THE VIABILITY OF SOUTH AFRICAN SUGARCANE ETHANOL AS FEEDSTOCK FOR SUSTAINABLE AVIATION FUEL PRODUCTION

Part III: GHG emissions

Joint publication by the Roundtable on Sustainable Biomaterials (RSB) and the South African Canegrowers Association (SA Canegrowers), made possible with the support of Boeing's Global Engagement Portfolio.

FUELLING THE SUSTAINABLE BIOECONOMY

A project of RSB, powered by Boeing's
Global Engagement Portfolio

The report was developed with the support of Blue North Sustainability

August 2020

Executive summary

Certification requirements for sustainable aviation fuel (SAF) under both the EU Renewable Energy Directive (EU-RED) and the RSB Global standards stipulate that SAF deliver a minimum 50% emission reduction across its lifecycle when compared against a fossil fuel baseline, which increase to 60% if produced in installations that started operations after 5 October 2015[1]. Under EU RED II, this increases further to 65% for installations commencing operation after 1 January 2021. Emission reduction is also a key requirement under ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which stipulates that SAF shall achieve lifecycle GHG emissions reductions of at least 10% compared to the baseline emissions values for conventional aviation fuel. CORSIA however also demands for the SAF to be certified against a recognised standard. The RSB CORSIA Standard requires that the certified SAF achieves a minimum 50% GHG emission reduction on its core life-cycle assessment (LCA) value, and a minimum 10% reduction on the core LCA *plus* the induced land use change value provided by CORSIA.

A recent revision of the Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK) processing pathway has included ethanol as an approved feedstock. This revision has particular relevance to the South African sugar industry, as it allows for the conversion of ethanol produced from local sugarcane to SAF. Given the current crisis that the industry is facing due to various factors including drought, falling prices, the sugar tax and the impact of cheap imports, the production of ethanol feedstock for the ATJ process could form part of a much-needed diversification strategy. An important criterion in evaluating the feasibility of this strategy, is whether this SAF can achieve the requisite emission savings over its lifecycle to meet global certification requirements.

The objective of this research was to determine the lifecycle GHG emission saving potential of SAF produced via the ATJ-SPK processing pathway using bioethanol produced from South African sugarcane as the ethanol feedstock. "well-to-wing" GHG emissions for three different scenarios differing in cane cultivation practices were modelled: irrigated cane, dryland cane and a hypothetical case for dryland cane with green cane harvesting. Input data were based on a combination of primary data (cultivation and feedstock transportation) and literature values (upstream processing and transport). The data was modelled in the RSB GHG Calculator (v2.11). Primary data for dryland and irrigated cane were provided by the South African Canegrowers Association (SA Canegrowers) and modelled according to the methodology as laid out in EU Directive 2009/30/EC. Data to model the production of ethanol, upgrading thereof to SAF, and transport to market, were taken from CORSIA data sets[2].

The results show that the emission saving potential of SAF produced via the ATJ-SPK process using bioethanol produced from South African sugarcane is 59% for irrigated cane, 72% for dryland cane and 74% for dryland cane with greencane harvesting when based on the EU RED II fossil baseline (94 g $CO_{2\,eq}$ / MJ). If the CORSIA baseline is used (89 g $CO_{2\,eq}$ / MJ), the emissions saving potential is 47% for irrigated cane, 60% for the dryland scenario and 63% for the dryland scenario with green cane harvesting. An important difference in the CORSIA approach as compared to the EU RED methodology is the inclusion of induced land use change (iLUC) emissions in the total life cycle emissions.

According to these results, SAF produced from irrigated sugarcane is not eligible under EU RED. However, dryland cane, and dryland cane with green cane harvesting, does meet the EU-RED emission reduction requirements. SAF produced from irrigated cane, dryland cane, and the hypothetical dryland cultivation with green cane harvesting scenario, are eligible under CORSIA and also qualify for the RSB CORSIA Standard.

When considering road transport, the estimated emission saving potential for fuel ethanol produced using South African sugarcane is 57% for irrigated cane, 78% for dryland cane, and 81% for dryland cane with green harvesting, when based on the EU RED fossil baseline (94 g $CO_{2\,eq}$ / MJ).

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[1] This cut-off serves to incentivise better GHG savings for new businesses

[2] CORSIA Supporting Document - CORSIA Eligible Fuels – Life Cycle Assessment Methodology. June 2019.

Table 1 Summary of GHG savings and market access potential for biofuels produced with South African sugarcane ethanol

	EU aviation market (based on EU RED fossil baseline)		Global aviation market (based on CORSIA baseline)		Road transport (local or export) (based on EU RED fossil baseline)	
	GHG savings	Qualifies?	GHG savings	Qualifies?	GHG savings	Qualifies?
Irrigated cane	59%	No	57% (LCA only) 47% (LCA + iLUC)	Yes	57%	Yes
Dryland cane	72%	Yes	60%	Yes	78%	Yes
Dryland cane + green harvesting	74%	Yes	63%	Yes	81%	Yes

In the irrigated cane supply chain, the majority (57%) of GHG lifecycle emissions are generated during feedstock cultivation and harvesting. For the dryland cultivation and dryland cultivation with green cane harvesting, the largest emission contributor is the conversion of ethanol to SAF with 52% and 57% respectively. Dryland cultivated cane has substantially lower emissions than irrigated cane due to the high electricity demand for pumping of water.

It should be noted that producers are allowed to use global default values in the determination of their supply chain GHG emission savings for both CORSIA and EU RED certification. While the default values can currently be used on any supply chain using sugarcane feedstock to produce SAF via the ATJ process, these default values are liable to change, particularly with regards to reflecting greater regional variations. Where supply chain steps reflect significant differences (e.g. region, production inputs, efficiencies, etc.) from default conditions, it is strongly recommended that the specific supply chain step is modelled, and the resulting process specific GHG emissions are used towards certification.

A low carbon footprint can be linked to operational efficiency. In general, any strategy or technology that aims to reduce energy consumption, minimise raw material and utility inputs, and reduce waste, will lead to a reduction in lifecycle GHG emissions. For example, replacing the current South African grid electricity used for pumping of water with renewable electricity, can reduce emissions from irrigated cane cultivation by 61%. From a processing perspective, alternative hydrogen production technologies (namely electrolysis using renewable electricity from wind, solar and biogenic waste, and gasification of biomass) can reduce emissions from this stage by 15 – 20%. Under the EU RED methodology, emission savings are allowed from excess electricity produced in sugar mill’s CHP plants using bagasse as feedstock. This was modelled using high-level South Africa data and results show a potential reduction of 2.1% in SAF GHG lifecycle emissions.

About the RSB

The Roundtable on Sustainable Biomaterials Association (RSB) is a global, multi-stakeholder organisation that offers advisory, membership and certification services for the bioeconomy on a global scale. Together with our partners, members and certified projects, we represent best practice in sustainability and proactively drive the development of a sustainable bioeconomy.

The RSB Principles and Criteria are the most robust and comprehensive indicators of why a biomaterial is sustainable. They are a one-stop solution for sector pioneers who need guidance in developing innovative products for a new world founded on social, economic and environmental considerations. The RSB certification system includes regulatory standards for compliance with the European Union's Renewable Energy Directive (EU RED) and ICAO's CORSIA.

RSB enjoys wide NGO support and is aligned with the United Nations' Sustainable Development Goals (SDGs). RSB certification is recognised by WWF, IUCN and the Natural Resources Defence Council as the strongest and the most trusted of its kind. It has been endorsed by SAFUG (Sustainable Aviation Fuel Users Group), ATAG (Aviation Transport Action Group), and ICSA (International Coalition for Sustainable Aviation) for its high level of sustainability assurance and is increasingly being requested by airlines as an essential part of their biofuel procurement.

RSB certified Sustainable Aviation Fuels (SAF) have a minimum 50% GHG reduction compared to fossil fuels, do not compete with food security or cause deforestation, and actively promote human rights and healthy ecosystems.

For more information visit www.rsb.org

About SA Canegrowers

The South African Canegrowers Association was established in 1927 to create a common platform to address grower issues. Today, our mission is to play a leading role in growing sugarcane and diverse production opportunities for cane growers through innovation, research, specialised services and products throughout the value chain

For more information visit www.sacanegrowers.co.za/

Abbreviations

ASTM	American Society for Testing and Material
ATJ	Alcohol-to-Jet
ATJ-SPK	Alcohol-to-Jet Synthetic Paraffinic Kerosene
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
$CO_{2\ eq}$	Carbon Dioxide Equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
EtOH	Ethanol
EU RED	European Union Renewable Energy Directive
GHG	Greenhouse Gas
ICAO	International Civil Aviation Organization
iLUC	Induced Land Use Change
LCA	Life Cycle Assessment
RSB	Roundtable on Sustainable Biomaterials
SAF	Sustainable Aviation Fuel
WWF-SA	Worldwide Fund for Nature South Africa

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1. INTRODUCTION

Aviation is one of the fastest growing transport sectors, pre Covid-19, with the demand for jet fuel increasing alongside it. Over the last 20 years, global greenhouse gas (GHG) emissions from aviation have more than doubled, making this the largest increase in emissions from the transport sector[3]. Currently, sectoral emissions from aviation account for approximately 2% of total anthropogenic GHG emissions[4] and as the sector continues to grow, there will be a corresponding growth in emissions. Although there has been significant technological progress in the aviation sector to date, projected annual improvements of 1 – 2% in terms of fuel efficiency, advances in air traffic management and other operational measures will be unable to offset the increased demand for fuel (and hence emissions) consequent of the predicted growth in air traffic[5]. The projected growth for the aviation industry and subsequent fuel demand, coupled with the stringent policy and regulatory environment surrounding GHG emissions, and growing consumer awareness around the need to reduce CO_2 emissions, are important drivers for sustainable aviation fuel (SAF).

SAF derived from biomass, wastes and other feedstocks (such as carbon off-gases) is capable of delivering significant GHG savings to the industry, having the potential to reduce the carbon footprint of aviation fuel by up to 94% over its full lifecycle[3]. An important benefit of SAF is that it can be used as a "drop in" to existing fuel supply networks, requiring no changes to existing aircraft and infrastructure. Consequently, SAF offers the most effective and immediate solution to an industry looking to decarbonize rapidly.

In a bid to reduce industry GHG emissions and promote the development of low carbon SAF, regulatory requirements and standards schemes have implemented minimum GHG emission reduction requirements on SAF. To be eligible under the relevant scheme, the SAF must be shown to deliver the stipulated GHG saving when compared to a suitable fossil baseline. GHG emission reduction requirements for the Roundtable on Sustainable Biomaterials (RSB), EU Renewable Fuels Directive II (EU RED II) and the International Civil Aviation Organization's (ICAOs) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) are shown below:

- RSB Global[6]:
  - Lifecycle GHG emissions of a biofuel produced in an installation established before 5 October 2015 should be on average 50% lower than the applicable fossil fuel baseline.
  - Lifecycle GHG emissions of a biofuel produced in a new installation that started operation after 5 October 2015 shall be 60% lower than the applicable fossil fuel baseline.

- EU RED II[7]:
  - Lifecycle GHG emission savings from biofuel produced in installations which started production prior to 5 October 2015 shall be at least 50%.
  - Lifecycle GHG emission savings shall be at least 60% for biofuels produced in installations in which production has started on or after 5 October 2015.
  - Lifecycle GHG emission savings shall be at least 65% for biofuels produced in installations starting operation after 1 January 2021.

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[3] https://rsb.org/wp-content/uploads/2018/09/RSB-Alternative-Aviation-Fuels-A-Sustainable-Future-is-Taking-Off.pdf

[4] https://www.atag.org/facts-figures.html

[5] https://www.unitingaviation.com/strategic-objective/environment/why-did-icao-develop-a-global-mbm-scheme-for-international-aviation/

[6] http://rsb.org/wp-content/uploads/2017/04/RSB-STD-01-001_Principles_and_Criteria-DIGITAL.pdf

[7] https://www.iscc-system.org/wp-content/uploads/2017/02/New-Regulative-Framework-in-the-EU-RED-II-Opportunities-for-North-America.pdf

- ICAO's CORSIA[8]
  - Biofuel shall achieve net greenhouse gas emissions reductions of at least 10% compared to the baseline lifecycle emissions values for aviation fuel on a lifecycle basis.
  - Biofuel shall be certified against an approved voluntary sustainability standard.
  - The RSB CORSIA Standard is in the process of achieving recognition by ICAO to be used for certification of CORSIA eligible fuels. In line with RSB's mission to significantly combat climate change, the RSB CORSIA Standard requires SAF to achieve a minimum 50% GHG emission reduction on its core life-cycle assessment (LCA) value, and a minimum 10% reduction on the core LCA *plus* the induced land use change value.

For bio based SAF, the GHG impact of the fuel is largely determined by the type and origin of the feedstock, as well as the specific processing pathway. For example, the lifecycle GHG emissions associated with SAF production from crops are strongly affected by how the feedstock is produced at farm level (i.e. electricity consumption, the use of fertilisers, land-use change effects etc.), upstream production utilities and material demands and transport energy consumption.

Despite the GHG emission saving potential of some SAFs, it should be noted that SAFs are not inherently more sustainable than conventional fossil-based fuels. Without sustainable practices in place (verified by reliable certification schemes), some of these fuels risk having negative social and environmental impacts, such as negligible GHG emissions reductions (or even increased emissions), reduced food security through the conversion of food-producing land to feedstock production, environmental degradation from deforestation, biodiversity loss and unsustainable soil and water usage. Consequently, in addition to the GHG emission saving requirements under the RSB Standard, EU RED and CORSIA, additional sustainability requirements are imposed on SAF. A strong focus of these requirements is on limiting land conversion, specifically land with a high biodiversity value, conservation value and/or carbon stock value. The cut-off date for conversion under all three schemes is 1 January 2008[9]. A detailed discussion on the sustainability requirements covered by the RSB Standard and an indication of the RSB "certification readiness" of the South African sugarcane industry is available in the adjacent report (*Supply Chain Mapping, Benchmark and Gap Analysis*) prepared under the scope of engagement.

1.1 Research Objectives

The key objective of this research is to determine the GHG emission saving potential of SAF produced via the recently approved Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK) processing pathway[10] using bioethanol produced from South African sugarcane as the ethanol feedstock. This key objective is in support of the broader objective to explore the Alcohol-to-Jet (ATJ) potential for the South African sugar cane industry, and feed into the long-term goal of equipping the industry with the necessary knowledge to develop an effective market development strategy.

The research is structured to address the following topics:

1. Determination of the lifecycle GHG emissions of SAF produced via the ATJ-SPK process using bioethanol produced from South African sugarcane as the ethanol feedstock.

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[8] https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2005%20-%20Sustainability%20Criteria.pdf

[9] The cut-off date stipulates that eligible fuel shall not be made from biomass obtained from land converted after 1 January 2008. Note that the specific definitions around land that cannot be converted is available under the relevant schemes.

[10] In April 2018, the American Society for Testing and Material (ASTM) D7566 standards were revised to include ethanol as an approved feedstock for the ATJ-SPK process. As a result of this revision, jet fuel produced by ATJ-SPK can use ethanol produced from any feedstock, using any conversion technology. This revision is relevant to the South African sugar industry, as it allows for the conversion of ethanol produced from local sugar cane to SAF.

2. Determination of the emission saving potential of SAF produced as per the specifications defined above.
3. Identification and understanding of supply chain emission "hotspots" and opportunities for GHG savings.

2. METHODOLOGY

2.1 Overview of Modelling Approach

This study covers the lifecycle GHG emissions of SAF produced via the ATJ-SPK processing pathway using bioethanol produced from South African sugarcane as the ethanol feedstock.

The GHG emissions associated with the production of SAF were determined using a lifecycle assessment "cradle-to-grave" approach. This approach covers all emissions across the lifecycle of the SAF, from the cultivation of sugarcane through to combustion of the final product (see Section 2.2 for a detailed description of the product lifecycle). While the lifecycle approach can be extended to cover a wide range of environmental impacts, the scope of this study was limited to quantifying GHG emissions.

Total lifecycle GHG emissions were determined as **g $CO_{2\,eq}$ / MJ SAF** and emission saving potential was determined relative to the following baseline values:

- EU RED II[11]: 94 g $CO_{2\,eq}$ / MJ
- CORSIA[12]: 89 g $CO_{2\,eq}$ / MJ

It should be noted that the difference in the baseline values reported is in part due to differences in the methodology and approach outlined under the different schemes[13]. Various methodologies, calculation tools and default values are available for the determination of lifecycle emissions, and these are generally standardised within a certain regulatory context. Certification or approval of GHG emission saving potential within a particular context therefore requires the consistent and accurate application of the relevant methodology across the entire supply chain.

As far as possible, this study followed the methodology as laid out in the EU RED 2009/30/EC[11]. However, due to the scope of the project and limitations in the availability of primary data and/or default values for all supply chain steps, it was necessary to use literature values to represent or model a supply chain step where no reasonable alternative was available. In particular, the availability of both primary data and literature values for upstream processing (namely the conversion of feedstock to SAF) were limited due to the novelty of the process. Given that calculation from primary South African production data was not possible, the LCA inventory data for the sugarcane ethanol ATJ pathway reported by CORSIA[12] was used. It should be noted that the input data available for this process was a) based on averages from various sources and b) not exhaustive. Therefore, several assumptions and approximations were necessary to model this data. This approach was considered acceptable given the exploratory nature of the study.

The resulting GHG values and emission saving potentials obtained from this approach should therefore be regarded as **indicative values only** and should be communicated and used as such.

2.2 System Boundaries

GHG Calculations

In line with the lifecycle assessment modelling approach, the system boundary for this study was from "well-to-wing". GHG emissions were determined according to the equation shown in Box 1. Each term in the equation corresponds to a step in a generic biofuel supply chain. It should be noted that this is

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[11] https://www.iscc-system.org/wp-content/uploads/2017/02/New-Regulative-Framework-in-the-EU-RED-II-Opportunities-for-North-America.pdf

[12] https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA%20Supporting%20Document_CORSIA%20Eligible%20Fuels_LCA%20Methodology.pdf

[13] Methodological differences typically include variation in the CO_2 equivalence of CH_4 and N_2O, excess electricity allocation and the inclusion/exclusion of emissions associated with equipment and infrastructure manufacture, maintenance, and disposal.

the generic equation used to determine GHG emissions according to the EU RED and ICAO’s CORSIA methodology, and not all terms are necessarily applicable to the specific supply chain under consideration.

$$E = e_{ec} + e_{l} + e_{p} + e_{td} + e_{u} - e_{sca} - e_{ccs} - e_{ccr} - e_{ee} + e_{iLUC}^{*}$$

E = total emissions from the use of the fuel
e_{ec} = emissions from the extraction or cultivation of raw materials
e_{l} = annualised emissions from carbon stock changes caused by land-use change
e_{p} = emissions from processing
e_{td} = emissions from transport and distribution
e_{u} = emissions from the fuel in use (= 0 for biofuels)
e_{sca} = emission saving from soil carbon accumulation via improved agricultural management
e_{ccs} = emission saving from carbon capture and geological storage
e_{ccr} = emission saving from carbon capture and replacement
e_{ee} = emission saving from excess electricity from cogeneration
e_{iLUC} = indirect land-use change emissions

* Currently only included in ICAO’s CORSIA methodology

Box 1 Lifecycle GHG emission calculation

A key difference between the EU RED and CORSIA methodology is the treatment of induced Land Use Change[14] (iLUC) emissions. Under the CORSIA methodology, the iLUC value must be included in the calculation. However, this is only possible via a default value, as no individual calculation is allowed. Currently, there is only a default value available for Brazil (8,7 g $CO_{2\,eq}$ / MJ)[15]. This value was therefore used indicatively as a proxy for iLUC emissions in South Africa.

The total GHG emissions for the production of SAF from South African sugarcane were determined from the specific inputs (material and/or energy) needed for each supply chain step. The basic SAF supply chain modelled in this research, including an overview of inputs contributing to total GHG emissions, is shown in Figure 1.

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[14] iLUC refers to the impacts consequent of diverting pasture or agricultural land previously destined for the food, feed and fibre markets to biofuel production. The non-fuel demand (previously satisfied by the biofuel feedstock) will still need to be satisfied either through intensification of current production or by bringing non agricultural land into production elsewhere. The latter case constitutes iLUC and when it involves the conversion of land with high carbon stock it can lead to significant greenhouse gas emissions.

[15] CORSIA Default Life-Cycle Emissions Values for CORSIA Eligible Fuels, November 2019: https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions.pdf

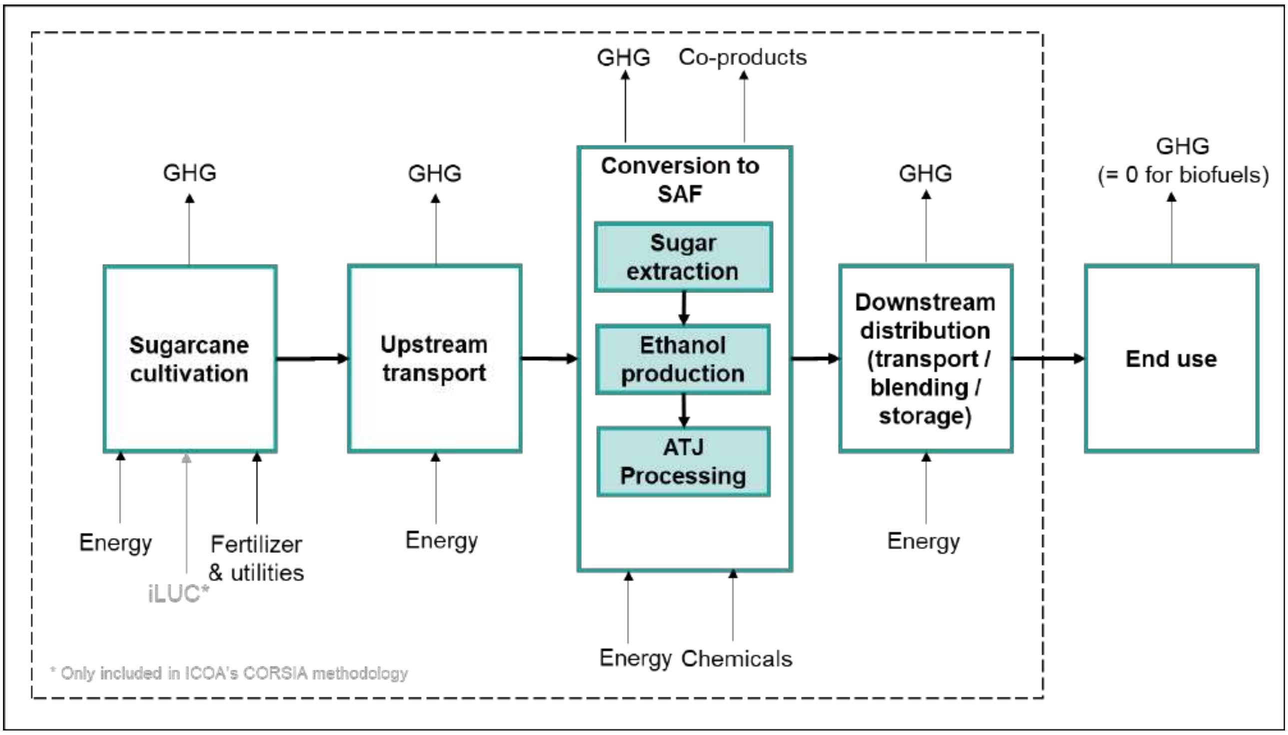

Figure 1 Schematic overview of the ATJ supply chain and system boundaries used in this study

Supply Chain Modelling Approach

Approximately 75% of the area of sugarcane harvested in South Africa is dryland (relying on rainfall) and 25% is irrigated. To accommodate these differences in cultivation practice, two different scenarios were modelled: dryland and irrigated cane production. A third hypothetical scenario was also modelled, based on dryland cultivation but assuming green cane harvesting. Cultivation is the only lifecycle stage affected by the different scenarios, and upstream transport and processing were modelled in the same way for all scenarios.

As discussed, due to the scope of the project and limitations in the availability of primary data for all supply chain steps, the total lifecycle GHG emissions for SAF production from sugarcane were modelled by a combination of primary data collection, default values and literature estimates. This approach is illustrated in Figure 2, followed by further detail regarding the assumptions. The specific approach towards, and data source/s for, each supply chain step is summarised in Table 2 (pg. 14).

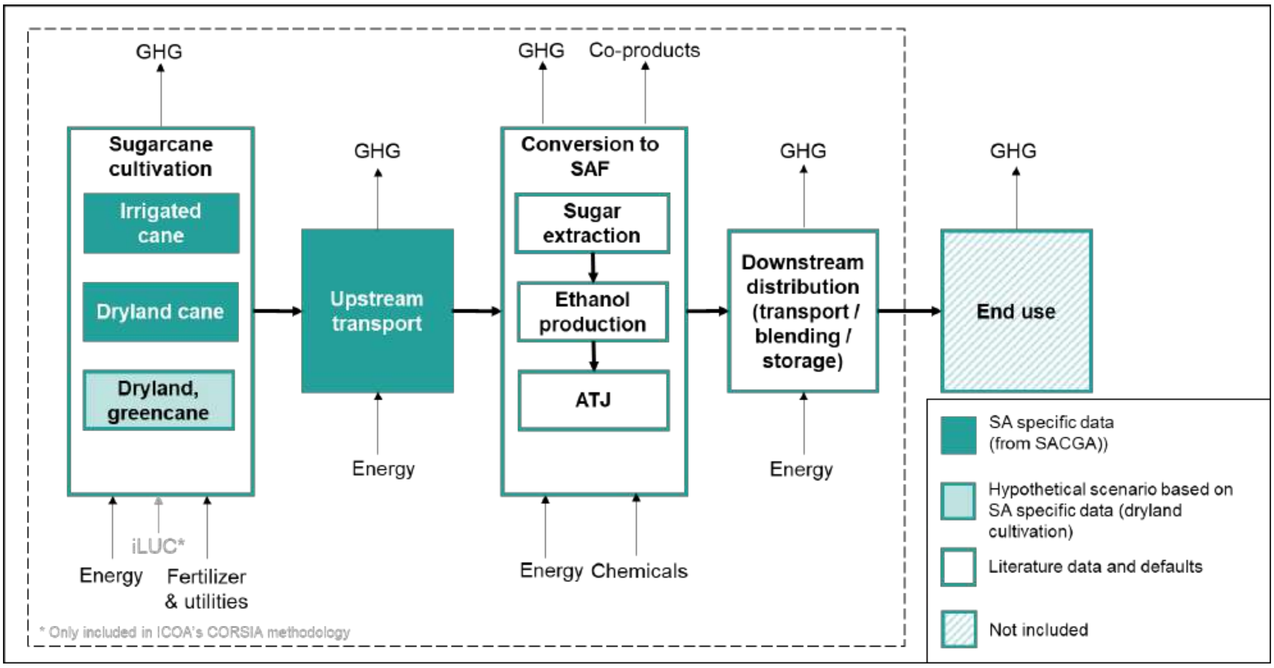

Figure 2 Overview of modelling approach used in this study

Key assumptions used in determining GHG emissions across the modelled SAF supply chain are as follows:

- Emission factors for calculated emissions:
    - Standard values were consistent with the EU RED 2009/30/EC requirements[16]. Where no default value was available, emission factors were taken from the Ecoinvent database.
    - South African grid electricity emissions (as used in the cultivation stage) = 0.93 kg CO2e / kWh[17]
- Yield efficiency:
    - Ethanol production: 0.514 kg sugarcane$_{wet}$ / MJ ethanol[18]
    - SAF production (ATJ-SPK): 1.49 MJ ethanol / MJ SAF[19]
- Trash burning (irrigated and dryland scenarios):
    - 100% of cropland is burnt at harvest
    - Dry trash yield = 12.3% of cane yield[20]
- Green cane harvesting scenario:
    - Cane is harvested manually, and no emissions associated with machinery were included.
    - All yield and input values are identical to conventional dryland practices.

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[16] For default values refer to: https://www.biograce.net/content/ghgcalculationtools/standardvalues

[17] Eskom 2019 report: http://www.eskom.co.za/OurCompany/SustainableDevelopment/Documents/Eskom_Factor_2.0.pdf

[18] BioGrace version 4d. Default value. Production of Ethanol from Sugarcane Pathway

[19] de Jong, S., Antonissen, K., Hoefnagels, R., Lonza, L., Wang, M., Faaij, A. and Junginger, M., 2017. Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. *Biotechnology for biofuels*, *10*(1), p.64.

[20] Smithers, J., 2014. Review of sugarcane trash recovery systems for energy cogeneration in South Africa. *Renewable and Sustainable Energy Reviews*, *32*, pp.915-925. It should be noted that this study does not explicitly indicate whether the basis for this estimation is based on dry or wet cane stalk. It was therefore assumed to refer to wet cane (i.e. total harvested mass of cane stalks).

- Ethanol production and ATJ processing:
    - The ethanol plant and SAF refinery are co-located with the sugar mill (hence no transport between processing stages).

The average of the reported lifecycle inventory input and output values for *Fermentation to Ethanol* and *Alcohol upgrading to drop-in fuels* reported by CORSIA[21] can be used as a proxy for South African primary production data to approximate GHG emissions for the production and upgrading of ethanol to SAF (for further detail regarding the assumptions used for this approach refer to the Appendix).

Table 2 Supply chain modelling approach and data sources

Supply Chain Stage	Modelling Approach		Data Source
Sugarcane cultivation	**Data Type**	Primary production data	SA Canegrowers: - Average irrigated farm data - Average rainfed farm data
	Modelling tool/approach	RSB offline GHG calculator v2.11	
	Methodology	EU RED	
iLUC	**Data Type**	Default value	CORSIA Eligible Fuels – Life Cycle Assessment Methodology[21]
	Modelling tool/approach	Default value; based on Brazilian cultivation	
	Methodology	CORSIA	
Upstream transport	**Data Type**	Primary production data	SA Canegrowers: - Average transport data: farm to mill
	Modelling tool/approach	RSB offline GHG calculator v2.11	
	Methodology	EU RED	
Ethanol Production	**Data Type**	Default values	CORSIA Eligible Fuels – Life Cycle Assessment Methodology[21]
	Modelling tool/approach:	Approximate inventory data, average of reported LCA inventories. RSB offline GHG calculator v2.11	
	Methodology	EU RED	
SAF production, (fermentation and ethanol upgrading)	**Data Type**	Literature values for processing inventory data	CORSIA Eligible Fuels – Life Cycle Assessment Methodology[21]
	Modelling tool/approach	Approximate inventory data, average of reported LCA inventories. RSB offline GHG calculator v2.11	

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[21] CORSIA Eligible Fuels – Life Cycle Assessment Methodology. Lifecycle inventory sugarcane ethanol ATJ pathway. Pg. 64 and 40Available: https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA%20Supporting%20Document_CORSIA%20Eligible%20Fuels_LCA%20Methodology.pdf

	Methodology	EU RED	
Downstream distribution	**Data Type**	Default value	CORSIA Eligible Fuels – Life Cycle Assessment Methodology[21].
	Modelling tool/approach	Approximate emissions, average of reported emissions	
	Methodology	GREET, E3db, ReCiPe	

3. RESULTS AND DISCUSSION

3.1 Supply Chain Emissions

Lifecycle GHG Emissions

The lifecycle “well-to-wing" GHG emissions for SAF produced via the ATJ-SPK process using bioethanol produced from South African sugarcane can be approximated at

- 38.3 g $CO_{2\ eq}$ / MJ SAF for irrigated cane
- 26.6 g $CO_{2\ eq}$ / MJ SAF for dryland cane, and
- 24.6 g $CO_{2\ eq}$ / MJ SAF for dryland cane with green harvesting

The breakdown of the emissions per supply chain stage are shown in Figure 3. Detailed discussion on each stage is provided in Sections 0 - 0.

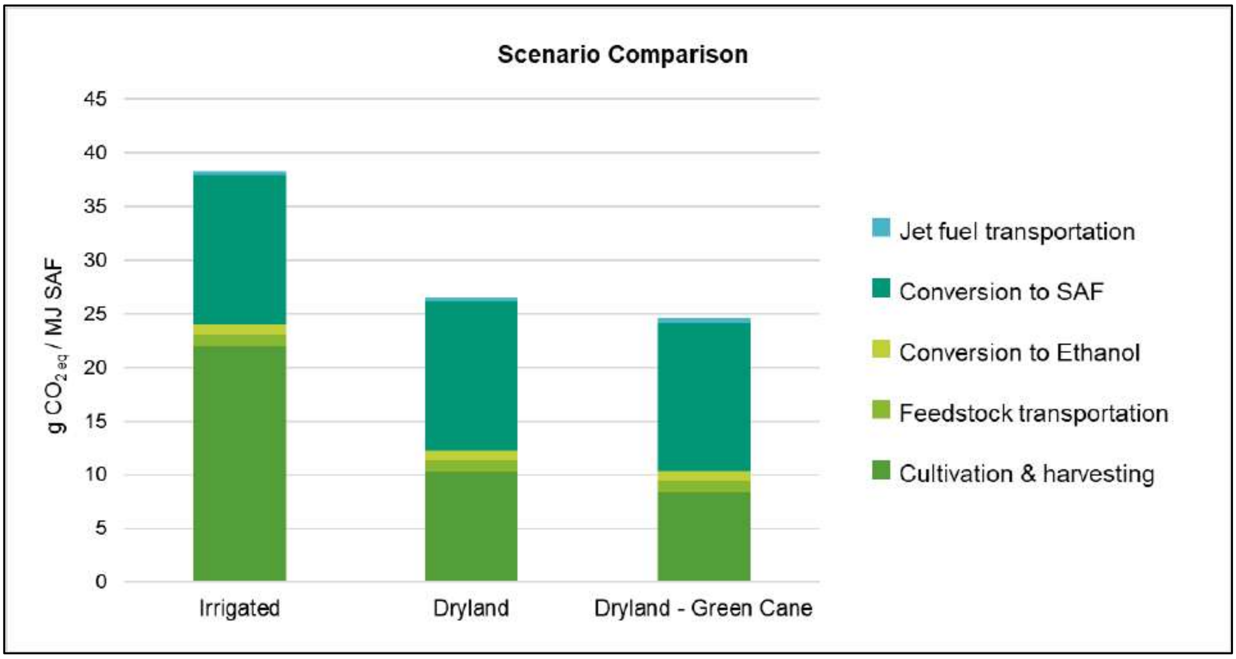

Figure 3 Lifecycle GHG emissions for SAF produced from South African irrigated and dryland sugarcane

In all three scenarios, cultivation and harvesting, and the conversion of ethanol to SAF, are the biggest contributors to the total GHG emissions. The difference in cultivation emissions between the irrigated and dryland scenarios can be attributed to the high electricity demand for pumping required for irrigation (see Section 0). The reduction in cultivation emissions exhibited by the green cane scenario, when compared to conventional dryland cultivation, is due to the lack of emissions from burning.

Cultivation and feedstock transportation were the only lifecycle stages modelled using primary production data and hence, are the only stages affected by the different scenarios. As processing and upstream transport were assumed to be independent of the cane cultivation regime, the GHG emissions from each upstream stage are identical for all three scenarios. However, the relative contribution of these upstream processes to the total lifecycle GHG emissions vary for each scenario.

While the cultivation and feedstock transportation stages were based on actual South African industry data, the upstream processing was based on literature values and modelled estimates. Consequently, the latter stages reflect a generic case and do not necessarily reflect local conditions. The results presented in Figure 3 should therefore be regarded as illustrative rather than representative. For a detailed South African case-specific study, primary production data and information should be obtained for all lifecycle stages reflecting the current or recent bioethanol and SAF industry, its plants, and their actual performance.

Cultivation and Harvesting

As shown in Figure 3, the cultivation and harvesting stage contribute significantly to the lifecycle GHG emissions for SAF production. Emissions associated with this stage are typically linked to energy and fuel consumption at farm level, as well as agricultural inputs such as fertiliser and agrochemicals.

The GHG emissions for the three specific cane cultivation and harvesting scenarios are shown in Figure 4. This figure presents the total GHG emissions for each scenario (as g $CO_{2\ eq}$ / kg $cane_{wet}$) as a sum of the emissions from each input. A percentage breakdown of the relative contribution of each input towards the total emissions is shown in Figure 5.

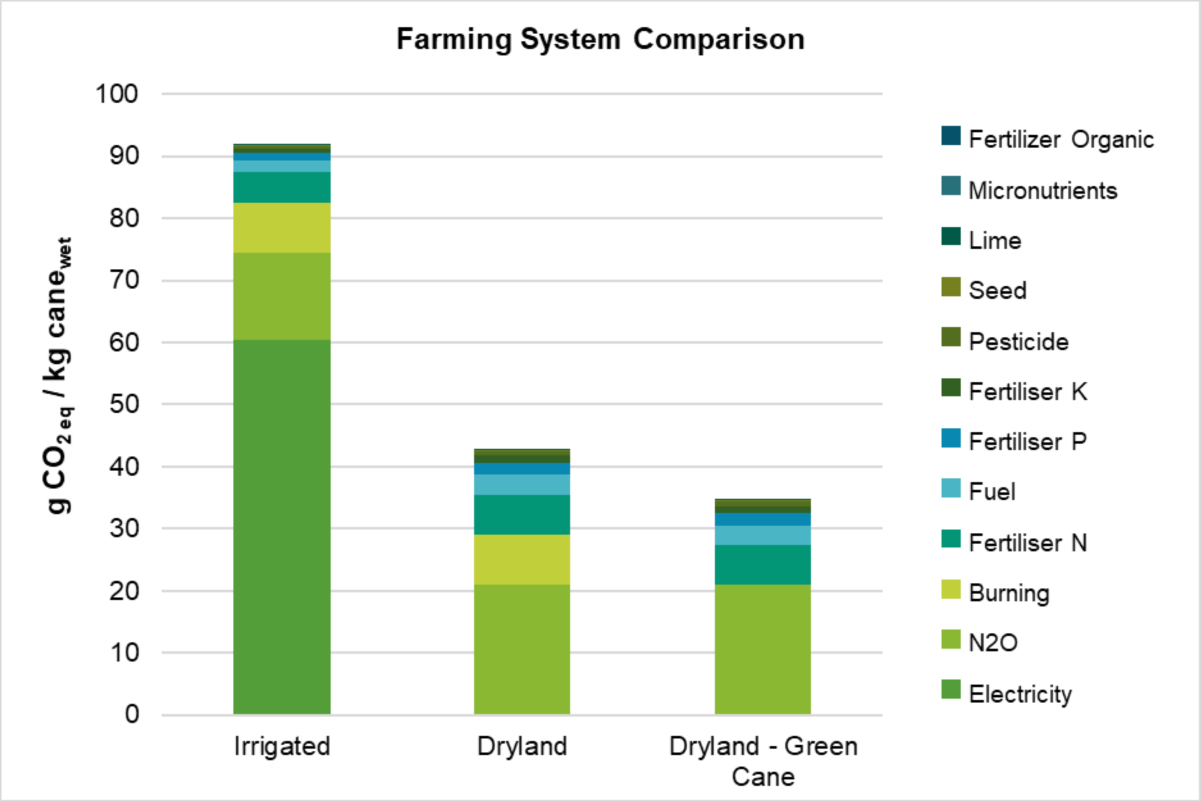

Figure 4 GHG emissions for the cultivation and harvesting of South African irrigated and dryland sugarcane

As shown in Figure 4, CO_2 emissions for irrigated cane cultivation are substantially higher than those associated with dryland cultivation scenarios. This can be attributed to the high electricity demand for pumping required for irrigation. For irrigated cane, electricity contributes 66% to the farm level CO_2 emissions. Farm electricity demand is typically met by grid electricity provided by the national utility, Eskom. Eskom's electricity generation mix is heavily dominated by coal (91%)[22] and consequently, CO_2 emissions attributed to electricity in South Africa are relatively high compared to countries with a high proportion of renewable energy sources in their national grid mix. Given the carbon intensity of electricity in South Africa, reducing the electricity demand at farm level will decrease farm level CO_2 emissions. Although irrigation improves the yield of sugarcane, this yield improvement is insufficient to offset the carbon intensity of South African grid electricity and has minimal impact on reducing the per kg CO_2 emissions of cultivated sugarcane. Renewable energies, such as solar power, have a substantially lower CO_2 footprint than coal-based electricity. Replacing the current grid electricity used for pumping with renewable electricity can reduce emissions from irrigated cane cultivation by 61%[23].

Emissions from the pre-harvest burning of sugarcane are another important contributor to farm level CO_2 emissions. In South Africa, burning is common practice, contributing 9% and 19% to total emissions for irrigated and dryland cane, respectively. The hypothetical dryland green cane harvesting scenario shows that by avoiding burning through green cane harvesting, total GHG emissions can be reduced by 8.2 g CO_2 / kg $cane_{wet}$ (19%) when compared to current preharvest burning practices. The uptake of green cane harvesting therefore provides enormous potential for farms seeking to reduce their carbon footprint.

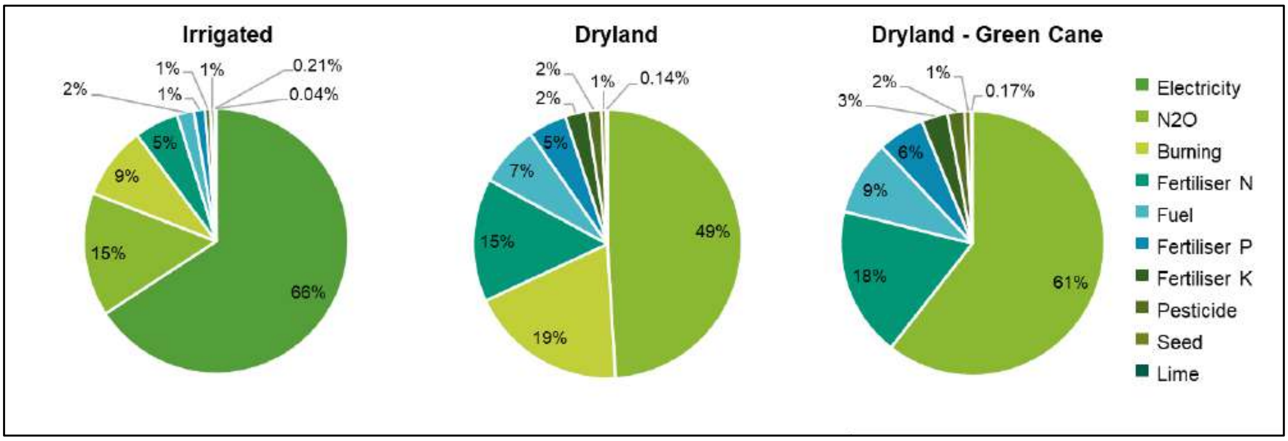

Figure 5 Percentage contribution of farm level inputs to the GHG emissions for the cultivation and harvesting of South African irrigated and dryland sugarcane

Processing and Conversion to SAF

The GHG emissions associated with the crushing of cane, fermentation and upgrading ethanol to SAF via the ATJ-SPK process can be approximated at 14.8 g $CO_{2\,eq}$ / MJ SAF. Ethanol production contributes 0.9 g $CO_{2\,eq}$ / MJ SAF and upgrading to SAF contributes 13.9 g $CO_{2\,eq}$ / MJ SAF. These results are based on production data reported by CORSIA and modelled using South African emission factors in the RSB offline GHG calculator. It should be noted that the input data available for this process was a) based on averages from various sources and b) not exhaustive. Therefore, some assumptions and approximations were necessary during the modelling process. This approach is likely to introduce uncertainty into the calculated result and consequently the results should be regarded as illustrative rather than representative.

An overview of the various inputs contributing to the total emissions are shown in Figure 6.

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[22] However, when adding electricity generated by independent power producers, municipalities and imports, the relative contribution from coal drops to 85%. https://www.get-invest.eu/market-information/south-africa/energy-sector/

[23] Total cultivation emissions from irrigated cane using solar electricity = 8.6 g $CO_{2\,eq}$ /MJ RJF.

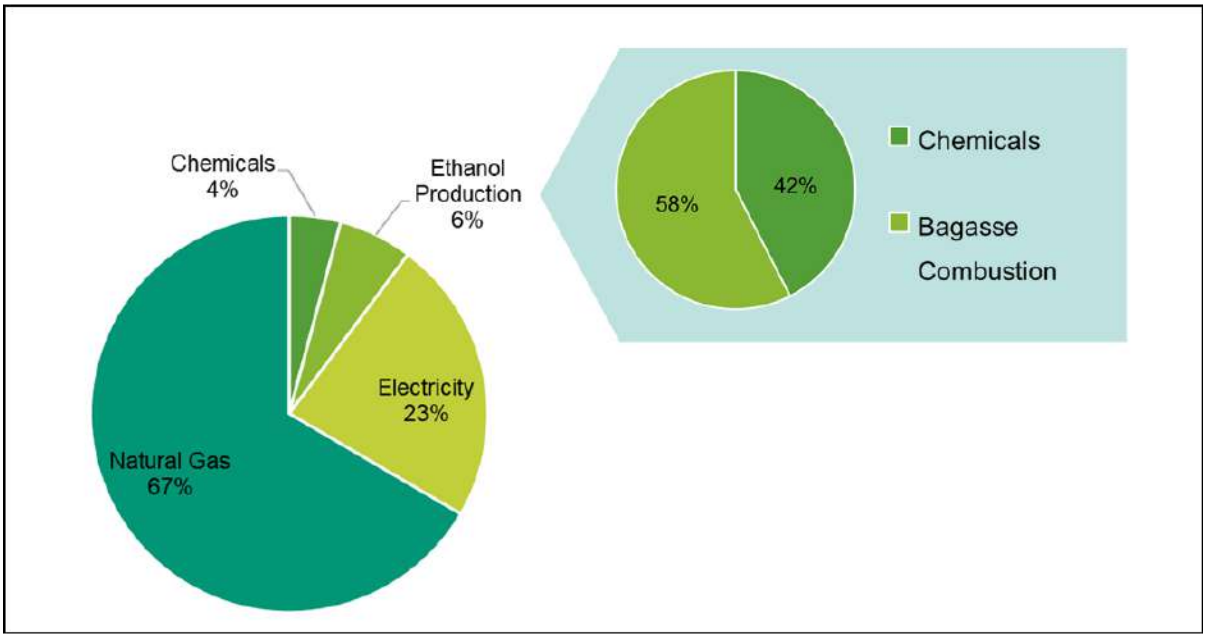

Figure 6 Estimated breakdown of emission sources for SAF production via the ATJ-SPK process

According to Figure 6, the most significant source of emissions in the production of SAF is linked to the use of natural gas. Natural gas is required for process heat and can be used as a feedstock in the production of hydrogen (also required as a feedstock for the conversion of ethanol to SAF) through steam methane reforming[24]. In view of the high contribution of natural gas and hydrogen production to the total emissions, a sensitivity analysis was undertaken by de Jong et al. (2017) on the source of hydrogen used for the process[24]. Results of this analysis showed that for the ATJ process, alternative hydrogen production technologies (namely electrolysis using renewable electricity from wind, solar and biogenic waste, and gasification of biomass) can reduce emissions from this stage by 15 – 20%. These results suggest that with technological advancements and a higher penetration of renewable electricity allowing lower carbon hydrogen generation, the GHG intensity of the ATJ-SPK process can be further reduced.

It should be noted that the processing inputs used reflect modelled estimates of global SAF production, as opposed to actual performance data from a South African process. While process design and plant performance are likely to be relatively similar for the ATJ-SPK process wherever it is established, the actual results for a South African case-specific scenario will be affected by spatiotemporal variability in input data, in particular the country-specific electricity mix and co-generation potential. Default values are typically determined for Brazilian operations. Brazilian grid electricity has a notably lower emission factor than South Africa due to a high share of hydropower in the national grid mix[25]. Consequently, processing emissions are generally higher in South Africa, given the coal-dominated electricity grid mix (see Section 0 for comparison).

With regards to co-generation, the processing of sugarcane to ethanol requires electricity and heat for both milling and processing. Most default pathways assume that these utilities are generated by an on-site combined heat and power (CHP) plant fed with bagasse. As bagasse is a biogenic agricultural residue, it is considered to have zero carbon intensity at the point of production (i.e. it is available "burden free") and is not assigned any CO_2 emissions from its use (biogenic carbon emissions are assumed to be carbon neutral, as CO_2 was taken up from the atmosphere to grow the biogenic

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[24] De Jong *et al. Biotechnology for Biofuels (2017) 10:64.* DOI 10.1186/s13068-017-0739-7. Available: https://biotechnologyforbiofuels.biomedcentral.com/track/pdf/10.1186/s13068-017-0739-7

[25] https://pdfs.semanticscholar.org/bd2a/69da81529a0f8dd16573dfd38e9d7468637e.pdf

material)[26]. The combustion emissions from a CHP plant also include NOx[27]. This indirect GHG contribution is comparatively small, but it was nonetheless included in the GHG model[28]. In some cases, excess electricity is produced by the CHP plant that is then fed into the grid. The EU RED methodology allows for the inclusion of emission savings from excess electricity from cogeneration, in relation to the excess electricity produced by fuel production systems that use cogeneration.

A University of Cape Town research report (Lütge, 2008) provides some cogeneration data for South African sugar mills using bagasse as feedstock. The data were incorporated in the GHG model under the EU RED methodology. If excess electricity is generated by the cogeneration unit using bagasse as feedstock, the EU RED GHG results for SAF reduces by 2.1%.

3.2 Emission Saving Potential

Calculated results

The emission saving potential for SAF produced via the ATJ-SPK process using bioethanol produced from South African sugarcane is shown in Table 3. The percentage saving is calculated by dividing the emission saving amount (baseline *minus* emissions) by the baseline amount.

Table 3 Estimated emission saving potential for SAF produced via the ATJ-SPK process using South African sugarcane

Scenario	Emission Saving Potential	
	EU RED II (Baseline = 94 g CO_2 / MJ)	CORSIA (Lifecycle emissions + iLUC emissions) (Baseline = 89 g CO_2 / MJ)
Irrigated cane	59%	57% (LCA only) 47% (LCA + iLUC)
Dryland cane	72%	60%
Dryland with green cane harvesting	74%	63%

The actual emission savings are dependent on the methodological approach and the relevant fossil fuel baseline. Using the EU RED II baseline, emission saving potential ranges from 59% for the irrigated cane scenario to 74% for the dryland scenario with green cane harvesting. If the CORSIA baseline is used, the emission saving potential ranges from 47% for irrigated cane to 63% for the dryland scenario with green cane harvesting. An important difference in the CORSIA approach as compared to the EU RED methodology is the inclusion of iLUC emissions in the total life cycle emissions[29].

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[26] https://pdfs.semanticscholar.org/b42b/7ad666ffe6322bbfb44c2bb6ac35b59d70be.pdf and https://rsb.org/wp-content/uploads/2017/08/RSB-STD-01-003-01-RSB-GHG-Calculation-Methodology-v2.3.pdf

[27] https://www3.epa.gov/ttnchie1/ap42/ch01/final/c01s08.pdf

[28] CHP plant combustion emissions (N2O and CH4) are not included in the Biograce default pathway.

[29] Other differences in the CORSIA approach as compared to EU RED concerns the allocation approach for excess electricity and the impact potential for CH_4 and N_2O. Under EU RED, the following impact potentials apply: CH_4 = 23 and N_2O = 296 and under CORSIA, the following apply: CH_4 = 28 and N_2O = 265. The higher impact potential of CH_4 in the CORSIA methodology has a notable effect on the emissions linked to burning. The feedstock cultivation and harvesting GHG emissions for the three scenarios considered were recalculated according to CORSIA methodology and these

As emphasised in previous discussion, while the cultivation and feedstock transportation stages were based on actual South African industry data, the upstream processing was based on literature values and modelled estimates. Consequently, the latter stages reflect a generic case and do not necessarily reflect local conditions. Therefore, the emission saving potentials presented in Table 3 are intended as approximations only and should be regarded as illustrative rather than representative. For a detailed South African case-specific study, primary production data and information should be obtained for all lifecycle stages reflecting the current or recent bioethanol and SAF industry, its plants, and their actual performance.

EU RED certification, which is required to access the EU market for both aviation and road transport biofuels and that RSB can provide, stipulates that lifecycle GHG emission savings shall be at least 60% for biofuels produced in installations in which production has started on or after 5 October 2015 and 65% for installations starting operations after 1 January 2021. Considering that any SAF production facility would only be operational after the 1 January 2021 deadline, a saving of 65% must be realised. Based on the results shown in Table 3, SAF produced via the ATJ-SPK process using South African sugarcane cultivated from dryland and dryland with green cane harvesting would be able to meet the 65% savings requirements. If electricity from renewable sources are used for irrigation, irrigated sugar cane production will also meet the 65% savings requirement.

Eligibility under ICAO's CORSIA by contrast requires SAF to achieve net GHG emissions reductions of at least 10% compared to the baseline lifecycle emissions values for conventional aviation fuel, with the RSB CORSIA Standard requiring a minimum 50% GHG emission reduction on its core life-cycle assessment (LCA) value, and a minimum 10% reduction on the core LCA *plus* the induced land use change value. According to these eligibility criteria, SAF produced from all three modelled sugarcane farming systems can achieve the requisite emission savings.

Default values

It should be noted that producers are allowed to use global default values in the determination of their supply chain GHG emission savings for both CORSIA and EU RED certification.

Currently, there is no default value for SAF produced via the ATJ process in EU RED I. However, default values cover production and processing steps up to and including ethanol production. The approved default values for EU RED are shown in Table 4. The CORSIA default values for the sugarcane ethanol ATJ pathway are shown in Table 5.

Table 4 Approved EU RED Default values[30]

Sugarcane ethanol ATJ pathway	g $CO_{2\ eq}$ / MJ Ethanol
Cultivation	14
Transport and distribution	9
Processing	1
Total	24

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updated values were used in the calculation of emission saving potential. For upstream transport and processing, the same lifecycle emissions were used for both EU RED and CORSIA.

[30] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0028&from=EN

Table 5 Approved CORSIA default values[31]

Sugarcane ethanol ATJ pathway	g $CO_{2\,eq}$ / MJ SAF
Core lifecycle value (includes all production and processing steps)	24.1
iLUC	8.7
Total	32.8

While the default values can currently be used on any supply chain using sugarcane feedstock to produce ethanol (in the case of EU RED) and SAF via the ATJ process (CORSIA), these default values are liable to change. Currently, the default values are based on Brazilian sugarcane production. This means default values could be changed to reflect regional variations. Consequently, supply chains certified on the basis of an outdated default value could be at risk. Although the use of default values is currently permitted, where supply chain steps reflect significant differences (e.g. region, production inputs, efficiencies etc.) it is strongly recommended that the specific supply chain step is modelled and the resulting process specific GHG emissions used towards certification.

Ethanol production

It is also worthwhile to understand the emission savings related to the production of fuel grade ethanol. The estimated emission saving potential for fuel ethanol produced using South African sugarcane is shown in Table 6.

Table 6 Estimated emission saving potential for fuel ethanol produced using South African sugarcane

Lifecycle stage	Scenario		
	Irrigated cane	Dryland cane	Dryland with green cane harvesting
Cultivation and harvesting[a]	36.0	16.8	13.6
Feedstock transportation[a]	1.8		
Ethanol production[a]	1.5		
Transport to filling station[b]	0.9		
Total (g CO_2 / MJ Ethanol)	40.2	21.0	17.8
Baseline	94 g CO_2 / MJ		
Estimated emission saving potential	57%	78%	81%

[a] Value based on calculated emissions using SA Canegrowers data

[b] Default values as available from BioGrace v.4d “Ethanol from sugarcane” pathway. Biograce reproduces the calculation of the greenhouse gas emission default values of the 22 biofuel production pathways listed in the EU Commission Directive 2009/28/EC Annex V part A, and is consistent with the methodology laid out in the same Annex, part C.

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[31] CORSIA Eligible Fuels – Life Cycle Assessment Methodology. Lifecycle inventory sugarcane ethanol ATJ pathway. Pg. 64. Available: https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA%20Supporting%20Document_CORSIA%20Eligible%20Fuels_LCA%20Methodology.pdf

The majority of fuel grade ethanol currently produced in South Africa has very high associated emissions. The largest producer is Sasol, with 285-million litres of non-renewable ethanol per year resulting from their coal to liquid process via Fischer-Tropsch synthesis[32]. Provided that sugarcane feedstock is produced from existing cultivated areas (thus avoiding the direct land-use change emissions associated with land conversion) the production of a lower carbon fuel grade ethanol using sugarcane as a feedstock could be expanded in South Africa.

3.3 Lifecycle Emissions in the Global Context

Comparison of Lifecycle Emissions for SAF Production

GHG emission performance is impacted significantly by methodological choices (particularly the allocation methods used for co-products and excess electricity generation[33]), as well as spatiotemporal variability in input data (for example, feedstock and processing yields, process design and/or electricity grid mixes and emission factors). A comparison of reported lifecycle emissions for SAF produced via the ATJ-SPK process using a sugarcane feedstock is shown in Table 7.

Table 7 Comparison of lifecycle GHG emissions for ATJ production

Supply Chain Step g CO_2 / MJ SAF	Literature Values				South African Estimate		
	De Jong et al. (2017)	CORSIA: MIT	CORSIA: JRC	CORSIA: CTBE	Irrigated	Dryland	Dryland green cane
Cultivation & harvesting	9.9	13.7	17.5	19.9	22.0	10.2	8.3
Feedstock transportation	1.5	1.6	1.6	2.1	1.1	1.1	1.1
SAF production: Fermentation & ethanol upgrading	3.8	4.6	7.7	5.3	0.9[a]	0.9[a]	0.9[a]
Hydrogen production	5.4				13.9[a]	13.9[a]	13.9[a]
Jet fuel transportation	5.4[c]	0.4	0.4	0.4	0.4[b]		
Total	26.0	20.3	27.2	27.7	38.3	26.6	24.6

[a] South African specific case study modelled using the average of reported CORSIA data

[b] Average of the reported CORSIA values

[c] This value reflects the transport of ethanol produced in Brazil to the USA for upgrading and the transport to distribution

The results in Table 7 illustrate the variability in emission performance consequent of specific supply chains and modelling approaches. Direct comparison of results is challenging due to diverging

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[32] https://www.dailymaverick.co.za/article/2019-10-16-future-fuels-and-the-coming-ethanol-revolution-is-sasol-facing-technological-redundancy/

[33] GHG emissions can be allocated to the co-products according to their energy, mass, or economic value. Alternatively, the displacement method (or system expansion) awards an emission credit to co-products based on the yield of the co-product and the GHG emission intensity of the displaced product.

methodologies and input data. The largest differences occur in the cultivation and harvesting, as well as SAF production stages.

For cultivation and harvesting, the following are important parameters influencing the GHG emissions:

- Sugarcane yield[34]
- Farming inputs included in the inventory
- Harvesting practices (i.e. greencane harvesting vs burning / manual vs. mechanical)
- Electricity and diesel sources used in farming operations[35]

For fermentation and ethanol upgrading, key parameters influencing the emission potential include:

- Yield/conversion efficiency: ethanol yield from sugarcane and SAF yield from ethanol
- Electricity and heat co-generation (i.e. operation of a CHP plant, feedstock, and excess electricity generation)
- Hydrogen source
- Utility requirements and supply chain impacts (i.e. country specific electricity grid mix)
- Fuel specifications and quality standards[36]

Emission Reduction Potential

In general, any strategy/technology that aims to reduce energy consumption, minimise raw material and utility inputs, and reduce waste will lead to a reduction in lifecycle GHG emissions. A low carbon footprint can therefore be linked with operational efficiency. Various improvements are available to the sugarcane industry to improve efficiency and reduce carbon emissions across the supply chain. These improvements are as follows[37]:

- Install renewable energy capacity (i.e. solar power) to reduce grid electricity dependence
- Cogenerate and export excess power to the maximum extent possible
- Maximise cane and processing yields
- Reduce the amount of fertiliser and chemical inputs, particularly nitrogen fertiliser
- Reduce the extent of cane burning by green cane harvesting
- Reduce the quantities of supplementary fuels purchased
- Minimise irrigation power input
- Reduce cane transport distances
- Onsite generation of biogas from waste[38]

The production of renewable, low-carbon ethanol (that could subsequently be upgraded to SAF) could also be expanded with second-generation technologies which utilise lignocellulosic waste – such as bagasse. An important advantage of using bagasse is that it is classified as a waste under both EU RED and RSB Global certification schemes and hence is available “burden free” to producers[39].

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[34] Highly efficient sugar production with a high per hectare output will reflect reduced emissions

[35] For example, all literature scenarios are based on Brazilian cane production: Brazilian grid electricity has a notably lower emission factor than South Africa due to a high share of hydro-power in the national grid mix and farming operations frequently utilize green diesel.

[36] These standards generally require more stringent upgrading, thus affecting yields and/or hydrogen consumption.

[37] Rein, P.W., 2010. The carbon footprint of sugar. In *Proc. Int. Soc. Sugar Cane Technol* (Vol. 27, p. 15).

[38] Vinasse from 1 m^3 of ethanol treated anaerobically produces ~ 115 m^3 of biogas, which in turn can generate 169 kWh of power, after deducting the power used in processing. This can help to augment the amount of power available for export. Source: Sugarcane-Based Bioethanol: Energy for Sustainable Development. BNDES/CGEE, Rio de Janeiro, 304

[39] According to these methodologies, waste (including agricultural crop residues, such as straw, bagasse, husks, cobs and nut shells, and residues from processing) shall be considered to have zero life-cycle greenhouse gas emissions up to the process of collection of those materials.

Existing sugar mills have the potential to upgrade their systems to utilise bagasse for ethanol production through biochemical conversion technologies. According to WWF-SA[40], these technologies are already being commercialised in Brazil by Raizen and Granbio and could be implemented in South Africa with equal success, provided current pre-harvest burning practices are at least partially replaced with green cane harvesting, and/or inefficient old boilers in mills are replaced with more efficient ones. These measures will liberate a portion of the bagasse currently used to meet the mill's energy requirements, hence enabling second-generation ethanol production without displacing the mill's energy source. An alternative option for lignocellulosic waste highlighted by WWF-SA, is thermal treatment to produce a bio-synthetic gas that can then be converted to ethanol either via the traditional Fischer Tropsch process (as used by Sasol) or through microbial digestion.

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[40] https://www.dailymaverick.co.za/article/2019-10-16-future-fuels-and-the-coming-ethanol-revolution-is-sasol-facing-technological-redundancy/

4. CONCLUSIONS

SAF can be produced via the ATJ-SPK process using sugarcane as the ethanol feedstock. Given the current crisis that the South African sugar industry is facing due to a combination of factors including drought, falling world sugar prices, the sugar tax and impact of cheap imports, the production of ethanol as a feedstock for the ATJ process, could form part of a much-needed diversification strategy for the industry. An important criterion in evaluating the feasibility of this strategy, is whether the resulting SAF can deliver the requisite emission savings over its lifecycle to meet global certification requirements.

The objective of this report was to determine the "well-to-wing" GHG emissions and emission saving potential of SAF produced via the ATJ-SPK processing pathway using bioethanol produced from South African sugarcane as the ethanol feedstock. Input data were based on a combination of primary data and literature values. In-field cultivation and transport data for dryland and irrigated cane were provided by the SA Canegrowers and modelled according to the methodology as laid out in EU Directive 2009/30/EC. Upstream processing emissions were modelled using lifecycle inventory data from CORSIA[41] and EU Directive 2009/30/EC, Annex V, and upstream transport was based on lifecycle data reported by CORSIA. Three different scenarios, differing in cane cultivation practices, were modelled: irrigated cane, dryland cane and a hypothetical case for dryland cane with green cane harvesting.

The results show that the "well-to-wing" GHG emissions for SAF produced via the ATJ-SPK process using bioethanol produced from South African sugarcane can be approximated at 38.3 g $CO_{2\ eq}$ / MJ SAF for irrigated cane, 26.6 g $CO_{2\ eq}$ / MJ SAF for dryland cane, and 24.6 g $CO_{2\ eq}$ / MJ SAF for dryland cane with green harvesting. Using the EU RED fossil baseline (94 g $CO_{2\ eq}$ / MJ), emission saving potential ranges from 59% for the irrigated cane scenario to 74% for the dryland scenario with green cane harvesting. If the CORSIA baseline is used (89 g $CO_{2\ eq}$ / MJ), it results in savings of 47% for irrigated cane, 60% for the dryland scenario and 63% for the dryland scenario with green cane harvesting. An important difference in the CORSIA approach as compared to the EU RED methodology is the inclusion of iLUC emissions in the total life cycle emissions.

Based on these results, SAF produced via the ATJ-SPK process using irrigated South African cane does not meet the required 65% savings. SAF produced from dryland cultivation, and dryland cultivation with green cane harvesting, meet the EU-RED emission reduction requirements. Eligibility under ICAO's CORSIA by contrast requires that biofuel shall achieve net GHG emission reductions of at least 10% compared to the baseline lifecycle emission values for aviation fuel on a lifecycle basis, with the RSB CORSIA Standard requiring a minimum 50% GHG emission reduction on its core life-cycle assessment (LCA) value, and a minimum 10% reduction on the core LCA *plus* the induced land use change value. According to these eligibility criteria, SAF produced from South African sugarcane cultivated from all three modelled farming systems can achieve the requisite emission savings.

It should be noted that only the cultivation and feedstock transportation stages were based on actual South African industry data, while the upstream processing was based on literature values and modelled estimates. Consequently, the latter stages reflect a generic case and do not necessarily reflect local conditions. Given that GHG emission performance is impacted significantly by methodological choices and spatiotemporal variability in input data, the emission saving potentials are intended as approximations only and should be regarded as illustrative rather than representative. For a detailed South African case-specific study, primary production data and information should be obtained for all lifecycle stages reflecting the current or recent bioethanol and SAF industry, its plants, and their actual performance.

For the irrigated cane scenario, the feedstock cultivation stage showed the highest contribution to total GHG emissions – at 57%. For dryland cultivation and dryland cultivation with green cane harvesting, the largest contribution is from the SAF production stage at 52% and 57% respectively. The difference in cultivation emissions between the irrigated and dryland scenarios can be attributed to the high

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[41] CORSIA Eligible Fuels – Life Cycle Assessment Methodology. Available: https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA%20Supporting%20Document_CORSIA%20Eligible%20Fuels_LCA%20Methodology.pdf

electricity demand for pumping required for irrigation. South African grid electricity is heavily dominated by coal (91%) and consequently, CO_2 emissions attributed to grid electricity use in South Africa are relatively high compared to countries with a high proportion of renewable energy sources in their national grid mix. The reduction in cultivation emissions exhibited by the green cane scenario, when compared to conventional dryland cultivation, is due to the exclusion of emissions from burning.

A low carbon footprint can be linked to operational efficiency. In general, any strategy that aims to reduce energy consumption, minimise raw material and utility inputs, and reduce waste, will lead to a reduction in lifecycle GHG emissions. Various improvements are available to the sugarcane industry to improve efficiency and reduce carbon emissions across the supply chain, most notably reducing the grid electricity input for irrigation (either by increasing renewable energy generation capacity or improving operational efficiency), reducing fertiliser inputs and increasing green cane harvesting. With increased green cane harvesting there is also potential for this excess trash to be used for cogeneration, increasing the generation of “surplus electricity”, which can be assigned carbon credits.

Following the results discussed above, the use of approved default values available for both CORSIA and EU RED would provide an alternative route to producers seeking certification for sugarcane ethanol and ATJ supply chains. However, these values are typically based on Brazilian production data, which exhibits several differences to South African production, particularly with regards to cultivation. Cultivation not only has a significant contribution to total lifecycle emissions for ATJ production, but as shown in the results, also reflects regional variations in inputs and efficiencies in the determination of emissions. It is strongly recommended that for any process seeking certification using South African cane, the specific supply chain should be modelled, and the resulting process specific GHG emissions should be used towards this certification.

The production of fuel grade ethanol also provides a feasible alternative market for sugarcane. The estimated emission saving potential for fuel ethanol produced using South African sugarcane is 57% for irrigated cane (not elidable under EU RED), 78% for dryland cane, and 81% for dryland cane with green harvesting (both eligible under EU RED). The majority of fuel grade ethanol currently produced in South Africa has very high associated emissions, and expanding the production of a lower carbon, fuel grade ethanol could become an important part of an industry diversification strategy.

Considering the negative impact of new cultivation on ecosystems and GHG emissions (i.e. the direct land-use change emissions associated with land conversion), expansion of the industry is a concern. It is therefore important to develop plans that maximise the value of the current industry as opposed to pushing greenfield expansion. In this regard, second-generation technologies capable of using lignocellulosic material such as bagasse to produce ethanol could be considered. These technologies that have already been commercialised in Brazil, could be implemented in South Africa with equal success, provided there is investment into more efficient boilers and an end to pre-harvest burning, so as to bring more biomass to the mills. It is therefore necessary to understand whether the demand and subsequent value of ethanol is high enough to make such investments into new plants and practices financially attractive.

5. Appendix: Ethanol production and ATJ processing

5.1 Data Inputs

The CORSIA LCA inventory data on Pg. 64 of the *CORSIA SUPPORTING DOCUMENT: CORSIA Eligible Fuels – Life Cycle Assessment Methodology* was used as an input to the RSB GHG calculator (Table 8). The necessary unit conversions to use the inventory values as input to the RSB GHG calculator were undertaken using the data shown in Table 9.

The LCA data provided was not exhaustive. Various assumptions were necessary to provide all the required modelling inputs for the processing stage in the RSB calculator. Key information that was missing from the inventory data were as follows:

- Moisture content of ethanol intermediary (i.e. hydrated or anhydrous)
- Moisture content of SAF
- Sugarcane feedstock moisture content
- Process used to produce excess electricity in the ethanol production step i.e. CHP
- Amount of co-produced bagasse used for co-generation
- Source of electricity in the ethanol upgrading step i.e. grid electricity or co-location of the upgrading plant with ethanol plant and use of excess electricity produced on-site
- Use of natural gas for process heat inputs i.e. used to supply process heat only or also steam methane reforming for hydrogen production

The main assumptions stemming from these uncertainties were as follows:

- Intermediate product is **anhydrous ethanol** (moisture content = 0%)
- Moisture content SAF = 0%
- Moisture content of sugarcane feedstock = 69.5%
- Feedstock efficiency reported is based on **wet mass** i.e. g wet cane / MJ EtOH
- Excess electricity in the ethanol production step is produced in a CHP plant fed with bagasse
- Bagasse is treated as a biogenic feedstock, therefore no CO_2 emissions from the use of the fuel*. Excess electricity produced therefore also has no associated CO_2 emissions that can be credited (electricity produced from bagasse in a power plant also has no CO_2 emissions as a biogenic feedstock)
- Electricity inputs in the ethanol upgrading step are from **grid electricity.** Grid electricity was based on SA specific values (0.93 kg CO_2/kWh)
- Natural gas inputs are used to provide process heat and in steam methane reforming to provide process hydrogen. Emissions from steam methane reforming were based on the emission factor for natural gas consumption.

*This is an important assumption. The amount and type of feedstock was not provided, and without this input no emissions from the CHP plant could be determined.

A major source of uncertainty in the CORSIA data was around the **feedstock conversion for ethanol production.** This is reported as 2.19 g CO_2/MJ EtOH. This value does not correspond to the value reported in the Biograce default pathway for ethanol production (0.514 $kg_{sugarcane}$ / $MJ_{ethanol}$) or similar processes. This value was used as reported in the CORSIA inventory data.

Table 8 LCA inventory data

			CORSIA DATA pg. 64				Converted values
			MIT	JRC	CTBE	AVG	kg_{input} or $kWh/kg_{product}$
Fermentation to Ethanol	Inputs	H2SO4 [g/MJEtOH]	-	0.43	-	0.43	0.0123
		Cyclohexane [g/MJEtOH]	-	0.028	-	0.028	0.00079
		CaO [g/MJEtOH]	0.6	0.51	0.37	0.493	0.01394
		Lubricants [g/MJEtOH]		7.30E-06		7.3E-06	0.00000
		Sugarcane [g/MJEtOH]	2.25	2.93	2.19	2.457	0.0694
	Outputs	Electricity [MJ/MJEtOH]	0.2	0.018	0.28	0.166	1.303
		Ethanol [MJ]	1	1	1	1	
Alcohol upgrading to drop-in fuels	Inputs	EtOH [MJ/MJSAF]	1.78	1.02	2.1	1.633	2.494
		Electricity [MJ/MJSAF]	-	0.021	-	0.021	0.252
		Natural gas for process heat [MJ/MJSAF]	-	0.23	-	0.23	9.925
		Hydrogen [MJ/MJSAF]	0.072	0.03	0.11	0.0707	0.025
	Outputs	Jet [MJ/MJSAF]	1	1	1	1	-
		Diesel [MJ/MJSAF]	0.25	-	0.083	0.167	0.167
		Naphtha [MJ/MJSAF]	0.36	-	0.46	0.41	0.399
		Heavy oil [MJ/MJSAF]	0.078	-	-	0.078	-

Table 9 Additional data

Addition parameters required in GHG calculator	Value	Units	Source
Anhydrous ethanol LHV	28.26	MJ/kg	From Aurea
SAF LHV	43.15	MJ/kg	Kerosine A-1
Conversion MJ to kWH	3.6	MJ/kWh	Unit conversion
Moisture content sugarcane	69.5	%	SA Canegrowers
Excess electricity	1.3031	kWh/kg	Calculated
Diesel LHV	43.1	MJ/kg	Biograce
Naptha LHV	44.38	MJ/kg	https://chemeng.queensu.ca/courses/CHEE332/files/ethanol_heating-values.pdf
Hydrogen LHV	120.21	MJ/kg	https://chemeng.queensu.ca/courses/CHEE332/files/ethanol_heating-values.pdf
Sugarcane LHV	19.6	MJ/kg	Biograce

SA Grid electricity	0.93	kg CO2/kWh	Eskom
Natural gas (EU Mix quality)	0.06759	kg CO2/MJ	EU Commission

5.2 Results

The results obtained are shown in Table 10.

Table 10 Overview of results

Literature Results			
g $CO_{2\ eq}$/MJ SAF	**MIT**	**JRC**	**CTBE**
Fermentation and EtOH upgrading	4.6	7.7	5.3
Results from RSB GHG Calculator			
kg CO2 e/ kg product	**Current step emissions**	**Allocation factor**	**Conversion factor**
EtOH production	0.0166	1	0.0578
EtOH upgrading	0.6007	0.634	0.0232
g CO2 e/MJ SAF	= kg CO_2/kg product x AF X CF		
EtOH production	0.961		
EtOH upgrading	8.826		
Sum (cumulative emissions)	**9.787**		

The results obtained for the SA specific case are higher than the average results reported by CORSIA. The natural gas emissions contribute 71% to the total emissions for the upgrading stage. The emission factor used was based on the EU commission value of 0.067 kg CO_2 / MJ. If natural gas is used for steam methane reforming, then this result is consistent with literature[42]. The contribution from electricity is relatively high due to the coal-heavy SA grid mix.

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[42] De Jong *et al. Biotechnology for Biofuels (2017) 10:64.* DOI 10.1186/s13068-017-0739-7. Available: https://biotechnologyforbiofuels.biomedcentral.com/track/pdf/10.1186/s13068-017-0739-7