude. This syncrude is then transported with tankers to a separate, centralised refinery to produce Fischer-Tropsch – Synthetic Paraffinic Kerosene plus Aromatics (FT-SPK/A) SAF.

RESULTS OF OPTIMISATION ANALYSIS

Intermediate facilities: 29

Final facilities: 5

IAPs utilised: 94% (202 million tonnes over a 20-year period, or 10,1 million tonnes per annum)

PRODUCTION COSTS AND VOLUMES

Cost component ranking:

1. Primary/intermediate processing (66–80%)
2. Feedstock (27%)
3. Primary transport (5%)

SAF OUTPUT AND PRODUCTION COST RANGES

	Max output across all facilities	Weighted average production cost across all facilities	Lowest cost facility	Highest cost facility
Self-sufficiency scenario (SS)	1 746 Ml/a	R35/ℓ	R34/ℓ	R37/ℓ
External energy scenario (EE)	2 964 Ml/a	R32/ℓ	R31/ℓ	R33/ℓ

FACILITY LOCATIONS

● Ga-Nkoana ● Rustenburg ● Greytown ● Queenstown ● Montagu



● Ga-Nkoana ● Greytown ● Montagu ● Queenstown ● Rustenburg

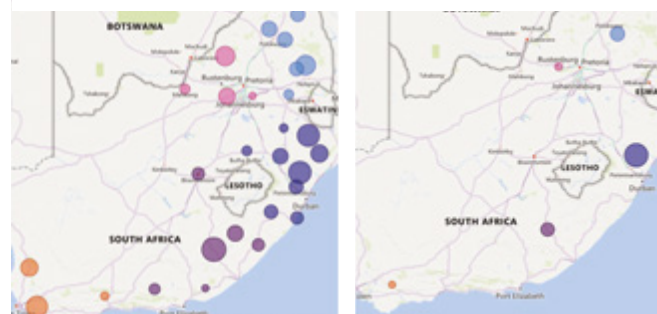


Figure 16: Pathway 6a – Flow map (above), intermediate facility (left) and final facility locations (right)

6a CUMULATIVE SAF POTENTIAL, AVERAGE AND MARGINAL PRODUCTION COSTS

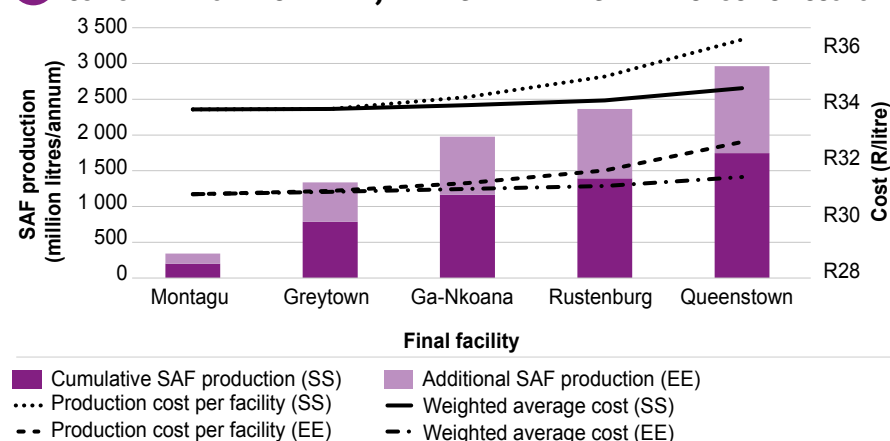


Figure 17: Pathway 6a – Cumulative SAF production potential, average and marginal production costs (per facility)

The contribution of the intermediate processing costs is high because Fischer-Tropsch technology is relatively more expensive than the hydrolysis-fermentation technology used in the 2G AtJ pathway (Pathway 4). Although the total secondary transport distance was longer for Pathway 6a than for Pathway 4 (155 km vs 103 km per one-way trip on average), the contribution to total SAF cost was similar at 1%.

AVERAGE SAF PRODUCTION COST AND SAF POTENTIAL ACROSS PATHWAYS

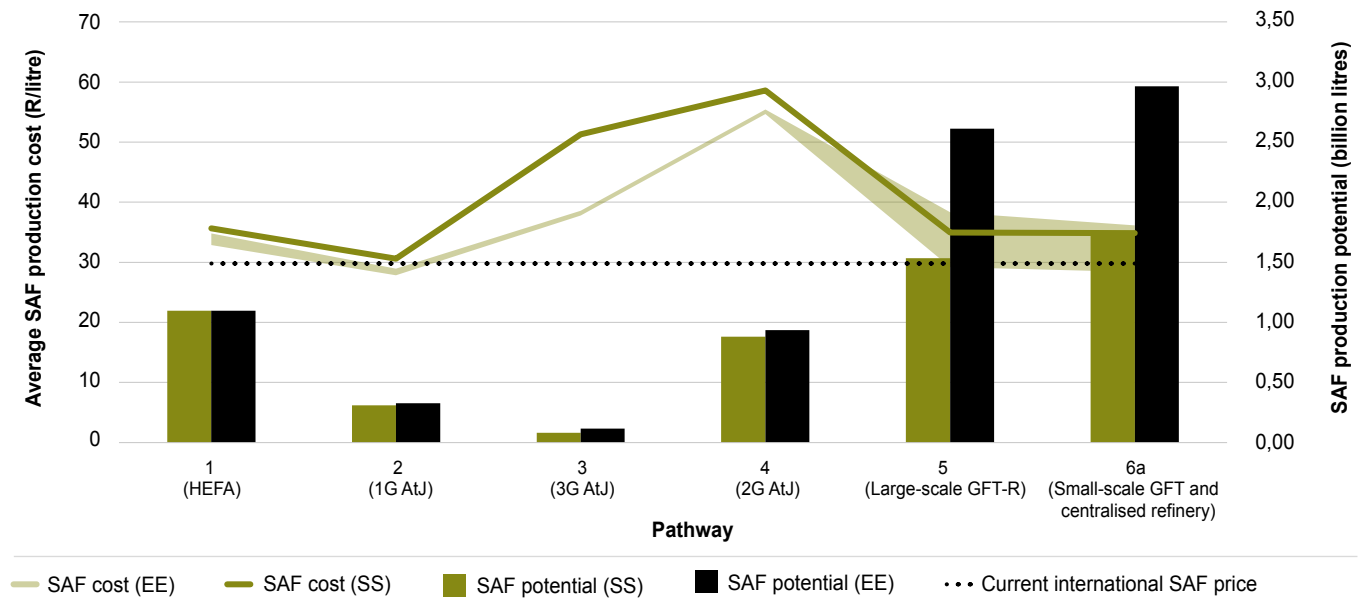


Figure 18: Average SAF production cost per litre and total SAF production potential per pathway

PATHWAYS COMPARISON

After analysing individual pathways, it is useful to compare them with one another on the same metrics. Figure 18 compares the SAF production pathways with regard to production potential and cost effectiveness for the self-sufficiency and external energy scenarios.

The upper part of the band for SAF cost under the external energy scenario represents the case for a green hydrogen cost of US\$4,4/kg, whereas the lower band is for a cost of US\$2/kg.⁴

The comparison shows that:

- Pathway 2 is the most cost-efficient with an average production cost of R31/ℓ under the self-sufficiency scenario, and R29/ℓ if supplemented with externally produced green hydrogen. Pathways 1, 5 and 6a could produce SAF at a slightly higher cost of approximately R28–R38/ℓ, depending on the price of green hydrogen.
- As already shown in Table 6, introducing externally produced green hydrogen has a different level of impact on SAF production potential per pathway. It makes no difference to Pathway 2 (HEFA), but increases the SAF yield by almost 40% for the GFT pathways (Pathways 5 and 6a), from 1,5 and 1,7 billion litres in the self-sufficiency scenario, to 2,6 and nearly 3 billion litres.
- The direction of impact of introducing externally produced green hydrogen on the production cost of SAF also differs per pathway:
 - For the HEFA and AtJ pathways, it will immediately lower the cost of SAF produced by R1–R4/ℓ for the assumed green hydrogen costs of US\$2–US\$4,4/kg.
 - For Pathway 3, it has a dramatic reduction in SAF production cost of about R13/ℓ on average.
 - For the GFT pathways (Pathways 5 and 6a), it ranges from increasing to decreasing the production cost of SAF. Assuming a “current” hydrogen price of US\$4,4/kg, the GFT pathways produce SAF that is R1–R4/ℓ more expensive than that produced under the self-sufficiency scenario. At a “near-term” (by 2025) (IHS Markit, 2021) hydrogen price of US\$3/kg, GFT SAF becomes R2–R3/ℓ cheaper than that produced under the self-sufficiency scenario. At a “long-term” (post-2035) (IHS Markit, 2021) hydrogen price of US\$2/kg, GFT SAF becomes R5–R7/ℓ cheaper than under the self-sufficiency scenario.
- Of the pathways and scenarios considered, only SAF produced via Pathway 2 is cost-comparable with the current prevalent international SAF price, based on the assumptions included in this study. The GFT-based pathways become cost-comparable at green hydrogen prices closer to the US\$2/kg mark. Other factors affecting SAF production costs are discussed in the sensitivity analysis on the next page.

⁴ The figures for the six pathways in the previous sections were based on a mid-point estimate of external green hydrogen cost.

EFFECTS OF FEEDSTOCK COST AND WEIGHTED AVERAGE COST OF CAPITAL ON FINAL SAF COST

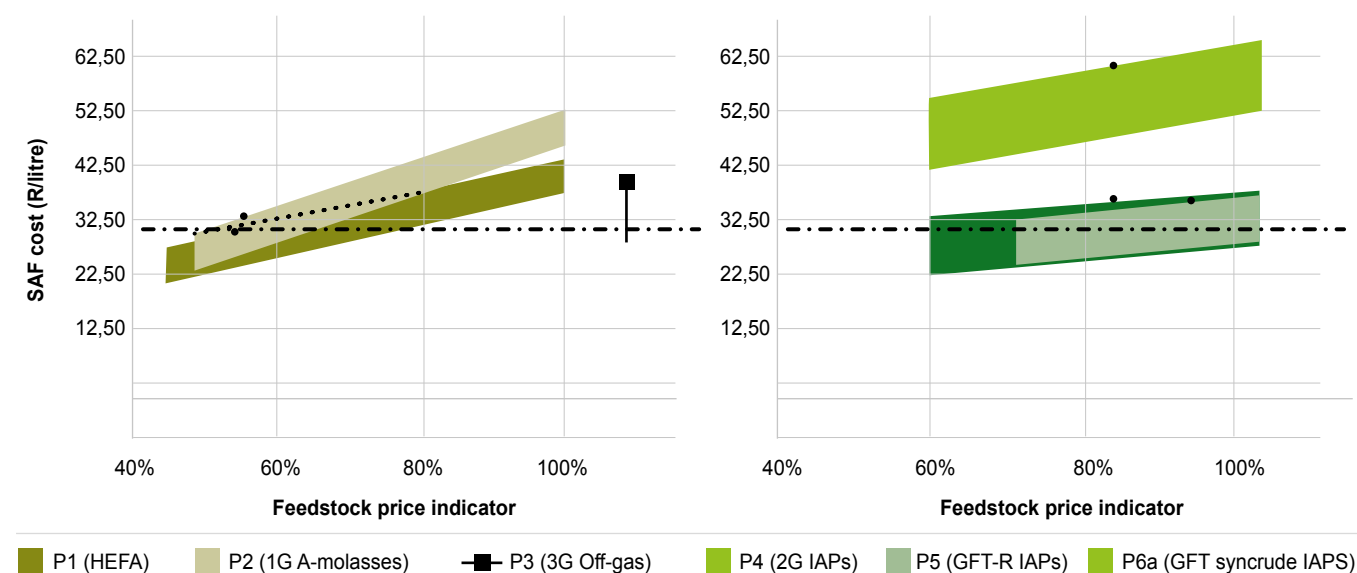


Figure 19: Effects of feedstock cost (x-axis) and weighted average cost of capital (y-axis) on final SAF cost

SENSITIVITY ANALYSIS

As with any industrial process, the SAF production cost will be affected by a number of variables. To understand the impact of two key inputs into the process – feedstock and capital – a sensitivity analysis of different costs for both inputs was carried out for the self-sufficiency scenario for facilities with the baseline scales considered in Table 1.

Figure 19 shows the effects of different feedstock costs and the weighted average cost of capital (WACC) on the production cost of SAF. The slope of the bands shows the impact of the different normalised feedstock prices (x-axis) and the breadth of the band the lower and upper WACC considered (10% and 20%). The black dots on the upper edge of the bands show the reference values for each of the pathways presented in the previous section. The dotted line indicates the current international SAF price of about R30/ℓ.⁵

The sensitivity analysis shows that:

- The steeper the band, the higher the sensitivity of the SAF price to feedstock cost. Unsurprisingly, the biggest effect of variation in feedstock price is seen for Pathways 1 and 2, where feedstock costs represent the largest share of total production costs. For Solaris seed-based SAF, a 17% reduction in the price of Solaris seed from the 5-year average reference price (seen in Figure 19 as a 10 percentage point reduction on the x-axis) would bring the HEFA-based SAF production cost down to R30/ℓ, making it competitive with the current international SAF price.
- By contrast, feedstock costs are a smaller constituent of the overall production costs of 2G fuels; therefore, for Pathways 4, 5 and 6a, a relatively smaller effect of feedstock price variation on SAF production cost can be observed.

- The effect of a change in WACC is prominent for all pathways, but more so for the capital-intensive ones (Pathways 3, 4, 5 and 6a). Lowering the cost of capital from 20% to between 13% and 15% would probably lead to the production of competitive SAF through these pathways, except Pathway 4, compared to the reference scenario.

What the sensitivity analysis also implies is that there is less risk from feedstock price volatility for the advanced fuel pathways (Pathways 3, 4, 5 and 6a) once the initial capital is paid off. However, the challenge with these pathways lies in raising the high capital investment required. The technology risk linked to their relative novelty generally also means higher cost of capital.

Policy instruments and financial measures that achieve lower WACC, such as capital subsidies and concessional finance, would go a long way in supporting the production of SAF in South Africa, especially from lignocellulosic feedstocks like IAPs and garden waste. Long-term purchase agreements or financial support mechanisms to producers to lower feedstock prices would greatly support crop-based SAF.

Other factors not explicitly addressed by this sensitivity analysis will also play a role in the final price of SAF that is produced in South Africa. As mentioned before, the cost of green hydrogen plays a role, especially for the GFT-based pathways, where a hydrogen price of US\$3/kg results in cheaper SAF compared to the reference self-sufficiency scenario. A price of US\$2/kg pushes it towards the current international benchmark price, if everything else is equal to the reference scenario.

⁵ 2021 Price estimate from S&P Global Platts.

Furthermore, the International Energy Agency Bioenergy (IEA Bioenergy) estimates that production costs of GFT processes could decline by up to 25% (Brown et al., 2020) in the medium term. This implies that a SAF cost of R35/ℓ and R32/ℓ for Pathway 6a could decline to R26/ℓ and R24/ℓ in the self-sufficiency and the external energy scenario, respectively.

Finally, premiums for green co-products (as opposed to selling the co-products at prices of their fossil-fuel equivalents) can also affect SAF pricing, with the largest effect expected for the AtJ scenarios (Pathways 2, 3 and 4).

GREENHOUSE GAS REDUCTION POTENTIAL

The GHG intensity of each pathway under the self-sufficiency scenario was calculated following the global Roundtable on Sustainable Biomaterials (RSB) standard, EU RED II and CORSIA methodologies. The calculations show that:

- Most pathways achieved at least a 70% emissions reduction compared to conventional fossil-based jet-fuel across all methodologies (although the comparator differs slightly per methodology). Exceptions are Pathway 1 (HEFA) if land-use change is considered, in which case it achieves a 45% GHG saving; and Pathway 3 if Eskom grid electricity is used, in which case it achieves only a 29% GHG saving based on the CORSIA calculation methodology. However, because the CORSIA methodology only requires GHG savings of 10%, such SAF would still be eligible for certification and use in the CORSIA scheme.
- Among the lignocellulosic pathways, Pathway 4 resulted in the lowest emissions savings. The GFT-based pathways all saved more than 96% emissions under all three RSB methodologies, demonstrating the highest emissions savings potential in the self-sufficiency scenario.

It is important to note that the baseline assumption was that IAPs are a waste product with no GHG footprint. However, it must be considered that, notwithstanding their negative impacts on the ecosystem, IAPs are a carbon sink and their removal will result in carbon loss. This could be compensated for or not, depending on the land use following the eradication of IAPs.

Figure 20 shows the overall GHG emissions savings for the lignocellulosic pathways by land-use type after clearing for a specific area in the Eastern Cape following the EU RED II methodology. The dotted line is the emissions savings threshold for the applicable standard. SAF produced via Pathways 5, 6a and 6b would also be compliant with the minimum GHG savings criteria of this standard for all the considered land uses after clearing, due to the low life-cycle emissions associated with these pathways. In fact, these pathways resulted in GHG savings of over 100% when IAPs were replaced by dense forest and thicket, because these land-use types have a higher carbon stock than IAPs, leading to a net gain in carbon stock. Pathway 4 would not meet the minimum GHG savings threshold if, after clearing, the land is converted to cropland, pastures, grassland or even fynbos.

While this assessment is specific for the Eastern Cape province, the direction of the impacts of different land uses will be the same for all IAP-based SAF and the magnitude will be similar for areas with similar IAP invasion density. This analysis underscores that to maximise the GHG savings of SAF produced from cleared IAPs, the clearing should ideally be followed by the rehabilitation of indigenous vegetation to restock the carbon in the landscape as swiftly as possible.

GHG EMISSIONS SAVINGS BY LAND USE AFTER CLEARING

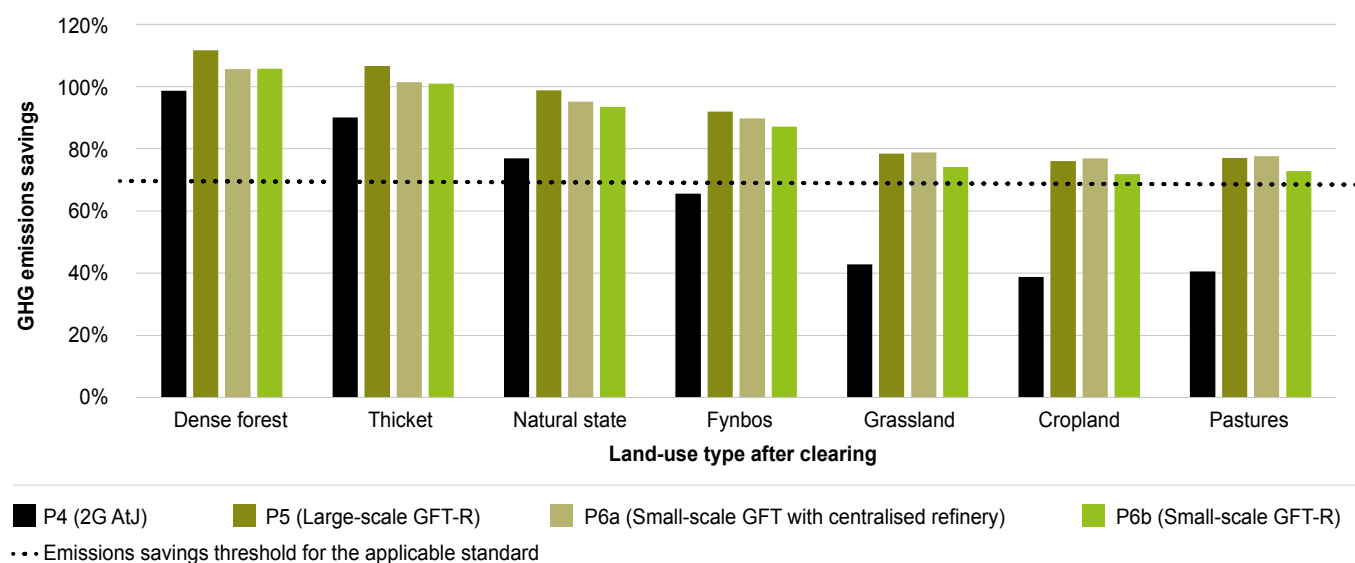


Figure 20: Overall GHG emissions savings by land-use type after clearing, for the EU RED II standard



LIMITATIONS TO THE STUDY

The results presented in this report hinge on a number of key assumptions that have not been tested in the “real world”:

- First, it was assumed that all the crop/waste biomass or industrial off-gas available in a particular region will be available for SAF production. In reality, much of the biomass will be allocated to competing applications, meaning that only a portion of the total resource as assessed in this report will be available for commercial SAF production.
- Since the study focuses on a high-level, nationwide scale, no routing analysis was done for lignocellulosic biomass. For individual supply chains, it is recommended that a detailed primary transport analysis be carried out to further optimise this cost component in order to reduce the number of trips and less-than-truckloads trips, i.e. where the full carrying capacity of the vehicle is not used.
- Finally, this study assumes that all the lignocellulosic pathways (Pathways 4 to 7) are mutually exclusive, i.e. all the lignocellulosic biomass will either be used to produce SAF via the AtJ, hydropyrolysis or one of the Fischer-Tropsch routes. However, in practice it is likely that due to industry competition, there will be different project developers, with each one implementing a different SAF technology and/or biomass supply network.

A BLUEPRINT FOR DEVELOPING A SAF INDUSTRY IN SOUTH AFRICA

The choice of pathways and the degree of their development will depend on decisions made early in the process. Balancing government and investor priorities will determine whether the focus falls on job creation or low-cost production.



Based on the previous sections, there is clearly significant potential, and a strong case, for the production of SAF in South Africa. Considering the multitude of options, which pathways or facilities are the low-hanging fruit that could pave the way for this emerging green sector? What type of facilities should be built, and where, to maximise SAF production and the development opportunities that come along with a new industrial sector?

First, one needs to consider the best way in which to utilise a resource where several options exist. Since the lignocellulosic waste-based pathways (Pathways 4 to 7) compete for the same feedstock (IAPs and garden waste), they are mutually exclusive. A multi-criteria analysis was therefore carried out to select the preferred production pathway for this feedstock. The alternative pathways were evaluated on a techno-economic and socio-economic basis for the self-sufficiency scenario. Pathway 6a emerged as the best choice for processing IAPs and garden waste into SAF, offering the highest SAF yield and only marginally smaller employment creation potential compared to Pathway 5 per unit of investment.

Considering Pathway 6a as the likely investor-preferred pathway for producing SAF from IAPs and garden waste, if the SAF production potential in South Africa were to be

SELF-SUFFICIENCY SCENARIO (SS): SAF COST PER FACILITY AND CUMULATIVE SAF POTENTIAL

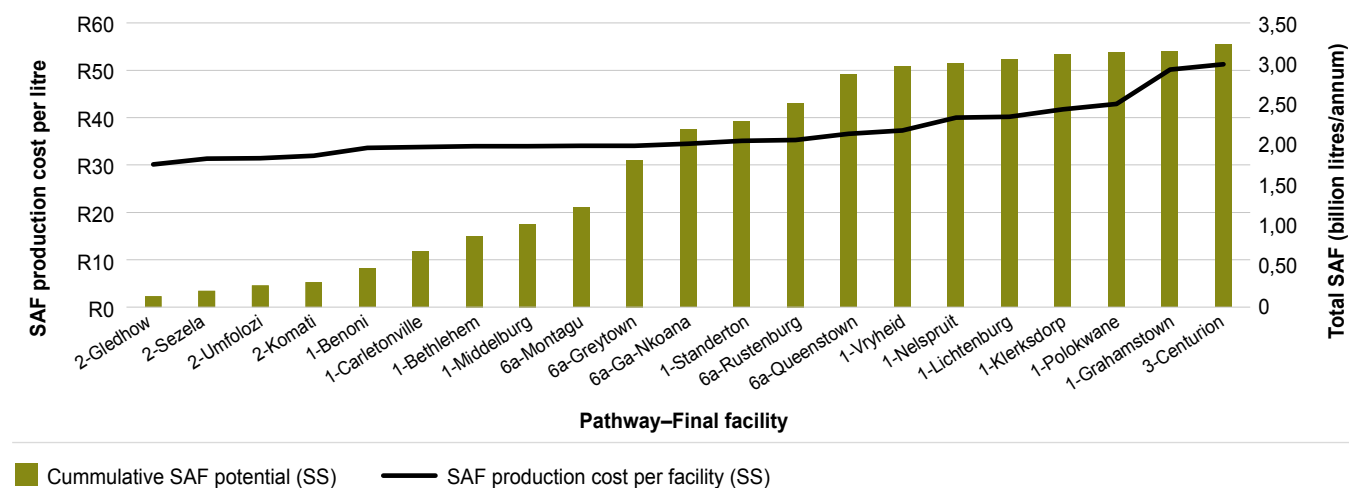


Figure 21: Proposed SAF production facilities in South Africa, cumulative production output and cost for the self-sufficiency scenario

EXTERNAL ENERGY SCENARIO (EE): SAF COST PER FACILITY AND CUMULATIVE SAF POTENTIAL

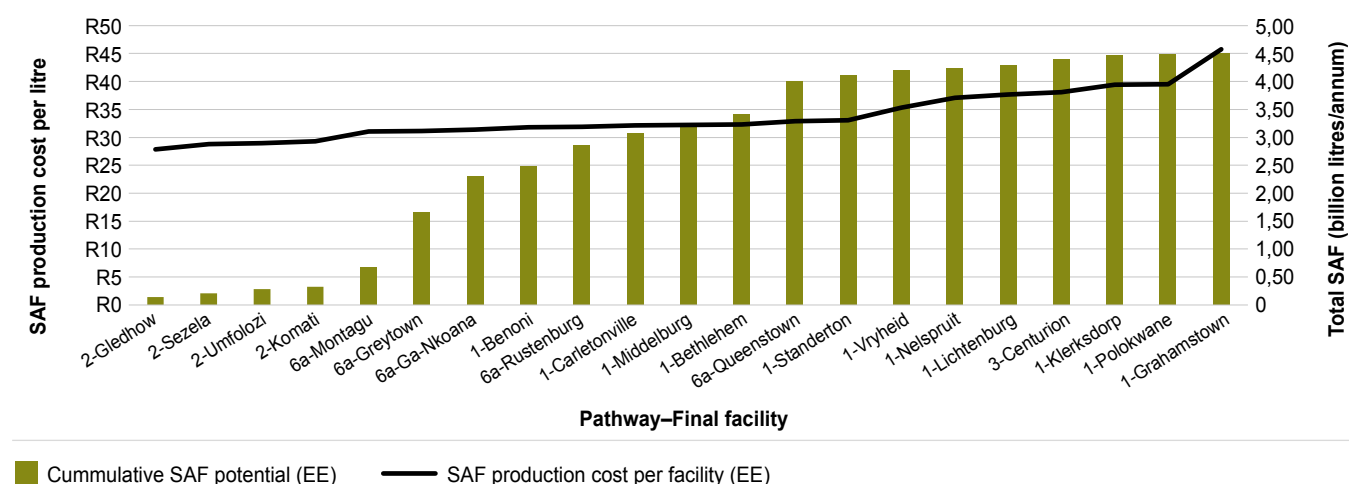


Figure 22: Proposed SAF production facilities in South Africa, cumulative production output and cost for the external energy scenario

realised in the most cost-efficient way, it would require the facilities shown in Figures 21 and 22. These pathway-final facility combinations are ranked based on SAF production cost, from the lowest to the highest. A comparison of the two figures shows how introducing externally produced green hydrogen changes the ranking of facilities.

The proposed locations of the final SAF facilities are shown in Figure 23, with the size of the dots corresponding to the volume of SAF output under the self-sufficiency scenario. The largest facility, in Greytown, KwaZulu-Natal, is a decentralised lignocellulosic SAF refinery (Pathway 6a), with a potential annual SAF output of 585 million litres

for the self-sufficiency and 993 million litres for the external energy scenario. In comparison, the HEFA facility in Bethlehem, Free State has a potential annual SAF output of 189 million litres (for both the self-sufficiency and the external energy scenarios).

As anticipated, most of the SAF facilities are located in the north and north-eastern parts of the country, which is where most of the feedstock base is located. The 1G AtJ facilities are located in the sugarcane-growing regions.

Since the north-eastern regions are also the dominant coal-mining regions in the country, the SAF facilities provide an opportunity for alternative

By using the most efficient processing technologies, South Africa could produce approximately 3,2–4,5 billion litres of SAF per annum in the self-sufficiency and the external energy scenario, respectively. This is enough to meet South Africa's potential demand for SAF of 1,2 billion litres per annum (under current SAF-blending limits) and still export 2–3,3 billion litres per annum.

LOCATIONS OF PROPOSED SAF FACILITIES IN SOUTH AFRICA

● P1 (HEFA) ● P2 (1G AtJ) ● P3 (3G AtJ) ● P6a (Small-scale GFT and centralised refinery)

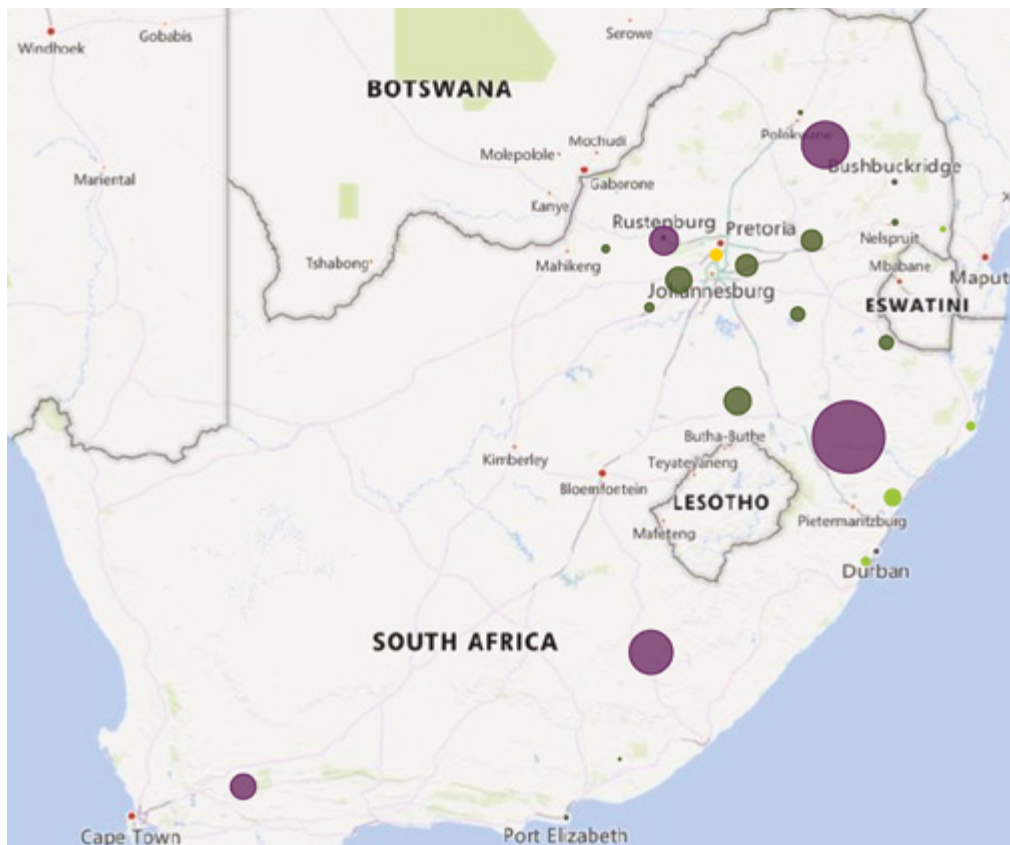


Figure 23: Locations of proposed final SAF facilities in South Africa per production pathway

employment for those affected by the energy transition away from coal. Another advantage is that most of these facilities are close to OR Tambo International Airport, which accounts for approximately 65% of the total jet-fuel consumption in the country (Maseko, 2009). OR Tambo is also the most polluting airport in Africa in terms of flight GHG emissions by departure (Pickard and Gençsü, 2021); therefore, using SAF at this airport will significantly reduce the GHG emissions of the continent's aviation sector.

Other proposed SAF facilities are also close to major airports. The Montagu SAF facility (output of 202 million and 343 million litres per annum for the self-sufficiency and the external energy scenario, respectively) can potentially supply Cape Town International Airport. Additional SAF required for Cape Town International Airport and SAF for George Airport could be supplied by the SAF facility (Pathway 6a) in Queenstown (353 million and 599 million litres per annum

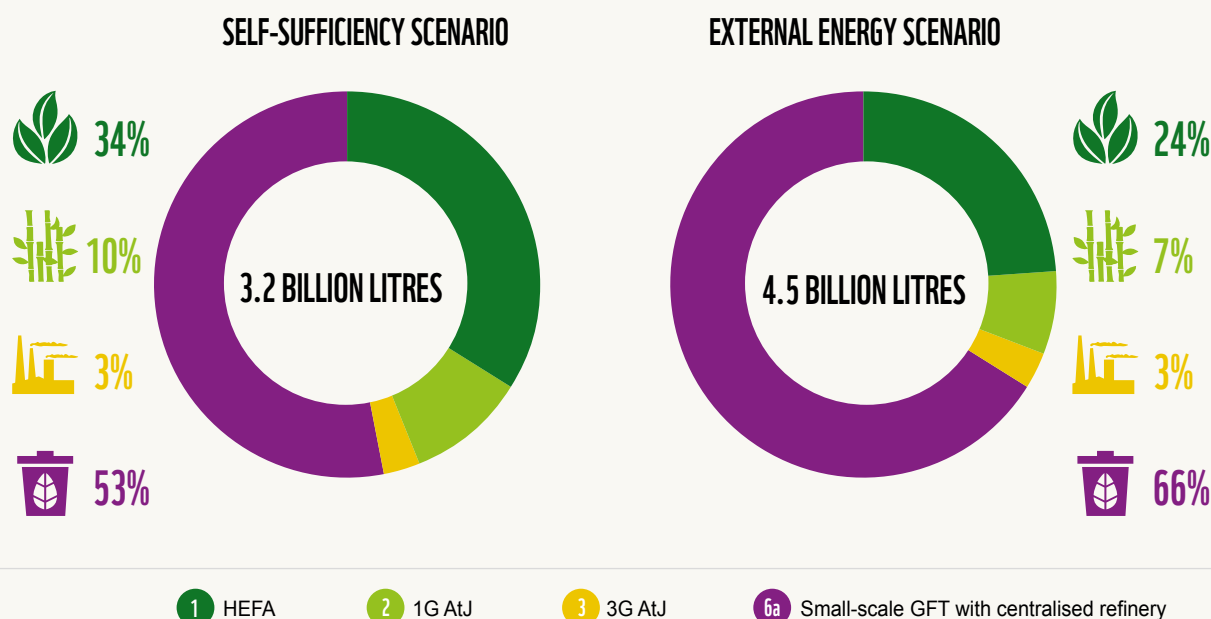
for the self-sufficiency and the external energy scenario, respectively). There are a number of facilities that could supply King Shaka International Airport, such as the 1G AtJ facilities in KwaZulu-Natal and the Greytown lignocellulosic facility. Proximity to airports also presents a good opportunity for SAF to be sold via SAF certificates (WEF, 2021), while facilities closer to the coast are obvious candidates for the export market.

There are numerous arguments in favour of the 1G AtJ SAF production (Pathway 2) in South Africa, which uses sugarcane A-molasses as feedstock. It could be the quickest and cheapest way to achieve initial SAF quantities in South Africa due to the existence of established sugarcane supply chains. Jobs that might otherwise be lost by shrinkage in the sugar industry would be preserved by implementing this pathway. It is competitive even in the high hydrogen price scenario (US\$4,4/kg) and thus could be a hydrogen sink for the initial green hydrogen projects. Even

though its production potential is smaller compared to other pathways (300 million litres per annum), Pathway 2 could still meet 10% of the total jet-fuel demand in South Africa at a price of approximately R30/ℓ and R28/ℓ under the self-sufficiency and the external energy scenario, respectively, which is competitive with current SAF prices on the international market (approximately R30/ℓ).

Similar to the 1G AtJ, the 3G AtJ SAF of Pathway 3 has potential to scale relatively quickly. No new feedstock supply chain needs to be developed because the off-gas is already available at the industrial mills. Although this pathway produces a more expensive SAF (approximately R51/ℓ under the self-sufficiency scenario and R38/ℓ under the external energy scenario) it could also be an early supplier of South African SAF since ethanol production would be integrated with the off-gas sites (ferroalloy and steel plants), removing the need for intermediate supply chains.

SAF PRODUCTION POTENTIAL IN SOUTH AFRICA



The Hydroprocessed Esters and Fatty Acids (HEFA) route (Pathway 1) is the most mature technology for SAF production. Solaris production has been successfully trialled in South Africa, making it another good candidate for early SAF sector development. In fact, South African Airways flew two flights using Solaris-derived SAF in 2016. If coupled with selling refined co-products at a premium, SAF produced in South Africa could be competitive on the international market. This pathway could produce 1,1 billion litres of SAF per annum at a cost of approximately R34–R36/ℓ.

Invasive alien plants and garden waste have the potential to produce the largest quantity of SAF in the country (1,75 and 2,96 billion litres per annum under the self-sufficiency and the external energy scenario, respectively) via gasification and Fischer-Tropsch (GFT) synthesis (Pathway 6a). This is also the most economic route to produce SAF from IAPs and garden

waste, at a cost of R32–R35/ℓ. However, implementation of this pathway would require a significant IAP-clearing programme to provide the biomass required. IAP clearing in the country is mostly done through Working for Water, the national government's Natural Resource Management (NRM) programme. This programme was established in 1995 with the goal of restoring landscapes by eradicating IAPs and could initially provide biomass for the GFT plants.

R30
APPROXIMATE SAF
PRICE PER LITRE ON THE
INTERNATIONAL MARKET

GREENFIELD FACILITIES

It should be noted again that this analysis focuses on greenfield facilities; however, there are production-ready facilities in South Africa that could produce initial quantities of SAF at lower cost, utilising the AtJ and FT-SPK pathways. Including those facilities in the SAF blueprint for South Africa would not change the total SAF production potential (which is restricted by the availability of sustainable feedstock) but could make initial quantities available at a lower cost. For more information on potential SAF production at these facilities, see previous work done by Bole-Rentel et al. (2019, 2021).

SOCIO-ECONOMIC IMPACTS OF A DOMESTIC SAF INDUSTRY

The development of a new SAF industry could generate tens of thousands of jobs over at least 20 years, strengthen South Africa's fuel security and improve the balance of trade by between R109 billion and R171 billion per annum.



JOB IMPACTS

Jobs are generated through the construction phase of supply chain development (assumed to be roughly three years for each facility), as well as over the entire 20-year minimum operational period of the supply chain. Jobs are presented as full-time equivalents (FTE), i.e. total full-time jobs provided over the course of a year.

The I-JEDI model provides for direct jobs, indirect jobs and induced jobs. Direct jobs are those directly related to the operations of the supply chain, including plant operations, transport and feedstock provision. Indirect jobs are those relating to the upstream supply, maintenance and operations of inputs to the processes, including electricity, water supply and financial operations, among others. Induced jobs are those generated by the additional expenditure of salaries from the supply chain employees.

The default approach for the installation of new plants with imported technology is to provide turnkey installations that effectively import all major plant requirements and equipment. However, there is potential to localise several elements of the construction phase, drawing on South Africa's industrial base and on guidance from the Department of Trade, Industry and Competition (DTIC). This potential varies between

JOBS GENERATED IN CONSTRUCTION PHASE FOR MAXIMUM LOCALISATION SCENARIO

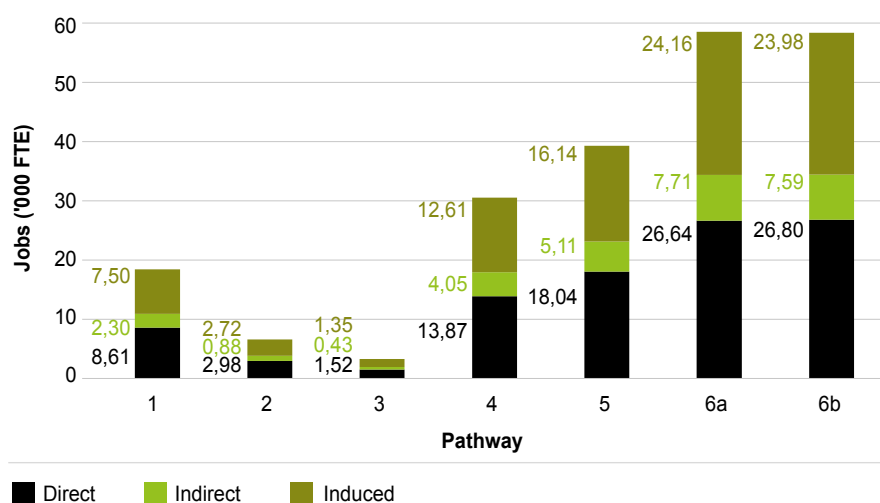


Figure 24: Jobs generated in the construction phase for the maximum localisation scenario

IMPACT OF LOCALISATION ON CONSTRUCTION PHASE JOBS

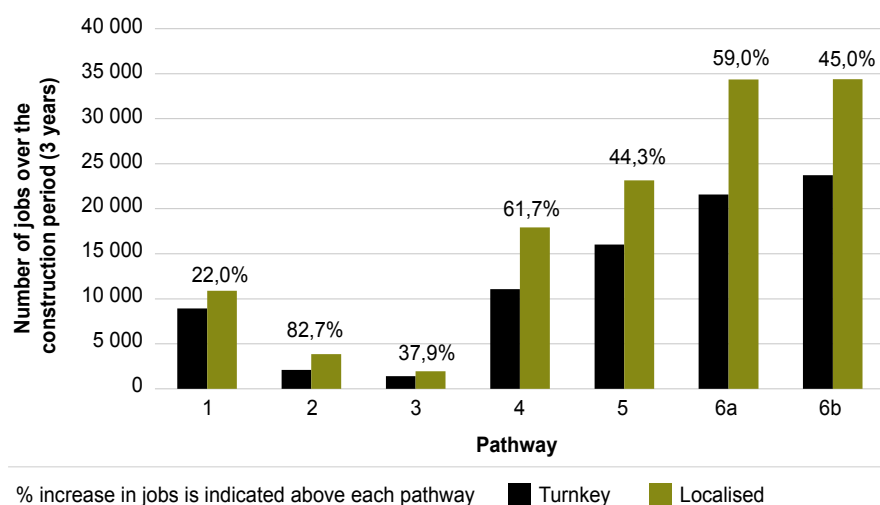


Figure 25: The impact of localisation on direct and indirect jobs during the construction phase

pathways, but in all cases there are elements of the plant design that can be met by local suppliers.

For the scenario where as much as possible of the construction materials and equipment is manufactured in South Africa, along with the plant construction itself, the I-JEDI model estimates almost 40 000 direct jobs for full implementation of SAF Pathways 1, 2, 3 and 6a, as can be seen in Figure 24. This phase could generate an additional 11 300 indirect jobs across the pathways considered.

Pursuing a localised approach for the construction phase will realise more jobs than in the turnkey case, as can be seen in Figure 25. The additional job creation potential between the turnkey and maximum localisation scenarios ranges from 22% more in the case of the latter for Pathway 1, to 84% for Pathway 2, and averages 50,4% more for optimal implementation. Localisation does not change the operational jobs, since it is assumed in all cases that these jobs will be met by local supply. The I-JEDI model estimates almost 46 500 direct



IF AS MUCH AS POSSIBLE OF THE CONSTRUCTION MATERIALS AND EQUIPMENT IS MANUFACTURED IN SOUTH AFRICA, THE CONSTRUCTION PHASE ALONE COULD CREATE ALMOST 40 000 DIRECT JOBS

jobs and 3 600 indirect jobs during operations for full implementation of SAF Pathways 1, 2, 3 and 6a, as can be seen in Figure 26. It should be noted that, whereas Pathway 4 has the most operational jobs of all the IAP-based pathways (Pathways 4, 5 and 6a), Pathway 6a was selected for consideration in the full implementation because it provides the largest volume of lowest-priced SAF, which is a key criterion for access to international markets. Pathway 1 has the most operational jobs, primarily in the agricultural sector and linked to growing Solaris feedstock.

JOBS GENERATED IN THE OPERATIONS PHASE

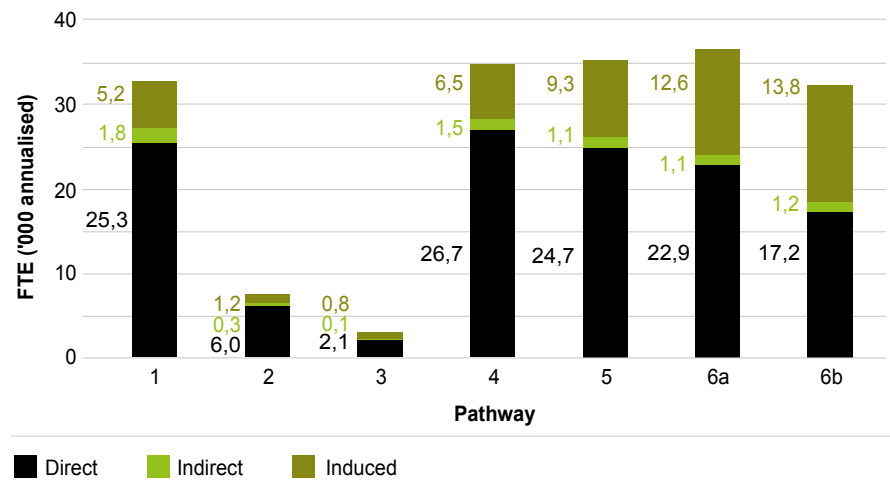


Figure 26: Jobs generated in the operations phase



GROWING SOLARIS IS LABOUR INTENSIVE AND COULD RESULT IN THE CREATION OF OVER 19 700 PERMANENT AGRICULTURE JOBS



HOME BASES FOR BIOMASS TRUCKERS

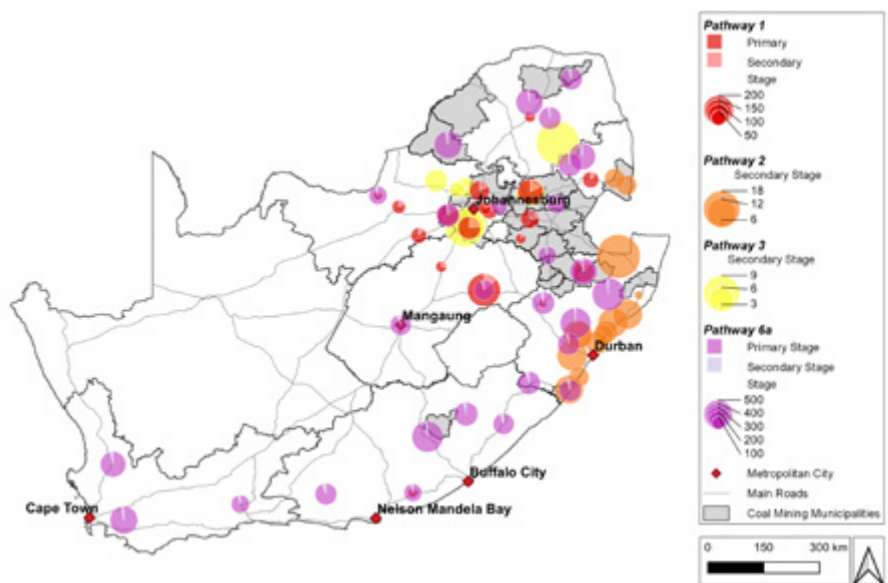


Figure 27: Distribution of home bases for truck drivers required to transport biomass in South Africa
Note: Primary = Intermediary; Secondary = Final

Growing Solaris is labour intensive and could result in the creation of over 19 700 permanent agriculture jobs. For most pathways, the jobs generated are new jobs, although a portion of the jobs in Pathway 2 are securing at-risk agricultural jobs in the sugar industry. These estimates only consider self-sufficient plants. It is expected that if green hydrogen is produced externally, direct construction jobs may be reduced for those pathways no longer using a water-gas shift reactor, but that the increased production volumes may balance the jobs. In addition, there would be considerable upstream employment linked to the implementation of green hydrogen and expanded renewable energy generation.

The I-JEDI jobs analysis was complemented by the detailed jobs analysis for new trucking routes (Chireshe and Bole-Rentel, 2022). For pathways with no significant additional supply chain, the job numbers in the transport, communications and public utilities (TCPUP) sector were similar. However, for Pathways 4, 6a and 6b, which entail the development of comprehensive logistics chains for IAP collection, the detailed analysis provides a much higher estimate for transport jobs.

The lignocellulosic supply chains require significant transport capabilities to move IAP feedstock and in some cases intermediate products. Full implementation of the most promising IAP-based pathway (Pathway 6a) would entail the creation of nearly 7 500 trucking jobs and an additional 837 support jobs. Of the trucking jobs, approximately half would be based in coal-producing districts, where biomass supply chains would also be located (Figure 27). The SAF sector could consequently provide employment for 75% of all drivers of side-tipper trucks currently hauling coal and 114% of all superlink drivers. It could also potentially provide jobs for 320 tanker drivers, who would need to be retrained from coal-supply jobs (Chireshe and Bole-Rentel, 2022). The SAF supply chains in the coal-producing regions could consequently provide employment for roughly 95% of all current coal-supply drivers, making it a critical part of the just energy transition process.

IMPACTS OF SAF PRODUCTION ON SA's BALANCE OF TRADE FOR LIQUID FUELS

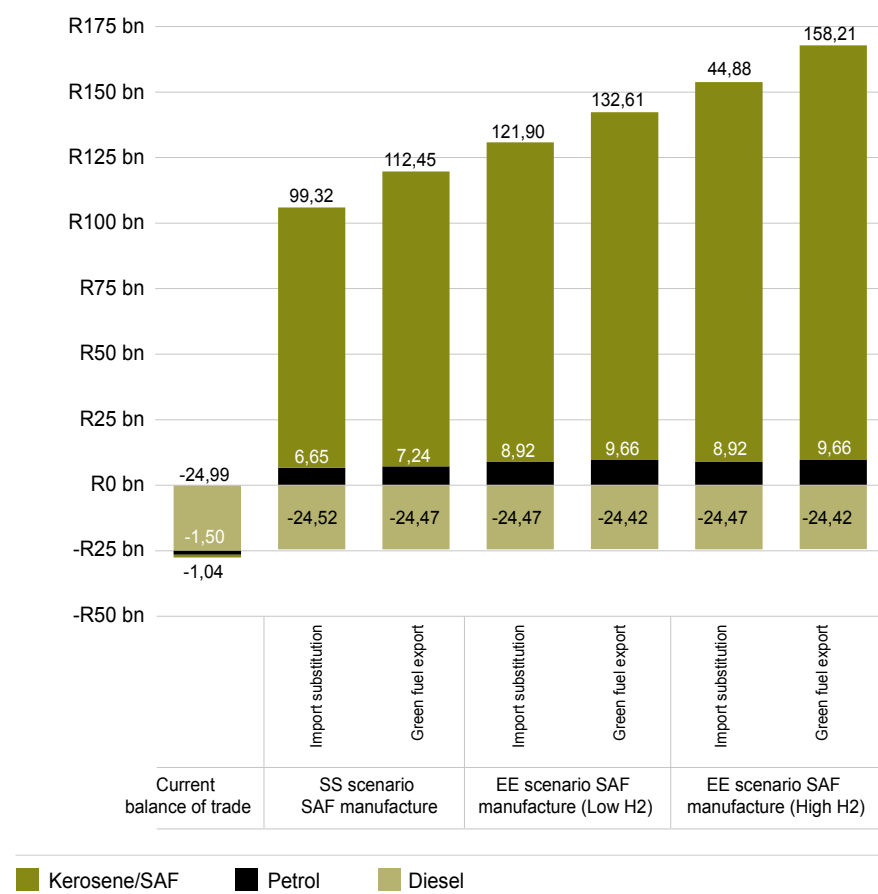


Figure 28: Impacts on the national balance of trade for liquid fuels, depending on whether SAF and co-products are prioritised for import substitution or for export as a high-premium product

TRADE BALANCE IMPACTS

In 2019, South Africa had a net import balance of about 4,3 billion litres of light fuels (diesel, jet-fuel and petrol), of which 4% was jet-fuel. Assuming a full SAF supply chain implementation (Pathways 1, 2, 3 and 6a), a self-sufficiency SAF approach will be able to cover all jet-fuel imports, with an excess of close to 3 billion litres still available for export. If external energy was used to support SAF manufacturing, the increased volumes of co-products and SAF mean that both jet-fuel and petrol imports could be replaced. Although this would not cover South Africa's current consumption of diesel, it would go some way towards addressing the shortfalls in vehicular fuels due to the ongoing refinery crisis.

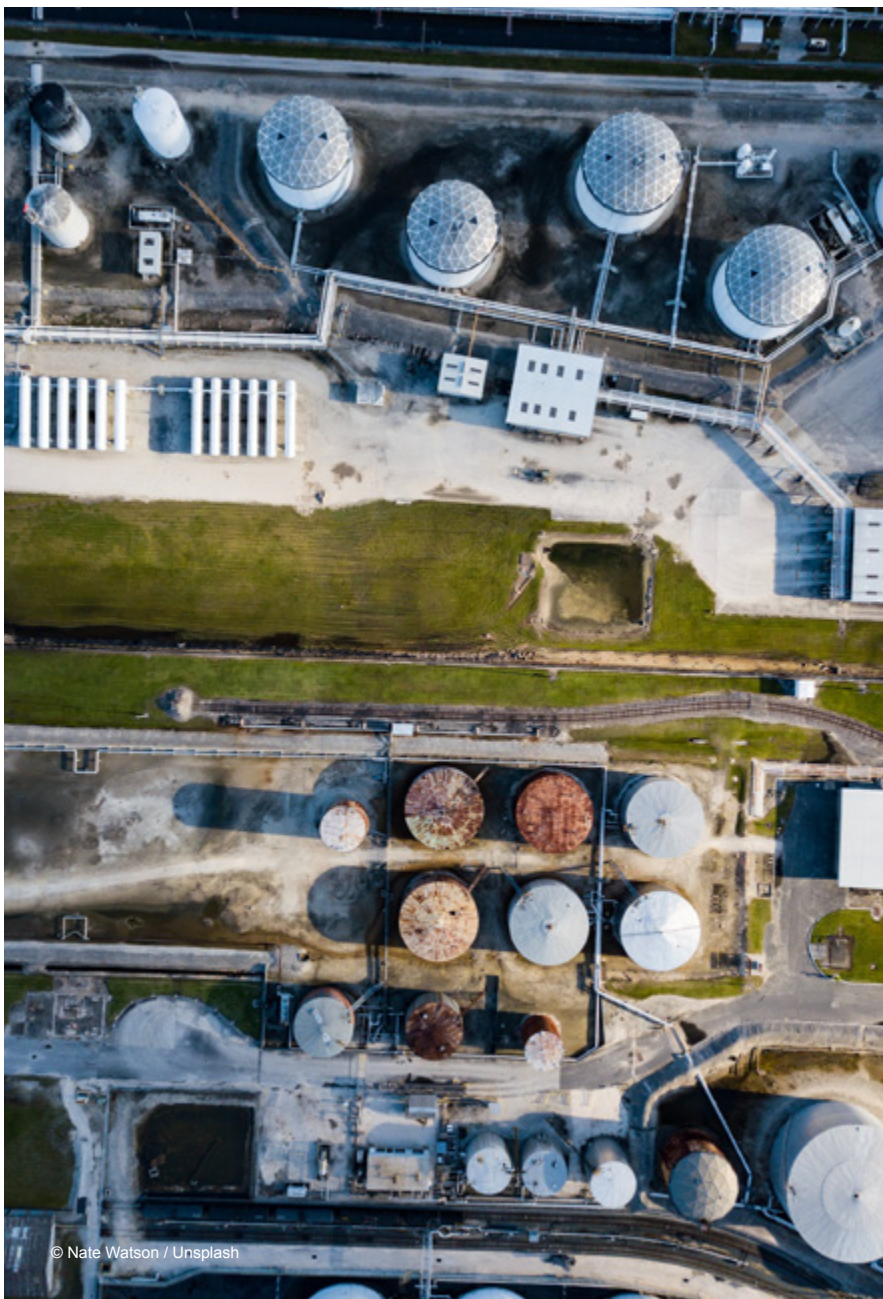
Production of SAF and the associated co-products will help South Africa to address the deficit in its balance of trade caused by fuel imports exceeding exports. Depending on priorities,

locally produced SAF can be directed either to local consumption to replace jet-fuel imports, or to exports, which may provide a better return in terms of the balance of trade because of its green premium (see Figure 28).

Regardless of the model used, SAF implementation can improve South Africa's balance of trade by at least R81,5 billion per annum. This improvement could be as high as R170 billion per annum if the maximum SAF production potential can be achieved by introducing externally produced green hydrogen and if the market is able to absorb the initially higher prices of such SAF. Exporting SAF and other green fuel at the lower-margin hydrogen price of US\$2/kg will still generate R117,9 billion per annum, a R145 billion improvement on the current annual balance of trade.

POLICY IMPLICATIONS

A domestic SAF industry could be a pillar of South Africa's low-carbon economy, with the potential to provide decent new jobs and alternative employment opportunities for those affected by the energy transition. To deliver these multiple dividends, the SAF sector would benefit from initial policy support.



While all SAF is considerably more expensive than conventional jet-fuel, some of the assessed pathways are already competitive with the current international SAF price. Several more could also become competitive if the cost of capital for the processing facilities and the feedstock prices could be lowered through policy support or concessional funding.

The price of feedstock was determined to be a critical variable on the price of SAF produced from vegetable oil or A-molasses. At present, South Africa's Biofuel Regulatory Framework only envisions farmer support mechanisms for 1G feedstocks such as sugarcane and sorghum, on the premise that 1G feedstock production is labour intensive and thus meets the framework's socio-economic objectives. However, growing Solaris, a non-food crop, and clearing IAPs are both labour intensive and would also benefit from policy support aimed at encouraging employment in rural areas.

Capital subsidies, government guarantees and concessional finance would go a long way towards lowering the risks of newer processing technologies, thereby decreasing their cost of capital and improving the competitiveness of capital-intensive SAF, such as that produced from lignocellulosic waste.

The SAF that can be produced in South Africa mostly meets various greenhouse gas (GHG) criteria and standards,

which makes it highly marketable on the international market. In some cases, SAF from IAPs might not achieve the desired GHG emissions reduction, depending on land use after clearing and the processing technology that is used. To maximise the benefits of SAF produced from cleared IAPs, a concerted effort should be made to coordinate ecosystem restoration programmes with IAP-based SAF supply chains.

Refinery co-products such as renewable diesel and petrol can attract a premium on the international market, which could reduce the cost of SAF. These co-products also have a low GHG footprint and can be used locally to decarbonise other sectors of the economy. However, the current Biofuels Regulatory Framework only makes provisions for the use of bio-ethanol and biodiesel in South Africa's fuel pool. Revising the regulations to include renewable diesel and petrol, and allowing for their use in South Africa, could help lower the emissions profile of the transport sector and facilitate the development of the SAF market.

SAF can also help the South African aviation sector to meet its forthcoming international emissions reduction requirements and lower its liability under the domestic carbon tax. A modest SAF blending mandate similar to those in several other jurisdictions would go a long way towards providing the security of demand required for initial production facilities to come online.

SAF production could indirectly be considered in South Africa's just transition planning process. South Africa cannot construct all plants independently, but their construction can be localised to a large degree. Existing local content regulation should be reviewed to ensure that the best outcome in terms of employment and revenue generation are achieved in local supply chains.



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**SOUTH AFRICA HAS THE
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