Project Title : *"Technical and economic pre-feasibility of biomass waste utilization for production of sustainable aviation fuel by PetroSA"*

(Contract Number 3000082110/UNIDO Project SAP ID 130310)

Full pre-feasibility of ethanol supply for production of sustainable aviation fuel

Compiled by:

Tjaša Bole-Rentel & Farai Chireshe (WWF-SA)

Based on the research by:

Dr William Stafford, Greg Forsyth, David Le Maitre and Ryan Blanchard (CSIR)

Professor Johann Görgens, Dr Oseweuba Valentine Okoro and Dr Abdul Petersen (SU)

Avania Ravinath, Geoffrey Ellis and Lerato Mnyakeni (Imperial Logistics)

February 2021

ACKNOWLEDGEMENTS

We would like to thank Mr Carel Steyn, Business Development Manager of GTLR Operations at PetroSA and Mr John Wilson, Mr Etienne Basson and Mr Ismail Wambi from the Department of Environmental Affairs and Development Planning of the Western Cape Government for their independent review and useful comments on the analysis presented herein.

We would also like to thank Mr Nokwazi Moyo and Mr Alex Eruwa from the United Nations Industrial Development Organisation for financially supporting this study and providing constructive comments through each progress report.

Executive Summary

PetroSA is South Africa's National Oil Company (NOC) with its primary operating asset being the GtL Refinery in Mossel Bay. The current operation of this facility is severely restricted due to a lack of affordable feedstock, especially natural gas. Should operations at this site be discontinued, it will have a severe impact on socio-economic aspects in the Southern Cape, including local employment.

At the same time, the country has a plethora of alternative feedstock options in the form of various wastes that could be converted to sustainable advanced liquid fuels. Introducing biogenic feedstock into PetroSA processes could go some way towards alleviating the critical shortage of natural gas. PetroSA is able to absorb biogenic waste feedstock in its processes in many ways, however with sustainable aviation fuel (SAF) a growing and premium market, **this study focuses on supply chains of the intermediate feedstock (ethanol) that would allow PetroSA to produce SAF via the certified alcohol-to-jet (AtJ) process in its oligomerization plant, which is also referred to as the Conversion of Olefins to Distillate (COD) plant**. It shows how a technically feasible supply of ethanol would look like and how much would it cost, by identifying suitable types and quantities of waste biomass (and gasses) that could be used as raw feedstock for its production, their locations, conversion processes and transport options, and estimate the costs along each step of the chain to determine the full cost of the ethanol supplied at the gate of PetroSA's refinery in Mossel Bay, for further processing into SAF. Throughout this analysis, we work on the assumption that the COD plant would process up to 300 million litres of ethanol into SAF annually. The figure below provides an overview of the candidate ethanol supply chains that are investigated in this pre-feasibility.

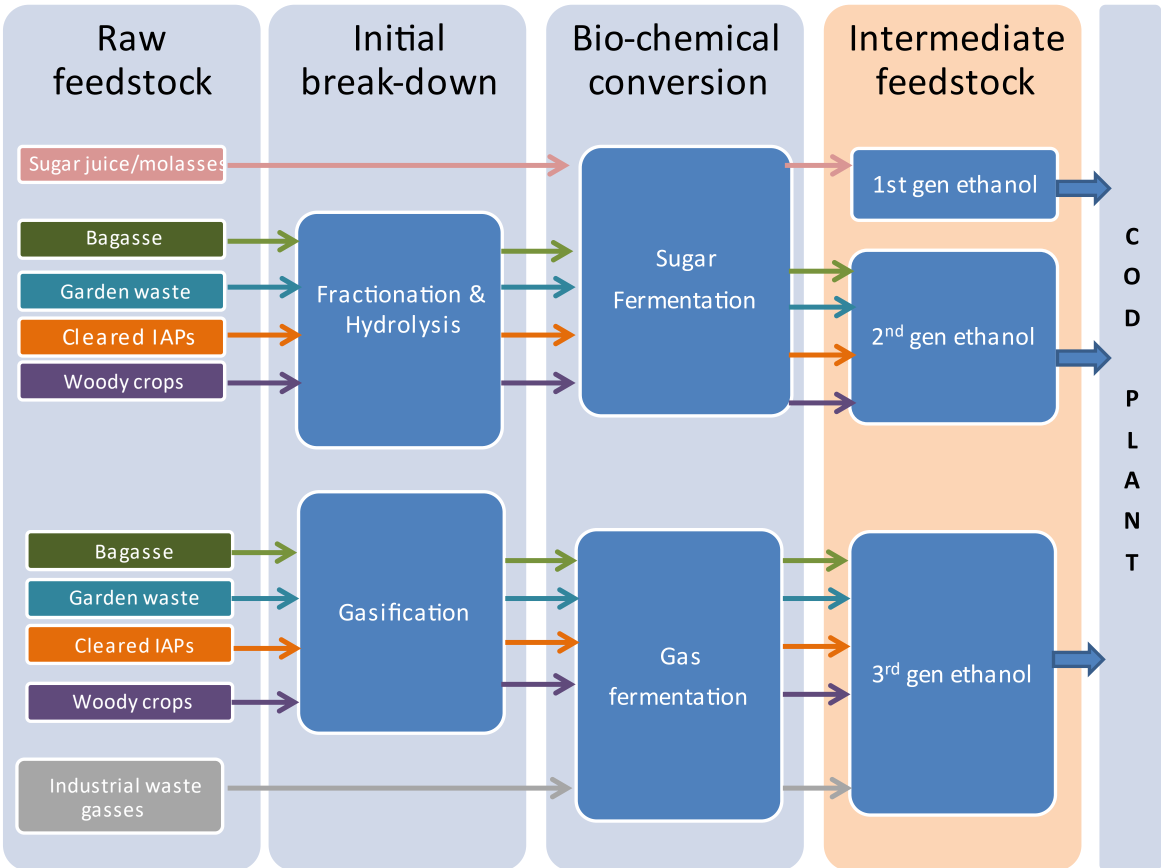

Figure E.1 Schematic representation of raw material candidates, intermediate conversion and utilization options at PetroSA refinery

An assessment of raw feedstock availability is a fundamental aspect of the feasibility and sustainability of SAF production. Invasive alien plants (IAPs) are recognised as being a substantial candidate resource for the production of advanced fuel in South Africa and they are also the preferred second-generation ethanol feedstock of those considered in this pre-feasibility because its usage would meet multiple ecological and social objectives. An up-to-date estimate of the spatial distribution of biomass from invasive alien plants commissioned as part of this pre-feasibility found that 37.1 million tonnes of dry alien biomass (or over a third of all alien biomass) in the Western and Eastern Cape, the two provinces most likely to represent catchment areas for raw feedstock for SAF production at PetroSA, is easily accessible on slopes of up to 20%. An additional 26.7 million tonnes are fairly accessible on slopes between 20 and 35%. Considering potential annual demand for lignocellulosic feedstock to produce enough ethanol to meet PetroSA's processing capacity of 300 million litres per annum is in the region of 1 – 1.5 million tonnes per annum, the identified easily accessible biomass in these two provinces alone could supply enough raw feedstock for the required ethanol supply, even if any further spread of IAPs was fully contained. It is however important to note that invasive alien plant biomass is strictly a non-renewable resource, and the biomass stock will need to be apportioned for harvesting over the project lifetime.

In addition to IAPs, we estimate that industrial off-gasses and sugar processing co-products molasses could also individually supply more than enough ethanol to meet potential demand from PetroSA, indicating sufficient technical potential of this intermediary feedstock for SAF production (and other uses).

Despite many of the materials considered as raw feedstock in this study being perceived as waste, this does not mean there are no sustainability risks associated with their collection and usage. A sustainability risks assessment against the sustainability principles of the Roundtable for Sustainable Biomaterials, the gold standard of sustainability schemes for bioenergy and biomaterials, identifies molasses and bagasse as high sustainability risk especially due to potentially high GHG impacts; IAPs as a medium sustainability risk feedstock, on account of possible ecological impacts and improper labour practices employed during eradication operations; and garden waste and industrial off-gasses as low risk. This means that an ethanol supply chain based on the high or medium sustainability risks feedstocks would require a comprehensive sustainability risk assessment and management plan to address them, before even attempting further development steps.

The technoeconomic assessments of alternative ethanol producing scenarios were obtained from the simulations of models developed in ASPEN plus V11, and combined with engineering costing approaches in plant design, for use in a discounted cash flow analysis. The minimum ethanol selling price (MESP) that will provide an acceptable return on a private investment in a manufacturing facility was selected as the preferred metric for assessing comparative economic performances. The MESPs for the different ethanol scenarios were calculated "at the factory gate". Assuming energy self-sufficiency for all ethanol scenarios, thereby reducing the risks associated with external sources of process energy, the economic results showed that ethanol production costs ranged from R7.95/litre up to R37/litre, depending on the cost of feedstock supply and conversion technology. The economic performance of the ethanol production system that employs off-gas for ethanol production was enhanced by the absence of feedstock cost, while the disproportionately large demand for electricity created an economic disincentive in the energy self-sufficient scenario. First generation ethanol based on molasses provided a cost-effective alternative, with few modifications required to sugarcane harvesting and processing. A more advanced approach incorporating upgrades in energy efficiencies to sugarcane mills and collection of under-utilised harvesting residues, provided a low-cost approach to ethanol production from lignocelluloses in the combined first-and-second generation scenario. IAPs conversion to ethanol via the hydrolysis-fermentation approach was preferred to gasification-fermentation, due to the estimated high cost of the latter. The MESPs of several of the ethanol scenarios could be reduced through the buy-in of substantial amounts of "baseload" renewable electricity to these facilities.

The results of the techno-economic assessment for a sub-set of ethanol production pathways were combined with the centre of gravity study in the network optimisation analysis, to derive the approximate total annual costs of procuring ethanol for conversion to SAF by PetroSA, while not exceeding the capacity of individual feedstock facilities and minimizing transport costs. The specific ethanol supply chains analysed further were: first generation ethanol from molasses fermentation, second generation ethanol from lignocellulose via the hydrolyses-fermentation route and third generation ethanol from industrial off-gas fermentation in an energy self-sufficient configuration. We considered single feedstock scenarios, where the demand of 300 million litres per annum was fully met by ethanol produced from each raw feedstock individually, and different combinations thereof.

The table below provides the breakdown of cumulative annual costs for each of the ethanol supply chains analysed in the network optimisation study. It shows the supply chains differ substantially on their main cost drivers. Lowering feedstock acquisition costs in the lignocellulosic scenario, for example by teaming up with subsidised clearing programmes or integrating clearing operations in the ethanol business case as opposed to relying on external commercial clearing operations, might affect the relative economic attractiveness of the ethanol supply options under consideration. Importing electricity to meet the process energy needs and hence releasing syngas for expanding the ethanol output in the industrial off-gas scenario might have the same effect.

Table E.1 Annual ethanol costs for single feedstock scenarios

	Lignocellulosic		Industrial Off-Gas		Molasses	
Feedstock cost	R	2,098,408,813	R	-	R	1,450,075,485
Primary transport cost	R	295,099,733	R	-	R	-
Secondary transport cost	R	158,540,031	R	461,781,256	R	400,338,653
Processing cost	R	3,217,718,304	R	4,022,147,880	R	1,014,475,076
Total cost	**R**	**5,769,766,880**	**R**	**4,483,929,136**	**R**	**2,864,889,214**

The network optimisation analysis indicates different optimal solutions depending on the objectives of the ethanol sourcing strategy. If the goal was cost-efficiency alone, then sourcing all ethanol from molasses would be the obvious choice since it carries the lowest cumulative annual cost of about R2.86 billion, compared with R4.48 billion for industrial off-gas ethanol, while lignocellulosic ethanol appears as the most expensive option at about R5.77 billion, or about twice as much as the molasses-based option. The supply chain based on molasses does not incur primary transport cost and has the lowest processing cost, leading to the lowest overall cost compared to ethanol supply based on lignocellulosic feedstock and industrial off-gas.

If the ethanol sourcing strategy was to meet a number of objectives, including job creation and improving drought resilience, then it would need to include at least some ethanol produced from IAPs. Our analysis suggests that a combination of 1 IAP-based facility (in Ceres), 2 molasses-based facilities in KZN and 1-2 industrial off-gas based facilities would be able to achieve multiple objectives at an additional cost of about R1 billion per year.

Contents

List of Acronyms

ASTM	American society for testing and materials
AtJ	Alcohol-to-jet
CAPEX	Capital expenditure
CDM	Clean development mechanism
COD	Conversion of olefins to distillate
COG	Centre of gravity
CO_2	Carbon dioxide
DEA&DP	Department of environmental affairs and development planning
GHG	Greenhouse gas
GtL	Gas-to-liquids
IAP	Invasive alien plant
MESP	Minimum ethanol selling price (MESP
NOC	National oil company
OPEX	Operating expenditure
SAF	Sustainable aviation fuel

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1 Introduction and study objective

South Africa's national oil company PetroSA was been operating on less than 50% of capacity for an extended period of time, due to limited availability of natural gas, the main feedstock in its process, and by the end of 2020 its Mossel Bay gas-to-liquids (GtL) refinery was not able to maintain even minimum commercial operations, with disastrous consequences for local employment, and export earnings derived from few niche products only PetroSA was able to produce.

At the same time, the country has a plethora of alternative feedstock options in the form of various wastes that could be converted to sustainable advanced liquid fuels. Introducing biogenic feedstock into PetroSA processes could go some way towards alleviating the critical shortage of natural gas. PetroSA is able to absorb biogenic waste feedstock in its processes in many ways, and all are potentially interesting and warrant exploring, however with sustainable aviation fuel (SAF) being a growing and premium market it makes sense to focus on this opportunity first.

The main objective of the study is thus **to prove the pre-feasibility of a waste-based sustainable value chain for the commercially viable production of SAF by the National Petroleum, Gas and Oil Corporation of South Africa (PetroSA)**. It will show how a technically feasible and commercially viable supply of feedstock would look like by identifying suitable types and quantities of waste biomass (and gasses), their locations, pre-treatment processes and transport options, and estimate the costs along each step of the chain to determine the full cost of the intermediate feedstock supplied at the gate of PetroSA's refinery in Mossel Bay, for further processing into SAF.

The main outcome of the study will be to **determine the most suitable feedstock supply chains in terms of availability and price for the production of SAF by PetroSA at its Mossel Bay refinery**. This will allow PetroSA to:

- Independently assess bids from service providers offering technology or bio-feedstock in usable form;
- Complete the cost build up for the SAF that could be produced from the identified biogenic feedstocks and assess its commercial viability relative to prevalent market conditions;
- align its operations with a number of governmental socio-development objectives, including improving draught resilience, generate employment opportunities in the SMME sector and broaden the scope of the green economy.

The project is a key initial step in the development of a waste biomass-based value chain for SAF in South Africa, with a long-term view to addressing a number of environmental and economic challenges in South Africa and beyond, including:

- Improving waste management through the collection and utilization of biomass waste;
- Reducing environmental hazards such as fire risk, groundwater toxicity and pressure on endemic biodiversity;
- Alternative feedstock supply to the national oil company;
- Decarbonisation of the aviation sector;
- Provision of economic opportunities in a new green supply chain with significant upstream opportunities for SMEs; and others.

This pre-feasibility report represents the main output of the study and is structured as follows: Section 2 defines the scope of the pre-feasibility among all SAF production routes that could – in principle – be pursued by PetroSA. Section 3 describes the feedstock base, Section 4 presents the techno-economic assessment of the intermediary product that PetroSA would further process into SAF, while Section 5 presents the results of the optimisation of supply logistics. Section 6 ties these different components of the analysis into a complete cost build up for the intermediate product to provide an estimate of its likely price supplied to the gate of the Mossel Bay refinery. Section 7 discusses these results and provides recommendations for next steps.

2 Study scope

Based on discussions with PetroSA, it was established that – in principle - biogenic feedstock could be introduced into PetroSA's refinery in Mossel Bay in a number of ways:

- as bio-methane (generated via anaerobic digestion of biomass wastes) to be used as fuel gas and/or liquefied into bio-LNG (liquefied natural gas) and/or mixed with natural gas in the GtL process;
- bio-syngas (produced from biomass by an external gasifier) to be introduced upstream of the FT reactor;
- ethanol (produced by fermenting sugarcane, carbon monoxide-rich waste gasses or lignocellulosic waste) through its oligomerization unit via the so-called 'Conversion of Olefins to Distillate' or 'COD' process;
- bio-crude (produced from pyrolysis) to be introduced in the downstream refinery.

The biogenic feedstocks mentioned above are actually intermediates compatible with PetroSA processes and can be produced from a variety of raw materials following different intermediate conversion technologies. The complete "bio-based production chains" are presented in Figure 2 below.

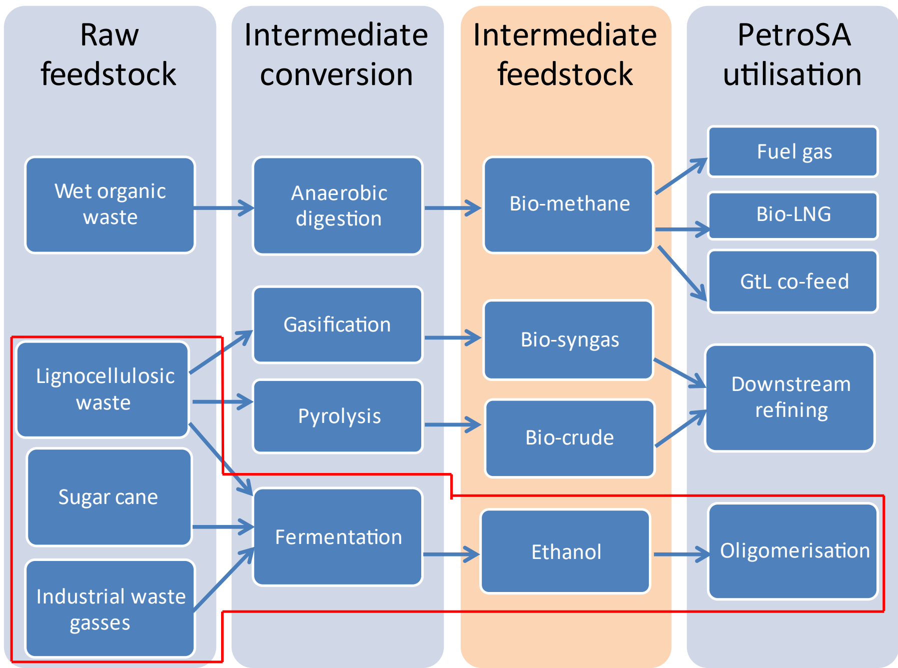

Figure 2 Schematic representation of raw material candidates, intermediate conversion and utilization options at PetroSA refinery

The above processes can result in a number of final bio-products, including a variety of biofuels and bio-chemicals. Because of the planned restructuring of PetroSA and the focus of this project on SAF, **this pre-feasibility focuses on supply chains of the intermediate feedstock (ethanol) that would allow PetroSA to produce SAF via the**

ASTM-certified alcohol-to-jet (AtJ) process in its oligomerization plant (**also referred to as the Conversion of Olefins to Distillate (COD) plant)** which could be re-started despite the potential mothballing of the Mossel Bay refinery.

The pre-feasibility study thus analyses availability of the raw feedstock (biogenic and non-biogenic), the costs associated with collecting it, processing it into a usable inter-mediate feedstock (ethanol) and delivering it to the gate of PetroSA's refinery in Mossel Bay[1]. Throughout, we assume that PetroSA's COD plant would process 300 million l of ethanol to SAF annually.

A more detailed breakdown of candidate first generation (1G), second generation (2G) and third generation (3G) ethanol supply chains is shown in Figure 3.

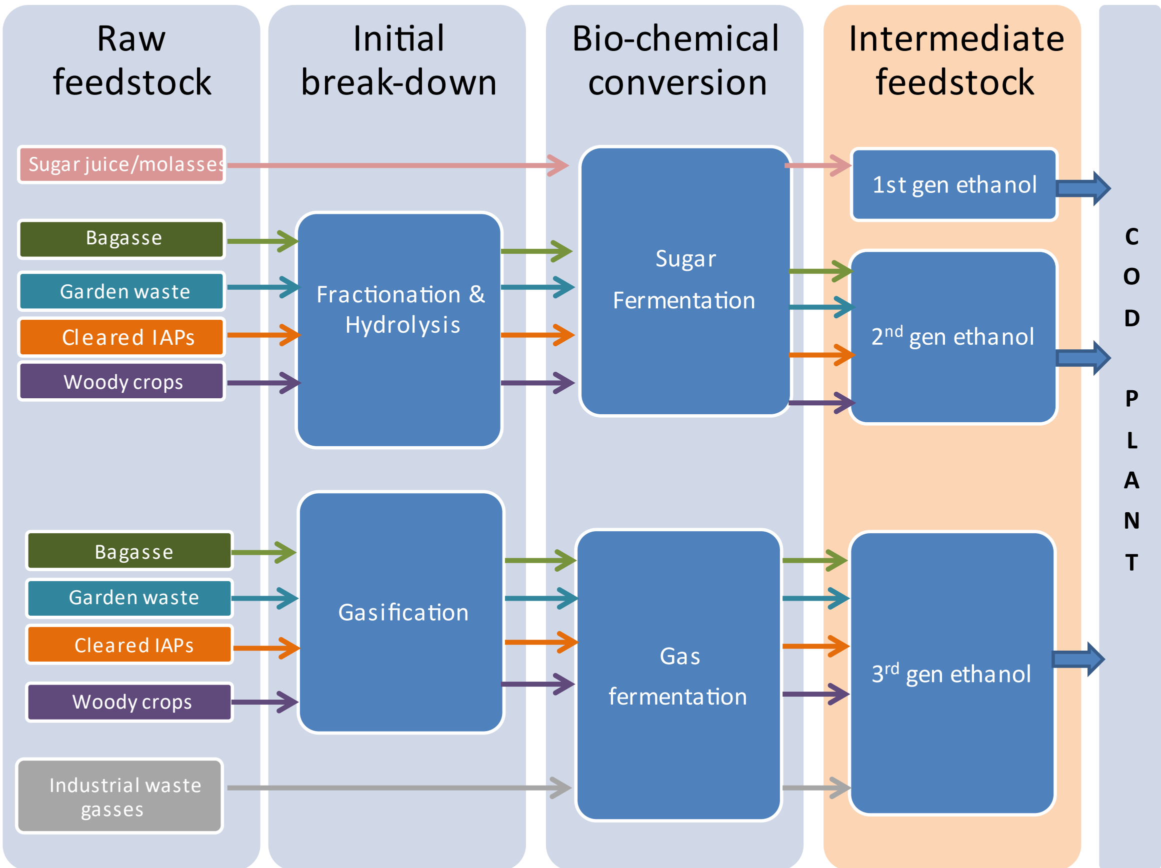

Figure 3 Candidate ethanol supply chains for PetroSA's oligomerization plant

[1] The ethanol will have to be denatured before transporting to PetroSA; this is not a requirement for either compatibility with the COB plant or the tankers used for transportation, but to avoid taxation attracted by ethanol that can be used for human consumption and avoid illicit use in this regard.

BOX 1 The case for Sustainable Aviation Fuels

As the global community advances in its implementation of the Paris Agreement and the shared ambition to limit climate change, sectors deemed “harder to abate”, including aviation, that were initially not the focus of decarbonisation efforts, are starting to see emission reduction regulation, as well as voluntary initiatives to reduce its impact on the climate. Ever more countries are regulating emissions from domestic aviation through carbon tax and emission trading schemes, as well as mandatory blending rates for low-carbon alternatives to conventional fossil-based aviation fuels, while emissions from international aviation are regulated through the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) under the auspices of the International Civil Aviation Organisation.

Sustainable Aviation Fuels are widely regarded as a key mitigation option for aviation emissions. SAF manufactured today are used by airlines as drop-in fuel blends, completely interchangeable and compatible with conventional aviation fuel, which does not require adaptation of the aircraft/engine fuel system or the fuel distribution network and can be used “as is” on currently flying turbine-powered aircraft.

ASTM International (formerly known as American Society for Testing and Materials), the international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services including aviation fuels, has certified 8 SAF production processes for use in aircraft engines as drop-in blends of varying levels (from 10%-50%). To date, over 300 000 commercial flights have used a blend of SAF and conventional jet A1, and 13 airports around the world are refuelling SAF on a regular basis. While overall SAF still constitutes >1% of jet fuel used worldwide, a number of SAF refineries are under construction around the world, with many more in the development pipeline.

For more information on SAF please refer to ICAO Global Framework for Aviation Alternative Fuels (https://www.icao.int/environmental-protection/GFAAF/Pages/default.aspx)

3 Biomass feedstock assessment

3.1 Overview of feedstock candidates

The overview of candidate feedstocks and the conversion processes for the production of an inter-mediate feedstock (ethanol) compatible with PetroSA’s oligomerization unit is shown in Figure 3. It is important to note, that all the “raw feedstocks” considered in this study can also be used as “fuel” to meet the process energy requirements of the ethanol plant. To estimate the techno-economic viability of their utilisation as feedstocks and fuel for the production of ethanol, an assessment of their spatial and temporal availability is required. A survey of availability data for each candidate feedstock revealed that:

- Most information regarding sugarcane production is collected at the level of the individual sugar mills. Access to information for individual growers is patchy and there is no central database for field data. We have therefore turned to the South African Environment Observation Network (SAEON) for a comprehensive dataset on sugar production at field level, from which they have already derived estimates of sugar juice and bagasse availability, and more recently the amount of in-field residue production potential (Hugo et al., 2016).
- The research conducted by SAEON for the Bioenergy Atlas of South Africa also pointed to invasive alien plants (IAPs) as the single biggest potential feedstock for production of advanced low-carbon fuels. However, as infestation of IAPs expands very rapidly, the existing estimates that rely on the 2008 National Invasive Alien Plans Survey (NIAPS) are considered too outdated by now. Therefore, the Council of Scientific and Industrial Research (CSIR) was commissioned as part of this pre-feasibility to develop a more up-to-date estimate of

IAPs in the Western and Eastern Cape that could potentially be used to manufacture SAF by PetroSA at its Mossel Bay refinery.

- Estimates of garden waste was obtained by the Department of Environmental Affairs and Development Planning (DEA&DP) from the "Integrated Pollutant and Waste information System" (IPWIS), which in turn receives data from facilities that have a registered activity as per the National Waste Information regulations.
- Point sources of suitable industrial waste gasses are stainless steel and ferroalloy smelter plants, and the locations of these are well known in South Africa[2]. The amount of waste gas available at each source has been estimated by WWF from publicly available carbon monoxide emission reports of each smelter.
- The estimate of potential production of woody crops (specifically miscanthus) is available from WWF's recent research into the potential for sustainable biofuel feedstock production in sub-Saharan Africa[3]. However, miscanthus and other woody crops are not currently being produced commercially in South Africa and considering the vast amounts of lignocellulosic waste in the form of cleared alien invasive plants and garden waste that are readily available, it would make little sense - from an environmental point of view at least - to turn to cultivation of dedicated crops before existing waste streams have been at least partially re-directed. For this reason, while acknowledging woody crops as a potential medium-to-long term opportunity to ensure continuous supply of lignocellulosic feedstock for production of advanced liquid fuels, they are excluded from this study.

The following sections elaborate on the modelling approach to provide more up-to-date estimates for sugar cane-based feedstocks and IAPs and the data collected for actual confirmed availability of garden waste and industrial waste gasses. These datasets have been used in the supply chain optimisation analysis to conduct a centre of gravity study and transport costing, to be added to the costs of processing the feedstocks into 1G, 2G and 3G ethanol for conversion into SAF by PetroSA in its Mossel Bay refinery.

3.2 Sugar cane

Acknowledging that the ailing South African sugar sector is 'collapsing' under the 'weight' of global sugar glut, the sector is assessing different opportunities to diversify, including SAF, as evidenced in the recently released South African Sugar Cane Value Chain Master Plan (2020)[4]. One approach to achieve this sought-after diversification is to consider the utilisation of sugar intermediates such as juice or molasses for so-called first generation (1G) ethanol production.

3.2.1 Sugar juice or molasses-based ethanol

Farming and processing of sugarcane in South Africa predominantly occurs in KwaZulu-Natal, with some farming and milling occurring in Mpumalanga, as shown in Figure 4. There are 14 Sugar mills in operation in South Africa operated by six milling companies. Data regarding sugarcane production is collected by the South African Sugar Association (SASA).

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[2] Basson et al. (2007): South Africa' s ferro alloys industry - present status and future outlook, in: Infacon XI: Innovation in Ferroalloy Industry.

[3] WWF (2019) Taking off: Understanding the sustainable aviation biofuel potential in sub-Saharan Africa. WWF South Africa, Cape Town, available on https://wwfafrica.awsassets.panda.org/downloads/sustainable_biofuel_potential_ssaf_summaryreport_finalized_v7_2_digital_pages.pdf?26941/taking-off-understanding-the-sustainable-aviation-biofuel-potential-in-sub-saharan-africa

[4] Available online at https://sasa.org.za/wp-content/uploads/2020/11/SA-Sugar-Master-Plan-1.pdf

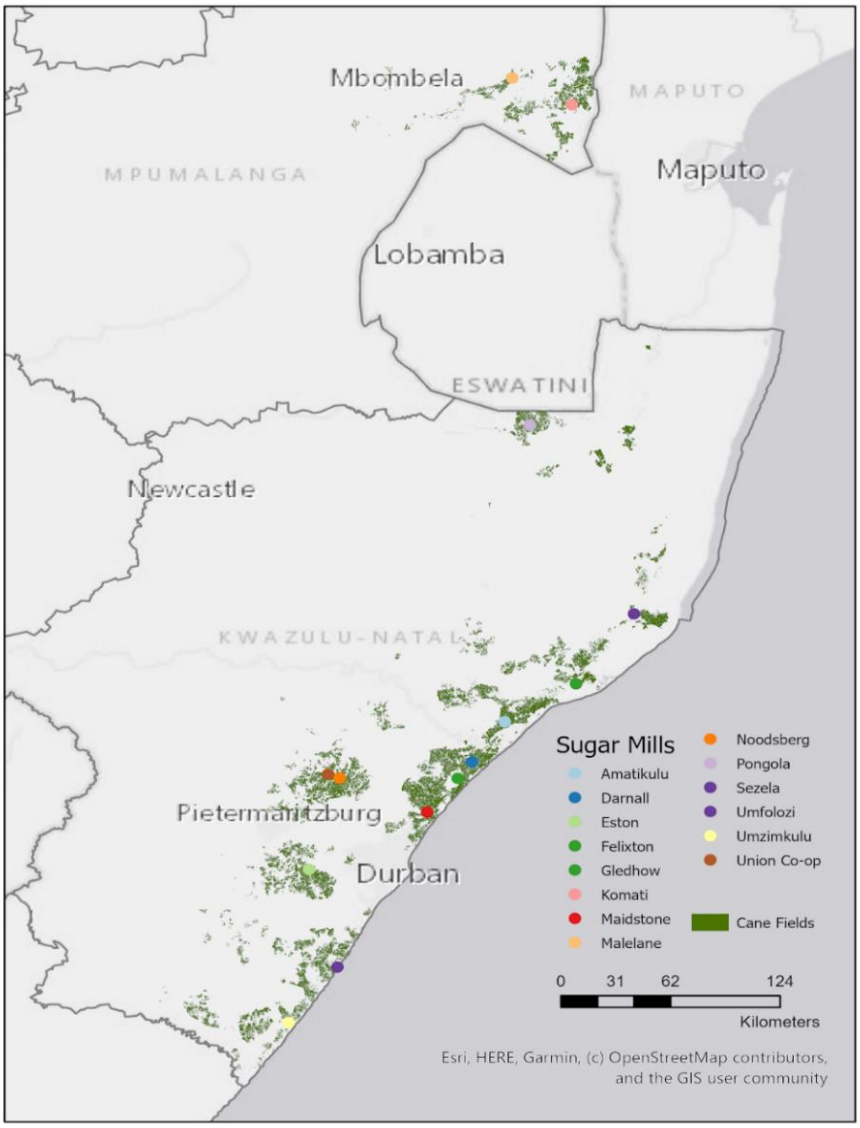


Figure 4 Distribution of Sugarcane and sugar mills in South Africa

The South African Cane Growers Association (SACGA) estimates that if the sugar that is typically exported to world markets below production costs is diverted for ethanol production, 700-million litres of ethanol can be produced per annum, without having to plant a single extra hectare (thus avoiding the direct land-use change emissions associated with land conversion). Just this would meet the ethanol requirements of PetroSA's COD plant more than twice over.

Ethanol production is also possible through processing of molasses, a co/by-product of the sugar production. In its quest to maximise revenues a sugar mill can either:

- Optimise its sugar juice extraction to remove as much as possible crystal sugar, then the remaining liquid is called C-molasses (also called black strap), which can be further processed into ethanol.
- Use one of the intermediate streams in juice processing, called A-molasses. For the same amount of sugar cane, using this stream for ethanol production means a reduction in the amount of crystal sugar output, but a higher ethanol output.

Production of 1G ethanol may be augmented by the available supply of lignocelluloses (2G), achieved primarily through upgrades to the existing sugarcane mills and collection of harvesting residues presently not utilised for economic gain, in so-called 1G2G scenarios.

In this pre-feasibility, the techno-economic analysis of ethanol from sugar cane is focused on the A-molasses option, as the one that would provide the best economic outcome for the sugar mill. Ethanol facilities are assumed to be co-located with sugar mills, and their capacities in line with known quantities of cane delivered to the mills. Therefore, a separate study on cane flows was not required.

3.2.2 Sugar cane-based lignocellulosic wastes and residues

While availability of sugar juice or molasses is well understood, this is less the case for bagasse and other residues that could be used for fuel to meet the process energy needs of the ethanol plant or be used as raw feedstock in 2nd generation conversion processes. SAEON derived an estimate of those by using the datasets listed in Table 1.

Table 1 Datasets used to derive sugarcane-based biomass availability for ethanol production

Dataset	Description	Reference
NGI Topo data for South Africa	A database of topography information for South Africa including roads	
South African National Landcover 2018	A land cover dataset for 72 land cover classes for South Africa - including classes for Cultivated Commercial Sugarcane Pivot Irrigated and Cultivated Commercial Sugarcane Non-Pivot (all other)	https://www.environment.gov.za/projectsprogrammes/egis_landcover_datasets
South African Sugarcane Association Mill locations	Locations of the 14 Mills that currently operate in South Africa	https://sasa.org.za/facts-and-figures/
South African Sugarcane Association Production information	Tons of sugarcane produced by each mill from 2011 to 2018	
Bagasse production Statistics	An estimate of the bagasse yield from South African sugar cane	Devnarain, 2003 PRODUCTION OF ACTIVATED CARBON FROM SOUTH AFRICAN SUGAR-CANE BAGASSE, MSc Dissertation UKZN.
Sugarcane trash yield information	A dataset showing the sugarcane trash to stalk component for sugarcane cultivars	Romero, Eduardo & SCANDALIARIS, J. & Digonzelli, Patricia & ALONSO, L. & NEME, F. & GIARDINA, J. & CASEN, S. & Tonatto, Javier & Fernández de Ullivarri, Juan. (2007). Sugarcane potential trash estimation: Variety and cane yield effect. Proc. Int. Soc. Sugar Cane Technol. 26.

By combining this information, SAEON derived a mean, upper limit, lower limit and standard deviation for the area under cultivation (AUC) and production volumes[5]. To derive an estimate of dry bagasse, they used a conversion ratio of 32% for volume of wet bagasse produced annually, from which the recoverable volume of dry bagasse was estimated at 16% of the total cane processed at each of the mill facilities. Using the national landcover information,

[5] A complete overview of the methodological steps and full set of results will be available in Hlahane K., Mfopa C. & Wilson H.T. (2021): The potential of Sugar cane as a Bioenergy Feedstock in South Africa. The Bioenergy Atlas for South Africa [in press]. SAEON

on field locations, as well as the NGI roads data it was possible to calculate a supply catchment area for each of the sugar mills.

Minimum and maximum production of bagasse at each mill is summarised in Table 2. It is important to note that these figures *do not include an estimation of the current exploitation of bagasse within each of the mills*. In reality, much of the bagasse produced at South African sugar mills is burnt for process heat by the mills themselves, most often in very old and inefficient boilers. These figures presented here must therefore be interpreted as the upper threshold of *potential* bagasse availability for other purposes, likely to become gradually available as sugar mills invest in more efficient boilers, which use-up less bagasse.

Table 2 Range of bagasse production per sugar mill

Mill	Minimum estimated production of dry bagasse (in tonnes/annum)	Maximum estimated production of dry bagasse (in tonnes/annum)
Komati	278 783	409 157
Malelane	207 799	306 683
Pongola	145 222	236 848
Eston	176 814	257 466
Noodsberg	136 730	243 250
Union Co-op	94 069	192 492
Darnall	74 655	251 015
Gledhow	135 434	243 955
Maidstone	102 378	343 067
Sezela	194 029	381 662
Umzimkulu	128 519	234 469
Amatikulu	144 612	297 507
Felixton	148 941	409 979
Umfolozi	126 965	212 388
TOTAL	**2 094 949**	**4 019 937**

In terms of in-field sugarcane residue production, the area under cultivation and the production volume for each mill was used to calculate an average production (t/ha) for each of the mill catchment areas. Field area (ha) was then used in conjunction with this value to derive an estimated stalk production volume for each of the fields. From this, the yield of brown leaves per ton of stalks is estimated at 10% of the volume of stalks produced and the yield of mulch material is estimated at 20% of the stalk yield. The overview of in-field residues production is summarised in Table 3. The in-field yield estimates are based on an average t/ha production value derived from mill statistics and as such it is likely that the actual in-field values will be different based on farming practices, rainfall and soil fertility.

Table 3 Aggregated estimates of in-field residues

Stalk yield (t/a)	23 475 344
In-field residue - Brown leaves (t/a)	2 347 534
In-field residue - Mulch (t/a)	4 695 069
TOTAL (t/a)	**7 042 603**

Together, bagasse and in-field residues could amount to a very substantial 9 – 11 million tonnes of lignocellulosic waste annually. If all was converted to ethanol, it could result in approximately 1.4 – 1.8 million litres of ethanol.

Again, it is important to note that these figures do not consider the existing exploitations of feedstock. Additionally, the in-field estimates for mulch and brown leaf residue production are premised on a change in farming practices. Currently, the majority of sugarcane in South Africa is burnt prior to harvest in order to ensure that no sugarcane trash is accidentally transported to the mill. Changing the harvest practices will require a paradigm shift and will have associated changes in terms of harvest and transportation costs, as well as social implications in terms of job losses if the changes involve more widely utilised machine harvesting.

3.3 Invasive alien plants

Invasive alien plants are recognised as being a substantial candidate resource for the production of SAF in South Africa. Approximately 750 tree species and close to 8 000 shrubby, succulent and herbaceous species are recorded as having been introduced into South Africa. Of these, 161 are regarded as invasive. The majority (approx. 68%) of these invasive alien plants are woody trees and have been the focus of control efforts. The introduction of invasive alien plants (IAPs) in South Africa has led to the conversion of species-rich vegetation to single-species stands of trees. This conversion threatens biodiversity, water security, the productive use of land, and the ecological functioning of natural systems. Invasive alien trees also intensify the impact of fires and floods, increase soil erosion, and have increasingly negative impacts on ecosystem services. The regulations of the National Environmental Management: Biodiversity Act (NEM:BA, 2014) lists invasive alien species which require a range of control measures including removal, permits and appropriate management. While the progress and investment are significant, there are notable missed opportunities for value adding. The CSIR have been tasked to provide an up-to-date estimate of the spatial distribution of biomass from invasive alien plants, in order to assess availability for the production of sustainable aviation fuel at PetroSA's refinery in Mossel Bay[6].

3.3.1 Approach

Based on existing data, spatial analysis has been used to estimate the distribution and amounts of invasive alien tree biomass in the Western and Eastern Cape, as these two provinces are the most likely to fall in the economically feasible feedstock catchment area of PetroSA once the cost of transport is taken into account. While awaiting the new national invasive alien plants survey (NIAPS), we can estimate the contribution that indigenous species make to the total mapped biomass and thereby *deduce* an estimate for invasive alien plants. The analysis uses existing datasets of the CSIR remote sensing derived above ground biomass (AGB) map at 100 m resolution (see Appendix A for a detailed description of the approach used to compile the AGB map) , National land-cover data (2018) and estimates of the biomass of indigenous vegetation types, in order to derive a relatively up-to-date national map of invasive alien plant biomass in South Africa. To estimate availability of IAPs, the following steps were followed:

1. Determine the "natural areas" in the Western and Eastern Cape from the National landcover database (2018) and exclude indigenous forests, as well as urban areas, agriculture and managed forestry plantations (abandoned plantations are included).
2. Overlay "natural areas" with "fire ecotypes and age" to generate map of "natural areas classed according to fire eco-type".
3. Overlay the "natural areas classed according to fire eco-type" with "above ground biomass" map to generate map of "biomass of natural areas classed according to fire eco-type".

[6] This report provides a high-level overview of the approach and results produced by the CSIR. A more detailed technical report with links to all datasets and descriptions of all modelling tools used is available on request.

4. Using the accessory data of estimated “biomass of fire ecotype”, we can adjust the “biomass of natural areas classed according to fire eco-type” to remove the biomass contribution of underlying indigenous vegetation and generate a map of “deduced invasive alien plant biomass”.
5. Deduced invasive alien plant biomass (t/ha) are calculated as biomass of natural areas classed according to fire eco-type and age (t/ha) subtracted by biomass of pristine areas classed according to fire eco-type and age (t/ha).

   This will provide a conservative estimate of invasive alien plant biomass since the assumption is the indigenous vegetation of each ecotype is at its maximum biomass for its age and the total above ground biomass is adjusted by this amount. In areas where there are young invasive trees (having less biomass than the natural ecotype vegetation) or where invasive trees intermingle with indigenous forests, the deduced invasive biomass will likely be an underestimate.
6. Overlay the map of slope (DEM) and class with the “deduced invasive alien plant biomass of natural areas” to generate a map of “deduced invasive alien plant biomass classed according to slope”.

   Accessibility is dependent on terrain and slope: forestry machinery is typically limited to slopes of under 35% (Warkotsch, Brink & Zietsman 1990), although specialized machinery for slopes greater than this exists. Currently most forestry plantations are under 20% slope. Therefore, 35% was chosen as the upper limit of accessibility to determine available biomass for harvesting and supply (NB 35% = 19° slope).

3.3.2 Results

Table 4 provides an overview of the estimated quantity of alien biomass in the Western Cape, grouped according to slope classes, while Figure 5 shows its spatial distribution. There is a total of 42 954 392 oven dry tonnes (odt) of deduced invasive biomass in the Western Cape, of which 24 400 506 oven dry tonnes (56.8%) are accessible on slopes up to 35%.

Table 4 Western Cape deduced invasive plant biomass

Western Cape Deduced IAP biomass by slope classes	**Western Cape Deduced IAP biomass (odt)**
0 - 10%	7 658 424
10 - 20%	6 982 664
20 - 35%	9 759 418
Total <35% slope	**24 400 506**
Total deduced invasive alien biomass in the province	42 954 392

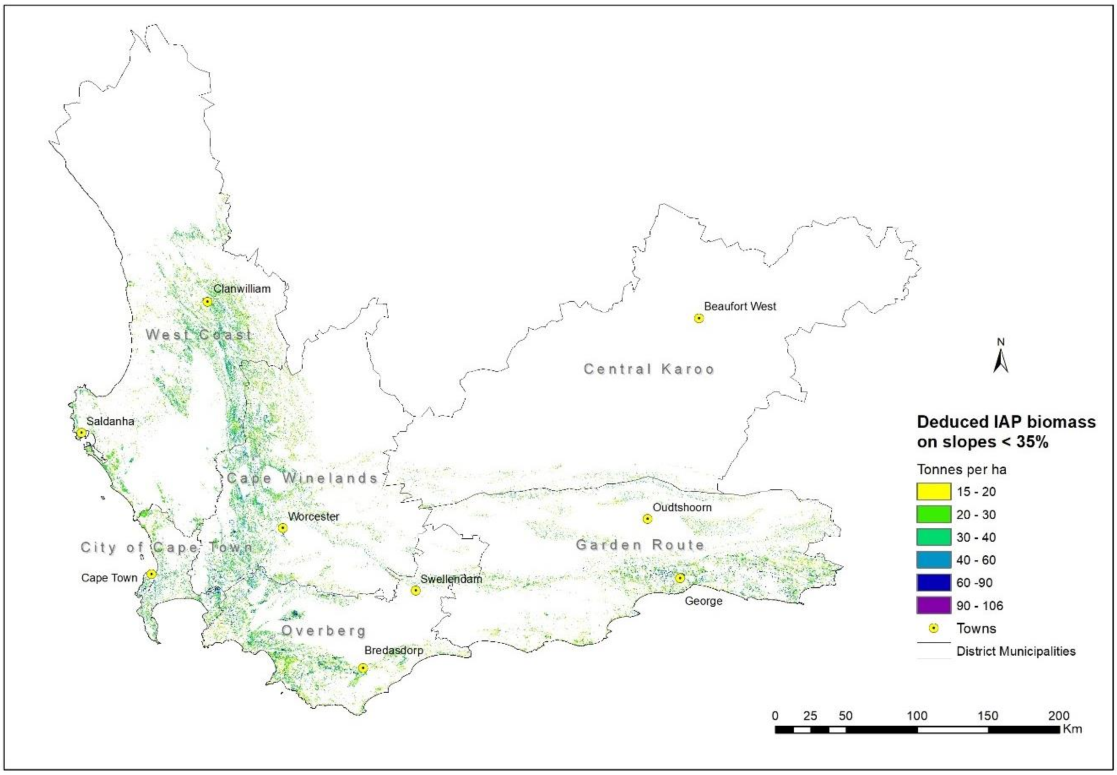


Figure 5 Deduced invasive alien plant biomass <35% slope for Western Cape

In the Eastern Cpe, there is a total of 59 633 346 oven dry tonnes (odt) of deduced invasive biomass, as shown in Table 5, but only 39 537 036 odt (66.3%) of the deduced invasive biomass in the province is considered accessible (<35% slope). Figure 6 shows the spatial distribution of the alien biomass in the Eastern Cape.

Table 5 Western Cape deduced invasive plant biomass

Eastern Cape Deduced IAP biomass by slope classes	Eastern Cape Deduced IAP biomass (odt)
0 - 10%	10 201 768
10 - 20%	12 330 788
20 - 35%	17 004 480
Total <35% slope	**39 537 036**
Total deduced invasive alien biomass in the province	59 633 346

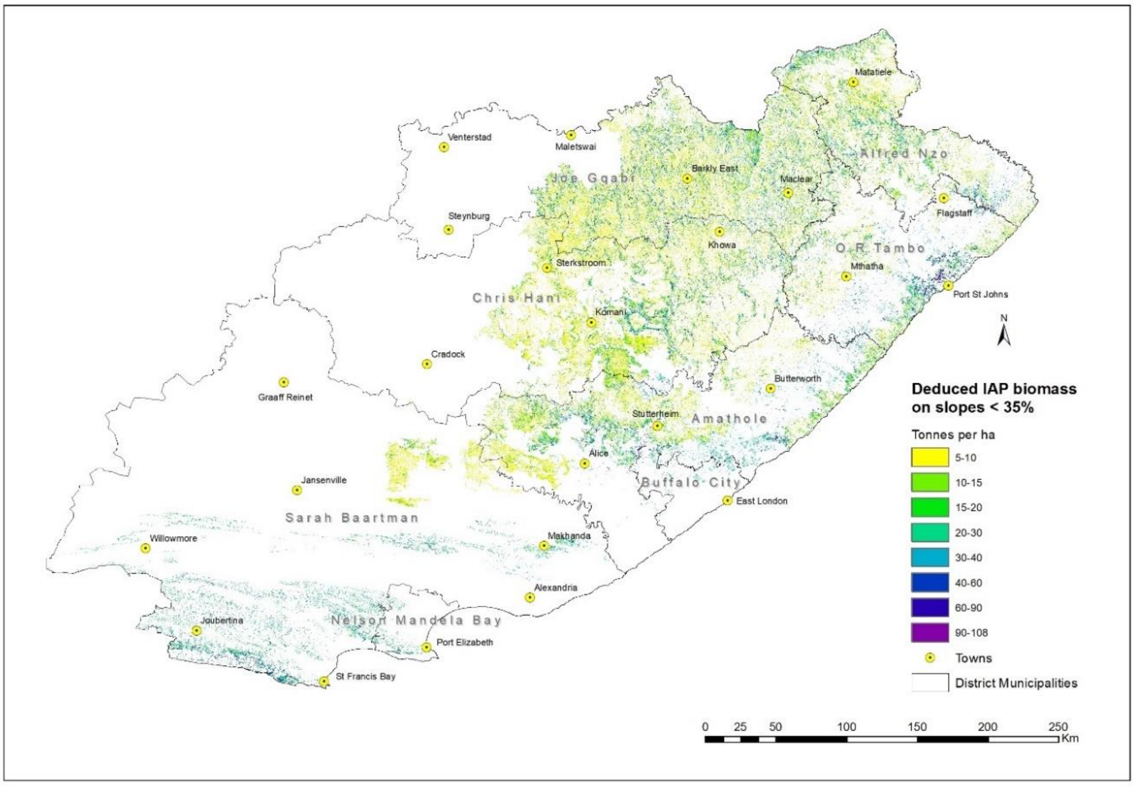


Figure 6 Deduced invasive alien plant biomass <35% slope for Eastern Cape

Together, the Western and Eastern Cape have more than 100 million dry tonnes of alien invasive biomass. By comparison, the most recent National Invasive Alien Plants Survey, now over a decade old, estimated the total amount of IAP biomass in these two provinces at about 65 million tonnes. The difference suggests a significant spread of infestation over the past decade and re-enforces the need to find a productive use for this biomass.

Over a third of the estimated alien biomass in the two provinces most likely to represent catchment areas for raw feedstock for conversion into ethanol as intermediary and further processing into SAF at PetroSA is easily accessible on slopes of up to 20% (37.1 million tonnes). An additional quarter is fairly accessible on slopes between 20 and 35% (26.7 million tonnes). Considering the annual requirement for lignocellulosic feedstock to produce enough ethanol to meet PetroSA's potential demand of 300 million litres is in the region of 1 – 1.5 million tonnes, the identified easily accessible biomass in these two provinces alone could supply enough raw feedstock for the required ethanol supply, even if any further spread of IAPs was fully contained.

Table 6 Total deduced IAP biomass in the Western and Eastern Cape provinces

Province	Total deduced invasive plant biomass estimate, 2018 (million odt)	Easily accessible (up to 20% slope)	Fairly accessible (20 to 35 % slope)
Western Cape	43	14.6	9.7
Eastern Cape	60	22.5	17.0
TOTAL	**103**	**37.1**	**26.7**

As the composition of the lignocellulose will affect the ethanol yield of the various ethanol conversion pathways, and hence SAF output, a species decomposition is needed. A detailed species mapping would require extensive ground truthing and is beyond the scope of a pre-feasibility. For this study, we rely on the average species break-down that was identified in the most recent NIAPS study (2010), that found plant invasions are dominated by certain tree genera. The most prominent species was found to be Acacia, which cover an estimated condensed area of more than 0.4 million ha, with the next most-extensive alien trees being Eucalyptus, covering 0.25 million ha and then Pinus, covering 0.12 million ha (NIAPS, Kotze et al 2010). Other invasive alien tree species include Hackea, Poplar, Prosopis etc. For the purpose of this project, the % composition can be assumed to be as shown in Figure 7 below: 52% Acacia, 32% Eucalyptus and 16% Pinus[7].

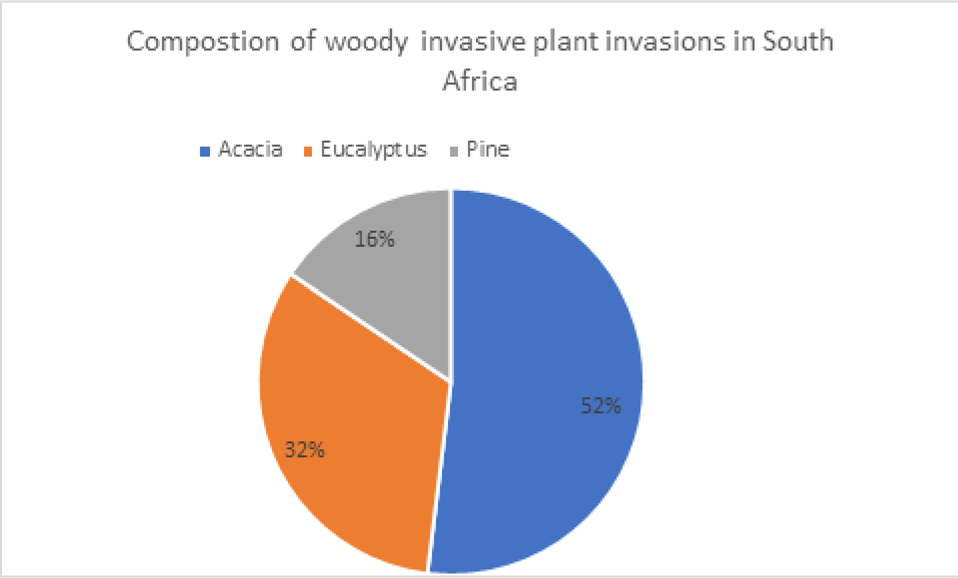


Figure 7 Species composition of woody invasive plant in the areas under investigation

3.3.3 Discussion

Since invasive plants need to be removed permanently in terms of relevant legislation, after clearing there should be no re-emergence or recruitment. In other words, invasive plants are not a renewable resource and a given area should only be harvested once, and then treated to prevent re-sprouting or re-seeding of invasive plants by follow-up treatments to comply with legislation and the imperative to eradicate listed invasive plants (NEM:BA). However, unharvested individual trees will continue to grow and the additional biomass from 2018 and into the future needs to be accounted for over the project lifetime (i.e. over 20 years of project lifetime). The mean annual increment (MAI) refers to the incremental growth of trees of forestry plantations and ranges from 2-22 m^3/ha/annum. For invasive trees we estimate the average MAI is 8m^3/ha/annum which is equivalent to approximately 5 odt/ha. Note that these values apply to dense forests and therefore can only be applied to dense invasions. Furthermore, since the invasive trees should not re-grow or re-emerge after clearing (to comply with legislation) the future growth will need to be accounted for in time-steps that follow a clearing and extraction plan to ensure that future supply estimates are maintained. The modelled biomass extraction rate will be impacted by the locality, removal rate and size selection criteria, as these will reduce the extent and density of available biomass in a particular area. In other words, after harvesting it is only the remaining biomass that grows so the future growth depends on which areas are harvested- when and where, as well as in which sequence.

An accurate assessment of the biomass available for extraction from a particular location would require an estimate of the area and the density at which the plants occur. The area covered by invasive biomass can be converted to condensed hectares if the density is known. At a national scale, the cover or density of invasions is approx. 16%. This can be converted to condensed hectares, i.e. 10 ha at 16% density is the same as 1.6 ha at 100%. After adjusting plant invasions to 100% cover or condensed ha, the annual increment of 5 odt/ha can be applied to plant

[7] This assessment of biomass would greatly benefit from the updated NIAPS in order to accurately identify the invasive plant component of biomass; this product is anticipated to be completed by the end of March 2021 (Andrew Wannenburg, pers commun).

invasions to account for future growth using standard equations to calculate compound growth or interest. An alternative approach is to assume that biomass >80 odt/ha is likely to constitute dense invasions or approaching 100% cover and to apply 5 odt/ha compound growth to these areas annually in order to capture individual tree growth, whilst not including recruitment and re-emergence of invasive plants (re-sprouting plants and germination of seeds in cleared areas and beyond).

There will also be unexpected loss of biomass in the future due to fires. In fire-prone vegetation types, the probability of fire generally increases with veld age, so the typical fire-return interval should be factored in to harvesting plans. Furthermore, plant invasions often increase the risk and intensity of wildfires. Therefore, biomass supply and harvesting should put in place management plans to reduce and manage these risks[8].

In addition, other factors may reduce the available amount of IAPs for SAF production, such as clearing operations and areas/biomass already allocated to other industries. Although on a national level both clearing and the current utilisation of alien biomass is minuscule relative to its potential, on a local level, the combined impact might be more pronounced.

To conclude, this desktop assessment of deduced invasive plant biomass provides an indication of amount and location of the main woody invasive alien plants in the Western and Eastern Cape provinces. The Western and Eastern Cape provinces which represent the most intuitive catchment areas for IAP biomass for conversion into SAF at PetroSA's refinery in Mossel Bay together hold over 100 million tonnes of biomass that needs to be cleared, of which about a third is estimated to be easily accessible on slopes up to 20% and about a quarter fairly accessible on slopes between 20-35%. This means that if an effective 20-year clearing plan was implemented, just the easily accessible IAPs in these two provinces could theoretically meet all the 1 – 1.5 million tonnes annual biomass requirements to produce enough ethanol to feed PetroSA's COD plant at its assumed ethanol processing capacity.

And while the availability on a provincial level is sufficient, the actual availability will on a local level will of course be reduced by access and logistics; namely the distance to road and the costs of extracting and delivering the biomass to the upgrading and conversion facilities, and competing uses. As invasive alien plant biomass is strictly a non-renewable resource, the biomass stock will need to be apportioned for harvesting over the project lifetime, taking into account any other secondary industries using IAPs as raw material. Future bankable feasibility studies will need to carry out more detailed and refined biomass assessments, including ground-truthing of biomass amounts and species identification, as well as competing demand for this resource.

Finally, it is worth noting that sourcing large amounts of biomass for conversion into ethanol for further processing into SAF will inevitably represent a significant logistical challenge. While transport logistics are addressed in Section 5, here it is worth raising the issue of having to collaborate with a large number of clearing operations and landowners to access the cleared IAPs, leading to potentially high transaction costs, which are not included in this pre-feasibility.

3.4 Woody crops

Beside existing available lignocellulosic feedstock in the form of alien biomass growing independently, woody biomass can also be produced in the form of woody crops. WWF has conducted an assessment into the potential of woody crops as part of its wider research into the sustainable biofuel potential form a variety of energy crops. Of these, miscanthus is the woody crop most widely used for energy production and is also well suited to the prevalent agro-ecological conditions in South Africa.

[8] The National Veld and Forest Fire Management Act, Act 101 of 1998 – administered by DAFF- is the most relevant piece of legislation that can be referred to support this as it sets out responsibilities and mandates of government and the private sector on fire prevention and fire management, see http://landworksnpc.com/wp-content/uploads/2018/05/A-Guide-to-IFM_Complete_Display.pdf

Miscanthus is a perennial crop with high yield potential for cellulose fibre production. From the second season onwards, it grows to a height of 2.5 – 3.5 m and is productive for over 15 years (up to 25 years), which compensates for the relative high cost of planting material. Bio-energy feedstocks for second-generation technology chains produce relatively high energy yields with modest use of agro-chemicals and low tillage intensities. Miscanthus can be grown on a wide range of soils from sandy to clay soils as well as on peat soils. However, it does not tolerate prolonged dry periods or periods with stagnant water; its biophysical requirements are similar to those for maize.

Giant miscanthus, *Miscanthus x giganteus*, a hybrid of *Miscanthus sinensis* and *Miscanthus sacchaiflorus* is an important non-invasive species with similar ecological requirements and productivity compared to *Miscanthus sinensis*. The research commissioned by WWF South Africa identified almost 600 000 hectares of suitable and very suitable land for cultivation of giant miscanthus without impacting on food production, water availability, or highly biodiverse areas (WWF, 2019). If moderately suitable areas are included, the potential cultivation areas expand by an additional 1.7 million hectares. The red shading in Figure 8 shows the areas in South Africa that are suitable for cultivation of this woody crop.

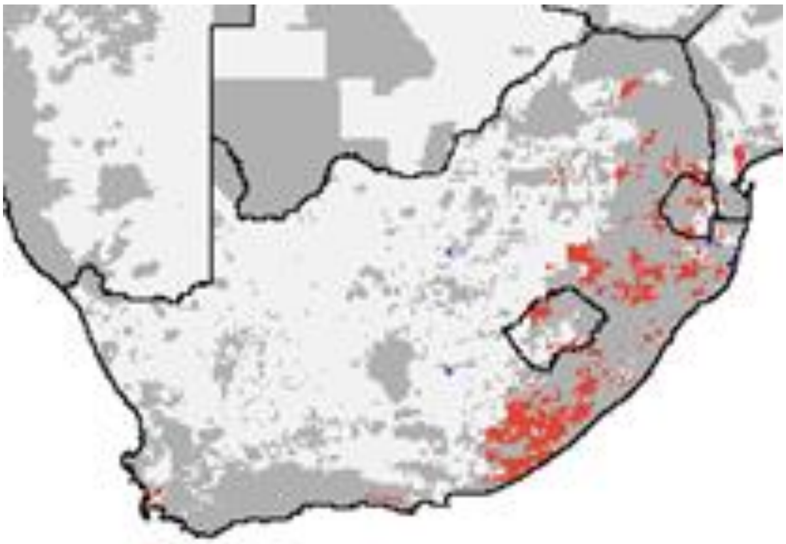


Figure 8 Potential miscanthus cultivation areas

If the sustainable miscanthus potential for production of SAF was fully exploited, it could provide approximately 6.6 billion litres of fuel per annum. Interestingly, the future potential for miscanthus production in South Africa is estimated to grow slightly, as opposed to most other regions in sub-Saharan Africa, where it is expected to decline.

While acknowledging this significant potential, because of the lack of experience with growing miscanthus in South Africa, and the major ecological gains of using invasive biomass as feedstocks for 2G ethanol production, we do not further consider this woody crop in this pre-feasibility. Should the ethanol market in South Africa grow significantly beyond its current prospects however, miscanthus and other woody crops could be re-considered as viable feedstocks for the longer-term development of the sector.

3.5 Garden waste

Garden waste is another under-utilised resource in South Africa, taking up valuable landfill space instead of being utilised as a highly sustainable, easily exploitable source of lignocellulose, considering it is already delivered in significant quantities to single locations by municipal waste management services. Apart from the high landfilling cost, landfilling is also recognised as an unsustainable waste management practise, since it can lead to uncontrolled release of GHGs (i.e. CH_4) to the atmosphere and the pollution of underground water bodies due to the leaching of garden waste contaminants. Employing garden waste as a feed for ethanol production is therefore anticipated to lead to favourable environmental outcomes both in terms of waste management and climate impact.

While municipalities in South Africa are meant to keep waste inventories, their availability is patchy and the quality is inconsistent, making comparisons and tallying difficult. For municipalities in the immediate vicinity of Mossel Bay, including Mossel Bay itself, the overview of garden waste, where data is available, is presented in Table 7, for the latest available full year[9].

Table 7 Garden waste availability in municipalities closest to PetroSA refinery

Municipality	Year	Waste classification	Weight (tons/a)
George	2019	GW20 – organic waste	3 306.6
Mossel Bay	2019	GW2001 – organic waste (garden waste)	7 327.5
Knysna	2019	GW2001– organic waste (garden waste)	210.9
TOTAL			16 418.8

From the available data it appears that up to approximately 16 000 tonnes of garden waste could be available in the immediate vicinity of PetroSA's refinery in Mossel Bay. Unfortunately, the George municipality does not seem to differentiate between fractions of organic waste, and the figure reported here is for total organic waste, of which garden waste is a non-identifiable fraction. Nevertheless, these figures are broadly in line with the approximately 19 300 tonnes per year of garden waste that is collected in the greater Garden Route District Municipality, as identified by the organic waste characterisation study undertaken by the District Municipality itself[10].

Based on the above, we make the conservative assumption that some 16 400 wet tonnes (or 12 139 dry tonnes) per annum could be available as feedstock for a potential ethanol plant in Mossel bay. Considering a typical size ethanol plant would require some 300 000 tonnes of feedstock per annum, the available garden waste represents approximately 5% of such a plant's feedstock demand.

3.6 Industrial waste gasses

South Africa's significant base of heavy industry also presents a unique opportunity for carbon recycling via the utilisation of CO (carbon monoxide)-rich industrial off-gases as feed for third generation (3G) ethanol production. The primary sources of these gases 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. CO is a poisonous gas, and it is flared in typical smelter operations to produce CO_2, which is a greenhouse gas. The conversion of the industrial off gas to ethanol is achieved under the action of specially engineered microbes.

The quantities of off-gasses available at some smelter sites were found from publicly available CO emission reports. An example of such reports is the CDM project design report for Hernic Ferrochrome (CDM EB, 2011). In the cases where direct CO emission data could not be found, metal production quantities at each site, together with off gas yield data available in literature, where used to estimate the off-gas potential. An average waste gas composition based on the typical composition of a South African ferroalloy smelter[11] (Swedish Stirling, 2020) was used to estimate the ethanol production at each site using Aspen modelling (see Table 8). The waste-gas sources identified have the potential to produce 410 million litres of ethanol, which is more than enough to meet PetroSA's requirements of 300 million litres ethanol per year.

[9] The data presented here is based on the Integrated Pollutant and Waste Information System (IPWIS).
[10] Personal communication with the District Waste Management Director or the Garden Route District Municipality.
[11] Swedish Stirling (2020), Product Information. Available online at: https://swedishstirling.com/wp-content/uploads/Swedish_Stirling_PWRBLOK_400-F_SV_web_version.pdf

The geographic distribution of potential production sites for ethanol from industrial off-gasses is shown in Figure 9.

Table 8 Overview of industrial waste-gas sources and ethanol production potential

Company Name	City/Town	Industry	Off gas production		Ethanol production (ML/yr)	
			Nm³/h	tons/yr	with external energy	Self-sufficient plant
Richards Bay Minerals	Richards Bay	Smelter (Titania Slag)	17 268	147 058	29	20
Tronox, Namakwa Sands	Saldanha Bay	Smelter (Titania Slag)	11 898	101 326	20	14
South32, Metalloys	Meyerton	Smelter (Fe-Mn)	41 585	354 149	69	48
Afarak, Mogalle Alloys	Krugersdorp	Smelter (Fe-Chrome)	10 396	88 537	17	12
ArceloMittal Works (SS)	Vanderbijlpark	Smelter (Fe-Chrome)	47 565	405 072	79	54
ArceloMittal Works (SS)	Newcastle	Smelter (Fe-Chrome)	20 385	173 602	34	23
AssMang Carto Ridge	Carto Ridge	Chrome	6 453	54 954	11	7
Samancor - DCR	Brits	Smelter (Fe-Chrome)	25 400	216 313	42	30
Samancor - Ferrometals (FMT)	Witbank	Chrome	22 400	216 005	42	30
Samancor - MFC	Middleberg	Smelter (Fe-Mn)	28 600	250 899	49	34
Samancor - TCS	Mooinooi	Smelter (SS)	21 600	183 951	36	25
Samancor - TAS	Steelpoort	Smelter (SS)	25 558	217 654	42	29
Glencore Xstrata Alloys	Boshoek	Smelter (SS)	19 926	169 696	33	23
Glencore Xstrata Alloys (Lion Smelter)	Steelpoort	Smelter (SS)	29 456	250 856	49	34
Glencore Xstrata Alloys	Lydenburg	Smelter (SS)	23 790	202 602	39	27

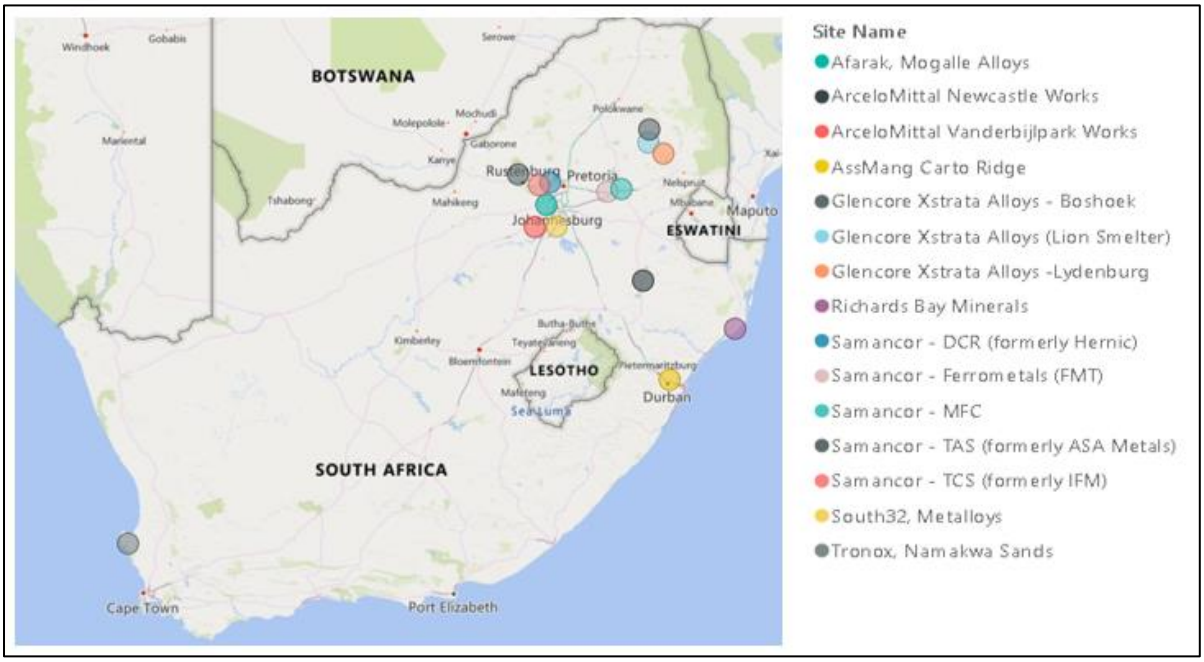


Figure 9 Potential sites for production of ethanol from industrial off-gas

3.7 Sustainability risk assessment

Despite something being classified as a "waste", it does not mean that its utilisation for energy purposes poses no environmental or social risk. A high-level assessment of sustainability risks associated with the different candidate feedstocks has therefore been undertaken to flag possible areas of concern. In addition, the potential of feedstocks to be classified as having a low risk of causing indirect Land Use Change (iLUC) was considered, since this minimises additional emissions not accounted for in the current life-cycle accounting practices.

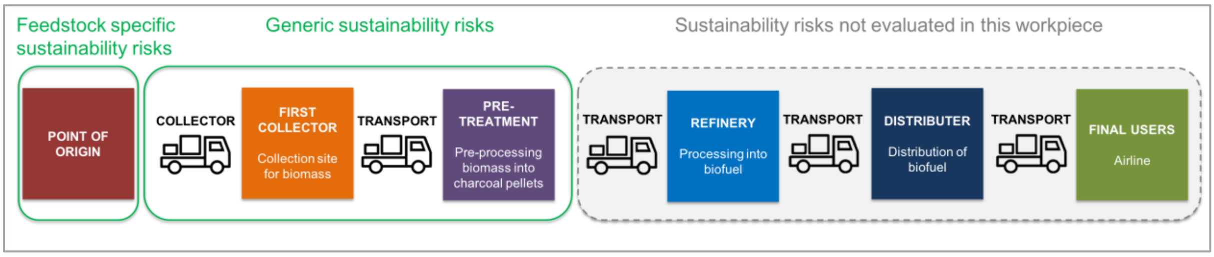
This sustainability risk assessment follows closely the work undertaken by the Roundtable on Sustainable Biomaterials (RSB)[12] under the Waste to wing project, which conducted a pre-feasibility for production of SAF at Sasol's Secunda facility[13]. As the gold standard of bioenergy sustainability, as well as the certification scheme preferred by the aviation sector, the RSB principles were used to assess sustainability risks associated with feedstocks that are being considered for PetroSA, with significant overlaps between the two facilities.

The scope of the sustainability risk assessment is limited to the production of the biomass feedstock and its pre-treatment, as shown in Figure 10.

[12] https://rsb.org/

[13] Bole-Rentel, T et al (2019): Optimising waste biomass supply for production of sustainable aviation fuel in South Africa, Waste to wing WP1 summary report, available on https://dtnac4dfluyw8.cloudfront.net/downloads/w2w_wp1_summary_report_final_21082019.pdf

Figure 10 Scope of the sustainability risk assessment



The biomass types included in the assessment were:

- Molasses
- Sugarcane bagasse
- Garden waste in major urban centres
- Cleared invasive alien species
- Woody crops (miscanthus)

The sustainability risk assessment is conducted against the RSB's sustainability criteria, that are summarised in Figure 11.

Figure 11 The sustainability principles of the Roundtable on Sustainable Biomaterials

The summary of key results for each biomass feedstock analysed are presented in Table 9 below. The table also identifies whether the biomass would qualify as a 'low iLUC' feedstock, namely a feedstock whose utilization has a low impact on indirect land use change.

Table 9 Summary of sustainability risks for the assessed feedstock candidates

Sustainability risks	Low iLUC	Overall risk
Molasses		
Molasses are a co-product or by-product of the sugar production process. The A-molasses considered in this study are a former, which means they reduce the sugar output of the mill. If the sugar market was a tight one, this could potentially lead to direct land use change through expansion of the sugar cane plantation, however, considering the global sugar glut, this is a highly unlikely outcome, at least in the short-to-medium term. On the other hand, as a co-product, molasses bear a proportion of the impacts of sugar cane production, especially with regard to local water impacts and GHG emissions. The latter are on average high in the South African context where irrigation is powered with coal-dominated grid electricity and where fields are routinely burnt prior to harvesting. This might make it challenging for the SAF manufactured from molasses-based ethanol to achieve the minimum GHG savings required for sustainability certification.	No	Medium
Sugarcane bagasse		
There is currently virtually no available sugarcane bagasse in South Africa, as all available volumes are being utilised for electricity co-generation at the sugar mills and for animal feed production (mixed with molasses). The displacement of sugarcane bagasse from above uses is expected to increase fossil fuel and other biomass demand, thus likely lead to increased GHG emissions and indirect land use change. The above risks could be significantly mitigated in the future should the sugarcane industry increase boiler efficiencies and introduce green harvesting methods.	No	High
Garden waste		
Although not reliable, available data on garden waste volumes show that only 40% of garden waste is currently used (i.e. for composting or biogas production), while the majority of it, 60%, is landfilled. Due to it being mostly landfilled, garden waste can qualify as a feedstock with low indirect land use change. This status may however change in the future in light of national waste diversion plans aimed to save landfill space, and the commercialisation of organic waste.	Yes	Low
Invasive alien plants		

Eradication operations may damage biodiversity and surrounding ecosystems through the release of chemical and biological agents contained in herbicides and other chemical control products, and through eradication over the boundaries of a farm (incentivised by demand for this feedstock). Inadequate actions taken to control and eradicate invasive species could lead to the risk of regeneration and propagation. The widespread use of subcontractor for eradication on agricultural farms bears the risk of poor labour rights. Changes to land use can result in a net negative carbon flux. If after IAPs have been eradicated the cleared land is turned to conventional commercial agriculture, there will be a loss of carbon with negative impacts for the climate. Conversely, if the cleared land is restored to indigenous forest, there will be a saving of carbon if the biomass is used for production of SAF.	Yes	Medium
Woody crops - miscanthus		
The perennial grass *Miscanthus* × *giganteus* seems to present a significant potential as energy crop, although this is only theoretical, as there is yet no experience with its cultivation in South Africa. Theoretical cultivation potential indicates that it would be well adapted to prevalent agro-ecological conditions in certain areas of the country, which would allow significant yields based on rain-fed agriculture only. As a perennial crop, it does not require annual tillage, which contributes to accumulation of soil carbon, in addition to the carbon accumulated in the non-harvested part of the crop. All this contributes to a favourable GHG balance for the fuel that is manufactured from this crop. While usually cultivated as a sterile hybrid, fertile varieties are being developed to reduce establishment costs, leading to concerns about potential invasion outside production fields. A full experimental demonstration of low invasiveness in the target region ahead of commercial production, along with post-introduction stewardship programs would be required to minimise risk of unplanned invasion of natural areas. Large-scale commercial cultivation would be prone to social risks associated with exploitation of agricultural workers. If miscanthus plantations caused land use change from indigenous forest or other high carbon stock to commercial plantation, that would significantly reduce or even negate any GHG benefits of the fuel.	No	Medium

The conclusion from the sustainability risk assessment is that garden waste and IAP that are eradicated following suitable ecological and social protocols are the obvious feedstocks to start with, as they are both available in significant quantities in specific locations and pose the lowest sustainability risks, including risk of indirect land use change. We did not conduct a specific risk assessment for industrial waste gasses, as we do not foresee any substantive issues.[14]

4 Comparative techno-economic analysis of alternative ethanol production routes

In order to continue with production at Mossel Bay, the use of renewable bio-ethanol has been identified as a viable intermediate product that could be employed upgraded to high-value products (i.e. jet fuels and speciality products), by utilising the refining equipment currently available at the Mossel Bay plant. This renewable ethanol is generated from biomass either via fermentation of biomass-derived sugars or the fermentation of syngas produced after biomass gasification. Alternatively, ethanol produced from industrial off-gases will also be considered. Recognising therefore the abundance of biomass resources in South Africa, this pre-feasibility study investigates the economic performances of processes employing the feedstocks of invasive alien plants (IAPs), sugarcane, garden waste and industrial off gases in the sustainable production of ethanol.

Figure 3 shows that the pre-feasibility assesses ethanol production via integrated processes of a) hydrolysis of biomass prior to a sugar fermentation step, b) gasification of biomass prior to a syngas fermentation step and c) an off-gas fermentation process. These technologies may be broadly classified as 1st generation (1G), such as the sugar juice/molasses conversion to ethanol, 2nd generation (2G), such as lignocelluloses from sugarcane, IAP or garden waste conversion to ethanol, combined 1st and 2nd generation (1G-2G), where both sugarcane juice/molasses and sugarcane bagasse are converted to ethanol at the same site and 3rd generation (3G), in our case the conversion of industrial off-gas to ethanol.

4.1 Approach

During the technoeconomic assessment study, the following basic steps were applied:

1. To feed the jet-fuel production process at PetroSA a suitable ethanol production rate was specified as 300 million litres (ML/y) per year.
2. From this, the required feedstock for the alternative ethanol production scenarios that can supply the 300 ML/y of ethanol was determined, as well as the number of plants needed to deliver the target ethanol supply.
    a. For industrial off-gas, the quantity of available feedstock is determined by the number of industrial sites that produce an off-gas with sufficient CO-content for conversion to ethanol.
    b. For sugarcane-based ethanol, the amount of feedstock available is considered in terms of the material flows in a typically-sized sugarcane mill, with A-molasses and lignocelluloses considered as potential feedstocks.
    c. Based on the review of industrial technologies for ethanol production from IAP and garden wastes, a suitable scale of industrial processing equal to 300 000 tons (dry weight) per year of lignocelluloses was identified (equivalent to 428 600 tonnes per year of chipped material at a moisture content of 30%). A number of industrial conversion technologies for lignocelluloses converge at this scale, and each processing facility will be designed accordingly.

[14] See RSB's sustainability gap analysis of South African sugar cane ethanol as feedstock for SAF production, available on https://rsb.org/wp-content/uploads/2020/10/Sugarcane-report_Part-II-Gap-analysis_compressed.pdf

d. All of the ethanol production scenarios/technologies depend on a number of different production sites, for which the cost of supply of feedstock, cost of conversion to ethanol and cost of ethanol transport to PetroSA in Mossel Bay, are to be combined to find the lowest-cost options.

3. Ethanol production processing models for the various scenarios were developed and simulated in the ASPEN (Advanced System for Process Engineering) plus® V10 process simulator (Aspen Technology Inc., Cambridge, MA, USA).
4. Classic chemical engineering plant design and economics assessment methods were integrated with the ASPEN plus simulation results and the economics of the different conversion technologies.
5. The minimum ethanol selling price (MESP) that will provide an acceptable return on a private investment in a manufacturing facility was selected as the preferred metric for assessing comparative economic performances[15]. The MESPs for the different ethanol production scenarios were calculated "at the factory gate," with subsequent fuel transport costs to be considered by other participants in the consortium. In a final step, the assessed conversion technologies were ranked in terms of the MESP of ethanol.

4.2 Assumptions

<u>Energy balances & operating time</u>

Sugar mill scenarios are assumed to be energy self-sustaining, while off gas fermentation is configured either with buy-in of external electricity for maximum ethanol (M.E.) output or as energy self-sustaining (S.S). In the latter case, all of the process energy demands (steam and electricity) are obtained from the feedstock, by using residues from the ethanol production process, and/or bypassing a portion of the available feedstock to energy supply sections of the plant. It is important to note that in the maximum ethanol scenarios using grid electricity to meet process energy demand will substantially impact the GHG footprint of the product (ethanol).

In the sugarcane 1G and 1G-2G technology option, the energy balance of the 1G, and 1G-2G ethanol production from cane sugars was based on an assumed capacity of the existing combined heat and power islands at sugar mills in South Africa, fed by bagasse and trash. The boiler pressure is set at 45 bars for a maximum generating capacity of 0.5 tonne of steam per tonne cane, while the sugar mills operates at 0.4 tonne steam per tonne cane. Therefore, the excess steam generating capacity is then directed to the steam needs of the ethanol production. The steam is expanded to 4 bars for electricity generation, and the demand of the sugar mill of 40kW per tonne cane is firstly subtracted, and the excess electricity is used for the electricity demands for ethanol production. The excess steam demands of ethanol production that is above this installed generation capacity is provided by a low-pressure utility boiler, fed by sugarcane residues. In the case of the 1G-2G, the low-pressure utility boiler is also fed with the fermentation residue. Additional generating capacity is provided by gas engines, fed by biogas provided by the digestion of the beer stillage.

In the 2G IAP and garden waste ethanol production case via hydrolysis-fermentation, the steam demands of ethanol production from IAPs via hydrolysis fermentation is generated by feeding the solid residue after fermentation to low pressure utility boilers. Onsite electrical generating capacity is provided by gas engines, fed by biogas provided by the digestion of the beer stillage. For the 2G IAP and garden waste conversion to ethanol via gasification for syngas production prior to fermentation, and in the 3G off-gas fermentation situation, steam is generated by a heat recovery steam generator installed on the stacks of furnaces that combusts the spent syngas/off-gas. The electricity demands for ethanol production are generated by diverting a portion of syngas/off-gas towards a gas engine. Additional fuel for energy production is provided by the digestion of an effluent stream that results from purging 10% of the recycle stream between the distillation column and gas fermenter.

[15] The acceptable IRR is assumed to be 20%.

Lastly, to ensure consistency with the previous approach taken by the Biorefinery Research Group at Stellenbosch University, within the group the operating time of 6480 h/ y (Diederichs et al, 2016; Farzad et al., 2017; Mandegari et al., 2017a; Mandegari et al., 2017b) for all sugarcane scenarios has been specified, considering that sugarcane mills do not operate for the full year. For the other feedstocks of IAPs, garden waste and industrial off gases, the operational time of 8000 h/y has been assumed.

Feedstock acquisition cost

For the feedstocks of sugarcane juice, sugarcane bagasse and molasses, in-house numbers sourced from Stellenbosch University's previous work have been employed as inputs in the determination of the MESPs of the different ethanol production scenarios. The values employed and their associated sources are presented in Table 10 and are based on several rigorous assessments of sugarcane mills performed by Stellenbosch University in previous projects.

Table 10 Sugar cane-based feedstock costs

Feedstock	Cost (US$/kg)	Source	Source year	Cost in 2019 (US$/kg)
Sugarcane residues	0.011	Petersen et al., 2014	2012	0.016
Molasses	0.13	Wamucii, S., 2020	2020	0.130

The costs of acquisition of IAPs includes eradication (harvesting), extraction from clearing site and chipping, prior to transport to the ethanol production plants. To estimate the acquisition cost for this feedstock we combined a number of quotes we received from public (Working for water) and private clearing operations, as summarised in Table 11.

Table 11 IAP feedstock acquisition cost estimates from private quotes[16]

Quote	Component of the cost	ZAR/tonne
1	Collection, delivery to 5km grid-point and chipping	903
2	Collection and delivery to 5km	208
3	Eradication, extraction and chipping	1089
4	Eradication and extraction	1000
Total cost: eradication → extraction → collection → chipping → delivery		
Lower	3+2	1297
Upper	1+4	1903
Average	rounded	**1600 (105 US$/ton)**

Based on the quotes received, the estimated lower end cost of alien invasive plants eradication and chipping at the clearing site was R1089/tonne. Adding in the transportation cost of R210/tonne to deliver the chipped biomass to roadside from which it can be transported to the ethanol plant, yielded the lower estimate for feedstock acquisition cost of R1299/tonne. On the other hand, the most expensive clearing cost was quoted at R1000/ton, to which we added collection, chipping and delivery costs of R961/tonne. Thus, the upper limit of feedstock

[16] Company details hidden for trade competitiveness protection.

acquisition cost ready for collection at the roadside added to R1961/tonne. For the purpose of this analysis we use an average total cost of R1630/tonne[17].

The feedstocks of industrial off gases and garden waste have been assumed to be available for free since they are currently recognised as waste streams responsible for unfavourable environmental outcomes via GHG emission and landfill disposal, respectively. The Mossel Bay landfills an annual amount of garden waste equal to 16 kilo tonne (wet mass), with only 90 % available for conversion to ethanol. This implies that some 14 kilo tonne (dry mass) of the garden waste could be available annually for ethanol production in Mossel Bay. To ensure all processes remain reasonably comparable, additional IAP biomass was combined to the garden waste stream such that a 300 kilo tonne/y feed rate (dry basis) specified for the mixed IAP-garden waste feedstock scenario was maintained in Mossel Bay.

4.3 Results

Based on the mass and energy balance data extracted from ASPEN plus and employing well-known economic relations, a discount cash flow table was developed and the associated MESP for the different ethanol production configurations determined and shown in Table 12.

Table 12 Summary of CAPEX and OPEX of different ethanol production processes

Ethanol scenario	Process Energy Supply	Feedstock	Mass (kton/y)	Ethanol (ML/y)	CAPEX (Million Rand)	OPEX excluding feedstock costs (Million Rand)	Net electricity (MW)
Sugarmill 1G	Self-Sustaining	Molasses	165	81.76	585	90	-
Sugarmill 1G-2G	Self-Sustaining	Molasses	165	147.62	1830	435	-
	Self-Sustaining	Sugarcane Residues	421				
2G - Hydrolysis fermentation	Self-Sustaining	Invasive alien plants*	304	98.04	1770	570	5.7
2G Gasification Fermentation	Self-Sustaining	Invasive alien plants*	304	52.27	3225	330	0.4
	Max. Ethanol		304	99.58	2850	480	-18.9
3G Off-gas fermentation	Max. Ethanol	Industrial off-gas	336	59.90	825	270	-8.9
	Self-Sustaining		336	38.18	930	345	0.3

**The invasive alien plants in the 2G scenarios can be substituted up to 10% with garden waste without significantly impacting the MESP.*

The results presented in Table 12 show that the highest volume 147 Ml/year is the achieved by using both molasses and residues in the integrated 1G-2G scenario at the sugar mill, which is about 80% higher than using only molasses in the 1G scenario.

[17] It has recently come to our attention that other studies assessing the viability of using alien biomass for pellet production use considerably lower feedstock acquisition costs. Those figures were supposedly derived from clearing operations around the Port Elizabeth region. We have not been able to independently verify those, but lower feedstock acquisition costs would have significant impact on the relative economic attractiveness of IAP-based ethanol.

When observing the 2G scenarios, the highest production is obtained when the gasification-fermentation processing route is optimised for maximum ethanol production mode, achieving almost 100 Ml/year, which was 2% higher than the hydrolysis-fermentation route, but which the important caveat that the latter output comes from an energy self-sufficient process, whereas the former needs substantial energy imports. In fact, the yield from the gasification-fermentation scenario is reduced to 52 Ml/year when operating in an energy self-sufficient mode. It is similarly observed for the 3G off-gas fermentation scenario that the production drops from 60 to 38 Ml/year when operating in an energy self-sufficient manner. Thus, self-sufficient operation requires ~ 45 wt. % of the off-gases be used for onsite electricity production.

It may be said that energy self-sufficiency is implicit in the hydrolysis-fermentation case, whereas gasification-fermentation offers the options of either producing maximum ethanol or being self-sufficient. For hydrolysis-fermentation, only the carbohydrates in the biomass fractions are converted to ethanol, leaving a solid lignin residue that is used for steam generation. The pre-treatment and the fermentation steps also generate residual soluble sugars streams, that can be converted to electricity. On the other hand, gasification converts the entire biomass into a fermentable syngas. Thus, there is the option to ferment the entire syngas stream for a maximum ethanol production mode, or the option of diverting a portion of the syngas towards steam and electricity generation in order to satisfy the processing needs. Evidently then, the use of syngas to generate process energy needs will lower its availability for ethanol production.

Figure 12 shows the minimum ethanol selling price (MESPs) of ethanol for the production pathways whereby the ethanol facility is co-located with the source of the feedstock, in our case sugar mills and industrial off-gas production sites. A sugar mill producing ethanol just from A-molasses through the 1G process of fermentation has the lowest MESP ex factory gate at R8.27/l, since it has the lowest CAPEX and OPEX expenditures at 585 and 90 million South African Rands (ZAR), respectively. Due to higher OPEX and CAPEX of the 1G-2G scenario, the MESP increases to R9.47/l. The off-gas fermentation scenarios have MESPs of R9.90/l and R13.50/l for the maximum ethanol production and self-sufficient routes, respectively. Therefore, even though gases are available at a cost of R0/kg, its low ethanol yield and large requirements of electricity for gas processing, do not allow for cheaper specific production costs.

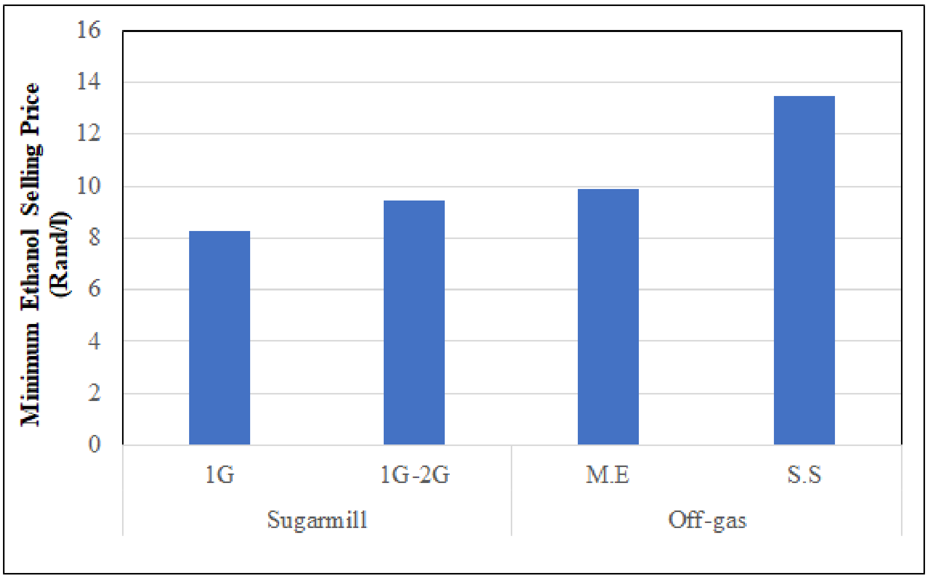


Figure 12 Minimum selling prices of ethanol for sugar mill and off-gas scenarios

Figure 13 and Figure 14 show how the MESP changes for the 2G production pathways where feedstock transportation costs also need to be taken into account. For the 2G hydrolysis-fermentation costs (Figure 13), the

MESPs range from a zero-value feedstock cost at R10.83/l to R18.55/l at a feedstock value at R2500/t. On the other hand, the MESPs of the 2G gasification-fermentation costs (Figure 14) range from R13.71/l - R21.34/l for the maximum ethanol production mode, and R23.77/l - R38.31/l for the self-sufficiency mode, again depending on the cost of the delivered feedstock.

Where in this range the actual MESP at the gate of PetroSA's facility in Mossel Bay will fall depends on the transport costs that will be calculated in Section 5 and added to the average feedstock cost presented in Table 11 and the processing costs (which equal the MESP at zero value feedstock cost) in Figure 13 and Figure 14.

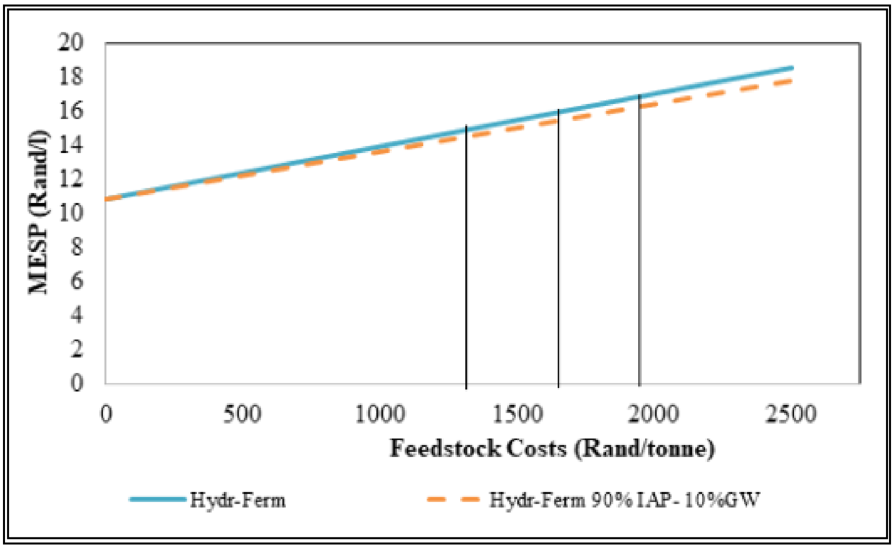


Figure 13 Minimum selling prices of ethanol for 2G hydrolysis fermentation process for different feedstock acquisition costs

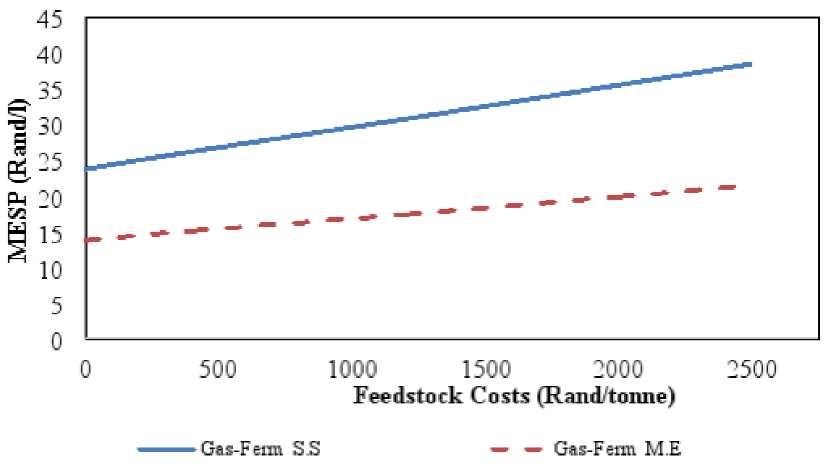


Figure 14 Minimum selling prices of ethanol for 2G gasification-fermentation process for different feedstock acquisition costs

Based on the results generated from the work above as well as technical information obtained from literature, some salient differences between the candidate ethanol production technologies can be identified, which are presented in Table 13.

Table 13 Salient differences between the different ethanol production technologies

	Ethanol production technologies			
Parameters	**1 G ethanol production (hydrolysis-fermentation)**	**2G ethanol production (IAPs, garden waste, sugarcane residues) (hydrolysis-fermentation)**	**2G ethanol production (IAPs, garden waste) (gasification-fermentation)**	**3G ethanol production (industrial off gases)**
Economic	Best economic performance based on the MSP of ethanol in an energy self-sufficient scenario	Third favourable	Least favourable	2nd best economic performance based on the MSP in an energy self-sufficient scenario
Maturity	Technologically mature configuration	Technologically mature configuration	New advanced technologies	New advanced technologies
Fermentative organism	Utilises well-known yeast microbe *Saccharomyces Cerevisiae*	Requires specialised and genetically modified *Saccharomyces cerevisiae; Pichia stipites* microbe	Requires specialised *Clostridium ljungdahlii* and *Clostridium carboxidivorans* microbes	Requires specialised *Clostridium ljungdahlii* and *Clostridium carboxidivorans* microbes
CAPEX	Typically less costly hydrolysis and fermentation processes compared to lignocelluloses	Typically requires a higher cost pre-treatment step prior to the hydrolysis and fermentation processes	Typically involves a high-cost gasification step.	Free available off gases are utilised leading to lower overall costs

4.4 Important considerations

Although the present study highlights a comprehensive comparative study of the economic performances of different ethanol production scenarios while also employing different biomass resources, some crucial considerations may be noted as follows;

- Economic parameters: The models developed have been based on several underlying assumptions such as the operating time, production capacity, plant lifetime etc. These assumptions are important, as they determine the economic performance of the proposed plants. Crucially however, to limit issues, validated assumptions, based on our historical knowledge, industry data and our expertise in the area have been employed. Additionally, the assumptions included were universally imposed on all scenarios considered such that the results of the study remain comparable.
- Feedstock composition: The garden waste feedstock, unlike the IAP feedstock does not have a representative composition, more so as its composition is not only unclear but also continuously changes, with location and season. Recognising the significant variability of the garden feedstock, attempts were made to present a pseudomodel composition based on the reported garden waste constituents of twigs, fruits and possible food waste. It was assumed that these constituents contributed equally to the garden waste feedstock. Due to the absence of a validated garden waste composition, we anticipate some difficulties in the economic outcomes of the garden waste conversion to ethanol scenarios reported earlier above. Regardless of this limitation, the consideration of the garden waste as a possible feedstock for ethanol production was retained in the study since it reinforced some salient information regarding the dependence of the economic performance on polysaccharide content. The effect on the economic performance of introducing a low polysaccharide containing feedstock into a high polysaccharide content feed, was also clearly highlighted in the study. It must be emphasized that future work should present the experimentally determined composition of locally sourced garden waste as a feedstock for ethanol production to limit issues associated with compositional uncertainties.
- The MESPs of gasification-fermentation and off-gas were shown to improve through an assumption that renewable, "baseload" electricity is available to these facilities. Such renewable electricity can typically be bought-in at a cost of R1.20/kWh and may then be used for various process energy demands. Such 'electricity buy-in' situations are typically characterised by higher ethanol yields, due to more feedstock being available for conversion. The energy self-sufficiency approach applied in this report provides a robust method of economic comparisons of feedstock conversion methods, giving a realistic view on the inherent efficiency and reliability of technologies, while also avoiding complications with external energy sources used for biofuels production, an area that has caused much difficulties for the ethanol industry in the past.

4.5 Discussion

The analysis presented in this section highlights the dominance of feedstock cost, feedstock nature and technological configurations in the determination of economic performances of ethanol production pathways. The key insights derived from the techno-economic analysis of the selected ethanol production pathways are:

- The economic performance of the ethanol production system that employs off-gas as a viable feedstock for ethanol production was enhanced by the absence of feedstock cost, while the disproportionately large demand for electricity creates a disincentive in the energy self-sufficient scenario.
- Sugarcane ethanol based on juice/molasses (1G) provided a cost-effective alternative, with few modifications required to sugarcane harvesting and processing. A more advanced approach to sugarcane-ethanol, incorporating upgrades in energy efficiencies to sugarcane mills and collection of under-utilised harvesting residues, provided a low-cost approach to ethanol production from lignocelluloses in the 1G2G scenario.

- IAPs conversion to ethanol via the hydrolysis-fermentation approach was preferred to gasification-fermentation, due to the anticipated high cost of the latter. Most of the process scenarios could be improved further through external energy sources such as renewable electricity. Many of the industrial sites where suitable off gas is available for processing, are located more than 1000km from Mossel Bay, indicating that transport costs may determine which of the ethanol production options will deliver the lowest cost to PetroSA.

Because of the relatively low potential ethanol demand by PetroSA (300 million litres per annum), only a sub-set of the candidate ethanol supply chains per feedstock were further analysed in Section 5: the 1G molasses-based option, the 2G IAP (and garden waste)-based hydrolysis fermentation route and the 3G off-gas self-sufficient scenario. While the latter is not the cheapest option to produce ethanol from off-gasses, it has been chosen for consistency reasons (all further analysed options are energy self-sufficient) and because this is also how the deepest greenhouse gas (GHG) savings would be achieved for the intermediary SAF feedstock.

5 Network optimisation

The final stage in the pre-feasibility analysis is to determine the best locations for the industrial facilities that will be converting the feedstocks analysed in Section 3 into ethanol with the processing technologies analysed in Section 4, and estimate the costs of transporting the raw feedstocks to the ethanol plant (where applicable) and from there the ethanol to PetroSA. The following sub-sections deal with these steps.

5.1 Network overview

The critical elements of a supply chain optimisation analysis are a) creating a consolidated single database of available raw feedstock, b) performing a Centre of Gravity (COG) study for the most geographically distributed feedstock (in this case IAPs) and c) building a costing model that simulates the optimal spend including sourcing, production, and transportation up the final delivery point.

Due to the vast reach of this project and the potentially large number of feedstock sources and processing locations across the country, it is necessary to establish a clear network overview. Figure 15 shows the overall network from the feedstock source points at the beginning of the process, the primary transport leg that transports the raw materials to the processing facility, where applicable. The lignocellulosic feedstocks (IAPs and garden waste) have a primary transportation leg as they are processed into ethanol off-site from the source sites. The molasses and industrial off-gases do not have a primary transportion leg as the ethanol production takes place at the same site where the feedstock originates. Once the feedstocks have been processed into ethanol at the respective production sites, the ethanol will be transported via a secondary transport leg to the PetroSA plant in Mossel bay for use in the production of SAF.

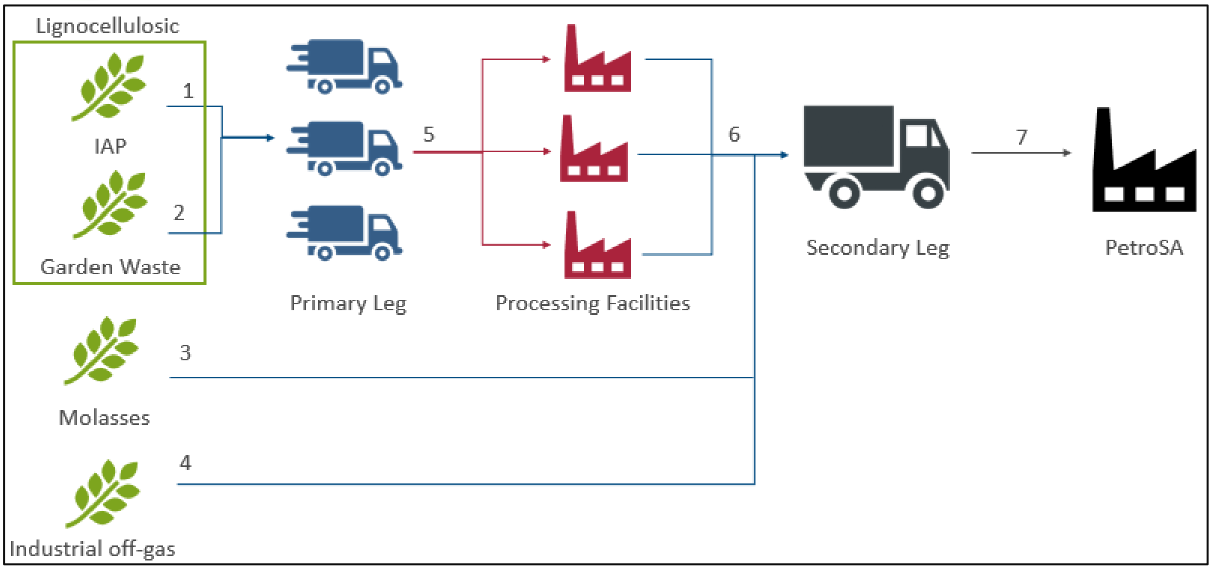


Figure 15 Generic network overview

The primary transport leg of IAPs, indicated by line 1, has a high level of complexity due to the vast amount of collection sites for this biomass source. Meeting the ethanol demand with lignocellulosic feedstocks requires transporting approximately 1.7 million tons of harvested IAPs (also referred to as wet feedstock) per annum. The collection sites are located across the Western and Eastern Cape and require an in-depth analysis to determine the optimal locations for the individual (ethanol) processing facilities. This is discussed in more detail in the COG study in Section 5.4.1 of the report.

The secondary leg of the network, shown in lines 3, 4 and 6 in Figure 15, transports ethanol from the ethanol production facilities to the end user, in this case PetroSA. Because in the molasses and industrial off-gasses supply chains the locations of feedstocks and ethanol production are the same, these supply chains only incur secondary transport cost. To meet the PetroSA requirement of 300 million litres of ethanol per annum, roughly 6,818 tanker loads will be required. This equates to an estimated 22 loads per day to PetroSA.

5.2 Approach

Centre of Gravity

The Centre of Gravity (COG) study was only conducted for IAPs. This is the case as the production sites for off-gas and sugarcane-based ethanol are predetermined by the location of the industrial facilities that emit the off-gas and sugar mills, respectively. The COG study, using a combination of R-programming and Excel, set out to determine the best locations for the ethanol plants that would use IAPs (and a small amount of garden waste) as feedstock such that the transport costs would be minimised.

Working backward from the minimum required ethanol output of 300 million litres per year and given the assumed 98 million litres output per facility (as specified by the techno-economic analysis in Section 4.3), it was calculated that 4 processing facilities would be required to meet PetroSA's demand for ethanol[18]. This implies that all lignocellulosic supply points would need to be grouped into four clusters. To determine the clusters, as well as centres of gravity, the following steps were followed:

[18] The surplus ethanol output is assumed to be sold to other markets.

1. Calculate the distance between each source point and PetroSA to rank sources based on proximity to end user.
2. Assign garden waste from Mossel Bay landfill and closest lignocellulosic points to facility 1 until capacity was reached.
3. Remaining points were run through a clustering model to create 3 additional clusters (for facilities 2-4).
4. The centre of gravity was calculated for each cluster.
5. A check was done on the feedstock quantity of each cluster
    a. If overcapacity, points farthest from COG were moved to a surplus pool.
    b. If under capacity, closest points from surplus pool to cluster were reassigned to the respective cluster.
6. The centre of gravity was then rerun for each cluster, optimising to minimize the number of trips required for each transport leg and the transport cost.
7. Each centre of gravity location was then checked again; if it was found to be in a remote, inaccessible area, it was relocated to the closest town with least cost increase incurred from the optimal.

Network Optimisation

The aim of the network optimisation model is to minimise the total cost of meeting the minimum ethanol requirement. The total cost is calculated as a simple sum of the following components:

1. Feedstock cost: This applies to the lignocellulosic and molasses feedstocks only. It is calculated by multiplying the total tons of feedstock per processing route by the feedstock cost per ton.

2. Primary transport cost: This refers to the inbound cost of transporting the raw material from its point of origin (approximated by the point of collection) to the processing facility. This cost applies to the lignocellulosic feedstock only. This cost is calculated as:

   $$Number\ of\ trips\ \times Distance\ travelled\ (km) \times CpK\ \times 2$$

   Where CpK refers to the cost per kilometre (in ZAR). The cost is multiplied by 2 to indicate return trips.

   The number of trips depends on the state in which the raw material is transported. In our case, the lignocellulosic feedstock will be transported as wet, chipped biomass. The number of primary trips is therefore:

   $$Feedstock\ in\ wet\ tons\ \div Chipped\ density\ \div Vehicle\ capacity$$

4. Processing cost: The intent is to build ethanol production facilities as indicated by the COG study for the lignocellulosic feedstock. Other ethanol facilities can potentially be set up at existing sugar mills and industrial off-gas sites. Each facility for the respective feedstocks incurs different costs, as per the techno-economic study (Section 4.3). The processing costs are based on the minimum ethanol selling price (MESP) at zero feedstock costs. It is the price set by production facilities to cover the capital cost of the facility, operational costs and the return on investment.

5. Secondary transport cost: This refers to the cost of outbound transport of the ethanol from the ethanol facilities to the end user, Petro SA. This cost applies to all processing scenarios and is calculated as:

   $$Number\ of\ trips\ \times Distance\ travelled\ (km) \times CpK\ \times 2$$

Where CpK refers to the cost per kilometre (in ZAR). The cost is multiplied by 2 to indicate return trips. The number of secondary trips is calculated as

$$Ethanol\ demand\ in\ litres\ \div Vehichle\ capacity$$

The network optimisation model is driven by two factors which affect the overall cost: the location of facilities used, and the quantity of ethanol produced at each facility. Selection of the facility is based on the processing costs, the distance between the feedstock sources and the facility and the distance between the facility and the end user. The distances will in turn affect the transport costs, on both the applicable primary and secondary legs.

The quantity of ethanol produced at each facility will determine the number of trips required to transport all the ethanol from each facility to the end user, as well as the quantity of feedstock to be transported via the primary leg from the feedstock sources to the facility for processing. If the primary transport cost is the major cost component, the optimal location will tend to be closer to the source of the feedstock; conversely, if the secondary transport cost is the major cost component, the optimal location will tend to be closer to the end user. Thereafter, using the next closest and cost-effective facility. It assumes that all facilities operate at full capacity to achieve the lowest possible cost per litre of ethanol produced.

Additional Considerations

- For the lignocellulosic feedstock solution, garden waste is allocated to the facility in Mossel Bay first. Thereafter, the shortfall of feedstock to make the required amount of ethanol is supplemented by IAPs.
- Since there is more lignocellulosic feedstock available than required to meet the minimum requirement in all scenarios, the closest feedstock source points to each facility are allocated until capacity is met.
- Seasonality is not considered. While there is enough supply of ethanol from molasses to meet the minimum requirement, typically, they are only produced 10 out of 12 months in a year when sugar production takes place. The ethanol producer will need to consider some storage method to provide buffer stock for the 2 months for which there will be no supply, which might affect the final cost of the ethanol.
- While sugar mills are situated close to Durban and Richards Bay harbours, there are currently no service lines to Mossel Bay to fulfil this requirement. These shipping lines would also be very expensive to establish and is considered not to be feasible within the scope of this project. Therefore, only road transport is considered.
- The use of a dedicated fleet is assumed due to the extensive nature of the operations. Detailed costing provided from Imperial Tanker Services to optimize the secondary transport cost further.

Input data and assumptions

A vast amount of data points was required to perform the analysis. These data requirements are listed for each individual feedstock and range from geocodes to the costs of various feedstock items as well as processing requirements. The complete list of assumptions and input data is available in Appendix C: Network optimisation assumptions.

Ethanol supply scenarios

To determine the optimal combinations of feedstocks, several scenarios were tested. These include:

1. Each individual feedstock option supplying the full demand:
    a. Ethanol from lignocellulosic only
    b. Ethanol from industrial off-gas only

c. Ethanol from molasses only

2. Combinations of two feedstock options at a time:
    a. Ethanol from lignocellulosic and industrial off-gas
    b. Ethanol from industrial off-gas and molasses
    c. Ethanol from lignocellulosic and molasses
3. Combination of all feedstock options

For the combination scenarios, the optimisation begins with assigning all demand to the cheapest feedstock option (this is evaluated in the individual feedstock scenarios). Thereafter, one-by-one, the most expensive facility of the first feedstock is replaced with the cheapest facility/facilities of the second feedstock. This continues until all ethanol production is assigned to the second and third feedstock option.

Carbon emissions

The total cost and transport carbon emissions are calculated for each scenario iteration to evaluate how the options compare in terms of cost and transport carbon emissions. A full GHG LCA of the ethanol to be used for SAF production was beyond the scope of this pre-feasibility.

Carbon emissions for transport are calculated using the consumption rate of fuel, as well as the total distance travelled. The total transport distance is calculated by summing the total distance travelled for each route on the primary and secondary legs, taking into account return trips:

$$Total\ distance\ travlled\ (km) = Total\ trips\ \times Distance\ \times 2$$

The carbon emissions from the transport are then calculated using a consumption rate of 1 litre of fuel per 2.2km travelled and 2.68kg of carbon emitted per litre of fuel consumed:

$$Carbon\ emission = (Total\ distance\ travelled\ \div 2.2km) \times 2.68kg\ of\ CO_2$$

5.3 Vehicle choice

Tipper trucks allow for easy loading and unloading at sites and can be universally used for all feedstocks requiring a primary leg. Other options could be trucks with a form of “bucket” system allowing for top loading. One option would be to use containers to transport the biomass, however, the capital expenditure required for trucks with the functionality to tip a container make this option inefficient. Alternatively, container trucks without the tipper functionality could be used but it would require for the material to be offloaded by hand. This would affect the offloading time immensely. A truck with an effective tipping mechanism could lead to offloading times being less than 30 minutes. Therefore, tipper trucks are assumed to be the most suitable mode of transport for this leg of transport given the type of materials and quantity to be transported.

For the secondary transport of ethanol from molasses, ocean export was initially considered. This option would utilise port pairs: Durban – Mossel Bay and Richards Bay – Mossel Bay. However, on enquiry, the shipping lines advised that they do not service these port pairs. Establishing a service for these port pairs would entail establishing port storage as well as loading and offloading facilities. Estimating the cost of these is beyond the scope of this pre-feasibility study, therefore, sea freight could not be considered. Tanker trucks are assumed to be the most suitable vehicles for this leg of transport given the type of materials and quantity to be transported, as well as existing networks for major routes. Tankers are specially designed to transport flammable materials and do not require additional storage points, as ethanol can be transported as it is produced directly to the end user.

5.4 Results

The results section presents the outcome of the lignocellulosic feedstock CoG study first, followed by the overall network overview and finally full ethanol supply costs.

5.4.1 Centre of gravity

The Centre of Gravity study was one of the initial analysis carried out for the lignocellulosic pathway. As shown in Section 3.3.2, IAPs infestations are widely distributed, which results in a very large number of possible collection sites. By contrast, garden waste is assumed to already be available centrally at the Mossel bay landfill site. Based on spatial data underlying Figure 5 and Figure 6, individual collection sites for IAPs can be seen in Figure 16. The various collection sites were organised into clusters in order to determine the optimal location for processing facilities to minimise transportation costs. Out of the 5 clusters analysed, 4 with lowest primary transport costs that would supply enough raw feedstock to meet PetroSA's ethanol demand were chosen. The result was that the facilities producing ethanol from lignocellulosic feedstocks should be based in Mossel Bay, Queenstown, Ceres and Mthatha, as can also be seen in Figure 17.

Figure 16 Supply point clusters for lignocellulosic

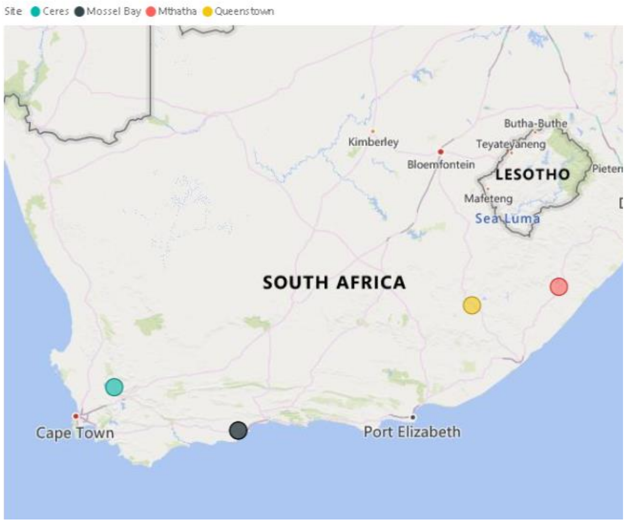


Figure 17 Centres of gravity for lignocellulosic processing facilities

Adding up primary and secondary transport costs for these centres of gravity revealed the cheapest lignocellulosic ethanol delivered to PetroSA in Mossel bay would be produced in Ceres, followed up Queenstown, then Mossel Bay, then Mthatha.

5.4.2 Overall network view

As discussed, ethanol will be produced from various feedstock options, at facilities located across the country. Figure 17 above shows the location of the processing facilities for lignocellulosic-based ethanol. For ethanol production from molasses, the potential processing facilities are assumed to be co-located with existing sugar mills, which are shown in Figure 4. Potential sites for the production of ethanol from industrial off-gas are also spread across various industries in different part of South Africa, as shown in Figure 9. Ethanol can be produced on site and then transported along the secondary transportation leg to PetroSA.

Plotting all the processing facilities identified for lignocellulosic, molasses and industrial off-gas feedstocks, provides a complete overview of all potential ethanol production sites. This is presented in Figure 18 below, together with the location of PetroSA in relation to all potential ethanol production sites.

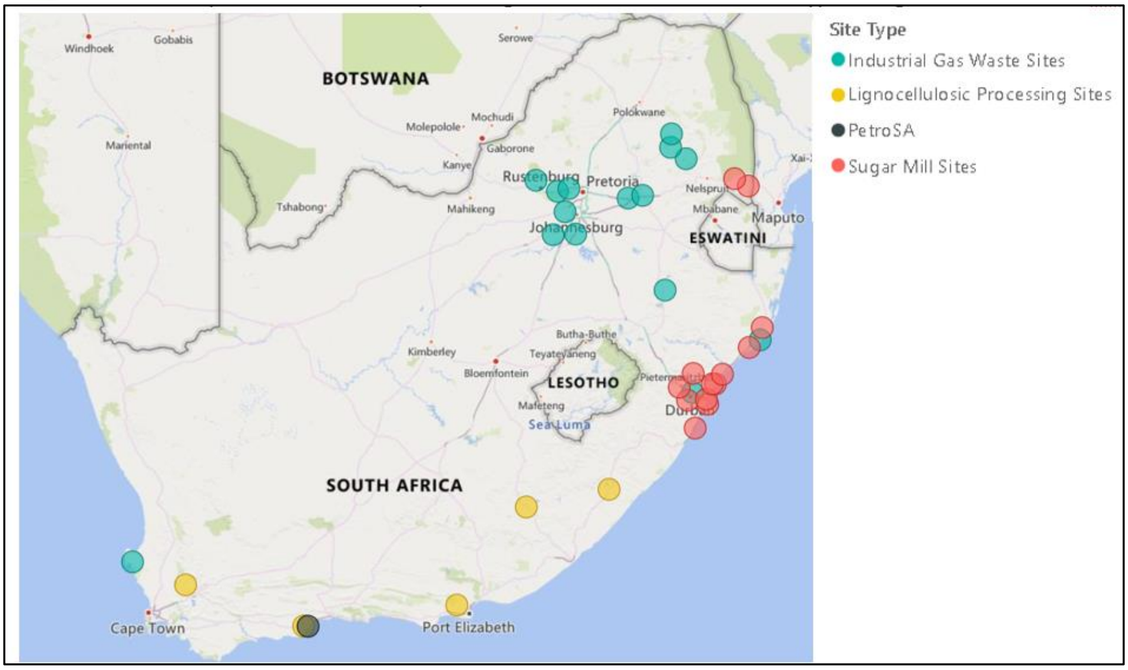


Figure 18 Overview of all potential ethanol production sites in relation to PetroSA

5.5 Total ethanol supply cost

The following sections reveal the full economic cost of supplying 300 million litres of ethanol to PetroSA in Mossel Bay for further processing into SAF. We present total annual costs and their breakdown per major cost component, cumulative supply cost over 20 years and cost per litre of ethanol for the three production pathways that were chosen for further investigation – 1G fermentation based on molasses, 2G hydrolysis fermentation of lignocellulosic biomass in the form of IAPs (and garden waste) and the 3G industrial off-gas fermentation route, as well as of all the possible combinations of those. The transport costs presented here are the result of the centre of gravity and network optimisation studies and were also used as the basis for the calculation of the CO_2 emissions associated to transport in these candidate ethanol supply chains.

5.5.1 Single feedstock scenarios

Economic costs

Table 14 shows the approximate total annual costs of procuring ethanol for conversion to SAF by PetroSA if all the demand was meet with ethanol from individual feedstocks. It shows that ethanol produced from molasses fermentation is the cheapest option on its own at a cumulative annual cost of about R2.86 billion, followed by that produced from industrial off-gas in the energy self-sufficiency scenario at R4.48 billion, while lignocellulosic ethanol produced via the hydrolysis-fermentation route appears as the most expensive option at about R5.77 billion, or about twice as much as the molasses-based option.

The cost breakdown from Table 14 is shown graphically in Figure 19 and illustrates how the cost components of different feedstock options compare against each other. The three scenarios exploring possible ethanol supply routes differ substantially on their main cost drivers. In the case of molasses-based ethanol, it is the cost of feedstock, for industrial off-gas-based ethanol it is processing cost and for ethanol produced from IAPs (the lignocellulosic scenario) it is a combination of feedstock acquisition cost and processing costs.

As shown by the techno-economic analysis in Section 4.3, 1G facilities processing molasses have substantially lower capital and operational costs, which results in lower overall processing costs than both lignocellulosic and industrial off-gas facilities, as shown in Table 14 and Figure 19. For the lignocellulosic route, despite it being based on the more cost-efficient hydrolysis-fermentation technology, the processing costs are still relatively high, and adding the substantial feedstock acquisition cost, makes this option the least economical. As mentioned before, a lower acquisition cost for cleared alien biomass, which could be achieved by integrating clearing operations in the ethanol production business as opposed to relaying on external commercial operators could significantly improve the economic attractiveness of lignocellulosic ethanol. The high cost of processing industrial off-gasses to ethanol could be lowered substantially by importing electricity to meet the process energy needs, as opposed to diverting a substantial amount of syngas for this purpose, resulting in substantially lower ethanol output, and thus higher relative processing costs. It is important to note that the type of electricity used (renewable vs non) would have a significant impact on the carbon footprint of the ethanol, and as such on the SAF manufactured from it.

Relative to feedstock and processing cost, transport costs do not appear to play a major role in total supply cost, representing only about 7% of total costs in lignocellulosic ethanol supply, 10% on off-gas ethanol supply and 14% of molasses-based ethanol supply, respectively. The cost of molasses-based ethanol and industrial off-gas-based ethanol do not include any primary transportation costs, because the assumption is made that the ethanol facilities using these feedstocks are co-located with the sources of these feedstock. We can see the cost of secondary transport – that of ethanol from the ethanol facilities to PetroSA's refinery in Mossel Bay, is not a key determinant of the overall costs; not even for the ethanol produced from industrial off-gasses that would travel the longest distances across the country to reach Mossel Bay.

Table 14 Annual ethanol costs for single feedstock scenarios

	Lignocellulosic	Industrial Off-Gas	Molasses
Feedstock cost	R 2,098,408,813	R -	R 1,450,075,485
Primary transport cost	R 295,099,733	R -	R -
Secondary transport cost	R 158,540,031	R 461,781,256	R 400,338,653
Processing cost	R 3,217,718,304	R 4,022,147,880	R 1,014,475,076
Total cost	**R 5,769,766,880**	**R 4,483,929,136**	**R 2,864,889,214**

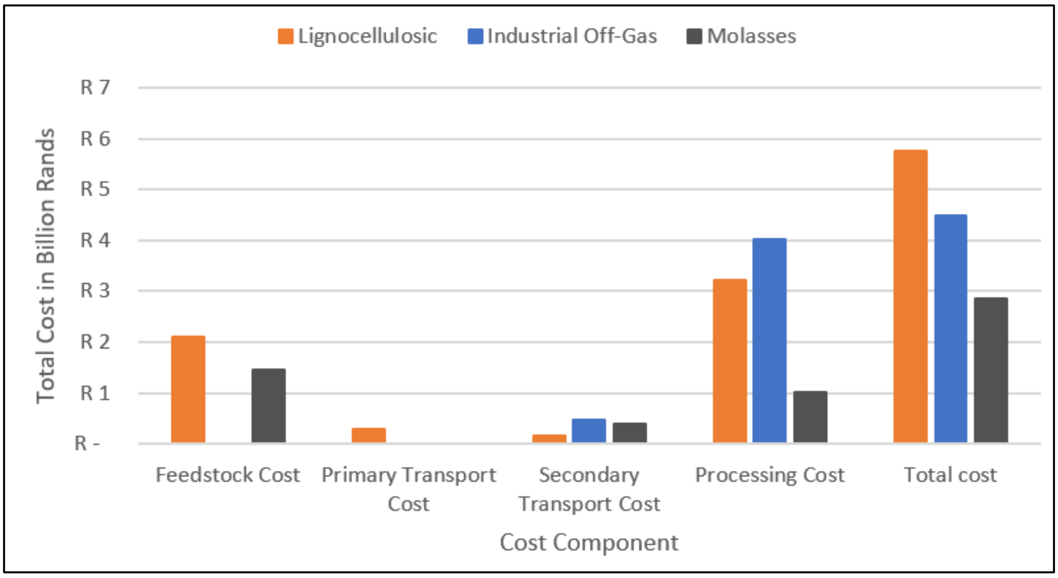


Figure 19 Annual costs of ethanol supply from single feedstock scenarios

The cost per litre of ethanol produced from the various feedstocks and delivered to the gate of PetroSA's refinery in Mossel bay is shown in Table 15. The cumulative cost for the 20-year project lifespan, in 2020 Rand terms, is given in Table 16 below. Comparing these with the MESP ex-factory gate shown in Section 4.3, we see that transportation costs on average add about R1.3/l to the total supply cost of molasses-based ethanol, and R1.5/l to supply of industrial off-gas-based ethanol production and lignocellulosic ethanol.

The cumulative costs of ethanol supply for the scenarios under consideration is given in Table 16.

Table 15 Average cost per litre of ethanol for single feedstock scenarios

	Lignocellulosic	Industrial Off-Gas	Molasses
Total cost (Rand per litre)	R 19.23	R 14.95	R 9.55

Table 16 Cumulative costs for single feedstock scenarios over 20 years

	Lignocellulosic	Industrial Off-Gas	Molasses
Feedstock cost	R 41,968,176,255	R -	R 29,001,509,693
Primary transport cost	R 5,901,994,651	R -	R -
Secondary transport cost	R 3,170,800,610	R 9,235,625,113	R 8,006,773,067
Processing cost	R 64,354,366,080	R 80,442,957,600	R 20,289,501,528
Total cost	**R 115,395,337,595**	**R 89,678,582,713**	**R 57,297,784,288**

Transport CO_2 emissions

Every supply chain will result in carbon emissions, which needs to be accounted for. The transport carbon emissions vary depending on the complexity of the logistics network required to transport the various feedstocks and intermediate products. The complexity of the logistics network depends on the location of the collection sites, the length of the primary and secondary transportation legs and the number of loads required for each leg.

Table 17 shows that not only is molasses the most cost-efficient solution but also the most carbon-efficient solution in terms of transport emissions, when compared to the other single feedstock scenarios. Transport emissions of the lignocellulosic ethanol supply chain are almost 43 % higher compared to the molasses-based ethanol supply chain. This can be attributed to absence of a primary leg in the molasses scenario. Industrial off-gas sites are on average further from PetroSA than sugar mill sites, hence the greater transport carbon emission observed in the industrial off-gas scenario (approximately 14 % more). These figures should be included in the full SAF GHG life cycle assessment (LCA) to determine the actual GHG savings compared to conventional jet fuel.

Table 17 Annual and per litre transport carbon emissions for single feedstock scenarios

	Lignocellulosic	Industrial Off-Gas	Molasses
Carbon emission	**26,983,010**	**21,635,905**	**18,757,126**
Carbon emission (kg per litre)	0.090	0.072	0.063

Figure 20 shows the comparison between the cost per litre of ethanol produced from respective individual feedstocks, and their associated transport carbon emission values. It shows that the economic ranking corresponds with the CO_2 ranking of the assessed ethanol supply chains.

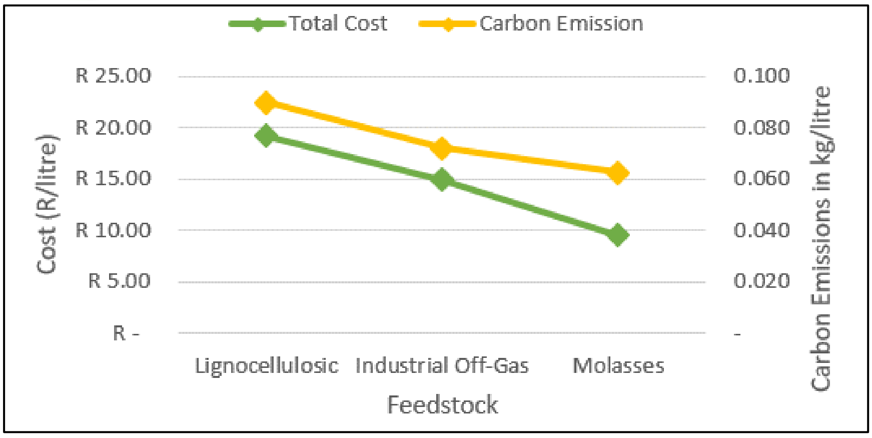


Figure 20 Cost and carbon emission per litre for individual feedstock scenarios

5.5.2 Combination scenarios

While meeting the ethanol demand from a single type of feedstock is possible, and might even be the most cost-efficient solution, in reality, it is more likely that a combination of feedstocks would be employed in a diversified sourcing strategy. The following sections explore the different possible combinations of feedstocks and their cost implications. The study investigates cost and transport emissions implications of all possible combinations of the three ethanol supply chains we consider in the network optimisation study. Here we present the results of the analysis into combining all three assessed ethanol supply chains. Appendix D shows the results of the pair-wise comparisons.

In the combinations given below for all three feedstocks, each feedstock is prioritised between iterations. One facility for each feedstock is fully allocated, using the cheapest facilities first. Once each feedstock option has one facility allocated, the remaining quantity of ethanol to be produced is allocated to facilities for each feedstock option.

The annual ethanol output per supply chain for the different combinations is given below in Table 18, while Table 19 provides an overview of the total annual costs associated with full ethanol supply of each combination, the total costs of meeting PetroSA's requirement, as well as the related carbon emissions from transport. Figure 21 and Figure 22 provide a graphic representation of these results. The difference between total annual costs and total costs of meeting PetroSA's demand is due to the surplus output over and above PetroSA's requirements, which fluctuates depending on the configuration of ethanol production facilities. As mentioned before, we make the assumption this surplus ethanol will be placed in other markets.

The modelling of combination scenarios provides some interesting insights. The results show that the cheapest combination of all three feedstocks is option 2, where unsurprisingly ethanol from molasses comprises over half of PetroSA's potential annual demand of 300 million l (so 163.5 million l). Interestingly, the second biggest contributor to the target supply is lignocellulosic ethanol at almost 1/3 of the total potential demand (almost 100 million l), with industrial off-gas-based ethanol supplying the balance of 42 million l. This is because the cheapest lignocellulosic ethanol plant (in Ceres) would be able to supply ethanol cheaper then the second or third cheapest industrial off-gas plant(s). Option 2 also has the least transport carbon emissions.

Table 18 Annual ethanol output for combination scenarios considering all feedstocks

Option	Lignocellulosic (ethanol in litres)	Industrial Off-Gas (ethanol in litres)	Molasses (ethanol in litres)	Total production (ethanol in litres)
1	-	-	327,040,000	327,040,000
2	98,040,000	42,089,911	163,520,000	303,649,911
3	98,040,000	120,480,445	81,760,000	300,280,445

4	-	302,350,654	-	302,350,654
5	196,080,000	23,200,270	81,760,000	301,040,270
6	392,160,000	-	-	392,160,000

Table 19 Annual costs and transport carbon emissions for combination scenarios considering all feedstocks

Option	Total cost (in ZAR)	Total cost for minimum requirement (in ZAR)	Transport carbon emissions (in kg CO_2)
1	3,123,111,229	2,864,889,214	20,447,768
2	4,016,114,100	3,967,839,892	18,661,565
3	4,413,389,489	4,409,267,633	19,502,728
4	4,519,063,022	4,483,929,136	21,805,433
5	4,846,086,744	4,829,340,683	22,170,562
6	7,542,239,265	5,769,766,880	35,272,191

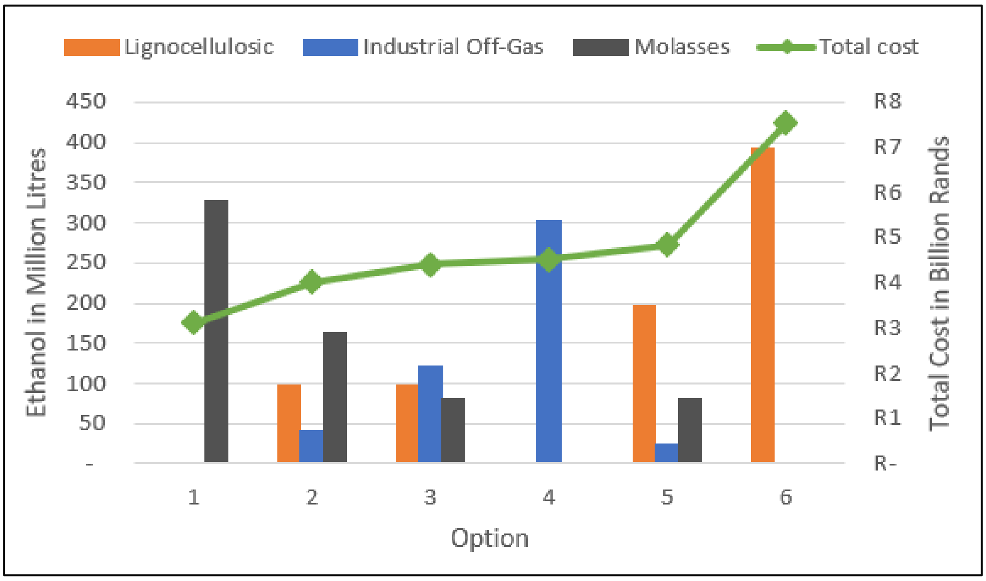


Figure 21 Annual output and cost of ethanol supply for the combination scenario considering all feedstocks

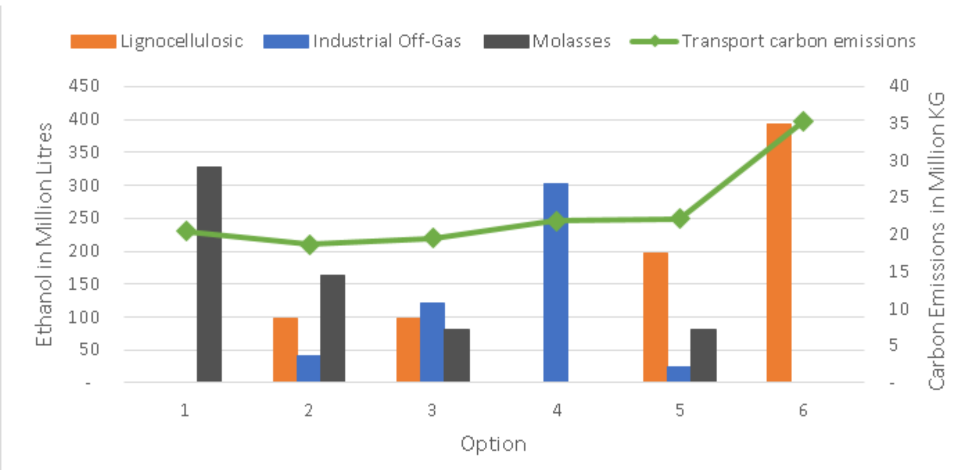


Figure 22 Annual ethanol output and transport carbon emissions per annum for the combination scenario considering all feedstocks

Table 20 and Figure 23 provide the combined overview of the cost and transport carbon emissions per litre of ethanol for each combination of feedstocks. It shows that a diversified ethanol sourcing strategy could increase the average cost of a litre of ethanol by a very substantial almost 40%, while reducing the average transport carbon emissions by a marginal 3%

Table 20 Average cost and transport emissions of ethanol per litre for the combination scenario considering all feedstocks

Option	Average cost per litre (in ZAR)	Average carbon emissions per litre (in kg CO_2)
1	9.55	0.063
2	13.23	0.061
3	14.70	0.065
4	14.95	0.072
5	16.10	0.074
6	19.23	0.090

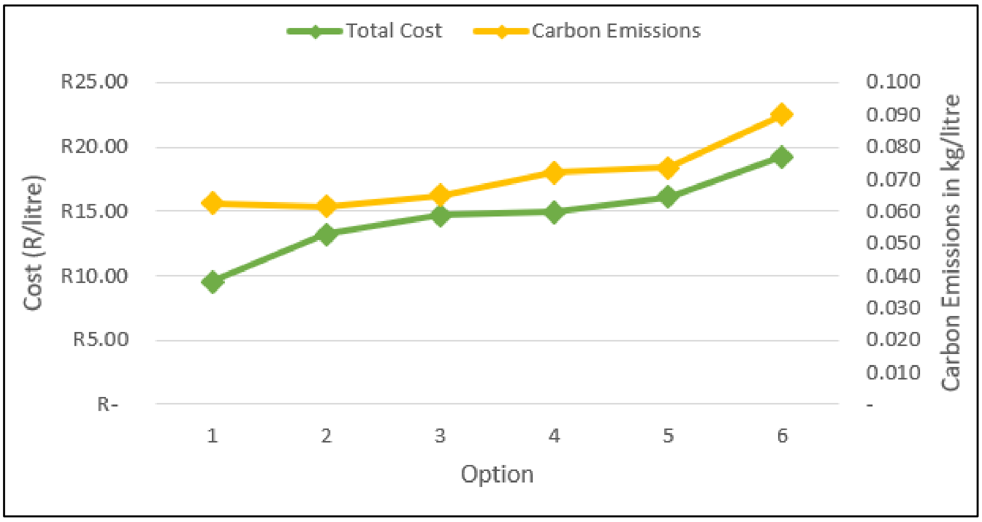


Figure 23 Average cost and transport carbon emission per litre of ethanol for the combination scenario considering all feedstocks

5.6 Conclusions

The results of the optimisation study yield important observations that can help define an ethanol sourcing strategy based on a single, or multiple objectives.

If the ethanol sourcing strategy was to be based on cost-efficiency alone, then sourcing all ethanol from molasses would be the obvious choice. This particular supply chain does not incur primary transport cost and has the lowest processing cost, leading to a lower overall cost compared to ethanol supply based on lignocellulosic feedstock and industrial off-gas. Additionally, the distances between the sugar mills that could process molasses into ethanol and PetroSA are shorter than for the industrial off-gas facilities, resulting in a shorter and thus cheaper secondary transport leg[19]. The long-term average cost of secondary transport for 1G ethanol could be lowered further if a

[19] Optimizing secondary transport for maximum vehicle utilisation and investing in infrastructure such as pumps at the loading and offloading points could reduce the overall cost of this supply chain by about 1.6%, see Appendix D: Optimised Secondary Transport Costing.

shipping lane were to be instituted between either Richards bay and/or Durban ports and the Mossel bay port, although the initial capital outlay for their establishment would be substantial.

By contrast, producing ethanol from IAPs (and garden waste) is the most expensive option, mainly owing to the high cost of extracting and preparing the biomass for transport (clearing and chipping) and the added primary transport cost, which is not incurred by supply chains based on the other two candidate feedstocks. Because primary transport contributes a much bigger portion of overall supply costs than secondary transport, even immediate proximity to PetroSA is not a cost-advantage for facilities producing ethanol from IAPs. The network optimisation study revealed that of the 4 potential ethanol production sites using IAPs as the primary feedstock, Ceres would be the location for the one potentially supplying PetroSA with the cheapest 2G ethanol, not the one located in Mossel bay itself. The reason for this is the relatively denser IAP infestation around Ceres, which on average requires the biomass to travel shorter trips to its processing facility.

In terms of cost-effectiveness, ethanol produced from industrial off-gas falls between the molasses and the lignocellulosic ethanol supply chains, with high processing and secondary transport costs, but no primary transport. Again, it is worth noting, that a configuration where the process energy needs of facilities manufacturing ethanol from industrial off-gases could be met by importing renewable electricity, the ensuing significant increase in ethanol output would position this option much more favourably.

Determining the best sourcing strategy if the objective was to minimise the GHG LCA of the SAF is slightly more complex and requires more information than is available in this pre-feasibility. While transport emissions are a major component of the ethanol supply scenarios considered in this study (all of which are energy self-sufficient when it comes to meeting their process energy requirements), they are not the only ones. Based on the information available herein, it is therefore not possible to determine the most carbon-efficient ethanol supply chain, despite the transport GHG analysis pointing to molasses-based ethanol as the best option. However, because A-molasses is a co-product, not a waste product of the sugar mill with a market value, it would need to be allocated a proportion of the emissions associated with growing, harvesting, transporting and crushing the sugar cane, which can be substantial, especially in the South African context of grid electricity being used for irrigation and field burning preceding cane harvesting[20]. Either way, delivering the molasses-based ethanol by ship instead of trucks would of course improve the GHG profile of the ethanol and thus SAF produced by PetroSA. Considering that industrial off-gasses are a) a waste and b) located at the point of processing, it is expected that a comparative GHG LCA across these three would favour this ethanol supply chain. The GHG burden of lignocellulosic feedstock such a IAPs are the subject of a fierce debate. Recent research points to the need of land and ecosystem restoration accompanying IAP clearing to compensate for the initial carbon debt of turning such woody material into fuel.

If the ethanol sourcing strategy was to meet a number of objectives, including job creation and improving drought resilience, then it would need to include at least some ethanol produced from IAPs. In this case, one of the combination scenarios could guide the sourcing strategy. Figure 21 suggests that a combination of 1 IAP-based facility (in Ceres), 2 molasses-based facilities in KZN and 1-2 industrial off-gas based facilities would be able to achieve multiple objectives at an additional cost of about R1 billion per year. The full social and environmental impact assessment of such a diversified sourcing strategy by PetroSA is beyond the scope of this pre-feasibility, but would likely justify government support for production of SAF by PetroSA.

In closing, it is hoped that the information contained in this pre-feasibility study will allow PetroSA to estimate the total production cost of SAF at its COD plant in Mossel bay and based on that gauge market interest for such a product.

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[20] A recent report by the Roundtable on Sustainable Biomaterials explores possible measures to lower the GHG footprint of ethanol-based SAF in SA, see RSB, SA Canegrowers Research Points to SAF Potential in South Africa | RSB

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Appendix A: The CSIR map of above ground biomass

The above ground woody IAP estimate is based on a full national coverage of a satellite derived woody vegetation product (see Appendix A). Above-ground biomass (AGB) is the total biomass of woody plants above 0.5m height and is expressed in oven-dry tonnes per hectare. The product was developed through the integration of SAR, optical vegetation indices, LiDAR tracks, and field data of woody biomass. The LiDAR tracks were processed to derive a canopy height model for woody vegetation above 0.5m at 1m pixel size. A detailed LiDAR AGB woody, product was generated using LiDAR woody cover and height products and field data. The remote sensing parameters were modelled using the LiDAR woody above-ground biomass as reference data for calibration and validation of the final SAR woody above ground biomass (AGB woody) map.

*The Above Ground Woody Biomass (AGB) map is at 100m x 100m resolution (1ha)

*Biomass is the mass in oven-dry tonnes per hectare (odt=oven dry tonnes, 0% moisture. In the field trees are 45-50% water and most value-added biomass has a moisture ranging from 3% (wood pellets) to 20% (wood chips)

* Mass in teragrams (Tg). 1 Tg = 1 million tonnes (Mt)

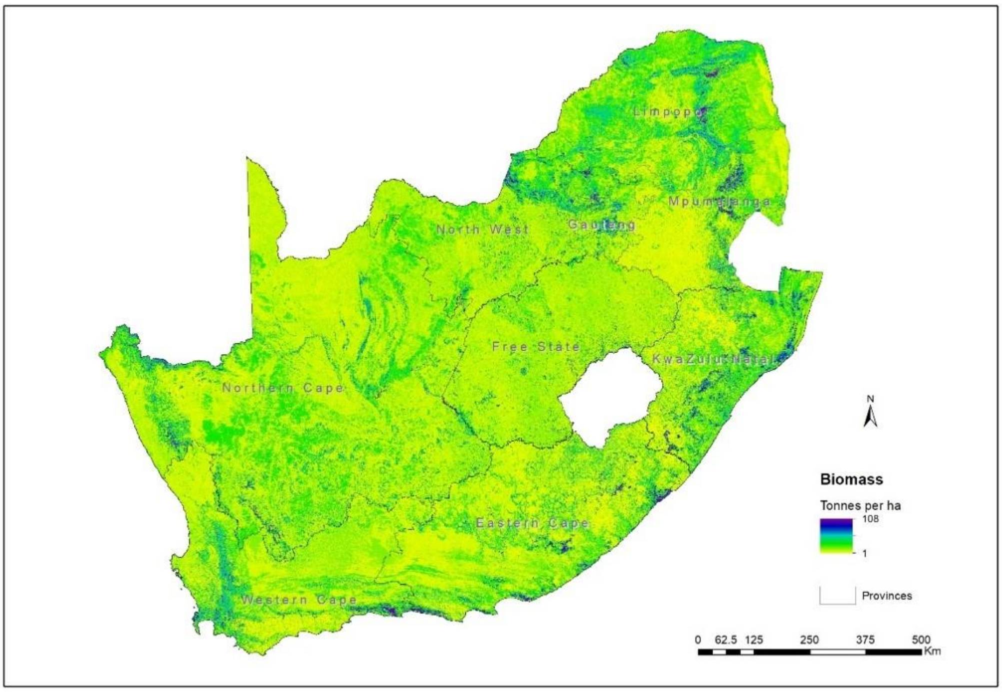
*The above ground biomass signal is known to saturate over about 120 t/ha and there may be erroneously high values on steep slopes. In thise biomass assessment, we have used the upper range of each class to take into account this signal saturation; since previous studies have indicated that the above CSIR AGB map underestimates total biomass and large trees in dense invasions contribute significantly to the total amount of biomass amounts.

*Slope is measured in percentage and not degrees in this report. To convert % slope to degrees: Degrees = Tan^{-1} (slope percent/100). For example, 35% slope = 19° slope which is the limit of accessibility for forestry machinery used to harvest biomass (Warkotsch, Brink & Zietsman 1990).

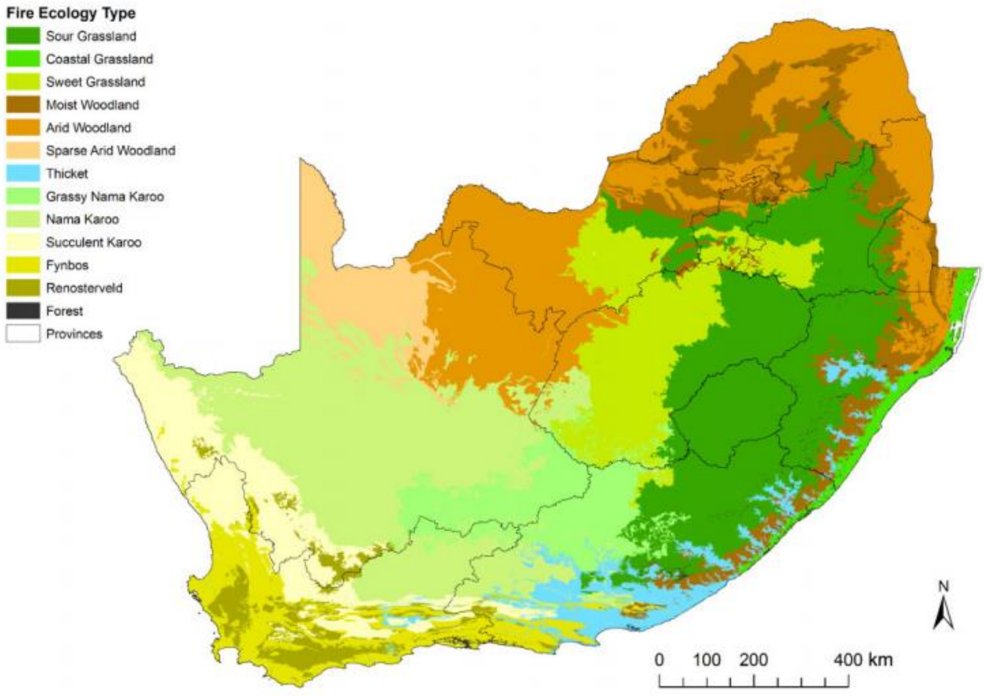
*The deduced invasive alien plant biomass uses deductions to determine indigenous biomass and deduce the invasive alien plants. The uncertainty of correctly deducing invasive alien plants depends on the background vegetation- there is greater uncertainty of correctly identifying deduced invasive alien plant biomass in moist woodlands of Limpopo, North-West and Kwa-Zulu Natal.

Supporting maps and data:

- Above Ground Woody Biomass (AGB) map at 100m x 100m resolution (Figure A1 and)
- Natural areas from national landcover (SANLC, 2018)
- Fire ecotypes for South African vegetation (Le Maitre *et al.* 2014, Figure A2)
- Slope (%) was the 30m digital elevation model (DEM) that was generated from the Shuttle Radar Topography Mission, (STRM) (Yang *et al.* 2012). Slope is categorized according to four classes: 0-10%, 10-20%, 20-35% and >35%
- Test sites for calibration of biomass of pristine vegetation/fire ecotypes 1 ha within natural areas/nature reserves



Appendix Figure 1 Above Ground Woody Biomass (AGB) at 100m x 100m resolution



Appendix Figure 2 Fire ecotypes for South Africa

Appendix B: Ethanol production from industrial off-gases for self-sufficient and external energy scenarios

Company Name	City/Town	Off gas production		Ethanol production (ML/yr)	
		Nm3/h	tons/yr	with external energy	Self-sufficient plant
Richards Bay Minerals	Richards Bay	17 268	147 058	29	20
Tronox, Namakwa Sands	Saldanha Bay	11 898	101 326	20	14
South32, Metalloys	Meyerton	41 585	354 149	69	48
Afarak, Mogalle Alloys	Krugersdorp	10 396	88 537	17	12
ArceloMittal Vanderbijlpark Works (SS)	Vanderbijlpark	47 565	405 072	79	54
ArceloMittal Newcastle Works (SS)	Newcastle	20 385	173 602	34	23
AssMang Carto Ridge	Carto Ridge	6 453	54 954	11	7
Samancor - DCR (formerly Hernic)	Brits	25 400	216 313	42	30
Samancor - Ferrometals (FMT)	Witbank	22 400	216 005	42	30
Samancor - MFC	Middleberg	28 600	250 899	49	34
Samancor - TCS (formerly IFM)	Mooinooi	21 600	183 951	36	25
Samancor - TAS (formerly ASA Metals)	Steelpoort	25 558	217 654	42	29
Glencore Xstrata Alloys	Boshoek	19 926	169 696	33	23
Glencore Xstrata Alloys (Lion Smelter)	Steelpoort	29 456	250 856	49	34
Glencore Xstrata Alloys	Lydenburg	23 790	202 602	39	27

Appendix C: Network optimisation assumptions

The analysis presented in Section 5 is based on the assumptions listed below:

1. IAP:
   - Supply point: 1 ha
   - Infestation density expressed in oven dry tons/ha
   - Slope cut-off: 35%
   - Chipped (wet) biomass density: 0.33 ton/m^3
   - Eradication cost (including cost to transport cleared IAP to roadside pick-up point): R1,600/ton
   - Dry to wet mass conversion factor: 1.429
   - Processing sites locations: to be identified through COG study
   - Ethanol conversion ratio: 327 litres/dry ton of feedstock
   - All lignocellulosic feedstock can be processed in the same facility

2. Garden waste:
   - Source: Mossel Bay landfill
   - Availability: 12,139 dry tons per annum
   - Dry to wet mass conversion factor: 1.429
   - Ethanol conversion ratio: 327 litres/dry ton of feedstock
   - All lignocellulosic feedstock can be processed in the same facility

3. Molasses:
   - 13 existing sugar mills considered for 1G ethanol production co-location [21]
   - Feedstock cost (comprised of feedstock and fuel cost): R2,395/ton
   - Ethanol conversion ratio: 496 litres/ ton of feedstock
   - No primary transport cost is applicable

4. Industrial off-gas:
   - 15 existing sugar mills considered for 3G ethanol production co-location
   - No feedstock or primary transport cost is applicable

5. Tankers:
   - Carrying capacity (Litres/Tanker): 44,000
   - Bulk density of ethanol produced: 772 kg/m^3
   - Cost: 26.00 R/km
   - Assume use of dedicated fleet and return trips

6. Tipper Truck:
   - For the primary inbound movement of lignocellulosic feedstock into processing facilities, the primary transport cost is calculated for wet, chipped biomass

$$Volume\ of\ lignocellulosic\ feedstock = Dry\ tons \times Dry\ to\ wet\ conversion \div Chipped\ density$$

[21] Illovo Merebank, not included in the analysis as it is already a distillery.

- Carrying capacity: 34 tons and/or 44 m^3/tipper truck
- Cost: 18.38 R/km
- Assume use of dedicated fleet and return trips

7. CO^2 emissions factor:
   - Fuel consumption: 1 litre/2.2km travelled
   - Emission per litre: 2.68kg

8. Project Lifespan: 20 years

Appendix D: Pairwise comparisons of economic and transport emission outcomes of assessed ethanol supply chains

Lignocellulosic and molasses only

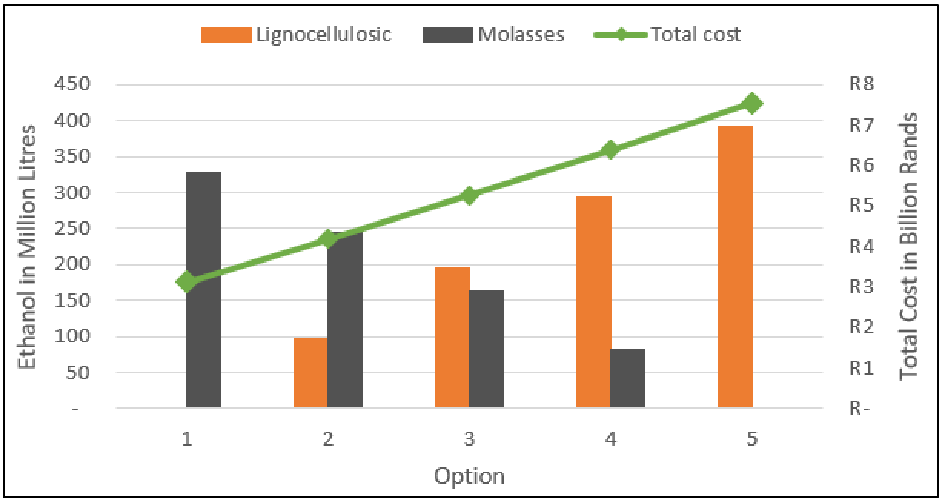
As shown above, ethanol based on molasses is cheaper than that produced from IAPs (and garden waste). Therefore, for this combination scenario, the solution of the optimization problem begins with the full ethanol supply based on molasses, and each iteration moves closer to all ethanol being produced from lignocellulosic feedstock, by removing from the ethanol supply mix the most expensive molasses-based facility and introducing the cheapest lignocellulosic-based facility. The facility replacement ratio is 1:1. Because the assumed production capacities of facilities differ depending on the ethanol production technology employed, this results in fluctuating total ethanol production. The assumption is maintained that an annual ethanol output 300 million litres is directed to PetroSA (therefore 6 billion litres over 20 years), and that a different market will be available for the surplus.

As expected, the total cost, as well as the cost per litre increase with increasing quantities of lignocellulosic-based ethanol in the ethanol supply mix. Likewise, the transport carbon emissions also increase. As discussed previously, the molasses option has no primary transport leg. The lignocellulosic however, has a significant primary transport leg. This results in both higher total cost and higher carbon emissions overall.

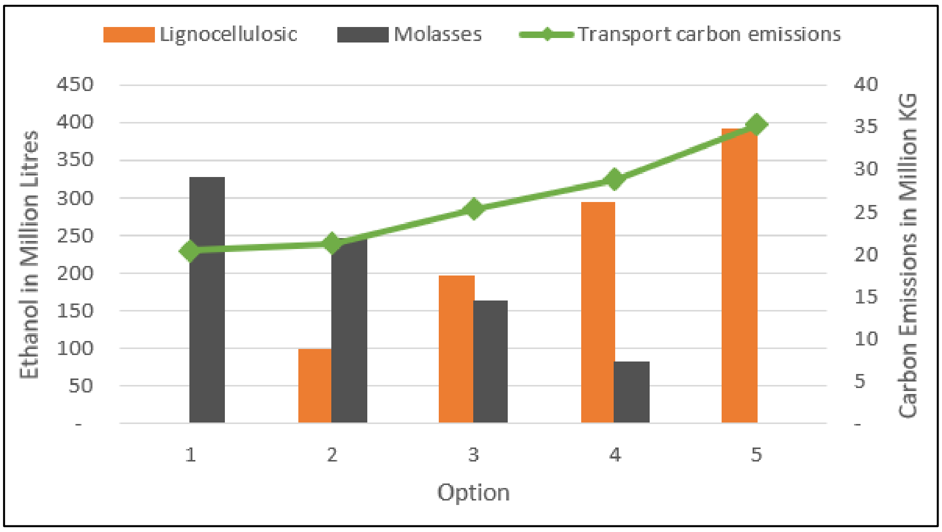
The annual ethanol output for the different combinations is given below in Appendix Table 1, and graphically in Appendix Figure 3 and Appendix Figure 4, together with the total costs of the full production output, and separately for the 300 million litres required by PetroSA, as well as the related carbon transport emissions. Appendix Table 4 provides the combined overview of the cost and carbon emissions per litre of ethanol for each combination of lignocellulosic and molasses option. It is shown graphically in Appendix Figure 5.

Appendix Table 1 Annual ethanol output, costs and transport emissions for the lignocellulosic and molasses combination scenario

Option	Lignocellulosic (ethanol in litres)	Molasses (ethanol in litres)	**Total production (ethanol in litres)**	Total output cost (in ZAR)	**Total cost for PetroSA requirement (in ZAR)**	**Transport carbon emissions (kg CO2/y)**
1	-	327,040,000	327,040,000	3,123,111,229	2,864,889,214	20,447,768
2	98,040,000	245,280,000	343,320,000	4,178,249,500	3,651,039,410	21,227,683
3	196,080,000	163,520,000	359,600,000	5,274,990,964	4,400,715,487	25,369,778
4	294,120,000	81,760,000	375,880,000	6,382,875,074	5,094,345,329	28,867,556
5	392,160,000	-	392,160,000	7,542,239,265	5,769,766,880	35,272,191



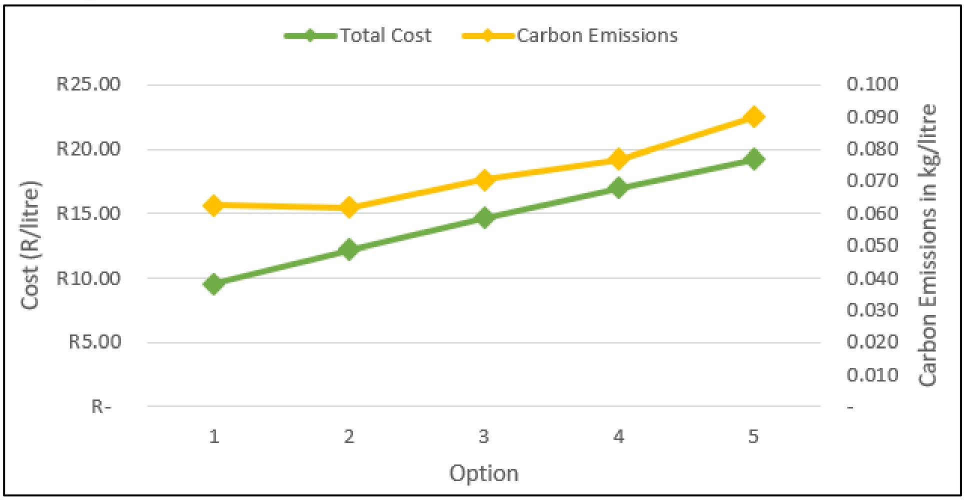
Appendix Figure 3 Annual output and cost of different lignocellulosic and molasses-based ethanol supply combinations



Appendix Figure 4 Annual output and transport carbon emissions for different combinations of lignocellulosic and molasses-based ethanol supply

Appendix Table 2 Average cost and transport emissions of ethanol per litre for different combinations of lignocellulose and molasses-based ethanol supply

Option	Average cost per litre (ZAR/l)	Average transport carbon emission per litre (kg CO2/l)
1	9.55	0.063
2	12.17	0.062
3	14.67	0.071
4	16.98	0.077
5	19.23	0.090



Appendix Figure 5 Cost and carbon emission per litre for different combinations of lignocellulosic and molasses-based ethanol supply

Lignocellulosic and industrial off-gas only

As previously mentioned, the highest cost ethanol supply is based on lignocellulosic feedstock. Similarly, to the previous feedstock combination, the solution of the optimization problem begins with all ethanol supply coming from the off-gas option and each iteration moves closer to all ethanol being produced from lignocellulosic feedstock, by removing from the ethanol supply mix the most expensive off-gas-based facilities and introducing the cheapest lignocellulosic-based facility.

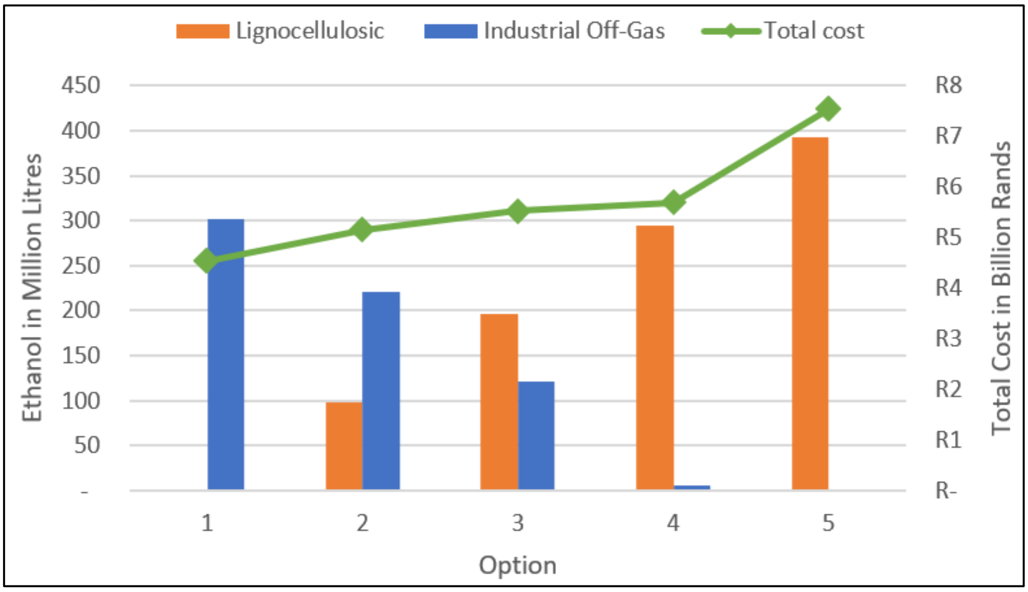
The capacities of individual industrial off-gas sites are, in some cases, a quarter of the capacity of a single lignocellulosic facility. Therefore, it would take approximately three to four industrial off-gas sites closing down, to fill up a single lignocellulosic facility. Since all facilities must be opened to full capacity, opening all lignocellulosic facilities results in 92 million litres more ethanol being produced per annum.

The carbon emissions increase significantly as more lignocellulosic facilities are used. This is due to the added primary transport leg for lignocellulosic feedstocks, that does not apply to industrial off-gas.

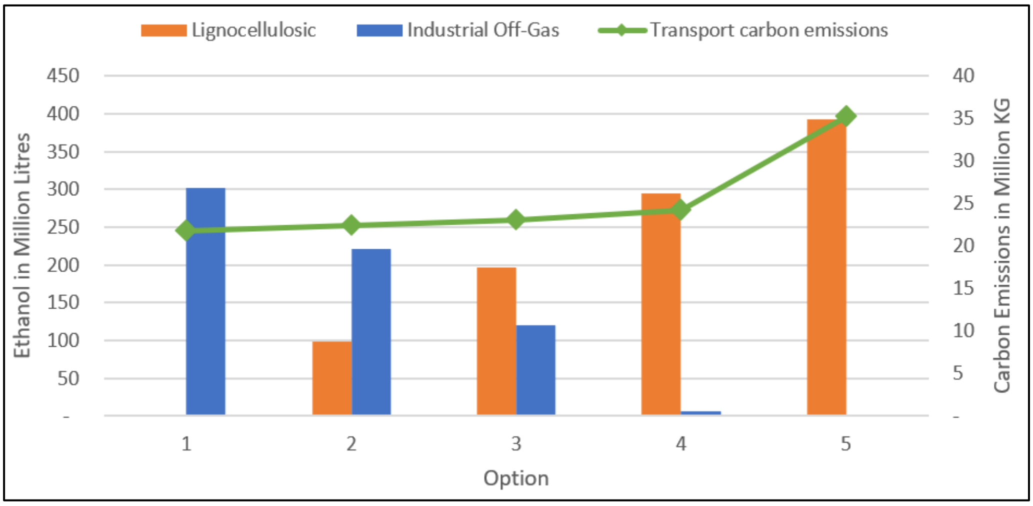
The annual ethanol output for the different combinations is given below in Appendix Table 3 Annual ethanol output, costs and transport emissions for the lignocellulosic and industrial off-gas combination scenario and graphically in Appendix Figure 6 and Appendix Figure 7, together with the total costs of the full production output, and separately for the 300 million litres required by PetroSA, as well as the related carbon emissions from transport. Appendix Table 4 provides the combined overview of the cost and carbon emissions per litre of ethanol for each combination of lignocellulosic and industrial off-gas option. It is shown graphically in Appendix Figure 8.

Appendix Table 3 Annual ethanol output, costs and transport emissions for the lignocellulosic and industrial off-gas combination scenario

Option	Lignocellulosic (ethanol in litres)	Industrial off-gas (ethanol in litres)	**Total production (ethanol in litres)**	Total output cost (in ZAR)	**Total cost for PetroSA requirement (in ZAR)**	**Transport carbon emissions (kg CO2/y)**
1	-	302,350,654	302,350,654	4,519,063,022	4,483,929,136	21,805,433
2	98,040,000	220,805,596	318,845,596	5,149,471,777	4,845,108,581	22,439,443
3	196,080,000	120,480,445	316,560,445	5,523,244,119	5,234,302,838	23,092,831
4	294,120,000	5,902,415	300,022,415	5,691,953,276	5,691,528,024	24,257,945
5	392,160,000	-	392,160,000	7,542,239,265	5,769,766,880	35,272,191



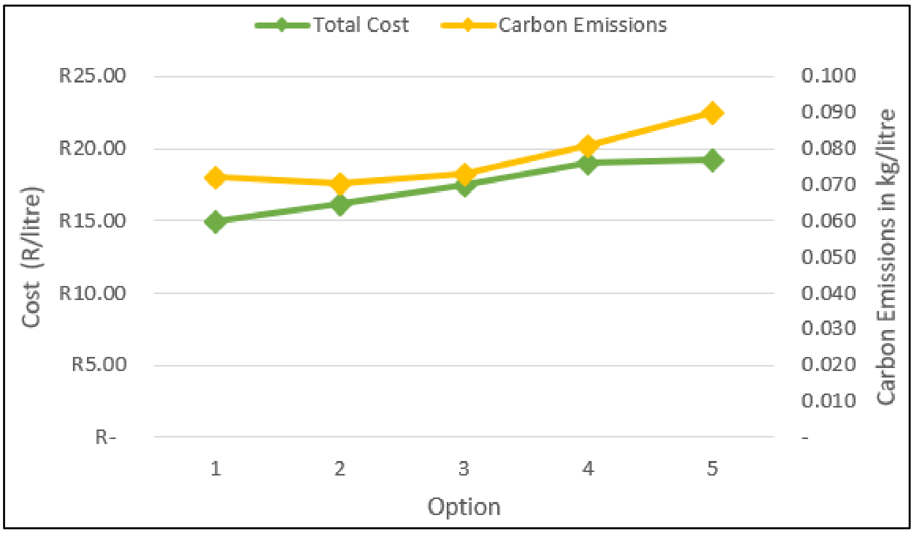
Appendix Figure 6 Annual output and cost for different lignocellulosic and industrial off-gas-based ethanol supply combinations



Appendix Figure 7 Annual output and transport carbon emissions for different lignocellulosic and industrial off-gas-based ethanol supply combinations

Appendix Table 4 Average cost and transport emissions of ethanol per litre for different lignocellulosic and industrial off-gas-based ethanol supply combinations

Option	Average cost per litre (ZAR/l)	Average transport carbon emission per litre (kg CO2)
1	14.95	0.072
2	16.15	0.070
3	17.45	0.073
4	18.97	0.081
5	19.23	0.090



Appendix Figure 8 Average cost and transport carbon emission per litre for different combinations of lignocellulosic and industrial off-gas-based ethanol supply

Molasses and industrial off-gas only

In this combination scenario, the solution of the optimization problem begins with all ethanol supply coming from the molasses option and each iteration moves closer to all ethanol being produced from industrial off-gases, by removing from the ethanol supply mix the most expensive molasses-based facilities and introducing the cheapest off-gas-based facility. The capacity of molasses facilities is much higher than industrial off-gas facilities. Since all facilities open at full capacity, the quantity produced in a pure molasses-based option is approximately 27 million litres more ethanol per annum than the minimum requirement. The average facility replacement ratio is 1:4.

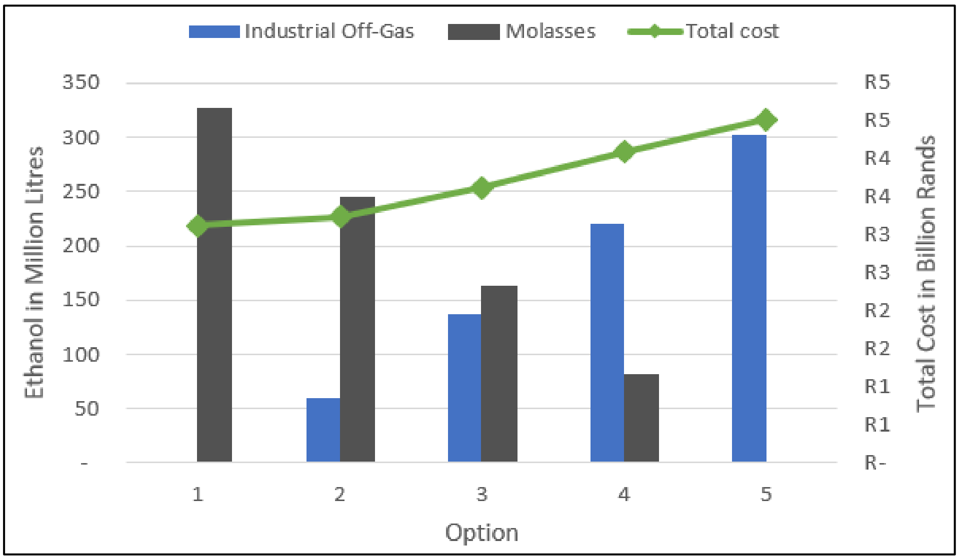
The annual ethanol output for the different combinations is given below in Appendix Table 5and graphically in Appendix Figure 9 and Appendix Figure 10, together with the total costs of the full production output, and separately for the 300 million litres required by PetroSA, as well as the related carbon emissions from transport. Appendix Table 6 provides the combined overview of the cost and carbon emissions per litre of ethanol for each combination of lignocellulosic and industrial off-gas option. It is shown graphically in Appendix Figure 11.

The increased carbon emissions for most of the industrial off-gas options can be attributed to the longer secondary transport leg as compared to the molasses options. Sugar mills are situated closer to PetroSA than industrial off-gas sites. As a result, there is a general increase in total carbon emissions, as more ethanol is sourced from industrial off-gas sites. The decrease in CO_2 emissions in options one and two can be attributed to the decrease in the quantity of ethanol produced and required to be transported to PetroSA.

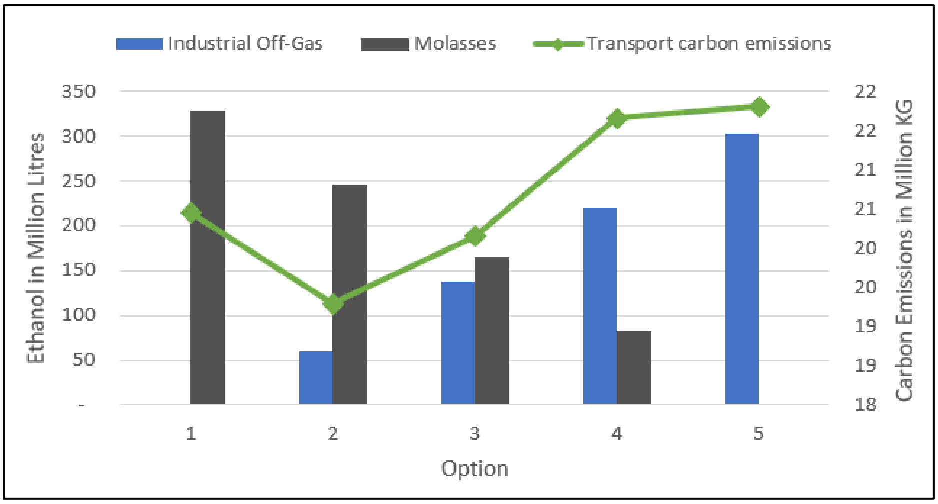
Appendix Table 5 Annual ethanol output, costs and transport emissions for the industrial off-gas and molasses combination scenario

Option	Industrial Off-Gas (ethanol in l)	Molasses (ethanol in l)	**Total production (ethanol in litres)**	Total output cost (in ZAR)	**Total cost for PetroSA requirement (in ZAR)**	**Transport carbon emissions (kg CO2/y)**
1	-	327,040,000	327,040,000	3,123,111,229	2,864,889,214	20,447,768
2	60,316,350	245,280,000	305,596,350	3,235,417,424	3,176,167,605	19,290,844
3	137,811,331	163,520,000	301,331,331	3,620,997,330	3,604,999,173	20,146,594

4	220,805,596	81,760,000	302,565,596	4,094,333,506	4,059,615,726	21,659,529
5	302,350,654	-	302,350,654	4,519,063,022	4,483,929,136	21,805,433



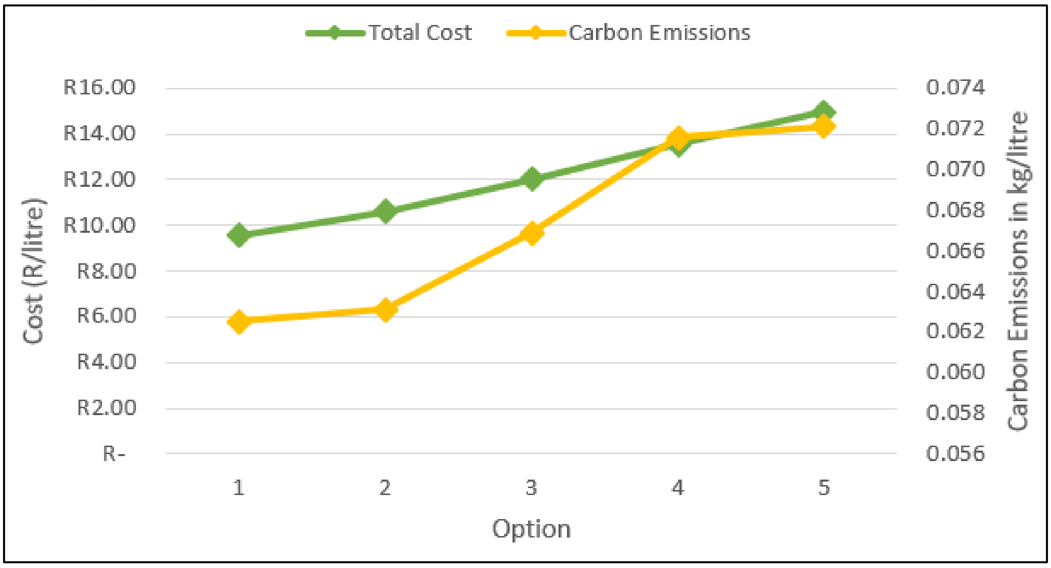
Appendix Figure 9 Annual output and cost for different industrial off-gas and molasses ethanol supply combinations



Appendix Figure 10 Annual output and transport carbon emissions for different industrial off-gas and molasses ethanol supply combinations

Appendix Table 6 Average cost and transport emissions of ethanol per litre for different industrial off-gas and molasses ethanol supply combinations

Option	Average cost per litre (ZAR/l)	Average transport carbon emission per litre (kg CO2/l)
1	9.55	0.063
2	10.59	0.063
3	12.02	0.067
4	13.53	0.072
5	14.95	0.072



Appendix Figure 11 Average cost and transport carbon emission per litre for industrial off-gas and molasses scenario

Appendix E: Optimised secondary transport costing

Leveraging the experience and extensive operations of Imperial Tanker Services, the CpK for secondary transport can be further optimised, taking the following into consideration:

- Costing is based on the premise of 24/7 loading and offloading parameters, with neither loading nor offloading taking longer than 3 hours respectively.
- Costing is based on the assumption of the achievable vehicle per-route utilisation.
- Double-Crew drivers are used to ensure 24/7 operational activity to drive efficiencies.
- The vehicles can load up to 35.43 Tons / 45 900 Litres (based on a product SG of 0.772 g/cm³ for ethanol).
- Pumps must be supplied at the loading and offloading points.

Based on the above, the optimised secondary transport leg CpK supplied by Imperial Tanker Services is R23/km. Using this new CpK, the total cost of each scenario was calculated and compared to the total costs for the full project lifetime calculated using the original assumed CpK of R26/km.

As shown in Appendix Table 7, the original secondary transport cost for the lignocellulosic only scenario is R3.1 bn for the full project lifetime. With a reduction to R23 per km, the secondary transport cost is reduced to R2.8 bn. Therefore, the total cost of the scenario can be reduced by 0.32%.

Appendix Table 7 Optimised CpK costs for the scenario using only lignocellulosic feedstock

	Lignocellulosic (Original CpK)	Lignocellulosic (Optimised CpK)
Feedstock cost	R 41,968,176,255	R 41,968,176,255
Primary transport cost	R 5,901,994,651	R 5,901,994,651
Secondary transport cost	R 3,170,800,610	R 2,804,939,001
Processing cost	R 64,354,366,080	R 64,354,366,080
Total cost	R 115,395,337,595	R 115,029,475,987
% Cost reduction	0.32%	

The original secondary transport cost for the industrial-off-gas only scenario is R9.4bn for the full project lifetime. With a reduction to R23 per km, the secondary transport cost is reduced to R8.2bn. Therefore, the total cost of the scenario can be reduced by 1.2%. Since industrial off-gas does not incur feedstock or primary transport cost, the secondary transport makes up a larger cost component of the total cost, hence the larger cost reduction potential as compared to other feedstocks. This is shown in Appendix Table 8 below.

Appendix Table 8 Optimised CpK costs for the scenario using only industrial off-gas feedstock

	Industrial Off-Gas (Original CpK)	Industrial Off-Gas (Optimised CpK)
Feedstock cost	R -	R -
Primary transport cost	R -	R -
Secondary transport cost	R 9,235,625,113	R 8,169,976,062
Processing cost	R 80,442,957,600	R 80,442,957,600
Total cost	R 89,678,582,713	R 88,612,933,662
% Cost reduction	1.20%	

The original secondary transport cost for the molasses only scenario is R7.9bn for the full project lifetime, as shown in Appendix Table 9 below. With a reduction to R23 per km, the secondary transport cost is reduced to R7bn. Overall, the total cost of the scenario can be reduced by 1.64%.

Appendix Table 9 Optimised CpK costs for the scenario using only molasses

	Molasses (Original CpK)	Molasses (Optimised CpK)
Feedstock cost	R 29,001,509,693	R 29,001,509,693
Primary transport cost	R -	R -
Secondary transport cost	R 8,006,773,067	R 7,082,914,636
Processing cost	R 20,289,501,528	R 20,289,501,528
Total cost	R 57,297,784,288	R 56,373,925,857
% Cost reduction	1.64%	

For the tables below, the various feedstock scenarios relate to the proportions for the full project lifetime mentioned in Section 0. The cheapest combination, Option 2, can be reduced from R73bn to R72.3bn (approximately 1% reduction).

Appendix Table 10 Optimised CpK comparison of the lignocellulosic and molasses option

Option	Total cost for minimum requirement (Original CpK)	Total cost for minimum requirement (Optimised CpK)	% Cost reduction
1	R 57,297,784,288	R 56,373,925,857	1.61%
2	R 73,020,788,191	R 72,294,030,630	1.00%
3	R 88,014,309,747	R 87,526,839,908	0.55%
4	R 101,886,906,580	R 101,486,807,479	0.39%
5	R 115,395,337,595	R 115,029,475,987	0.32%

For the lignocellulosic and industrial off-gas combination scenario, option 2 can be reduced from R96.9bn to R96bn. This is a 0.87% cost reduction. With a progression to a pure lignocellulosic feedstock combination, the cost reduction potential reduces. This is shown in Appendix Table 11 below.

Appendix Table 11 Optimised CpK comparison of the lignocellulosic and industrial off-gas option

Option	Total cost for minimum requirement (Original CpK)	Total cost for minimum requirement (Optimised CpK)	% Cost reduction
1	R 89,678,582,713	R 88,612,933,662	1.19%
2	R 96,902,171,621	R 96,063,472,488	0.87%
3	R 104,686,056,760	R 104,052,744,647	0.60%
4	R 113,830,560,475	R 113,556,324,017	0.24%
5	R 115,395,337,595	R 115,029,475,987	0.32%

For the industrial off-gas and molasses combination scenario, Option 2 can be reduced from R63.5bn to R62.5bn. This is a 1.47% cost reduction, which is the largest cost reduction opportunity compared to the alternative combinations of these feedstocks.

Appendix Table 12 Optimised CpK comparison of the industrial off-gas and molasses option

Option	Total cost for minimum requirement (Original CpK)	Total cost for minimum requirement (Optimised CpK)	% Cost reduction
1	R 57,297,784,288	R 56,373,925,857	1.61%
2	R 63,523,352,101	R 62,590,605,966	1.47%
3	R 72,099,983,464	R 71,112,072,673	1.37%
4	R 81,192,314,528	R 80,134,547,933	1.30%
5	R 89,678,582,713	R 88,612,933,662	1.19%

For the combination of all feedstock scenario, shown in Appendix Table 13 below, a cost reduction of 0.88% can be achieved on Option 2. The majority of this combination is allocated to molasses-based ethanol.

Appendix Table 13 Optimised CpK comparison of the option that makes use of all feedstocks

Option	Total cost for minimum requirement (Original CpK)	Total cost for minimum requirement (Optimised CpK)	% Cost reduction
1	R 57,297,784,288	R 56,373,925,857	1.61%
2	R 79,356,797,834	R 78,659,965,269	0.88%
3	R 88,185,352,651	R 87,439,309,189	0.85%
4	R 89,678,582,713	R 88,612,933,662	1.19%
5	R 96,586,813,662	R 96,161,547,753	0.44%
6	R 115,395,337,595	R 115,029,475,987	0.32%

In addition to the optimised CpK, it is further recommended approximately how many vehicles each feedstock option would require to fulfil the secondary transport demands per annum:

- IAP: 22 vehicles
- Industrial off-gas: 60 vehicles
- Molasses: 60 vehicles

This is calculated based on the same considerations applied to the optimised CpK. The distance between facilities and the end user affects the vehicle utilisation. The further the distance to be travelled, the longer the trip would be, and one vehicle would be able to perform a reduced number of trips per year as the distances increase. This takes into consideration driver rest time for multi day trips and any possible downtime due to maintenance.