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Sustainable Aviation Fuel Roadmap

2023

Citation and authorship

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Acknowledgements

CSIRO acknowledges the Traditional Owners of the lands that we live and work on across Australia and pays its respect to Elders past and present. CSIRO recognises that Aboriginal and Torres Strait Islander peoples have made and will continue to make extraordinary contributions to all aspects of Australian life including culture, economy and science.

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CSIRO Foreword

Australians are known worldwide for their love of travel, and as someone born overseas, I definitely count myself as one of the many who love to fly.

With more passengers expected to take flight in the coming decades, the aviation sector must continue to meet rising demand for its services while working towards diversifying its fuel supplies and reducing its environmental impact.

Interest and investment in sustainable aviation fuels (SAF) – made from organic matter, waste, or hydrogen to power aircrafts – are rapidly increasing as countries race to meet net-zero goals.

With alternative technologies such as battery and fuel-cell-powered planes still limited in capabilities, SAF offers Australia the largest potential for long-haul flights to reduce aviation emissions now and in the medium-term future while new technology evolves.

Working with our long-term partner Boeing Australia, we have developed the Sustainable Aviation Fuel Roadmap – a blueprint shaped in consultation with key players across the value chain. The roadmap is focused on developing a local sustainable aviation fuel industry, where Australia can begin to build liquid fuel security for commercial and military aviation.

We have a real opportunity now to be part of decarbonising our skies and securing our liquid jet fuel supply to keep Australians connected.

But the transition to sustainable fuel is complex. It needs active participation from a wide range of suppliers and stakeholders.

It needs multiple sources of biomass across different regions and seasons. This biomass must then be processed into suitable feedstock for the industry. The transition will require large quantities of green hydrogen both to process biomass feedstocks and as a feedstock itself in the longer term. This will in turn require large amounts of supporting renewable energy.

It needs innovative technology and novel ways to integrate existing technologies and collaborations between farmers, land managers, biomass processors, transport, fuel processing, manufacturers, airlines, and governments.

With more than 20 years of research on energy, emissions reductions and the economic futures for Australia, CSIRO is ideally placed to support these developments, through capabilities including land use decision-making, life-cycle assessments, biomass processing, gasification, hydrogen technologies, and fuel synthesis technologies.

Our Missions program assembles broad coalitions of partners to solve complex scientific challenges. This roadmap sits alongside our Towards Net Zero mission, which is focused on supporting hard-to-abate sectors, like aviation, achieve net zero by 2050.

This is no small ask, and no single energy technology will achieve this transition. Rather it will require a combination of existing and emerging technologies that will change in time as the market evolves and new innovations come to the fore. It will also require the continued partnership and collaboration between key players in the industry – as evidenced in this report and CSIRO's long and enduring partnership with Boeing.

There is good reason for Australians to feel optimistic about the future of aviation. With the help of this roadmap, Australia can be a leader when it comes to the development of sustainable aviation fuels – we have the capability, the strategic partnerships and now, the plan to take us there.

Kirsten Rose
Acting Chief Executive
CSIRO

Boeing Foreword

The societal benefits of aerospace are immense. It protects and connects people, enables livelihoods and trade, provides humanitarian relief and allows exploration of our world and beyond.

The Air Transport Action Group predicts that by 2050, air travel will carry over 10 billion passengers a year, support 180 million jobs and generate nearly $9 trillion in economic activity. Recognising the aviation industry contributes 2.5 percent of the world's carbon emissions, the commercial segment around the globe has committed to net zero carbon emissions by 2050.

Sustainable aviation fuel (SAF), currently used around the world in more than a quarter-million flights, is a drop-in replacement for fossil jet fuel that works with existing infrastructure and offers the largest potential to reduce carbon emissions over the next 30 years in all aviation segments. In support of the shared industry goal, Boeing has committed that all of our commercial airplanes will be compatible to fly on 100% SAF by 2030.

As science and technology continue to play a key role in ensuring the long-term sustainability of our business and our partnerships, we are proud to continue our 34-year relationship with CSIRO, one of our most innovative and trusted partners. The Sustainable Aviation Fuel Roadmap identifies opportunities to produce and meet the increasing demand for feedstocks required to establish and scale a new industry in the Asia Pacific region.

This aligns with one of our four strategies guiding our decarbonization activities as we continue to advance the safety and efficiency of our aircraft and operations: fleet renewal; operational efficiency; renewable energy; and advanced technology.

This year, Boeing launched a publicly-available version of its Cascade Climate Impact Model which gives customers, policymakers, academia and the industry at large, the power to quantify how the different aviation sustainability solutions outlined above, affect carbon emissions. This will help develop the most impactful strategies to reach net zero by 2050. Under any scenario for the introduction of advanced technology and new energy carriers, the Cascade tool clearly shows that massive amounts of SAF will be required towards 2050 and beyond.

Boeing also recently launched a SAF Dashboard, a data visualization tool that tracks worldwide publicly announced SAF production capacity and builds awareness around the disparity between availability and aviation's demand. The tool provides a realistic look at the challenges and opportunities in pursuit of a world with more SAF. Both the Cascade tool and SAF Dashboard can be found at sustainabilitytogether.aero.

Boeing forecasts a need for 42,600 new commercial jets over the next 20 years to meet growing commercial aviation demand, particularly in the Asia Pacific region. With only approximately 300 million litres of SAF produced globally in 2022, the ability for airlines to source vastly more SAF will be essential to ensure the aviation sector can meet its net zero commitment.

Boeing's intent is to help catalyze SAF through our subject matter experts, our investments in product compatibility, our own fuel use, industry and research partnerships, and policy advocacy. The opportunity to partner with CSIRO in developing a sustainable aviation fuel roadmap for Australia is timely. We hope it will assist Australian Government policy development, inform investors, and engage those who fly for pleasure and work to support aviation decarbonisation.

Maria Fernandez
President of Boeing Australia, New Zealand and South Pacific

Executive summary

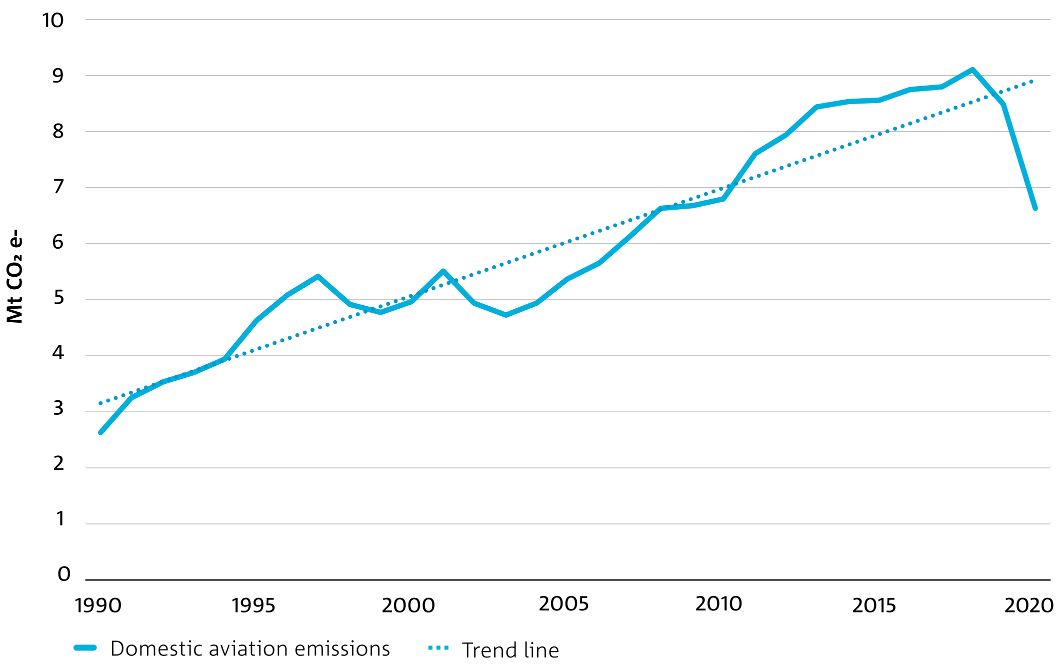
Aviation is an essential component of Australia's infrastructure and plays a vital role in connecting its dispersed population. With its large landmass, many of Australia's major cities and towns are separated by vast distances, making air travel the most efficient and practical mode of transportation. The aviation industry is responsible for enabling a range of services including passenger and cargo transportation, emergency response, medical evacuations, national defence and search and rescue operations. In addition, aviation plays a crucial role in supporting the country's economy by facilitating tourism, trade, and business travel. Australians rely on the aviation industry to stay connected with each other and the world, making it an integral part of the nation's social and economic fabric.

The aviation industry is projected to increase CO_2 emissions through growth in passenger demand, posing major challenges in the pursuit of net zero targets. The aviation sector generates approximately 2.5% of the world's carbon emissions which could grow as other sectors continue to decarbonise with mature technologies.[1] Domestic aviation emissions in Australia have more than tripled between 1990 and 2019. This is coupled with projections for Australian jet fuel demand increasing by 75% from 2023 to 2050.[2] Global airlines recognise this trend, and The International Air Transport Association (IATA), which represents 300 airlines and 83% of air traffic including Qantas and Virgin Australia, are aiming to achieve net zero by 2050.[3]

With limited technological options solutions available to lower emissions effectively, aviation is a challenging sector to decarbonise. Five main strategies can aid in emissions reduction:

- Improving fuel efficiency by adopting new fleets and implementing more efficient aircraft movements,
- Exploring new propulsion technologies such as battery and fuel cell electric planes as well as hydrogen combustion,
- Utilising carbon offsets,
- Considering flight alternatives like high-speed rail and video conferencing, and
- Sustainable aviation fuel (SAF).

Figure 1. Australian domestic aviation emissions[4]



1 Ellerbeck S (2022) The aviation sector wants to reach net zero by 2050. How will it do it? World Economic Forum. <https://www.weforum.org/agenda/2022/12/aviation-net-zero-emissions/> (accessed 20 April 2023).

2 CSIRO 2022, Electric vehicle projections 2022. https://publications.csiro.au/publications/publication/PIcsiro:EP2023-0235 See Section 2.1.4 for description of how the model is constructed. See Section 3 for a definition of the Step Change scenario underpinning the jet fuel demand projections used. Energy content of 34.7 MJ/L jet fuel is used.

3 International Air Transport Association (IATA) (2021) Net-Zero Carbon Emissions by 2050. <https://www.iata.org/en/pressroom/pressroom-archive/2021-releases/2021-10-04-03/> (accessed 20 April 2023).

4 Australian Government Department of Industry, Science, Energy and Resources (DISER) (2022) National Inventory Report Volume 1-3. DISER.

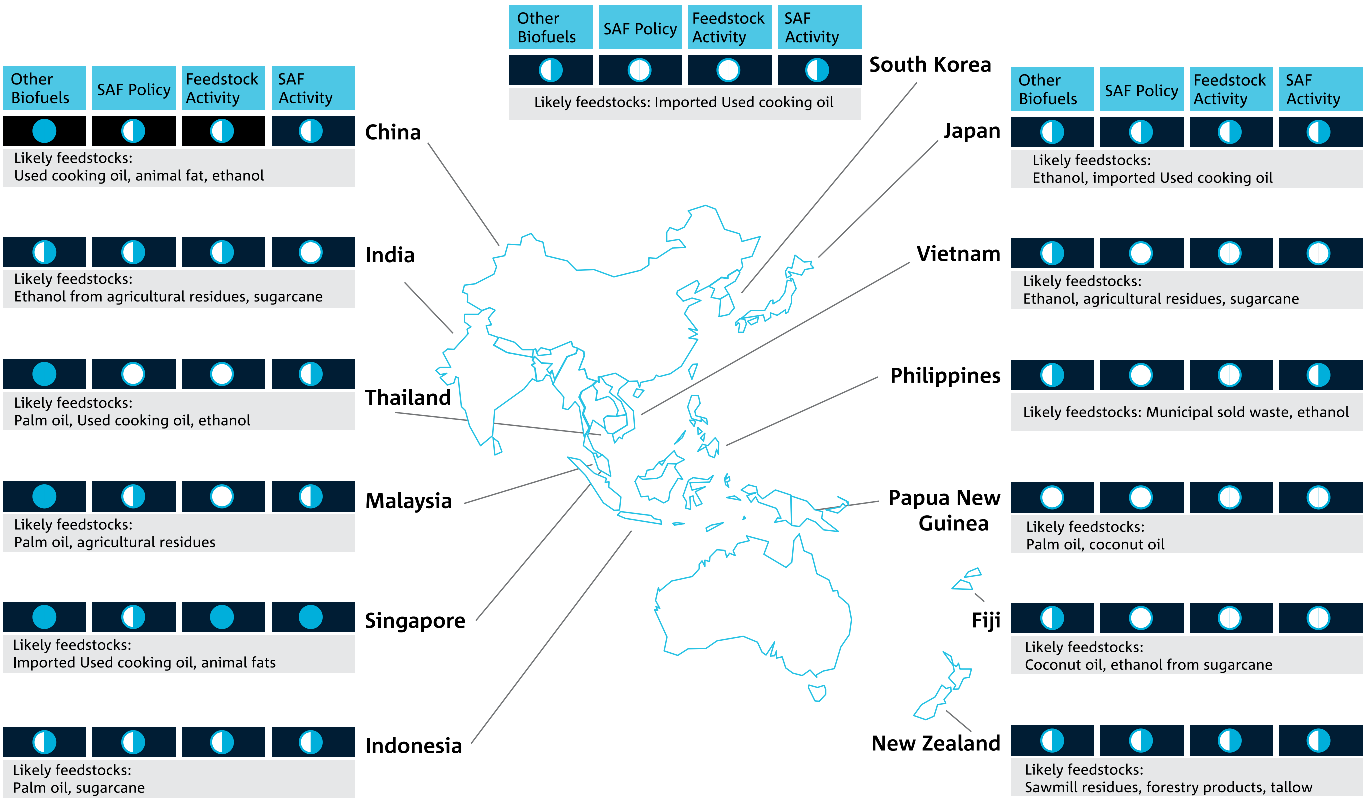
Although all need to be pursued, considering the limitations of operational efficiency gains, the early stage of alternative propulsion technologies, the growing competition for offsets, and the select use case applicability of flight alternatives, SAF emerges as a critical tool for decarbonisation.

Carbon emission reductions differ across feedstocks (or SAF raw materials) and production pathways, with most achieving a reduction of between 60–100% compared to conventional jet fuel (CJF).[5] These differences can be attributed to a number of factors such as the cultivation or composition of the feedstock, processing intensity of the various pathways and transport for collection and distribution of products.

In addition to the benefits of carbon emission reduction, SAF produces less particulate matter than CJF when combusted, which leads to fewer contrails and reduces atmospheric warming effects. SAF also has a higher energy density than CJF, requiring slightly less fuel to be carried and combusted during flight, thereby improving fuel efficiency.

The Asia Pacific (APAC) region has a significant presence of refiners and potential feedstock suppliers, making it a promising location for SAF production. Singapore and Japan are currently taking steps to establish themselves as SAF refiners by importing feedstock. Whereas countries with strong agricultural and biofuel backgrounds, such as China, Malaysia, and Thailand, are likely to become major feedstock producers and potentially develop refining capacity over time.

Figure 2. APAC region activity in biofuels, SAF policy, feedstock and SAF



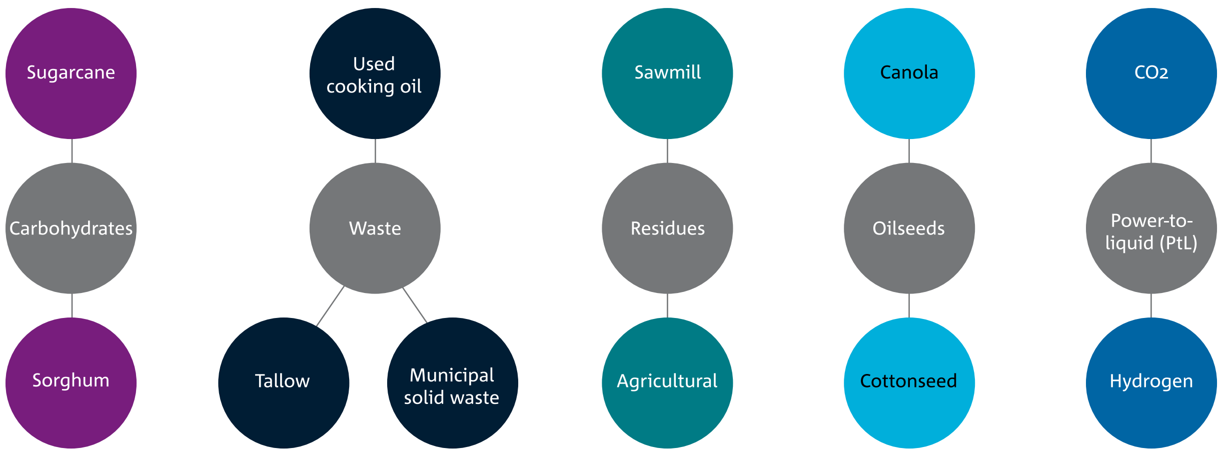
RANKING	STATUS	DESCRIPTION
	Developed	• Industry is established and operational, supported by strategy, investment, and outputs.
	Developing	• Activity is planned or under construction, with outputs forecasted.
	Undeveloped	• Little to no action taken with no strategy in place.

5 International Civil Aviation Organisation (ICAO) (2022) CORSIA default life cycle emissions values for CORSIA eligible fuels. <https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20June%202022.pdf> (accessed 20 April 2023).

A variety of locally sourced feedstocks can be used to make Australian SAF. The diagram below shows potential feedstocks in Australia that were analysed in this report. Feedstocks are broadly categorised as producing biogenic SAF, i.e. derived from organic matter or Power-to-Liquids (PtL) SAF derived from hydrogen and CO_2.

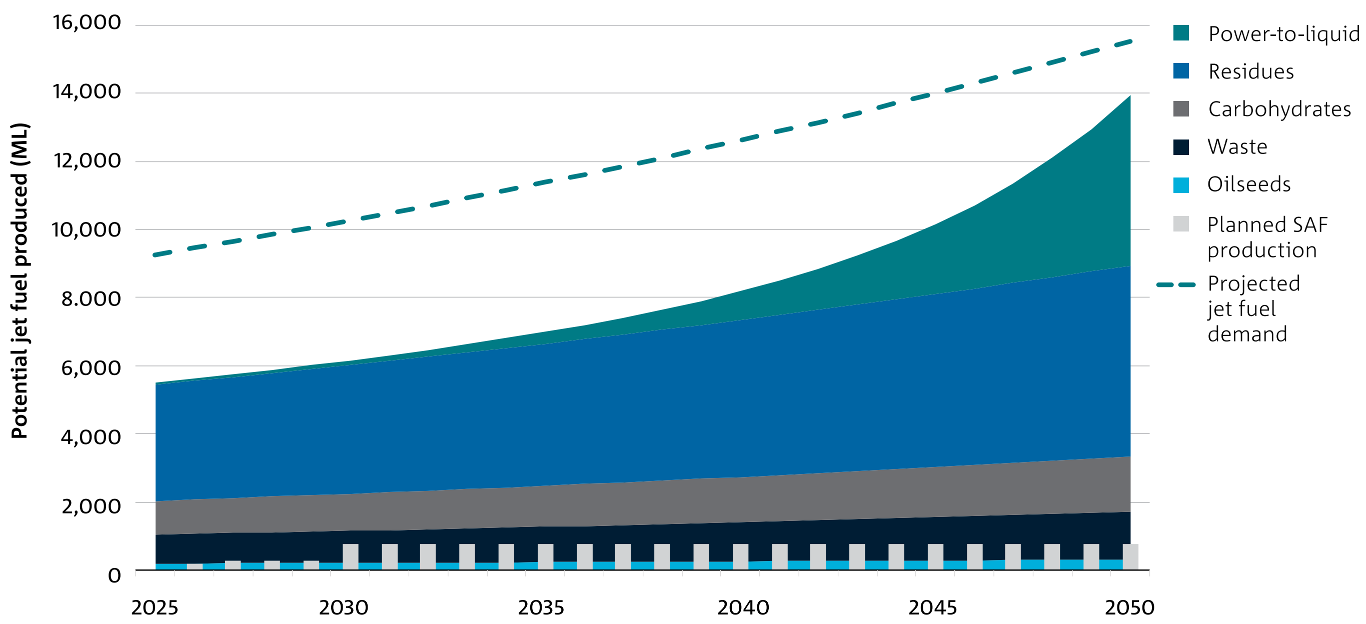
A local SAF industry can generate new sovereign capability, sustainability, and economic opportunities. Producing liquid fuels from local feedstocks can reduce the reliance on imports, where 90% of liquid fuels are presently sourced for Australia.[6] Without domestic production, SAF is currently limited to airlines that travel to international airports where SAF is available. SAF production is complemented by other low-carbon products, such as renewable diesel and lighter hydrocarbons, enabling further decarbonisation in road transport and heating. Some SAF production pathways use waste products that are difficult to manage, such as municipal solid waste (MSW) and industrial CO_2 streams, therefore helping to minimise waste management challenges. Finally, the design, construction, and operation of new biorefineries and their supply chains will create new jobs in regional and metro areas.

Figure 3. Potential Australian feedstocks for SAF production



6 Commonwealth of Australia (2019) Liquid Fuel Security Review—Interim Report. Department of the Environment and Energy

Figure 4. Potential fuel production from projected feedstock production

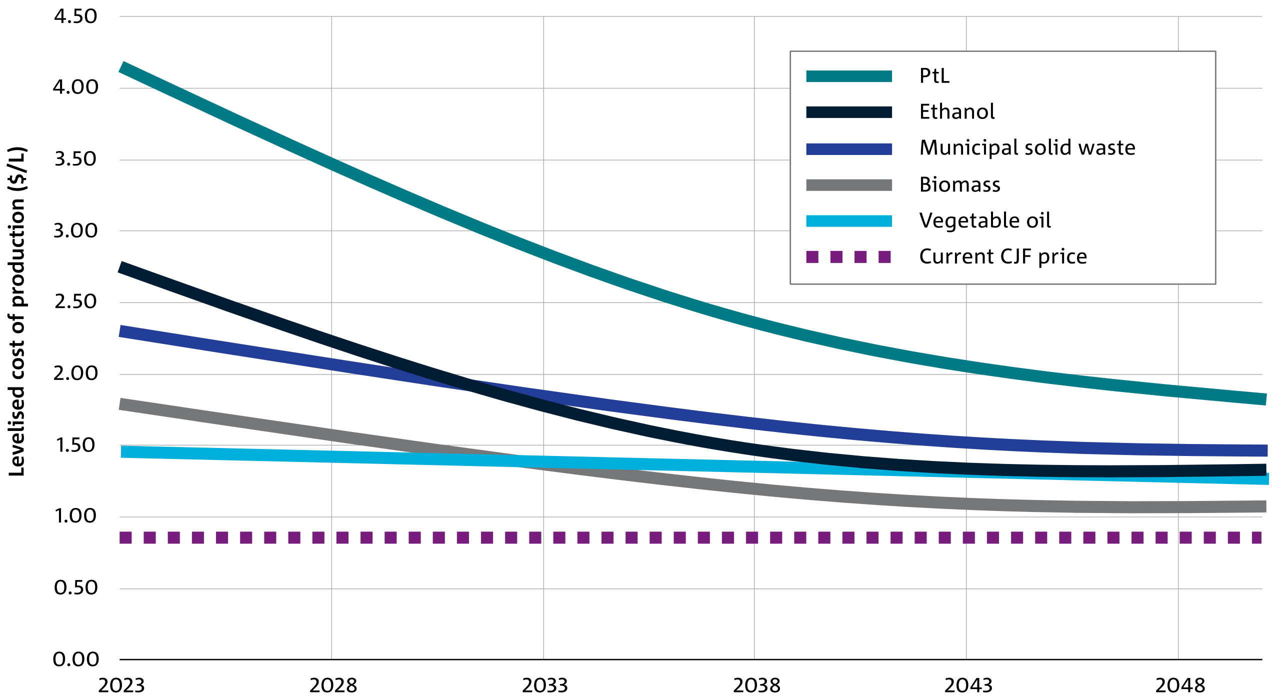


Through a combination of feedstocks and technologies, local feedstocks can meet a large and growing portion of Australia's jet fuel demand. However, domestic refining capacity is lagging and failure to capitalise could lead to lost opportunities. This report projects that in 2025, Australia will have enough feedstocks to produce 60% of local jet fuel demand using biogenic feedstocks, growing to 90% by 2050 as biogenic sources continue to grow and hydrogen production ramps up.

Although some Australian SAF plants have been announced, significant amounts of feedstock remain available for SAF production. By utilising the feedstock and technoeconomic cost modelling from the report's analysis, this opportunity equates to $10 billion of fuel at production costs in 2025 and $19 billion by 2050. However, feedstocks are being exported for SAF production in other jurisdictions, attracted by SAF investments and government policies. This could see more Australian feedstocks exported rather than upgraded locally.

7 The levelised cost of production (LCOP) describes the average cost of producing a unit of fuel over the lifetime of a production process, considering all costs associated with producing the product, as well as the expected amount of product that will be produced. The calculation considers the initial capital costs of the production process, the ongoing operating and maintenance costs, and the expected lifetime of the process. Additionally, the cost of raw materials, labour, energy, and any other inputs required for the production process are factored in. Profit margins are not included in the final figures. Although LCOP can inform analysis of cost drivers and allow a comparison across pathways, LCOP calculations have limitations and their real-world applicability is limited by available data, assumptions and the need to account for numerous products. In this case, each product of the biorefining process, such as diesel and naphtha, must be assigned the same value as the SAF produced, which is not reflective of market pricing at refineries.

Figure 5. Projected levelised cost of production for five key feedstocks[7]



A major challenge for the industry is that SAF comes with a green premium compared to CJF due to feedstock costs, additional processing steps and a lack of economies of scale, with the severity of the premium differing across pathways and time.

Modelling shows that biogenic pathways provide the most economical choice in the immediate to medium term. However, their continued economic favourability mostly depends on the price of feedstocks over time. With increased demand, feedstock prices may rise and therefore biogenic SAF prices. A fall in ethanol prices due to production from advanced fermentation could significantly drop SAF prices.

PtL begins with a greater green premium than biogenic pathways but falls as the hydrogen economy grows, driving significant reductions in hydrogen production costs. The cost and availability of CO_2 will also influence PtL costs, with a successful deployment of direct air capture at scale helping to drive costs down.

Actions from government, industry and research will be necessary to overcome the challenges the SAF industry faces. The challenges and recommendations to establish a SAF industry in Australia, developed through literature reviews and stakeholder consultations with industry, government and research institutions, are below.

Immediate term (2023–2025)

Aim: Develop supportive regulatory and social environment to build confidence for investors and empower organisations and individuals to purchase SAF and reduce their emissions.

MAJOR CHALLENGES	RECOMMENDATIONS
Balancing supply and demand: To balance supply and demand over time, it is crucial to reduce the price gap. **Assuring certification and provenance:** Lack of standardised and transparent sustainability verification for SAF supply. **Carbon accounting and reporting:** Lack of standardised approaches to claim the environmental benefits of of using SAF. **Building SAF literacy:** Current knowledge of the purpose and benefits of SAF is low. **Access to capital**: Emerging industries like SAF with higher risk profiles may struggle to compete for capital.	1. Consider policy frameworks and tools that support domestic distribution and the use of certified SAF with a clear long-term support strategy for the industry. 2. Encourage the signalling of local demand for SAF across government, commercial and defence users, giving investors certainty to establish new plants. 3. Educate consumers on the role and benefits of SAF, building social license for investment and demand for fuels. 4. Invest in research and development (R&D) to support emerging technologies and improve feedstock availability and sustainability understanding. 5. Scale-up of biogenic SAF production in appropriate locations, increasing market supply and reducing costs.

Medium term (2025–2035)

Aim: Unlock biogenic feedstocks for processing and begin small-scale PtL pilot projects.

MAJOR CHALLENGES	RECOMMENDATIONS
Overcoming green premium: High premiums over CJF negatively affect fuel demand. **Competing feedstock uses**: Almost all feedstocks have existing uses, and feedstock producers will aim to sell their products where they can get the highest returns. **Economic collection and processing of feedstocks:** Many feedstocks are low density, making them costly to transport. **Securing feedstock supply:** Biogenic feedstock supply can fluctuate in quantity, quality, and price annually, creating supply risk.	6. Scale-up second-generation biogenic feedstock collection and processing. 7. Invest in R&D to reduce the costs and logistical hurdles for biogenic supply chains and continue scaling up PtL pilots.

Long term (2035+)

Aim: Continue to support large-scale biogenic projects and scale up PtL.

MAJOR CHALLENGES	RECOMMENDATIONS
Lowering cost and increasing availability of hydrogen: The hydrogen economy is in the early stages, so hydrogen costs are high, and availability is low. **Guaranteeing supply of CO_2:** CO_2 sources and quantities will fluctuate over time. **Competition for green electrons:** Green hydrogen and direct air capture will require significant amounts of renewable energy and will need to compete with other industries.	8. Develop large-scale production of PtL at several hydrogen and CO_2 hub locations across Australia.

1 Introduction

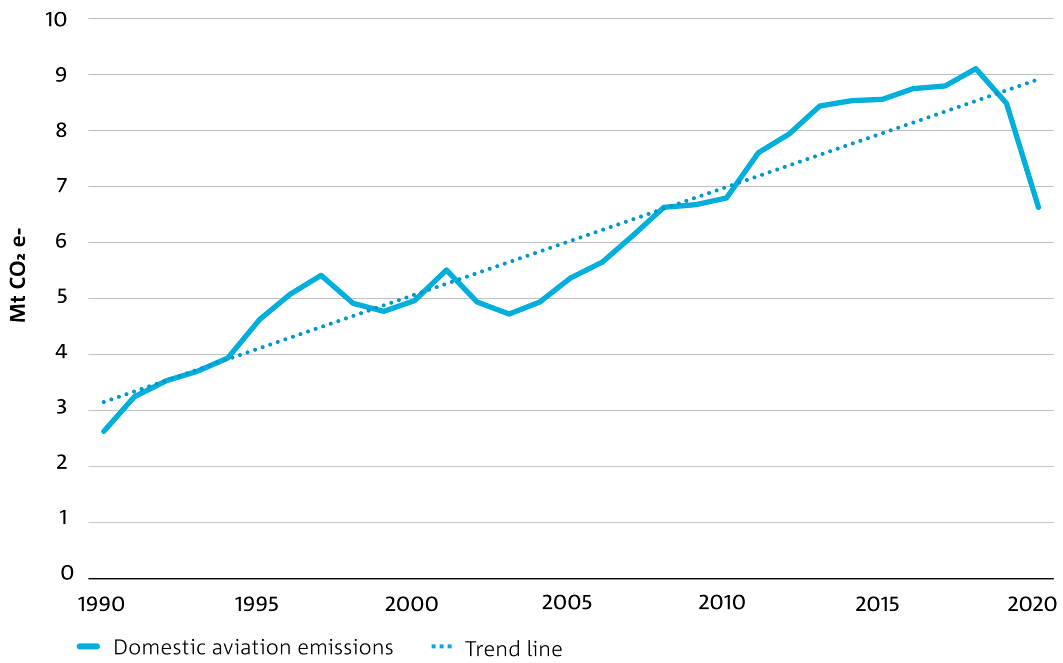
1.1 Decarbonising the aviation industry

The 27th Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCC) in 2022 identified the need for urgent action to address the climate crisis and achieve a resilient and sustainable future. The aviation sector generates approximately 2.5% of the world's carbon emissions which could grow as other sectors continue to decarbonise with mature technologies and passenger demand increases.[8] Domestic aviation emissions in Australia have more than tripled between 1990 and 2019 as per the figure below. The aviation sector recognises this trend and has made progressive commitments to sustainable aviation solutions. The International Air Transport Association (IATA), which represents 300 airlines and 83% of air traffic, is aiming to achieve net zero by 2050.[9]

There are five options that could achieve meaningful reductions in carbon emissions, if pursued.

1. **Efficiency gains:** Adopting advanced materials such as lightweight carbon fibre and implementing highly efficient engines in modern aircraft fleets enhances fuel efficiency, thereby reducing emissions. Moreover, embracing innovative operational management technologies can result in streamlined aircraft maintenance, optimised ground movements, and more effective airspace utilisation. While historical progress has yielded annual improvements of around 2%, it is worth noting that the inherent constraints of new materials and operational practices will eventually impose a natural limit on these gains.[11]
2. **New propulsion technologies:** While battery-powered planes have been successfully flown in demonstrations, it may take some time before they become widely available and without step changes in battery technology, will only be suitable for short-haul flights.

Figure 6. Australian domestic aviation emissions[10]



8 Ellerbeck S (2022) The aviation sector wants to reach net zero by 2050. How will it do it? World Economic Forum. <https://www.weforum.org/agenda/2022/12/aviation-net-zero-emissions/> (accessed 20 April 2023).

9 International Air Transport Association (IATA) (2021) Net-Zero Carbon Emissions by 2050. <https://www.iata.org/en/pressroom/pressroom-archive/2021-releases/2021-10-04-03/> (accessed 20 April 2023).

10 Australian Government Department of Industry, Science, Energy and Resources (DISER) (2022) National Inventory Report Volume 1-3. DISER.

11 The Boeing Company (2020) Global environment report 2020. <https://www.boeing.com/resources/boeingdotcom/principles/environment/pdf/2020_environment_report.pdf> (accessed 20 April 2023).

Using new fuels such as hydrogen in fuel-cells or combusted in turbines for longer-haul flights will face significant technological and supply chain challenges, such as developing onboard hydrogen storage and establishing large-scale production and distribution of green hydrogen fuel. Creating the necessary refuelling and recharging infrastructure and large-scale manufacturing capabilities will require significant time and investment, and costs are currently unclear.

3. **Carbon offsets**: Airlines use carbon offsets as an indirect measure to reduce their unavoidable carbon footprint. Offsets are generated by projects that reduce, remove, or capture atmospheric emissions. These projects, such as reforestation or renewable energy, are then used to cancel out some or all of the CO_2 emissions from flights through carbon accounting. However, concerns exist about the quality and transparency of these offsets and the reliability of the data that supports their accounting. While technological advancements and increased scrutiny have improved the legitimacy of offsets and demand has grown with net zero targets, social impact challenges remain with some options. High-integrity offsets will play a role in the near-term as other technologies scale and in the long term to address residual CO_2 emissions.[12]
4. **Flight alternatives:** Modal shift towards alternative transportation methods like high-speed rail and the increased use of video conferencing could reduce the demand for flights, consequently leading to emissions reduction. Countries like France and Austria have implemented bans on short-haul flights where train options with journey times under 2.5 hours are available. However, it is important to note that while these options exist in Australia, the country's relatively lower connectivity and geographical isolation from the rest of the world may limit its capacity to offer alternatives to flight.
5. **Sustainable aviation fuel (SAF)**: SAF is a replacement for fossil-derived conventional jet fuel (CJF), generated from non-fossil raw materials or feedstocks. To be considered sustainable, SAF must be sourced in a way that does not deplete natural resources, can be continuously and repeatedly replenished and produces fewer carbon emissions than CJF. SAF is blended with CJF in ratios of up to 50% to ensure compatibility with aircraft, engines and fuelling systems. Uncertainty in feedstock and technology choice, slow deployment and higher production costs have limited investment in large-scale projects, resulting in approximately 300 ML of global SAF produced in 2022, or approximately 0.09% of fuel sales that year.[13]

1.2 Why SAF?

Given the limits of operational efficiency gains, the nascency of alternative propulsion technologies, the increasing pressure to decarbonise directly rather than through offsets, and the select use case applicability of flight alternatives, SAF provides the main lever in the immediate and longer term to reduce unavoidable emissions. The utilisation of maturing technologies, compatibility with existing and new aircraft and airport infrastructure, scalability in production, and support for the decarbonisation of long-haul flights contribute to its effectiveness.[14] This relevance is particularly pronounced for Australia, given its dispersed population and relative geological isolation from the rest of the world, which increase the dependence on long-haul flights.

In addition to net carbon emissions reductions, the combustion of SAF also provides co-benefits when compared to fossil-derived jet fuel:

- **Reduction in particulates:** The combustion of crude-oil derived jet fuel produces a range of particulate matter emissions and soot which lead to the formation of ice crystals and contrails which, when accumulated and persistent, have significant warming effects on the atmosphere. SAF, however, has been shown to significantly reduce these types of emissions, reducing the overall warming effect of combustion.[15]

12 Air Transport Action Group (2021) Commitment to fly net zero 2050. <https://aviationbenefits.org/media/167501/atag-net-zero-2050-declaration.pdf> (accessed 20 April 2023).

13 IATA (2022) 2022 SAF production increases 200% - more incentives needed to reach net zero. <https://www.iata.org/en/pressroom/2022-releases/2022-12-07-01/> (accessed 20 April 2023).

IATA (2022) Fuel: Fact Sheet. https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet---fuel/ (accessed 8 May 2023)

14 ICAO (2022) Report on the feasibility of a long-term aspirational goal (LTAG) for international civil aviation CO2 emission reductions. <https://www.icao.int/environmental-protection/LTAG/Pages/LTAGreport.aspx> (accessed 20 April 2023).

15 Voigt, C., Kleine, J., Sauer, D. et al. (2021) Cleaner burning aviation fuels can reduce contrail cloudiness. Commun Earth Environ 2, 114.

European Union Aviation Safety Agency (2020) Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to the EU Emissions Trading System Directive Article 30(4). European Commission.

- **Renewable co-products**: The production of SAF leads to the production of other fossil fuel replacements, such as renewable diesel, lubricants and lighter hydrocarbons, allowing other local industries to access low-carbon alternatives.
- **Higher energy density and thermal stability:** SAF has a slightly higher energy density and thermal stability than CJF due to minimised aromatic hydrocarbon content.[16] Increased energy density results in reduced fuel consumption by engines. Additionally, with engine design changes, increased thermal stability of SAF would allow fuel molecules to combust more completely and efficiently.[17] This allows airlines to carry and burn slightly less fuel under current operating conditions or carry more passengers with the same amount of fuel. The benefits would be even more pronounced for ultra-long-haul flights, where passenger numbers are often restricted to carry enough fuel.

1.3 Why Australia?

Australia has a significant opportunity to develop a diversified portfolio of raw materials, or feedstocks, for a domestic SAF industry. Broad latitude and longitude, temperate climates, advanced farming practices and established supply chains are all potential assets to develop a range of biogenic feedstocks (those that are composed of organic matter). This can be seen through Australia's current production and export volumes in oilseeds and sugars and through its agricultural residue potential. Australia is a major exporter of canola seed to the European Union (EU), where a significant amount is converted into biofuels. Additionally, Australia processes large quantities of animal fat, and to a lesser degree used cooking oil, that is sold to countries such as Singapore and the US for processing.

As well as the potential for biogenic feedstocks, Australia is set to capitalise on its renewable energy potential to become a significant renewable energy and green hydrogen producer. Green hydrogen will be a crucial commodity in refining biofuels and, once scaled to significant production quantities, also as a feedstock for the power-to-liquids (PtL) process.

Becoming a sovereign SAF producer could present a range of opportunities for Australians.

- **Liquid fuel security:** Producing fuels from Australian feedstocks could provide a complete sovereign solution to mitigate the risk of supply interruptions, shortages and depleted storage. Australia imports 90% of its liquid fuels, including jet fuel, through long supply chains exposed to geopolitical and climate change risk and delays associated with contaminated batches.[18] Additionally, by securing domestic production of SAF and other fuels, Australia can buffer itself from international fossil fuel and oil price fluctuations. The need for alternative back-up fuel supply has also been identified in the Federal Government's Defence Strategic Review.[19]
- **Local options for decarbonisation:** A local supply of SAF would allow domestic airlines to access low-emission fuel and contribute to decarbonising Australia and achieving net zero by 2050. Without domestic production, SAF is currently limited to aircrafts that travel to airports where SAF is available. SAF production can be complemented by other low-carbon products, such as renewable diesel and lighter hydrocarbons, offering decarbonisation options for road transport, mining, remote power generation and heating.
- **Regional jobs and development:** Feedstock production and collection depend heavily on regional areas to construct and manage both supporting infrastructure, and supply chains, for biogenic SAF and synthetic fuels. Fuel production will also provide job creation opportunities that would be missed if feedstock was exported without domestic value added through local refining.
- **Waste management benefits:** Some production pathways can effectively utilise waste streams that are currently challenging to manage, including urban waste and emissions from hard-to-abate industries. By repurposing these waste streams as feedstocks for SAF, significant benefits are realised by both SAF producers and waste producers.

16 Vardon DR, Sherbacow BJ, Guan K, Heyne JS, Abdullah Z (2022) Realizing "net-zero-carbon" sustainable aviation fuel. Joule 6(1), 16-21.
17 Boehm R, Scholla L, Heyne J (2021) Sustainable alternative fuel effects on energy consumption of jet engines. Fuel
18 Commonwealth of Australia (2019) Liquid Fuel Security Review—Interim Report. Department of the Environment and Energy.
19 Australian Government (2023) National Defence: Defence Strategic Review. Department of Defence.

- **Asia-Pacific leadership:** Australia can become a leader in the production and upgrading of sustainable feedstocks for export to neighbouring countries looking to decarbonise their economies. Some of Australia's neighbouring countries face land mass limitations and cannot produce surplus renewable electricity or feedstocks to produce biofuels. As a result, Australia could play a role in supplying these countries with sustainable feedstocks and fuels.

1.4 Why now?

Fast approaching net zero targets, a more vocal and environmentally conscious consumer, commercial maturity of a range of technology options, supportive government policy, significant capital investments and widespread announcements of SAF goals and offtake agreements are positioning SAF production and uptake for strong growth.

Despite the current lack of supply, demand signals indicate a growing global market. For example, Qantas has announced a goal of procuring 10% of its overall fuel mix from SAF by 2030, increasing to 60% by 2050. This target matches many airlines around the globe, including airlines that make up the oneworld Alliance, such as British Airways, Cathay Pacific, Qatar Airways and Japan Airlines.[20]

The World Economic Forum also leads two global initiatives that aim to decarbonise the aviation industry and promote the production and use of SAF. The Clean Skies for Tomorrow Coalition sets a target of 10% SAF in the global aviation fuel supply by 2030, while the First Movers Coalition commits to replacing 5% of CJF demand with SAF by 2030.[21]

In some jurisdictions, a range of policy mandates and incentives have accompanied these targets. This includes tax incentives as part of the Inflation Reduction Act in the US and mandates of a minimum of 1% SAF in Sweden, Norway, and France.[22] The RefuelEU Initiative, starting in 2025, stipulates fuel suppliers are obligated to blend 2% into the jet fuel supply (increasing incrementally to 63% by 2050) and airlines must resupply 90% of their fuel needs at major EU airports.[23]

Countries around the world are already investing to build their SAF production capability and purchasing available feedstock. Last year Australia exported 400 kt of tallow and approximately 3.4 Mt of canola seed to Europe.[24] Historically, up to 60% of Europe's canola oil has been used for biofuels and according to stakeholder consultations, Australia's tallow is primarily upgraded to biofuels in the US and Singapore.[25] That is sufficient feedstock to produce over 1,000 ML of SAF or 11% of Australia's projected 2023 consumption.[26] Additionally, Japan is exploring opportunities to grow and pre-process feedstocks, such as wood pallets, in Australia which will be brought back to Japan for refining.[27]

In a scenario where Australia becomes only a feedstock provider rather than an integrated local processor and SAF producer, it risks missing out on several benefits of a regional bioeconomy. This includes local job creation for upgrading and processing feedstocks, renewable by-products such as other biofuels and bioplastics, and broader sustainability benefits of managing a complete value chain of a bioeconomy.

20 oneworld (2021) oneworld aspires to reach 10% sustainable aviation fuel target by 2030. <https://www.oneworld.com/news/2021-10-04-oneworld-aspires-to-reach-10percent-sustainable-aviation-fuel-target-by-2030> (accessed 20 April 2023).

21 World Economic Forum (n.d.) Clean Skies for Tomorrow Coalition. <https://www.weforum.org/cleanskies> (accessed 20 April 2023); World Economic Forum (2022) First Movers Coalition aviation commitment. <https://www3.weforum.org/docs/WEF_First_Movers_Coalition_Aviation_Commitment_2022.pdf> (accessed 20 April 2023).

22 Internal Revenue Service (2022) Treasury, IRS issue guidance on new Sustainable Aviation Fuel Credit. <https://www.irs.gov/newsroom/treasury-irs-issue-guidance-on-new-sustainable-aviation-fuel-credit> (accessed 20 April 2023); Gupte E (2022) TotalEnergies signs 10-year SAF deal with Air France-KLM. <https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/120522-totalenergies-signs-10-year-saf-deal-with-air-france-klm> (accessed 20 April 2023).

23 SkyNRG (n.d.) A summary of the proposed sustainable aviation fuel mandate. <https://skynrg.com/a-summary-of-the-proposed-sustainable-aviation-fuel-mandate/> (accessed 20 April 2023).

24 https://www.argusmedia.com/en/news/2370377-australia-canola-exports-on-track-to-exceed-targets, ABS 2007, Information Consultancy Services, cat. no. 9920.0, Canberra. Tallow exports AHECC codes: 15020041, 15020051, 15020059, 15020060, 15021000, 15021001, 15021002, 15021003, 15021041, 15021049, 15021060, 15021061, 15021062, 15021063, 15030000.

25 Australian Oilseeds Federation (2022) Australian canola and the EU biodiesel market. <http://www.australianoilseeds.com/__data/assets/pdf_file/0006/38571/AOF_education_factsheets-biodieselWEB20221025.pdf> (accessed 20 April 2023);

26 CSIRO (2022) Electric vehicle projections 2022. https://publications.csiro.au/publications/publication/PIcsiro:EP2023-0235

See Section 2.1.4 for description of how the model is constructed. See Section 3 for a definition of the Step Change scenario underpinning the jet fuel demand projections used. A ratio of 34.7 MJ/L of jet fuel is used.

27 Nakashima M (2023) Japan's Idemitsu eyes SAF production from pongamia oil. Argus Media. <https://www.argusmedia.com/en/news/2427110-japans-idemitsu-eyes-saf-production-from-pongamia-oil> (accessed 20 April 2023).

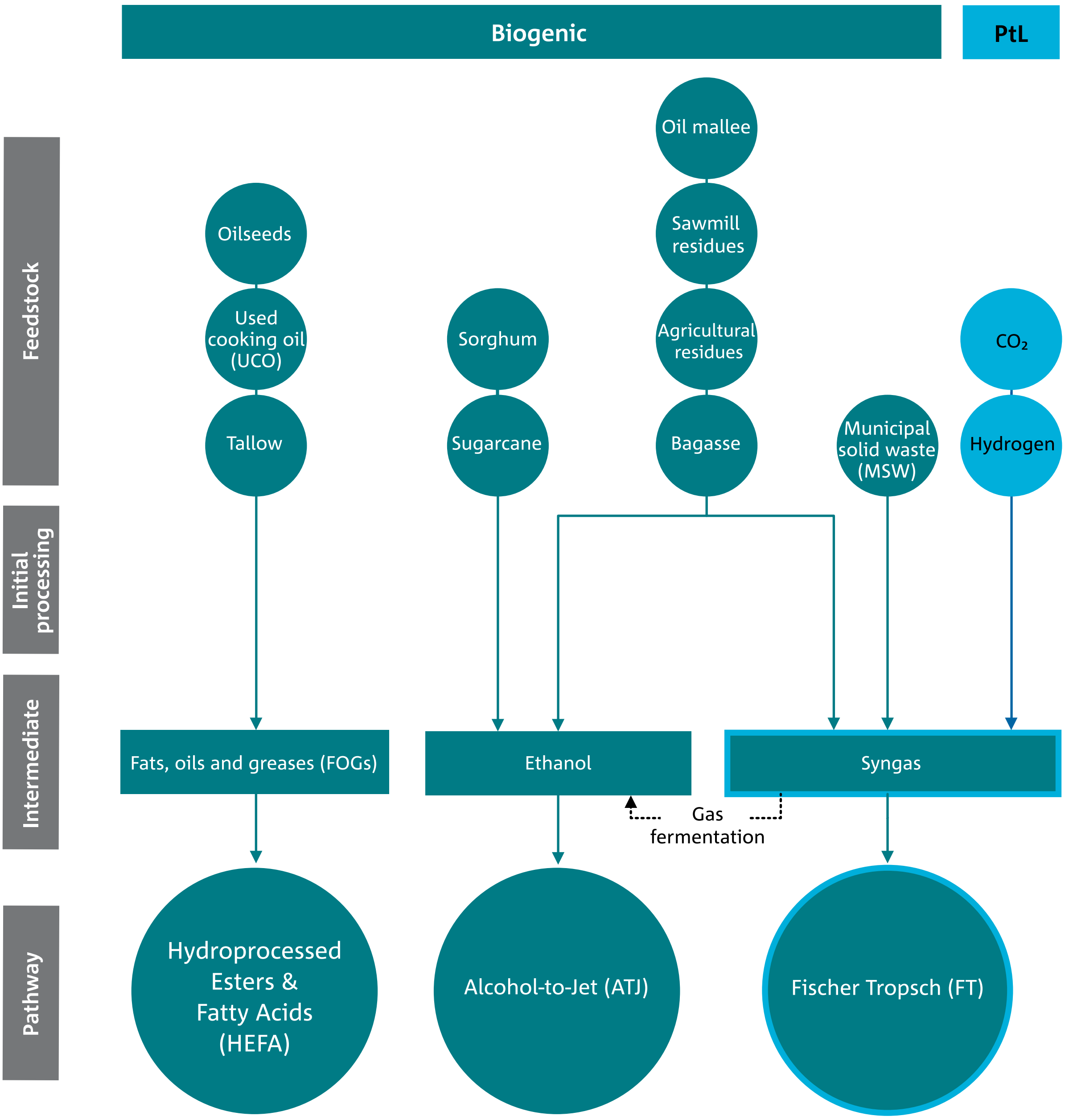
Finally, proactive development of sovereign production can minimise the chance of limited access to liquid fuels at short notice. New biofuel plants have a long lead time, with time needed for planning, permits, design and building, making it challenging to fast-track fuel production in a sudden time of need. In the event of geopolitical change in the region that impacts jet fuel supply, it could take some time to react to develop sovereign production. Investing now could enable Australia to respond quickly to sudden changes in supply.

1.5 How is SAF made?

SAF can be produced from a variety of feedstocks which fall into two main categories: biogenic feedstocks such as crops, vegetable oils and fats, agricultural and sawmill residues, and municipal solid waste (MSW), or non-biogenic sources such as waste gases, hydrogen and CO_2 through a process known as power-to-liquids or PtL.

Feedstocks can be upgraded into fuels through seven currently approved pathways. This report has focused on the three most popular pathways for simplicity, as shown in the figure 7.

Figure 7. Key SAF pathways and potential feedstocks for Australia



Note: For more detail on the initial processing steps required, refer to the Appendix Chapter 7.2

1.6 This report

CSIRO has partnered with Boeing to analyse the availability of sustainable feedstocks for producing SAF in the Asia Pacific (APAC) region, with a focus on Australia and New Zealand. The analysis covers various feedstocks, such as oilseeds, carbohydrates, waste products (e.g., tallow, used cooking oil (UCO) and MSW), agricultural and sawmill residues, and hydrogen. For each feedstock, the analysis estimates the current and future availability and the potential fuel output up to 2050. The analysis also considers the challenges of reallocating these feedstocks for SAF production, including commercial, sustainability, policy, and social impact considerations.

To understand the position of Australia and New Zealand in the APAC region, the report also analyses the likely role of other APAC countries in a regional SAF zone. Finally, a Roadmap is presented that outlines the key messages and a plan to scale the SAF industry in Australia in a coordinated manner across the entire value chain, considering evolving technology and feedstock risks. The report is informed by consultations with over 40 local and international organisations from business, government, and research, and an Advisory Group that was convened to discuss the findings.

2 Challenges and opportunities

In the pursuit of reducing reliance on fossil fuels, the aviation industry is faced with numerous challenges and opportunities that can be effectively addressed and capitalised on through strategic investments and long-term planning for the production, collection, and processing of feedstocks into SAF.

2.1 Economic

Overcoming green premium

The green premium is the difference in cost between a product that involves emitting carbon and an alternative that does not. In this case, there is an additional cost associated with SAF production due to a combination of difficulties in collecting and aggregating sustainable feedstocks, the low energy density and cost of these feedstocks, extra processing steps and lack of economies of scale. These factors produce a green premium that can result in SAF costing two to four times more than CJF. Since fuel represents 30–40% of an airline's cost base, even doubling these costs could have significant implications for consumers, airlines and the viability of the sector.[28]

To reduce green premiums, cost reductions across the value chain are needed. This includes more efficient collection and aggregation of feedstocks such as the use of higher density intermediates (where feedstocks are processed into an intermediate which can be transported more efficiently), development of large-scale plants to achieve economies of scale, de-risking of emerging technologies and continued R&D into new efficiencies and improved and lower cost materials. While these actions can reduce the green premium, without upwards pressure on fossil fuel prices they are unlikely to eliminate it. This can be exacerbated by global competition and competing government policy. If the cost of CJF remains low, government intervention may be necessary to bridge the price gap to make SAF more competitive or to introduce mandates to encourage the purchase of SAF.

Securing feedstock supply

Minimising feedstock supply risk in terms of quantity, quality, and price will be a crucial consideration for organisations making investment decisions for new SAF plants. While complete certainty is unlikely to be possible in any market, a range of strategies can be taken to minimise supply risk.

SAF facilities that can accept a range of feedstocks can improve supply certainty. By selecting technologies that can process several different feedstocks, SAF producers can diversify their supply chain. For example, processing a range of vegetable oils sourced from various locations can allow for numerous points of failure in feedstock sourcing and reduce risk of imports. Additionally, the adoption of feedstock hubs, where one technology such as gasification or advanced fermentation is used to process a range of biomass and waste feedstocks before further upgrading, could also reduce the risk of supply inconsistency or reliability. This diversification should extend to updating feedstock sources over time to incorporate emerging sources that may become available as biofuel demand increases. Although physical supply risk may decrease, traceability becomes more difficult as several feedstocks need to be considered in certification. Development of certification and traceability frameworks will need to account for the scenario of several feedstocks.

Long-term contracts are another potential tool to minimise supply risk. However, many feedstocks outlined in this report do not operate on long-term contracts in Australia for various reasons, such as concerns from farmers about committing to volume contracts which may be difficult to fulfil due to annual variability in climate. Area-based contracts, such as those used for niche crops, provide an alternative contracting option that reduces the grower's exposure to climate variability. To ensure growers are committed to maximising outputs, minimum quantities may need to be considered with bonuses for exceeding a set quantity to encourage greater yields.

28 IATA (2022) Fuel. <https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet---fuel/> (accessed 20 April 2023).

Australia can also look overseas for examples of long-term contracts in the agricultural space. In Brazil where mills are largely vertically integrated, the average contract between landowners and sugarcane producers varies between six to twelve years (one to two sugarcane cycles). There are three common types of contracts: (1) land rental contracts – which give the local mill use of the land for sugarcane production for a fixed rental rate; (2) agricultural partnership contracts – which give the local mill use of the land for sugarcane production for a percentage of the harvested crop; and (3) supply contracts – by which farmers agree to supply sugarcane to the local mill for an agreed price and quantity. Farmers have historically been willing to sign longer contracts with financially stable mills.[29]

Lessons can also be learned from established agribusinesses where dependence on biogenic feedstocks has long been business as usual. Australian sugarcane millers have been managing this agricultural supply risk for decades with a range of strategies that include collaborating with growers to share information and support and utilising stockpiling and risk management strategies with financial instruments.

Balancing supply and demand

To balance supply and demand, it is crucial to either reduce the price gap or explore alternative mechanisms to bridge it. Currently, demand outweighs supply despite the high prices, as there are only small volumes available for purchase. While some airlines can currently manage the premium associated with limited purchases, this approach will become unsustainable as supply increases, considering that fuel is a major expense for airlines. If prices remain high, there is a risk of a decline in demand, which could jeopardise future investments in supply.

A combination of actions will be needed from government, capital markets and airlines to overcome this. There are promising signs that these conditions are beginning to come together, particularly in the US, UK and EU, where government incentives and mandates are aligning with long-term offtake agreements and capital raising.

One mechanism that could influence balancing supply and demand of SAF in Australia is the recently legislated Safeguard Mechanism. Under this legislation, major Scope 1 emitters are required to remain below a specified baseline.[30] Meeting this baseline may require the purchase of SAF, however the effect of the Safeguard Mechanism on airlines requires further analysis.

Selecting SAF over renewable diesel

The production and yield of SAF is dependent on the operational and capital conditions chosen by the refinery which directly affects proportion of their products among SAF, renewable diesel, and others. Renewable diesel, with its fewer processing requirements in the HEFA pathway and broader regulatory mandates, tends to have a smaller green premium and a customer base with willingness to pay. The more favourable economics associated with renewable diesel production might lead biofuel producers to prioritise it over SAF and other products. Policy mechanisms may need to be explored to enhance the production yield of SAF at biorefineries. However, considering the anticipated future displacement of road transport by electrification and hydrogen, this challenge is more pressing in the short term and is expected to diminish over time.

Economic collection and processing of feedstocks

Biogenic feedstocks have a lower energy density than crude fossil sources, meaning more feedstock input is required to produce the equivalent amount of SAF. This is due to the oxygen and water content inherently present in biomass, which reduces the combustion properties of the feedstock and adds expensive processing steps.[31] Additionally, many feedstocks have a low value density, making them costly to transport. This creates a logistical bottleneck that constrains SAF production potential and requires facilities to be located close to feedstock supply for maximum cost-efficiency.[32]

29 Sant'Anna AC, Bergtold JS, Shanoyan A, Caldas MM, Granco G (2022) Biofuel feedstock contract attributes, substitutability and tradeoffs in sugarcane production for ethanol in the Brazilian Cerrado: A stated choice approach. Renewable Energy 185, 665-679.

30 Australian Government Clean Energy Regulator (2023) The Safeguard Mechanism. https://www.cleanenergyregulator.gov.au/NGER/The-safeguard-mechanism (Accessed 17 May 2023).

31 Schmidt-Rohr K (2015) Why Combustions Are Always Exothermic, Yielding About 418 kJ per Mole of O2. https://pubs.acs.org/doi/10.1021/acs.jchemed.5b00333> (accessed 18 May 2023).

32 Barclays SAFs 2022 report, ATAG: Waypoint 2050 - Fuelling Net Zero, September 2021.

Collection and aggregation are often not economical, particularly when the feedstocks are geographically dispersed like residues and wastes. Stakeholders denoted transport distances should be limited to 100 km and concentration placed on high-density farming areas.

R&D can improve the supply chain through developing efficient collection and harvesting systems, including transportation, storage, and pre-processing, which lower the cost and carbon intensity.[33] Logistics models will also need to consider the potential for integrating and co-locating existing processing or collection facilities to reduce cost. Another solution is to apply localised densification methods to obtain more energy per volume or mass of feedstock. This includes oilseed crushing nearby production sites, drying biomass or processing feedstock to higher density intermediates like ethanol or bio-crude before transportation. Much work is being done to explore bio-chemical and thermochemical pre-processing routes through technologies like advanced fermentation, pyrolysis and hydrothermal liquefaction or carbonisation.[34] These are explored further in the Technology Chapters.

Risks to landowners

By changing the economic purpose of their land and entering a new emerging market, landowners can take on new financial risks. New crops or significant changes to how the land is run may require new equipment and land management knowledge. Achieving levels of efficiency may take time and hinder short-term economic gains. Landowners will also become exposed to the volatility of the biofuel market. Landowners may also be weary of shifting to producing biofuel feedstocks given previous unsuccessful biofuel endeavours, such as the low uptake of bioethanol E10 and biodiesel.

It is essential to engage with local communities and landowners to provide them with adequate information to ensure they are informed and understand the risks of entering the biofuel market. Examples of similar programs from the past include the Region Forest Agreements (RFAs) which seek to balance economic, social and environmental demands on forests by setting obligations and commitments for forest management.[35] Landowner risk could also be mitigated through offtake agreements from SAF producers, policy certainty, government and industry demand signals, and support from a centralised body similar to the Grains Research and Development Corporation to research and advise on best farming and market practices.

Competing feedstock uses

The competition in domestic and international markets for agricultural commodities and biomass feedstocks can impact the decision of feedstock producers to sell to local SAF producers. Almost all feedstocks have existing uses and markets, including bioenergy and biofuels, human or animal feed, export, recycling, maintaining soil health, or as feedstocks for other products. Producers of feedstocks will try to sell their products where they can get the highest returns, which may include international markets when prices are high. This could lead to fluctuations in the supply and price of feedstocks for SAF producers. Feedstocks that will be less exposed to this risk include MSW and some agricultural residues, which are not traded internationally, making them less affected by price shocks and supply disruptions.

Access to capital

As an emerging industry in Australia, access to capital will be critical. The development of SAF plants at a scale that can meet demand and achieve cost efficiencies will require significant capital investment. Despite some local SAF production announcements, Australian projects are yet to reach the Final Investment Decision stage, and additional support may be necessary to attract sufficient private investment. In this regard, government agencies such as the Clean Energy Finance Corporation can play an important role in reducing investment risk through the issuance of green bonds, which can help to stimulate investment in the industry. Additionally, due to great global interest in SAF development, Australia could leverage its strong sustainability credentials to attract international capital.

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33 U.S. Department of Energy, U.S. Department of Transportation, and U.S. Department of Agriculture, in collaboration with the U.S. Environmental Protection Agency (2022) SAF Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel https://www.energy.gov/sites/default/files/2022-09/beto-saf-gc-roadmap-report-sept-2022.pdf

34 Sharma HB, Sarmah AK, Dubey B (2020) Hydrothermal carbonization of renewable waste biomass for solid biofuel production: A discussion on process mechanism, the influence of process parameters, environmental performance and fuel properties of hydrochar. Renewable and Sustainable Energy Reviews 123(109761).

35 Department of Agriculture, Fisheries and Forestry (2023) Regional Forest Agreements. <https://www.agriculture.gov.au/agriculture-land/forestry/policies/rfa> (Accessed 17 May 2023).

2.2 Sustainability

Assuring certification and provenance

Ensuring feedstock and fuel production processes are sustainable and transparently reported is essential in providing stakeholders with trust and confidence that any SAF produced meets the intended sustainability goals.

Sustainability certification is required to ensure transparent feedstock compliance against a defined set of criteria, traceability of materials through the supply chain and ultimately verify greenhouse gas (GHG) emissions reductions of the SAF product.[36]

Sustainability Certification Schemes manage compliance of commercial operators along the supply chain on a lifecycle basis. Compliance certificates are generated for producers following audits from recognised verification bodies. This confirms SAF is produced from feedstock that adhere to the relevant sustainability requirements and provides stakeholders with an overview of the environmental impacts from the point of cultivation and collection.

Australian producers could consider adopting one of the two available Sustainability Certification Schemes, as shown below, to provide transparency and traceability of feedstocks and supply chains and validate the sustainability of the SAF product.

Figure 8. SAF sustainability verification pathway for CORSIA compliance[37]

The International Civil Aviation Organisation (ICAO) governs aviation emissions of 193 member countries, including Australia.

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) was developed by ICAO.

CORSIA sustainability criteria is limited to two principles:

- SAF must achieve a minimum of 10% net GHG emissions reduction compared to fossil jet fuel baseline
- Land use change of high carbon stock land is not permitted (i.e. biomass obtained from primary forests, wetlands or peatlands)

There are currently two Sustainability Certification Schemes that meet the requirements of the CORSIA sustainability criteria and are eligible to certify SAF producers.

Roundtable on Sustainable Biomaterials (RSB)

Certified SAF enables claims around achieving minimum 50% GHG reductions and 12 sustainability principles including environmental protection, food security and human rights.

International Sustainability and Carbon Certification (ISCC)

Certified feedstocks that enable claims of 10% GHG reductions over the lifecycle and 6 sustainability principles met, centred around environmentally and socially responsible practices.

36 European Union Aviation Safety Agency (2023) European aviation environmental report 2022. <https://www.easa.europa.eu/eco/eaer/topics/sustainable-aviation-fuels/saf-policy-actions> (accessed 20 April 2023).

37 ICAO (2020) CORSIA approved sustainability certification schemes. <https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2004%20-%20Approved%20SCSs.pdf> (accessed 20 April 2023); Aviation: Benefits Beyond Borders (n.d.) CORSIA explained. <https://aviationbenefits.org/environmental-efficiency/climate-action/offsetting-emissions-corsia/corsia/corsia-explained/> (accessed 20 April 2023); International Sustainability and Carbon Certification (2021) ISCC certification for sustainable aviation fuels. <https://www.iscc-system.org/wp-content/uploads/2021/01/ISCC-for-Sustainable-Aviation-Fuels_sales-presentation.pdf> (accessed 20 April 2023); RSB (n.d.) RSB CORSIA ceritification. <https://rsb.org/rsb-corsia-certification/> (accessed 20 April 2023); Klepper G, Schmitz N (2019) CORSIA SAF certification with ISCC – the International Sustainability and Carbon Certification scheme. <https://www.iscc-system.org/wp-content/uploads/2019/09/ICAO-Environmental-Report-CORSIA-SAF-Certification-with-ISCC.pdf> (accessed 20 April 2023).

International feedstock acceptance

It is important to understand which sustainability certifications limit feedstock and technology choice to reduce investment risk before developing supply chains. Inconsistent sustainability standards depending on the region, and differences in the rigour of certification, make it difficult for Australia to appropriately assess this risk and align with international stakeholders. Certifications are changing overseas, and this may influence Australia's exports, feedstock and SAF production and prevent airlines from purchasing SAF at local airports. A primary example is the EU Renewable Energy Directive (RED II) and ReFuelEU Initiative which stipulate a minimum of 65% GHG reduction must be achieved for biofuels and excludes food or feed-based feedstocks.[38] To minimise exposure to changing attitudes and feedstock acceptance, SAF producers can prioritise low-risk feedstocks such as waste or choose flexible technologies that can process a variety of feedstocks.

Carbon accounting and reporting

Standardised and accepted approaches are required to enable the environmental benefits of SAF to be claimed by organisations following transactions and then reported transparently. Despite demand driven by corporate buyers seeking to reduce their Scope 3 emissions, SAF is not currently recognised as a potential mitigation option by reporting authorities like Greenhouse Gas Protocol.[39] In Australia, no obligation exists to report Scope 3 emissions under the National Greenhouse and Energy Reporting scheme and optional for the National Greenhouse Accounts.[40] Thus, emissions reduction claims cannot be fully realised.

For the market to scale efficiently and credibly, it is important that transaction outcomes allow buyers to compare fuel attributes on an equivalent basis and reward higher quality SAF. The recently developed SAF certificates (SAFc) framework could be considered to achieve this. Organisations would purchase the SAFc and bear the increased cost of the fuel, while claiming Scope 3 emissions reductions from travel. Traceability registry for corporate clients is included, like the concept of generating, selling and transferring renewable energy certificates. The initiative is currently undergoing endorsement and pilot testing as a viable method for organisations to decarbonise, as well as growing the demand for SAF. However, for SAFc to be scaled as a market mechanism and recognised by accounting and reporting bodies, formal definition to avoid double counting, as well as robust physical tracking mechanisms and independent registry would be needed.

A book-and-claim system offers the most practical solution, whereby the environmental attributes from a SAF batch can be purchased and owned, irrespective of the location the fuel is physically delivered and consumed. Several organisations are working to develop book-and-claim guidance including the Clean Skies for Tomorrow coalition, the Sustainable Aviation Buyers Alliance, the Roundtable on Sustainable Biomaterials (RSB) and Shell. The result should provide a single standardised system which considers Greenhouse Gas Protocol, Science Based Target initiative and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) requirements, and functions alongside SAFc to allow claiming of Scope 1 and 3 emission reductions from SAF by airlines and their customers respectively. Australia could support a recognised system, such as this one, as long as a transparent method for claiming SAF benefits exists, through a system that allows claims to be registered, transferred and retired in a standardised manner and with traceability.

While accounting and reporting standards are being developed, many lessons can be learned from pioneering SAF transactions. Some of this is being done through Qantas' SAF Coalition, which enables member organisations to contribute to purchasing SAF and meet their sustainability goals.[41] Yet more work is needed given the complexity and current lack of clarity surrounding the carbon emissions counting and mass balancing process.

38 European Union Aviation Safety Agency (2023) European aviation environmental report 2022. <https://www.easa.europa.eu/eco/sites/default/files/2023-02/230217_EASA%20EAER%202022.pdf> (accessed 20 April 2023); European Union (2018) Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN#page=123> (accessed 20 April 2023).

39 World Economic Forum (2022) Sustainable Aviation Fuel Certificate (SAFc) Emissions Accounting and Reporting Guidelines. <https://www3.weforum.org/docs/WEF_SAFc_Accounting_Guidelines_2022.pdf> (accessed 17 May 2023)

40 Clean Energy Regulator (2023) Greenhouse gases and energy. <https://www.cleanenergyregulator.gov.au/NGER/About-the-National-Greenhouse-and-Energy-Reporting-scheme/Greenhouse-gases-and-energy#n4> (accessed 19 May 2023)

Ker P, Greber J (2022) Australia urged to follow US push into scope 3 disclosures. <https://www.afr.com/policy/energy-and-climate/australia-urged-to-follow-us-push-into-scope-3-disclosures-20220322-p5a6vx> (accessed 19 May 2023)

41 Qantas (2023) Partnering for the future of flying. <https://www.qantas.com/au/en/qantas-group/acting-responsibly/our-planet/sustainable-aviation-fuel/saf-coalition-program.html> (accessed 19 May 2023)

The trial conducted by Air New Zealand demonstrated how difficult it is putting theory into practice.[42] A similar project that would see Australia import SAF in the immediate term could help identify the jurisdictions in which suppliers need to get comfortable with certain documents and processes. This includes matching the right documents with the applicable regulations, determining the role of fuel majors and others along the value chain, calculating pipeline emissions from well-to-wake, and considering local blending feasibility requirements. Additionally, this could provide domestic airlines, without access to foreign markets, with a source of SAF until domestic production can be scaled.

Not all SAF decarbonises equally

Emissions from SAF can differ greatly depending on the feedstock and production pathway. Fuels with higher emissions reduction potential should be prioritised from a sustainability standpoint and rewarded.[43] The perceived quality of SAF will also have a considerable impact on the price airlines are willing to pay. Australian airlines are particularly reliant on voluntary corporate and consumer actions due to the absence of incentives, which is likely to reinforce the importance of a SAF's sustainability credentials.

Numerous factors contribute to calculating the carbon equivalent emissions of SAF, more formally known as the carbon intensity (CI), over its lifecycle. To inform feedstock analysis, default lifecycle emissions values were sourced from the ICAO for CORSIA eligible fuels and presented in Figure 9. This allows a simplified comparison to be made across the different feedstocks and technology pathways.

Waste feedstocks generally have a lower CI compared to crops or feedstock used as food or animal feed. This is due to added emissions from induced land use change, which account for the effects of displacing food crops and changing land from natural biomass to a biofuel feedstock.

It is also worth noting that low CI feedstocks (resulting in greater reductions compared to CJF) are often more challenging to collect or source. This is due to factors such as high demand and scarcity, like with UCO, or lack of mature supply chains and difficulties in collection, like with agricultural residues. Conversely, higher CI feedstocks, such as canola, sugarcane and some non-biogenic MSW frequently benefit from mature industries and efficient supply chains. Investments in SAF therefore need to consider the trade-off between striving for the highest possible emissions reduction and selecting feedstocks and pathways that minimise the green premium and can be implemented in the immediate term, with a portfolio approach helping to spread the risk.

What is a life cycle assessment?

Life cycle assessments, or LCAs, are an analysis of the potential environmental impacts of products or services during their lifetime.

For fossil fuels, this includes the CO_2 required to extract, transport, refine and distribute the fuel, plus the CO_2 emitted when the fuel is combusted.

CORSIA's SAF methodology accounts for:

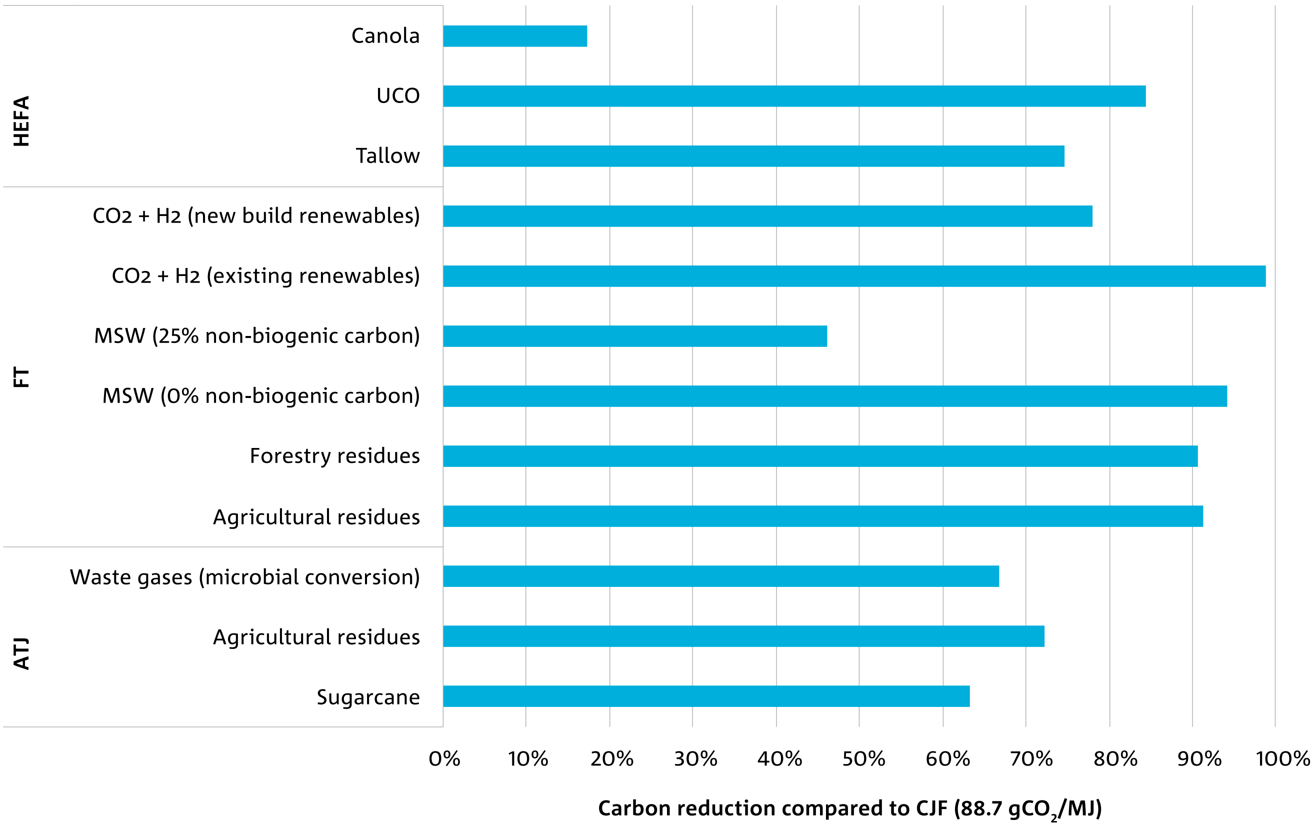
1. Production at source (e.g., feedstock cultivation)
2. Conditioning at source (e.g., feedstock harvesting, collection, and recovery)
3. Feedstock processing and extraction
4. Feedstock transportation to processing and fuel production facilities
5. Feedstock-to-fuel conversion processes
6. Fuel transportation and distribution to the blend point
7. Fuel combustion in an aircraft engine

As a point of reference, CO_2 absorbed by plants during their growth, or captured from industrial sources is roughly equivalent to the amount of CO_2 combusted.

42 Air New Zealand (2022) Air New Zealand to welcome first shipment of Sustainable Aviation Fuel into Aotearoa. <https://www.airnewzealand.com/press-release-2022-airnz-air-new-zealand-to-welcome-first-shipment-of-sustainable-aviation-fuel-into-nz> (accessed 17 May 2023)

43 ICAO (2019) CORSIA methodology for calculating actual life cycle emissions values. <https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2007%20-%20Methodology%20for%20Actual%20Life%20Cycle%20Emissions.pdf> (accessed April 2023).

Figure 9. LCA reductions for CORSIA eligible SAF pathways and feedstocks compared to CJF reference value[44,45]



The default values (Figure 9) are not specific to the Australian context, but the CORSIA framework allows fuel producers to apply for the calculation of the actual LCA values through an approved sustainability certification scheme (SCS).[46] Consequently, lower emissions reductions may be claimed, capturing local conditions and practices. As an example, CSIRO previously completed a canola lifecycle analysis to demonstrate compliance with EU RED II sustainability requirements. Australian canola seed was found to rank in the top 15% in terms of GHG efficient cultivation, compared to other countries' feedstock supply for EU biodiesel production.[47] This suggests better emissions reductions than 18% or a lower carbon intensity can be achieved.

44 Schmidt P, Weirndorf W (2016) Power-to-liquids: potentials and perspectives for the future supply of renewable aviation fuel. German Environment Agency. <https://www.umweltbundesamt.de/sites/default/files/medien/377/publikationen/161005_uba_hintergrund_ptl_barrierrefrei.pdf> (accessed 20 April 2023).

45 ICAO (2022) CORSIA default life cycle emissions values for CORSIA eligible fuels. <https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20June%202022.pdf> (accessed 20 April 2023).

46 ICAO (2022) Life Cycle Emissions of Sustainable Aviation Fuels. <https://www.icao.int/environmental-protection/pages/SAF_LifeCycle.aspx> (accessed 17 May 2023).

47 Eady S (2017) Greenhouse gas emissions from the cultivation of canola oilseed in Australia. CSIRO; Australian Oilseeds Federation (2022) Australian canola and the EU biodiesel market. <http://www.australianoilseeds.com/__data/assets/pdf_file/0006/38571/AOF_education_factsheets-biodieselWEB20221025.pdf> (accessed 20 April 2023); Sevenster M, Bell L, Anderson B, Jamali H, Horan H, Simmons A, Cowie A, Hochman Z (2022) Australian grains baseline and mitigation assessment. CSIRO.

SAF in the broader energy transition

The development of a SAF industry will not occur in isolation. While it has the potential to yield positive effects on the energy transition, it risks competing with other technologies and impacting the sustainability of other industries. For example, as demand for biogenic SAF increases, it will likely face competition for feedstocks from bioplastics and bioelectricity. Additionally, PtL pathways, and to a lesser extent biogenic SAF, will need to compete against export and new industries for green electrons, green hydrogen and CO_2. Long-term planning for the SAF industry should carefully consider its role within the broader context of the global energy transition.

It is important to recognise that scaling SAF will impact the supply of by-products, waste and residues that are produced sustainably for animal feed, high-value products or energy. By shifting their use to SAF, existing users may be forced to seek unsustainable alternatives. Although some energy users may adopt renewable electricity pathways, it risks being replaced with comparatively cheap fossil fuels. Displacement of tallow or animal fats from existing uses such as heat, power and oleochemicals, can lead to increased use of virgin vegetable oils.[48] This can increase indirect emissions, reducing the overall emissions reduction from SAF. Assessments of SAF should consider the environmental implications of feedstock displacement and downstream replacement materials to ensure holistic sustainable outcomes.

Recent developments in Australia's energy transition may have positive flow on effects for feedstock competition. Australia is investing heavily in decarbonising the electricity sector, which could free up more feedstocks for other industries. The Australian Budget (2022-23) has committed a record total $25 billion in funding for renewable projects, including modernising the electricity grid, electrifying road transport and delivering community energy storage.[49] Accelerating the decarbonisation of the electricity sector may benefit SAF, as more feedstocks can be made available.

Planning for the development of a SAF industry should be aligned to wider energy transition objectives, as well as recognise potential trade-offs. This should include consideration of hard-to-abate industries, like aviation, that have limited technology options available. To facilitate this strategic planning process, Australia has established a Net Zero Authority dedicated to supporting clean energy transformation.[50]

A changing climate

Times of drought have significant effects on crop yield which could severely impact the supply of oilseeds, sugarcane and crop residues to biofuel plants from year to year. Short-duration extreme events such as heatwaves, floods and bushfires can damage crops, pastures and infrastructures and are likely to increase in frequency and intensity in the future. With the State of the Climate report forecasting an overall warming trend across Australia and a drying trend across many regions in the south and east over the coming years, ensuring a stable and high-quality supply of feedstock for SAF production is a challenge that the industry will need to account for.[51]

Increasing crop heat resilience is one of many strategies to combat this challenge which involves genetic modification, targeted nutrient applications, plant growth regulations, microbial inoculation and smart agricultural technology.[52] As well as improvements in technology to maintain yields and protect plantings, diversification of feedstock type and location and the use of feedstock hubs can help mitigate the risks associated with climate change.

48 Pavlenko N, Searle S (2021) Assessing the sustainability implications of alternative aviation fuels. International Council on Clean Transportation. <https://theicct.org/wp-content/uploads/2021/06/Alt-aviation-fuel-sustainability-mar2021.pdf> (accessed 20 April 2023).

49 Australian Government (2023) Australian Budget commits A$25bn to clean energy and renewables projects. <https://www.globalaustralia.gov.au/news-and-resources/news-items/australian-budget-commits-a25bn-clean-energy-and-renewables-projects> (accessed 19 May 2023).

50 Australian Government (2023) National Net Zero Authority <https://www.pm.gov.au/media/national-net-zero-authority> (accessed 19 May 2023).
Australian Government (2023) A new national Net Zero Authority <https://www.pmc.gov.au/news/new-national-net-zero-authority> (accessed 19 May 2023).

51 Bureau of Meteorology, CSIRO (2022) State of the climate 2022. Bureau of Meteorology, CSIRO, Australia.

52 Ahmad M, Waraich EA, Skalicky M, Hussain S, Zulfiqar U, Anjum MZ, Rahman MH, Brestic M, Ratnasekera D, Lamilla-Tamayo L, Al-Ashkar I, Sabagh AE (2021) Adaptation strategies to improve the resistance of oilseed crops to heat stress under a changing climate: an overview. Fron. Plant Sci. 12.

Sustainable land management practices

The sustainability of feedstock production can be improved by implementing land management practices that prioritise positive environmental outcomes, such as agroforestry, silvopasture, and intercropping, while avoiding land use change. However, the production of biogenic or non-biogenic feedstocks will require using land for purposes outside of its primary use. Practices such as heavy fertiliser use, land use change, and monoculture, which are not environmentally sustainable, can lead to soil degradation, water pollution, and habitat destruction. Therefore, it is important to prioritise sustainable land management practices to ensure the long-term viability of feedstock production.

Ongoing RD&D is being conducted on non-edible oilseeds and energy crops like carinata and *Miscanthus* to investigate the potential for utilising marginally productive or unproductive land. Australia's oil mallees are another example of feedstock capable of growing on marginally productive or unproductive land, with the additional benefit of rehabilitating soil salinity. These are briefly mentioned in Chapter 3.6. Finally, certain bioenergy crops have been gaining interest for restoring contaminated lands post-industrial or mining activities.[53] Though beyond the scope of current feedstock analysis, future research opportunities could consider evaluating phytoremediation crops for biofuel production.[54]

2.3 Social impact

Building SAF literacy

The success of the SAF industry depends on building higher literacy levels across the value chain. As a relatively new industry, it is important to understand the key aspects of SAF, including their role in decarbonisation, production methods, tracking and reporting, and sustainability criteria. Clear and transparent strategies, along with public messaging, are needed to build trust and awareness of the industry, and to prepare consumers for the transition to SAF.

Industry players must be proactive in promoting the adoption of SAF through various communication pathways. This includes educating airline customers through existing programs and promotions, as well as showcasing SAF through flight demonstrations. Additionally, more data is needed to better understand social attitudes toward SAF. This information can be used to shape messaging around the role of SAF and counteract false claims, thereby encouraging uptake and bringing consumers along for the adoption journey. SAF literacy is essential for the growth and adoption of the industry, and all stakeholders must work together to increase understanding and promote the benefits of SAF.

Empowering the consumer

Empowering consumers is critical in driving the adoption of SAF. By providing consumers with more options and information, they can make more informed decisions that align with their values and priorities. This includes offering programs that allow consumers to purchase a portion of SAF or the emission reduction attributable to a portion of SAF for private and business flights. These could help drive local SAF production and provide access to SAF decarbonisation benefits, even in the absence of domestically available SAF via book and claim. Through such programs, consumers can directly contribute to the decarbonisation of aviation at scale and play an active role in supporting the growth of the SAF industry.

Land use rights

Land use, land rights, and area requirements of large-scale renewables need to be considered for SAF production facilities and supporting infrastructure. This is particularly important for PtL supply chains which will require vast renewable resources on land over which Indigenous traditional owners have rights and interests. Engaging with all stakeholders, including Traditional Owners, will be critical to understanding and driving long-term opportunities for the community and region.

53 Prasad MNV (2015) Phytoremediation Crops and Biofuels. Sustainable Agriculture Reviews. Sustainable Agriculture Reviews, vol 1.

Khan AG (2020) Promises and potential of *in situ* nano-phytoremediation strategy to mycorrhizo-remediate heavy metal contaminated soils using non-food bioenergy crops (*Vetiver zizinoides & Cannabis sativa*). Int J Phytoremediation.

Evangelou M, Conesa H, Robinson B, Schulin R (2012) Biomass Production on Trace Element–Contaminated Land: A Review. Environmental Engineering Science.

54 European Commission (2021) Bridging the gap between phytoremediation solutions on growing energy crops on contaminated lands and clean biofuel production <https://cordis.europa.eu/project/id/101006873> (accessed 19 May 2023).

2.4 Policy

Optimising the role of government

Government policy has enabled certain countries to establish a SAF industry. Renewable fuel mandates, in northern Europe, are already sufficient to encourage investment into new SAF production projects. Recently the US has attracted investment and import of renewable fuel feedstocks with the enactment of the Inflation Reduction Act, which provides tax credits for renewable fuel production, including SAF. This investment is supported by the Sustainable Aviation Fuel Grand Challenge and Roadmap which brings together federal government agencies to develop strategy to scale up SAF technologies.[55]

When considering the use of mandates or tax credits, it's important to consider who will bear the cost of intervention. If mandates are put in place, airlines and fuel suppliers will incur the cost of compliance, which could be passed on to passengers in the form of higher ticket prices. Conversely, if tax credits are used, it's likely that taxpayers will bear the cost, regardless of whether they fly or not.

As with any new industry, the government has several potential roles to play in setting a common vision, providing certainty for industry investment, mitigating investment risk and coordinating a synchronous approach, including across state and federal government levels. Suggestions from industry are included in the call out box.[56]

Funding from organisations such as the Clean Energy Finance Corporation is important for enabling technology providers to scale demonstration projects and overcome the 'valley of death'. This is where technologies approaching commercialisation lose momentum due to the larger investments needed to overcome first-of-kind risk. Inadequate access to capital grants, loans or tax incentives to help overcome these hurdles may stifle local investment and lead technology providers to seek capital elsewhere. A recent example of this can be seen with Australian technology provider Licella securing funding in Canada to meet scaled up demonstration requirements.[57]

SAF investments could also be considered in existing and upcoming government funds. The regional development of SAF feedstocks and synthesis could align closely with funds such as the Powering the Regions Fund (with $400M Industrial Transformation Stream recently announced that includes aviation)[58], National Reconstruction Fund and the Northern Australia Development Program.

Examples of industry recommendations

Industry groups including Bioenergy Australia and Airlines for Australia and New Zealand have released reports in the previous year outlining policy mechanisms that could be used to aid the development of a SAF industry in Australia.

Key recommendations include:

- Establishing a forum for industry and government bodies to discuss and provide input into government policymaking, such as a Jet Zero Council.
- National framework for voluntary consumer purchasing to enable customers to opt-in to procure SAF for their flights.
- Funding assistance through capital funding grants and low-interest loans.
- Inclusion of SAF in public procurement such as government flights and Defence.

55 US Department of Energy (2022) Sustainable Aviation Fuel Grand Challenge. <https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge> (accessed 17 May 2023).

56 Airlines for Australia & New Zealand (A4ANZ) (2022) An Australian Roadmap for Sustainable Flying. A4ANZ; Link P, Hallam M, Maloba S (2022) Bridging the price gap for sustainable aviation fuel. Bioenergy Australia.

57 Biomass Magazine (2021) Arbios moves forward with biofuels plant in British Columbia. <https://biomassmagazine.com/articles/18377/arbios-moves-forward-with-biofuels-plant-in-british-columbia/> (accessed 20 April 2023).

58 Prime Ministers Office (2023) National Net Zero Authority. <https://www.pm.gov.au/media/national-net-zero-authority> (accessed 17 May 2023).

Consistency of biofuel policy

The development and growth of the SAF industry will require careful consideration of policy mechanisms to create a level playing field for competition of feedstocks with other biofuels. Given there is precedent for policy intervention for biodiesel, renewable diesel and ethanol, when developing SAF policy, considerations should be made to any potential overlaps in liquid fuel policies.[59] As electrification and hydrogen technologies continue to advance, it will be critical to ensure that policy frameworks for SAF are flexible enough to evolve alongside emerging technologies and changing market conditions of road transport.

Competition from international incentives

The global market for SAF is highly competitive at present, and the availability of incentives in other countries is already impacting the potential development of a local industry in Australia, as feedstock exports to the US and Singapore grow. In particular, the California Low Carbon Fuel Subsidy, which provides financial incentives for the production and use of low-carbon fuels, has been successful in driving demand for SAF in the US.

Furthermore, the recent introduction of the Inflation Reduction Act in addition to other US state-based low carbon fuel incentives is seeing a demand for sustainable feedstocks and SAF supply into the US from around the world.[60] Without similar incentives in Australia, any fuel produced locally is unlikely to be available to local offtake markets in large volumes due to the higher SAF premium, and instead will be produced for export to the US market. While this could still support production of SAF in Australia in securing some local feedstocks and adding economic opportunities in regional Australia, it would not necessarily contribute to local decarbonisation goals. Policymakers in Australia may consider international incentives, investments and the potential impact on Australia when developing policies to support the growth of a domestic SAF industry.

Adapted from the World Economic Forum's "Clean Skies for Tomorrow: Sustainable Aviation Fuel Policy Toolkit" report, Table 1 and 2 below outline example policy interventions that can increase the supply and demand for SAF in Australia.[61]

59 Clean Energy Finance Corporation and the Australian Renewable Energy Agency (ARENA) (2019) Biofuels and Transport: An Australian Opportunity. GHD Pty Ltd.

60 Lavinsky C (2022) Inflation Reduction Act charts a new course for US biofuels industry. S&P Global. <https://www.spglobal.com/commodityinsights/en/market-insights/blogs/agriculture/090822-ira-inflation-reduction-act-us-biofuels> (accessed 20 April 2023).

61 World Economic Forum (2021) Clean Skies for Tomorrow: sustainable aviation fuel policy toolkit. <https://www3.weforum.org/docs/WEF_Clean_Skies_for_Tomorrow_Sustainable_Aviation_Fuel_Policy_Toolkit_2021.pdf> (accessed 19 May 2023).

Table 1: Policy interventions to increase SAF supply

TYPE OF POLICY INTERVENTION	BENEFITS/IMPACTS	EXAMPLES
Tax incentive or exemption	• Increase SAF production • Stimulate sustainable feedstock production and processing	• The Sustainable Aviation Fuel Credit in the US includes a US$1.25 baseline credit for each gallon of SAF used in aviation, with an additional tax credit of 1 cent for every percentage point of emissions savings above 50%, with an upper tax credit limit of $1.75 per gallon. • Under Brazil's National Biodiesel Production and Use Programme, biodiesel producers who acquire raw feedstocks from family farmers can claim tax reduction of up to 68%.[62]
Innovation fund	• Fund and promote RD&D • Promote innovation and best practice in SAF supply	• UK's Green Fuels, Green Skies Competition offers £15 million in grant funding to support early-stage development of SAF plants. • In 2022, Japan awarded ¥114.5 billion of grants to pilot projects developing e-fuel, SAF and other green innovation technologies. This initiative is part of a ¥2-trillion green innovation fund to help companies become carbon neutral by 2050.[63]
Capital funding (grants, low-interest loans)	• Support first-of-a-kind SAF production plants • Support the scale-up of SAF pathways with higher technology readiness levels (TRLs)	• The US Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Programme provides loan guarantees of up to US$250 million to fund the development, construction and retrofitting of commercial biorefineries and biobased product manufacturing facilities. • The US Innovative Energy Loan Guarantee Program offers up to US$3 billion in loan guarantees for commercial-scale SAF projects.
Contract-for-difference (CfD)	• De-risk first-of-a-kind SAF production plants	• The SDE++ (Stimulation of Sustainable Energy Production and Climate Transition) programme in the Netherlands subsidises companies and non-profit organisations that generate renewable energy and use CO_2-reducing technologies via the CfD mechanism. The subsidy is distributed over a period of 12–15 years with a limit varying from €60–300 per tonne of CO_2 avoided.[64]
Direct subsidies	• De-risk first-of-a-kind SAF production plants	• The Australian Fuel Security Services Payment pays refiners a production payment during loss-making periods based on the number of litres of fuels (petrol, diesel, jet fuel) they produce.[65]
Decarbonisation of other sectors, or fossil fuel levy	• Redirect feedstock for SAF production	• The EU's revised Energy Taxation Directive proposes a minimum tax rate of €10.75 per GJ, applicable to traditional aviation fuel used on intra-EU flights, while SAF benefits from a zero minimum rate. The policy will be gradually introduced from 2023 before being fully enacted in 2033.[66]

62 Brazilian Government (n.d.) National Program of Biodiesel Production and Use (PNPB). <http://images2.wikia.nocookie.net/superstruct/images/3/30/Brazilian_biodiesel_en.pdf> (accessed 17 May 2023).

63 Kumagai T (2022) Japan awards Yen 114.5 bil grants for e-fuel, SAF and other green technologies. S&P Global <https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/041922-japan-awards-yen-1145-bil-grants-for-e-fuel-saf-and-other-green-technologies> (accessed 17 May 2023).

64 Netherlands Enterprise Agency (2023) SDE++: Orientation <https://www.rvo.nl/subsidies-financiering/sde/werking> (accessed 17 May 2023).

65 Australian Government (2021) Fuel Security Services Payment. <https://www.energy.gov.au/government-priorities/energy-security/australias-fuel-security/fuel-security-services-payment> (accessed 17 May 2023).

66 EUR-Lex (2021) Proposal for a COUNCIL DIRECTIVE restructuring the Union framework for the taxation of energy products and electricity. <https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52021PC0563> (accessed 17 May 2023).

Table 2: Policy interventions to increase SAF demand

TYPE OF POLICY INTERVENTION	BENEFITS/IMPACTS	EXAMPLES
Blending mandate	• Create an obligation to increase the share of SAF in the jet fuel market • Obligates major CJF producers to ensure SAF is sold. • Create long-term, predictable demand	• The European Commission has proposed a SAF blending mandate for fuel supplied to EU airports, with minimum shares of SAF gradually increasing from 2% in 2025 to 63% in 2050.[67]
Emission intensity mandate	• Create an obligation to use low-carbon fuels, including SAF, which generates long-term demand	• Under the US State of California's Low Carbon Fuel Standard, the fuel carbon intensity is calculated and compared to a declining benchmark each year which determines whether a fuel provider receives a credit or deficit. A provider with deficits must earn or acquire from other parties the equivalent amount of credits.[68]
Voluntary SAF purchase	• Bridge the cost differential of procuring SAF • Improve awareness and transparency around SAF	• Swiss International Airlines allows customers to voluntarily purchase a certain amount of SAF to make their flight carbon-neutral.[69] • Travellers with Scandinavian Airlines can opt to purchase 20-minute blocks of SAF for US$10 per block, which in turn earns them bonus points. The amount of SAF purchased will be used to replace the equivalent amount of fossil fuels in the airline's operations as soon as possible and latest within 12 months.[70] • This intervention mechanism currently exists as airlines initiatives and not a national policy.
Domestic carbon pricing or cap-and-trade	• Increase the price of fossil fuels, which decreases their usage and increases SAF demand	• Under the EU emission trading system, air carriers must surrender carbon allowances from intra-EU flights, each representing one tonne of CO_2, equivalent to their emissions reported in the previous year.[71] • Under the US State of California's Low Carbon Fuel Standards, SAF producers can earn credits to compensate for fossil fuel generation obligations or sell the credit to other deficit generators.[72]
Minimum levels of public procurement	• Generate critical early demand that helps de-risk and kick-start SAF production • Provide leading example for private offtakers	• The Government of the Netherlands participates in KLM's Corporate SAF Programme whereby the premium difference between CJF and the SAF equivalent for their fliers are paid for by the government agencies.

67 European Union Aviation Safety Agency (2022) European Aviation Environmental Report. <https://www.easa.europa.eu/eco/sites/default/files/2023-02/230217_EASA%20EAER%202022.pdf> (accessed May 17 2023).

68 <https://ww2.arb.ca.gov/sites/default/files/2020-09/basics-notes.pdf> (accessed 17 May 2023).

69 SWISS (n.d.) Flying with sustainable aviation fuel. <https://www.swiss.com/magazine/en/inside-swiss/sustainability/flying-with-sustainable-aviation-fuel> (accessed 17 May 2023).

70 SAS (2021) SAS rewards travellers adding biofuel. <https://www.sasgroup.net/newsroom/press-releases/2021/sas-rewards-travelers-adding-biofuel/> (accessed 17 May 2023).

71 European Commission (n.d.) Aviation and the EU ETS. <https://climate.ec.europa.eu/eu-action/european-green-deal/delivering-european-green-deal/aviation-and-eu-ets_en> (accessed 17 May 2023).

72 California Air Resources Board (n.d.) Low Carbon Fuel Subsidy. <https://ww2.arb.ca.gov/sites/default/files/2020-09/basics-notes.pdf> (accessed 17 May 2023).

3 Feedstocks

Introduction

Consisting of a hydrocarbon of differing lengths, SAF can be produced from a range of feedstocks made up of carbon and hydrogen, including biogenic and non-biogenic sources. Each feedstock can be upgraded using a set of approved fuel synthesis pathways. The feedstocks being explored in this report are shown in the table below.

This chapter provides an overview of the production potential, technoeconomic analysis, and key challenges across feedstocks available in Australia.

Table 3: Summary of Australian feedstocks, current uses and main fuel pathways

			MAIN FUEL PATHWAYS		
	FEEDSTOCK	CURRENT NON-SAF USES	HEFA	FT	ATJ
Carbohydrates	Sugar	Food, ethanol			●
	Bagasse	Onsite heat and steam		●	●
	Sorghum	Food and animal feed			●
Wastes	Tallow	Biofuels, soap, candles	●		
	Used cooking oil	Biofuels	●		
	Municipal solid waste (MSW)	Landfill, bioenergy		●	●
Residues and coppicing	Agricultural residues	Left on the field for soil health, animal feed		●	●
	Sawmill residues	Woodchips, onsite energy		●	●
	Oil mallees	No commercial use		●	
Oilseeds	Canola	Cooking oil, biofuels, animal feed	●		
	Cottonseed	Cooking oil, biofuels, animal feed	●		
	Other oilseeds	Cooking oil, biofuels, animal feed	●		
Power to liquids	Hydrogen (H_2)	Chemical and industrial processes		●	●
	Carbon dioxide (CO_2)	Vented to atmosphere, food and beverage		●	●

HEFA – Synthesised paraffinic kerosene from hydroprocessed esters and fatty acids

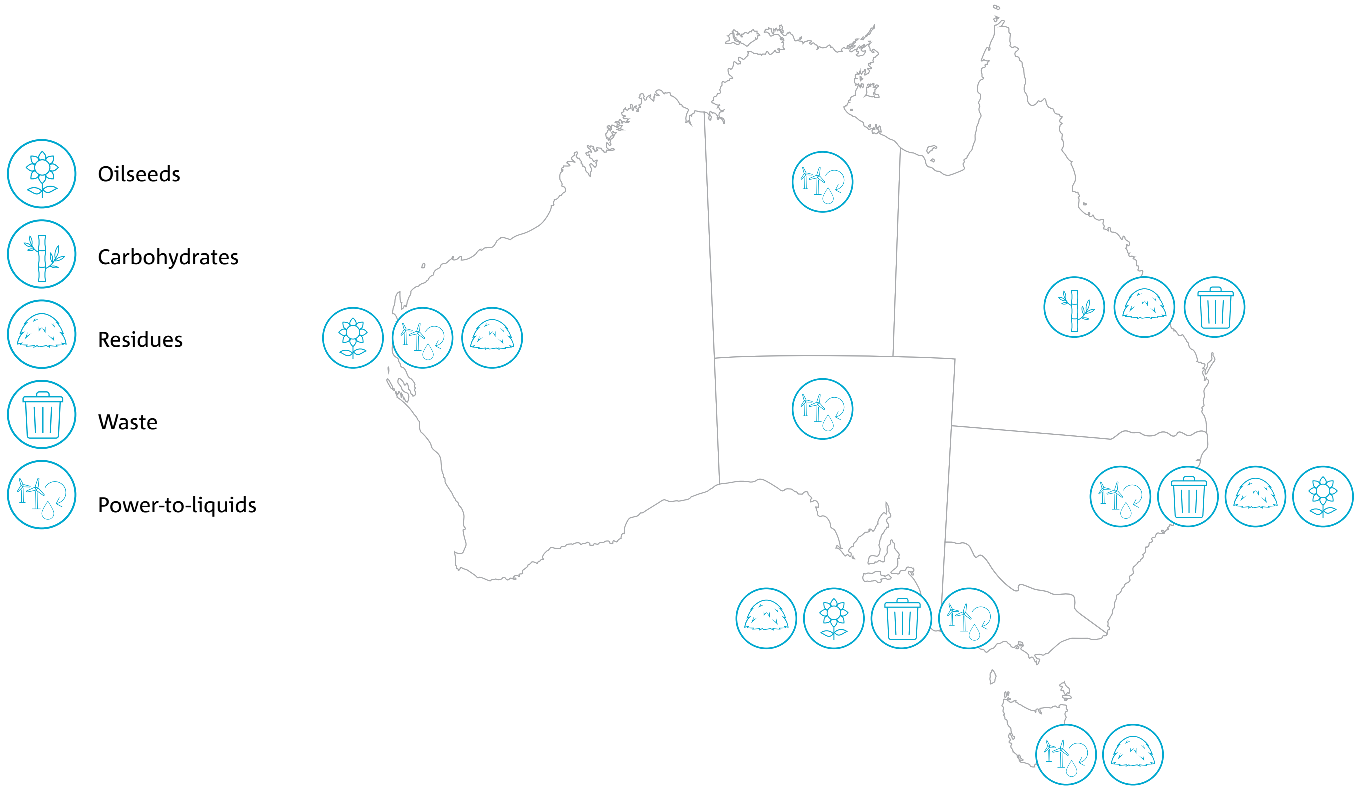
FT – Fischer-Tropsch hydroprocessed synthesised paraffinic kerosene

ATJ – Alcohol-to-jet synthetic paraffinic kerosene

Feedstock location

Each state and territory has its own feedstock advantages as shown below. These areas strongly correlate with arable land and hydrogen production strategies, with the east and southwest coast more likely to look to biogenic feedstocks and PtL being largely universal with large renewable energy potential nationwide.

Figure 10. Feedstock advantages of Australian states



Modelling approach

Feedstock modelling

To understand how much SAF feedstock Australia currently produces and what that means in terms of potential sovereign fuel production, key feedstocks were analysed and their projected growth modelled through to 2050. This process was underpinned by four key parameters:

1. **Historical feedstock data**: Historical data going as far back as 2010 was sourced for each feedstock. A line of best fit was calculated for historical feedstock production data using a least squares approach. Forecasts were then calculated based on the current production estimate from the trend line using feedstock growth rates.
2. **Feedstock growth rates**: Two feedstock growth rates (0.5% and 2%) were chosen and applied through to 2050 across all feedstocks except hydrogen, where an exponential growth rate was assumed.
3. **Jet fuel yield**: Two jet fuel yield scenarios were explored through low and high percentages of jet fuel yield from each feedstock type. Different percentages were chosen for each technology pathway.
4. **Feedstock allocated to jet fuel**: Two feedstock allocation hypotheticals were explored through a low and high percentage of feedstock allocated to jet fuel production. These figures were chosen because they are within the range of historical allocations to biofuels, they remain plausible out to 2050 based on the properties of the feedstock categories, and they allow the reader to create their own calculations through multipliers of the percentage.

Table 4: Feedstock modelling assumptions

<table>
<tr><th></th><th colspan="2">GROWTH RATE</th><th colspan="2">YIELD</th><th colspan="2">FEEDSTOCK ALLOCATION</th></tr>
<tr><td>Scenario</td><td>Low</td><td>High</td><td>Low</td><td>High</td><td>Low</td><td>High</td></tr>
<tr><td>Sugar, sorghum</td><td rowspan="7">0.5%</td><td rowspan="7">2%</td><td>20%</td><td rowspan="3">60%</td><td rowspan="2">5%</td><td rowspan="2">10%</td></tr>
<tr><td>Oilseeds</td><td rowspan="2">30%</td></tr>
<tr><td>Tallow</td><td rowspan="5">20%</td><td rowspan="5">40%</td></tr>
<tr><td>Municipal solid waste</td><td rowspan="4">5%</td><td>10%</td></tr>
<tr><td>Agricultural residues</td><td rowspan="3">15%</td></tr>
<tr><td>Sawmill residues</td></tr>
<tr><td>Bagasse</td></tr>
<tr><td>Hydrogen</td><td colspan="2">Exponential</td><td>25%</td><td>80%</td><td>12.5%</td><td>25%</td></tr>
</table>

Two scenarios were devised for parameters 2-4 that lead to low and high effects on variables. These parameters are assumptions based on literature review and stakeholder consultations of what could be achieved.

VARIABLE	LOW SCENARIO	HIGH SCENARIO
Feedstock production rates	Increased climate variability and slow adoption of sustainable farming practices leads to poor yield and little productivity improvements. Hydrogen economy and Direct Air Capture (DAC) scale does not eventuate in line with optimistic scenarios. Lack of supportive policy does not incentivise feedstock collection and production.	New technology adoption such as new plant strains, improved farm management, better waste collection or sorting allows for improved production rates and counters the effects of a changing climate. Hydrogen economy is supported by large-scale renewables and collaborative action on distribution.
Yield at biorefineries	High demand from road transport due to willingness to pay and lower premiums drives demand for renewable diesel, leading biorefineries to deprioritise SAF.	Pooled demand from several stakeholders and clear offtake commitments for SAF leads biorefineries to prioritise SAF yields.
Feedstock allocation	High competition for other uses such as food, recycling, bioenergy, animal feed restricts allocation of feedstocks to SAF production. High international activity continues trend of feedstocks being exported, leaving little available for domestic use.	Economic incentive encourages feedstock producers to sell their product to local SAF producers in large numbers.

A more detailed methodology can be found in the Technical Appendix.

To understand how SAF production relates to Australia's jet fuel demand over time, projections of Australian total jet fuel demand from 2025–2050 were obtained from CSIRO's transport demand model which considers a range of economic, infrastructure and policy drivers over time.[73] These projections were used to calculate the percentage of fuel demand that potential SAF production represents, allowing comparison across feedstocks and across time.

73 CSIRO (2022) Electric vehicle projections 2022. https://publications.csiro.au/publications/publication/PIcsiro:EP2023-0235
See Section 2.1.4 for description of how the model is constructed. See Section 3 for a definition of the Step Change scenario underpinning the jet fuel demand projections used. A ratio of 34.7 MJ/L of jet fuel is used.

Technoeconomic modelling

The report utilises technoeconomic modelling to understand and communicate the key cost drivers by calculating the levelised cost of production (LCOP) for SAF using different feedstocks and pathways.

LCOP describes the average cost of producing a unit of fuel over the lifetime of a production process, considering all costs associated with producing the product, as well as the expected production volume. The calculation considers the initial capital costs of the production process, the ongoing operating and maintenance costs, and the expected lifetime of the process. Additionally, the cost of raw materials, labour, energy, and any other inputs required for the production process are factored in. Potential profit margins were not examined.

Although LCOP can inform analysis of cost drivers and allow a comparison across pathways, LCOP calculations and their real-world applicability is limited by available data, assumptions, and the need to account for numerous products. In this case, each product of the biorefining process, such as diesel and naphtha, must be assigned the same value as the SAF produced, which is not reflective of market pricing at refineries.

Technologies assessed as mature inform the 'Today' scenario. The '2050' scenario considers projects currently in development and projections for feedstock costs and improvements in technology capacity in the medium term. Scale also informs these scenarios, with 'Today' scenarios at a small scale of 50 ML of SAF produced per year, and '2050' scenarios producing a large scale of 300 ML of SAF per year.

A large-scale plant producing 300 ML would fulfill approximately 3% of Australia's jet fuel demand today. Although a small portion of Australia's overall fuel consumption, it is still a sizeable contribution to liquid fuel security, especially when considering the Department of Defence's usage. As of 2016-2017, Defence had an annual fuel consumption of 423 ML, 70% of which was used by the Air Force (296 ML).

3.1 Carbohydrates

Potential carbohydrates for SAF in Australia include sugarcane, sorghum and maize. Maize was excluded from further analysis due to limited production intended for domestic consumption.

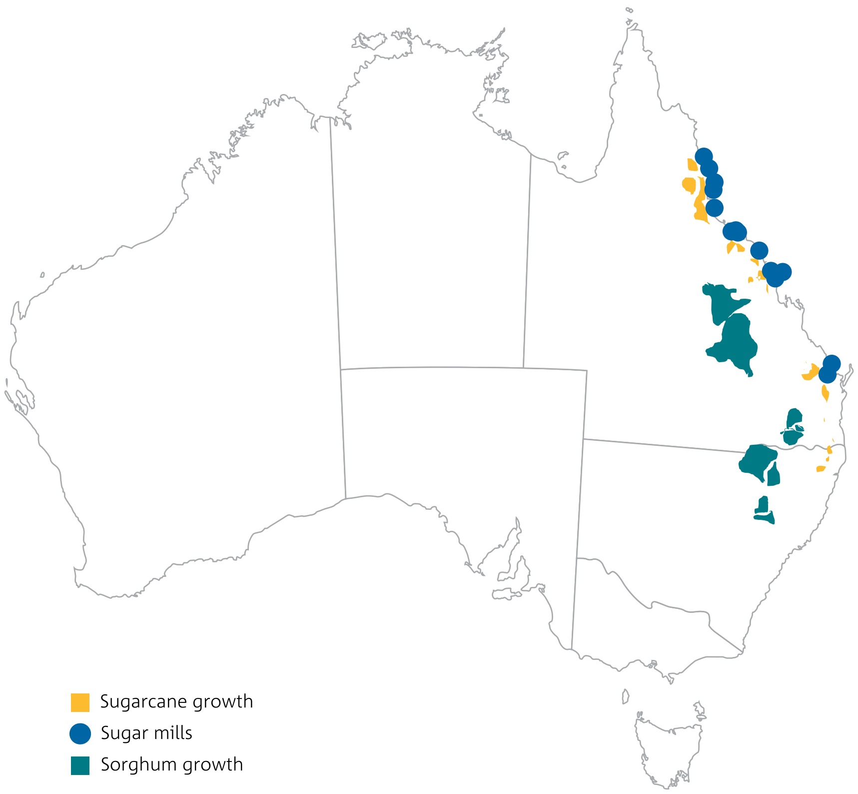
Sorghum is the largest summer crop grown in Australia and is typically exported to produce alcohol or used as animal feed locally. It is predominantly grown in the northern cropping belt of eastern Australia.[74]

The sugarcane industry in Queensland is firmly established, with a mature supply chain for sugar production which is predominantly exported. By-products such as bagasse are separated from the cane at sugar mills and used onsite to generate heat and steam.

While Australia currently produces ethanol from molasses and wheat starch, there are additional potential feedstocks such as sugar, sorghum, and bagasse that can be utilised for ethanol production through fermentation, followed by the Alcohol-to-Jet (ATJ) process. Alternatively, bagasse can undergo thermochemical processing, such as gasification, and subsequently be processed via Fischer Tropsch (FT). Although fermentation is already a commercial practice in Australia, the utilisation of ATJ and gasification for FT purposes has not been implemented. This report explores both opportunities in detail.

Queensland's sugarcane industry is well-informed of the potential to convert its products into biofuels and is primed to participate in a new market. Through a desire to diversify the industry's customer base and utilise more of the cane plant to maximise economic benefits, many previous studies have examined the opportunity. Most recently, Qantas and Airbus has announced a feasibility study examining the potential to turn bagasse into ethanol for the ATJ process.[75]

Figure 11. Carbohydrate production, aggregation and processing locations[76]



74 NSW Department of Primary Industries (2005) Grain Sorghum. <https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0006/146355/grain-sorghum.pdf> (accessed 17 May 2023).

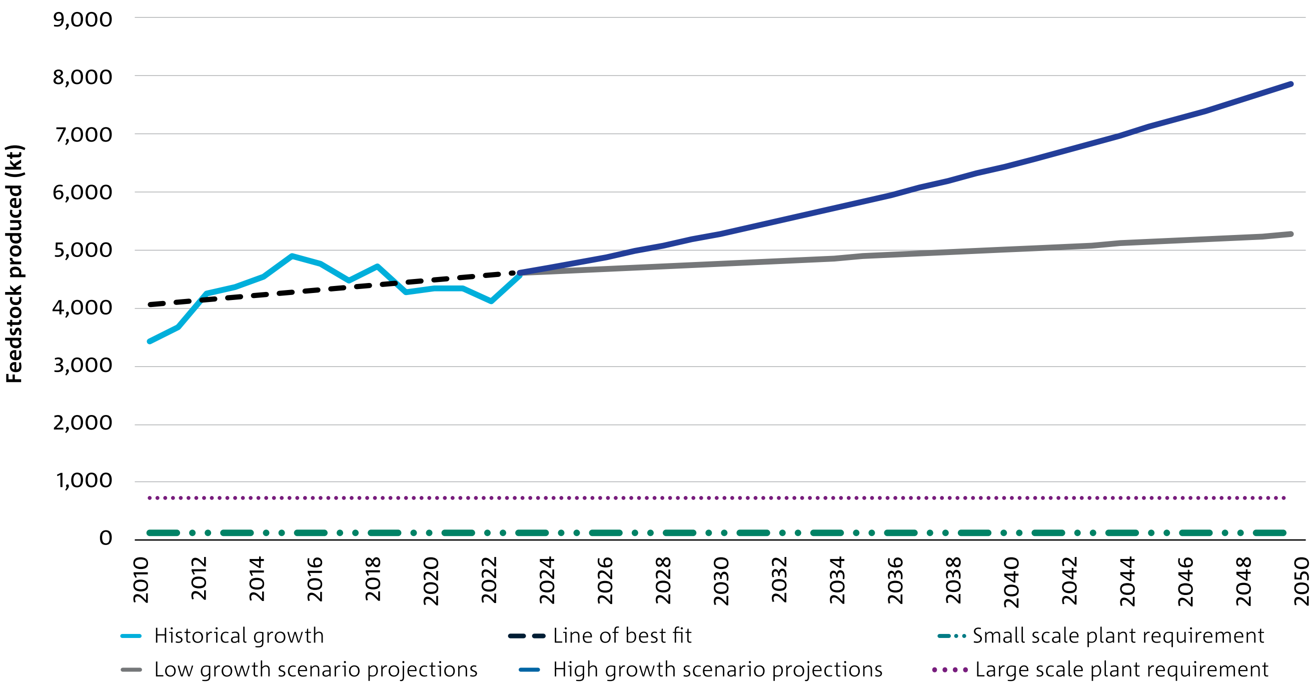
75 Qantas (2023) Queensland biofuel refinery to turn agricultural by-products into sustainable aviation fuel. <https://www.qantasnewsroom.com.au/media-releases/queensland-biofuel-refinery-to-turn-agricultural-by-products-into-sustainable-aviation-fuel/> (accessed 20 April 2023).

76 Sustainable sugarcane farms (2021) Canegrowers. <https://www.canegrowers.com.au/icms_docs/327030_canegrowers---sustainable-sugarcane-farms-july-2021.pdf> (accessed 12 February 2022); Raw Sugar Industry Overview (2013) Australian Sugar Milling Council <https://asmc.com.au/policy-advocacy/sugar-industry-overview/> (accessed 12 February 2022); Australian Grain Production (2021) Australian Export Grains Innovation Centre <https://www.aegic.org.au/australian-grain-production-a-snapshot/> (accessed 12 February 2022); Australia 2020/21 sorghum production rebounds (2021) United States Department of Agriculture <https://ipad.fas.usda.gov/highlights/2021/06/Australia/index.pdf> (accessed 3 March 2022).

Assuming a maximised SAF yield, a small-scale ATJ plant capable of producing 50 ML per year would require 3% of Australia's projected raw sugar production in 2025. A large-scale plant producing 300 ML, would require 15-16% of raw sugar production in 2025. These amounts are substantially lower than the volume of raw sugar that Australia currently exports, approximately 3.6 Mt annually.[77]

If ATJ is to be effectively scaled, Australia would need to increase ethanol production significantly. Maximising output at current ethanol plants, re-opening the Dalby refinery and exploring options for new centralised and distributed ethanol plants will be necessary.

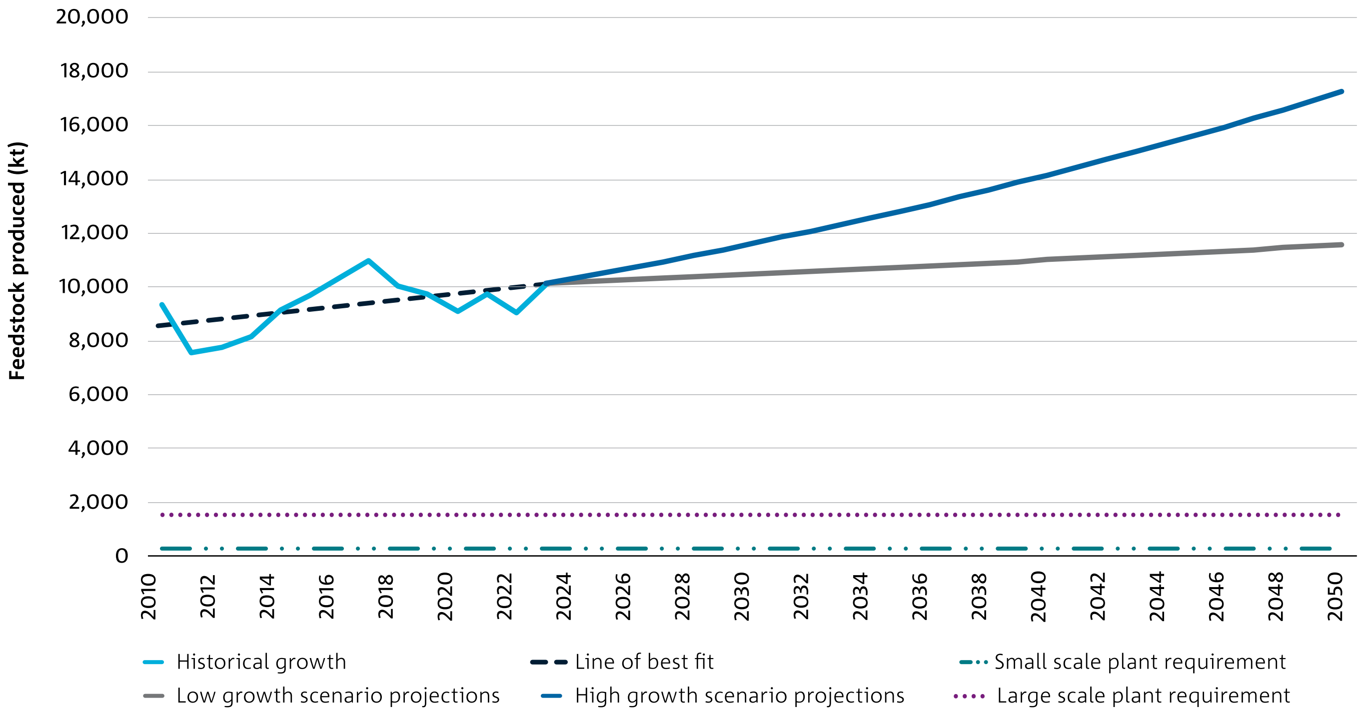
Figure 12. Australian raw sugar growth projections and ATJ feedstock requirements based on plant size



77 Parliament of Australia (2015) Current and future arrangements for the marketing of Australian sugar. Parliament of Australia, Canberra.

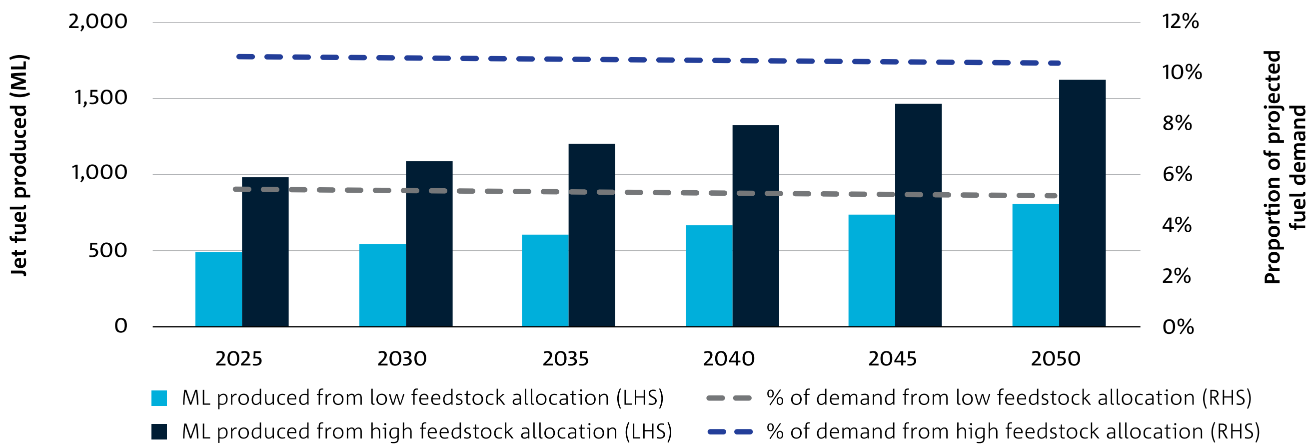
The report also examined the potential of using gasification and FT to process bagasse into SAF. A small-scale FT plant, capable of producing 50 ML of SAF per would require 3% of Australia's projected bagasse in 2025. A large-scale plant producing 300 ML per year would require 15-16% of bagasse production in 2025.

Figure 13. Australian bagasse growth projections and FT feedstock requirements based on plant size



Sugarcane (sugar and bagasse) and sorghum could supply increasing portions of Australia's fuel demand over time. As per figure 14 below, utilising 10% of projected sugar and 40% of bagasse production through to 2050 could produce enough SAF to meet 10% of the fuel demand.

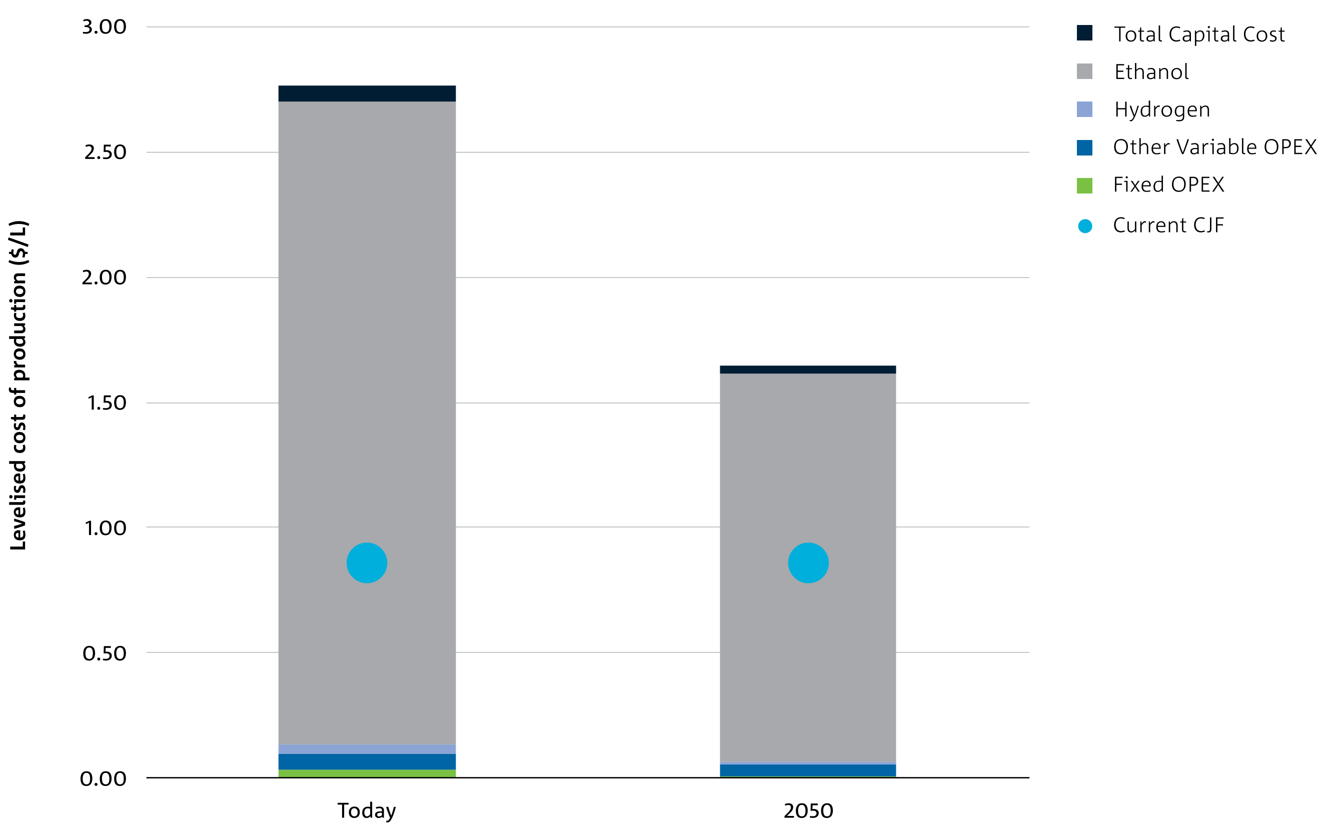
Figure 14. Potential SAF production from Australian sugar, bagasse and sorghum and contribution toward domestic fuel demand



ATJ is currently one of the higher cost methods to produce SAF due to a lack of commercial plants and the price of ethanol, which is the primary cost driver. A reduction in the price of ethanol is dependent on significant production costs reductions through advances in second generation fermentation solutions, thereby detaching the ethanol industry from food and sugar prices. To a lesser degree, decreased demand from road applications with improved electric vehicles uptake is assumed to also put downwards pressure on the cost of ethanol. If ethanol cost reductions fail to materialise, the levelised cost of production could plateau.

A key challenge to realising the full potential of bagasse is increasing its density to allow for economic transport to a centralised location by implementing a distributed technology such as onsite or nearby ethanol or other intermediate production. In parallel, displacement of bagasse will require the installation of replacement onsite energy production or installing more efficient heat and steam generators. Further feasibility studies are recommended to examine the technoeconomics of distributed solutions such as advanced fermentation and hydrothermal liquefaction.

Figure 15. Levelised production cost of jet fuel today and in 2050 – ATJ using ethanol



The use of sugarcane for ethanol production could face challenges due to its competing use as an additive to food. However, there is precedent for allocating more sugarcane for ethanol production, such as in Brazil where 55% of sugarcane revenue is from ethanol, compared to 3% in Australia. In Australia, the primary revenue for sugar millers is from raw sugar production.[78] By selling to SAF producers, the sugarcane industry can disconnect production from fluctuating international sugar prices.

Further challenges may be faced in navigating the strained relationship between sugarcane growers and millers. The Review into Sugar Code of Conduct in 2018 noted that "although the industry is working together on a number of challenges. Growers and millers may not reach agreement on commercial terms without regulatory support".[79] Working to ensure commercial outcomes are amenable to both parties will be needed to position sugarcane for a new industry.

The Australian sugarcane industry has improved the sustainability of sugarcane production in recent years by implementing initiatives focused on reducing water, fertiliser and pesticide use, enhancing biodiversity and crop resilience. This is supported by voluntary and incentivised practice change, new information and regulatory controls. Though the industry is improving, there is more work to be done to meet community and government expectations, particularly around managing downstream impacts. A key component is the water runoff, and pollutants within the runoff, affecting the water quality of the Great Barrier Reef. Concerns exist, that any physical expansion of the industry (in terms of production area) would risk the progress made toward water quality targets.

The opportunity for Queensland to produce SAF from sugar and bagasse is significant. Established supply chains, willing feedstock producers and mature technology options make ATJ an attractive option for SAF production in the immediate to medium term if sugar and bagasse can be liberated from current bioenergy uses at mills and upgraded to an intermediate product and transported economically.

What next

IMMEDIATE TERM (2023-2025)	MEDIUM TERM (2025-2035)
• Investment into sugar mill infrastructure to liberate bagasse from energy production. • Plan for increase of capacity at existing ethanol plants. • Examine opportunities for co-generation of ethanol and sugar at mills. • Examine feasibility for modular biorefineries to be located at mills, with excess heat and steam used to displace inefficient boilers.	• Begin breeding programs for energy canes to increase available plant biomass. • Re-open Dalby Refinery to maximise local ethanol production. • Utilisation of biotechnology such as genetic engineering to increase crop biomass yield, improve crop abiotic and biotic stress tolerance, and enhance sucrose accumulation.[80]

78 Industry consultations.

79 Department of Agriculture, Water and the Environment (2017) Post-implementation review: Competition and Consumer (Industry Code—Sugar) Regulations.

80 Kumar A, Tiwari V, Singh P, Bishi SK, Gupta CK, Mishra GP (2020) Advances and challenges in sugarcane biofuel development. Biotechnology for Biofuels: A Sustainable Green Energy Solution, 267-288.

3.2 Waste

Waste feedstocks include used cooking oil (UCO), tallow and municipal solid waste (MSW).

UCO and tallow

UCO is collected from commercial operations and brought to a central location and largely exported. According to industry stakeholder consultations, Australia produces approximately 100 kt of UCO annually, enough to produce 75 ML of SAF. Given this limited supply, local use for SAF production is a limited opportunity.

Tallow is a by-product of animal processing which is collected from abattoirs and brought to rendering plants before being exported to be upgraded into biofuels. After rendering, UCO and tallow can be converted to SAF via the HEFA pathway. These feedstocks provide a near-term opportunity to supply planned plants in Perth and Gladstone.

Assuming a maximised SAF yield a small-scale HEFA plant, capable of producing 50 ML of SAF per year, would require 15% of Australia's projected tallow production in 2025. A large-scale plant producing 300 ML of SAF per year would require 86–90% of Australia's projected tallow production in 2025.

MSW

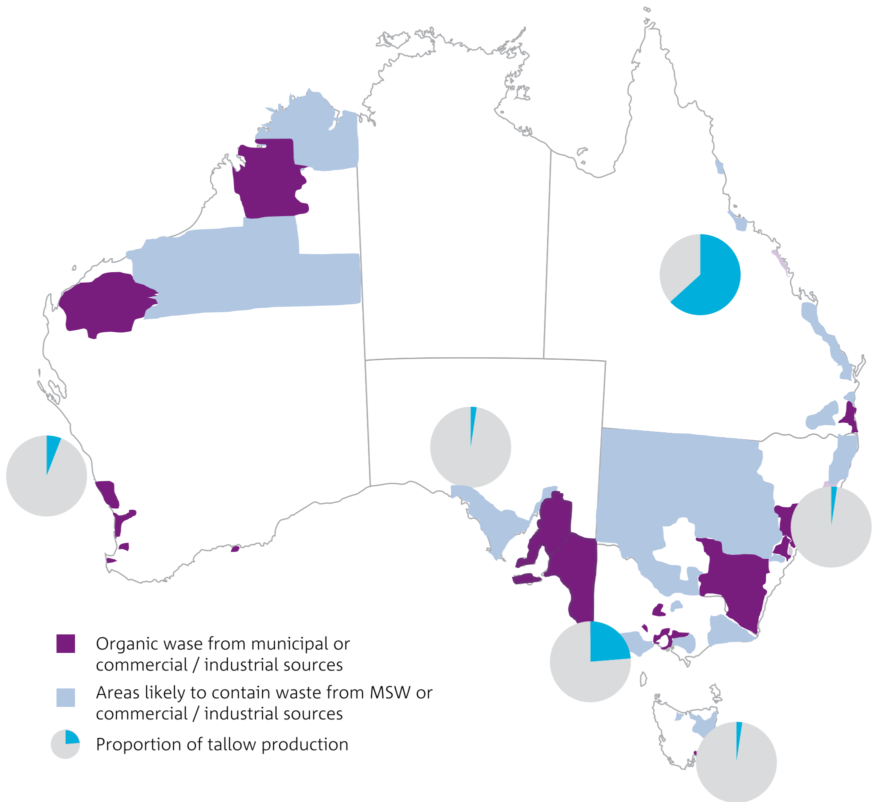
MSW is generated by households and other non-industrial activities in urban areas which is collected and aggregated at waste processing facilities utilising a mature supply chain. MSW can be upgraded to SAF through gasification and FT or via fuel intermediates like ethanol or pyrolysis oil. No such plants to upgrade MSW to SAF currently exist in Australia.

Assuming a maximised SAF yield, a small-scale FT plant, capable of producing 50 ML of SAF per would require 3% of Australia's projected MSW in 2025. A large-scale plant producing 300 ML per year would require 17–18% of collected MSW production in 2025.

Tallow and MSW could supply increasing quantities of jet fuel over time. Utilising 20% of these wastes through to 2050 could produce 5% of fuel demand, whereas utilising 40% of projected available wastes could produce 9% of fuel demand.

Tallow is limited and highly sought after by international SAF producers, restricting its potential as a sole feedstock. Instead, it is likely to be used in conjunction with other fats and oils as part of a portfolio of feedstocks.

Figure 16. Waste production, aggregation, and processing locations using local government areas[81]



81 NationalMap (2023) Geoscience Australia. <https://nationalmap.gov.au/renewables/> (accessed 12 February 2022); Tallow production estimates based on industry stakeholder consultations.

Figure 17. Australian tallow growth projections and HEFA feedstock requirements based on plant size

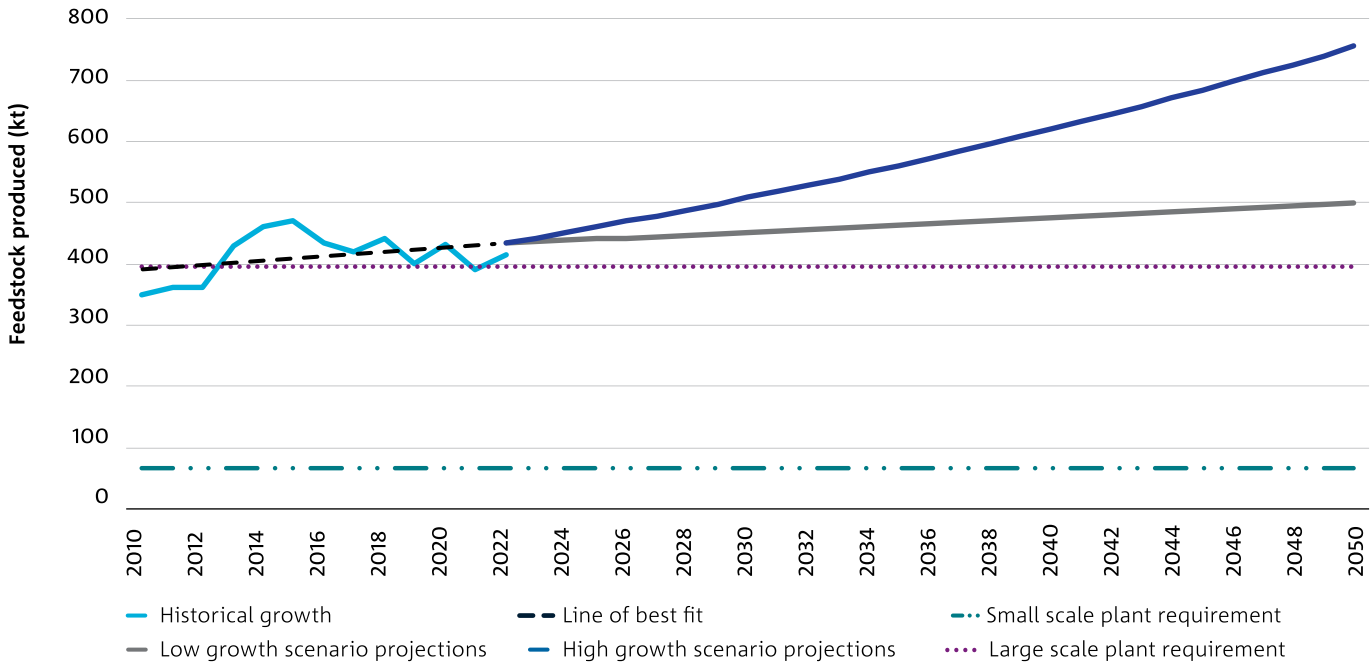


Figure 18. Australian MSW growth projections and FT feedstock requirements based on plant size

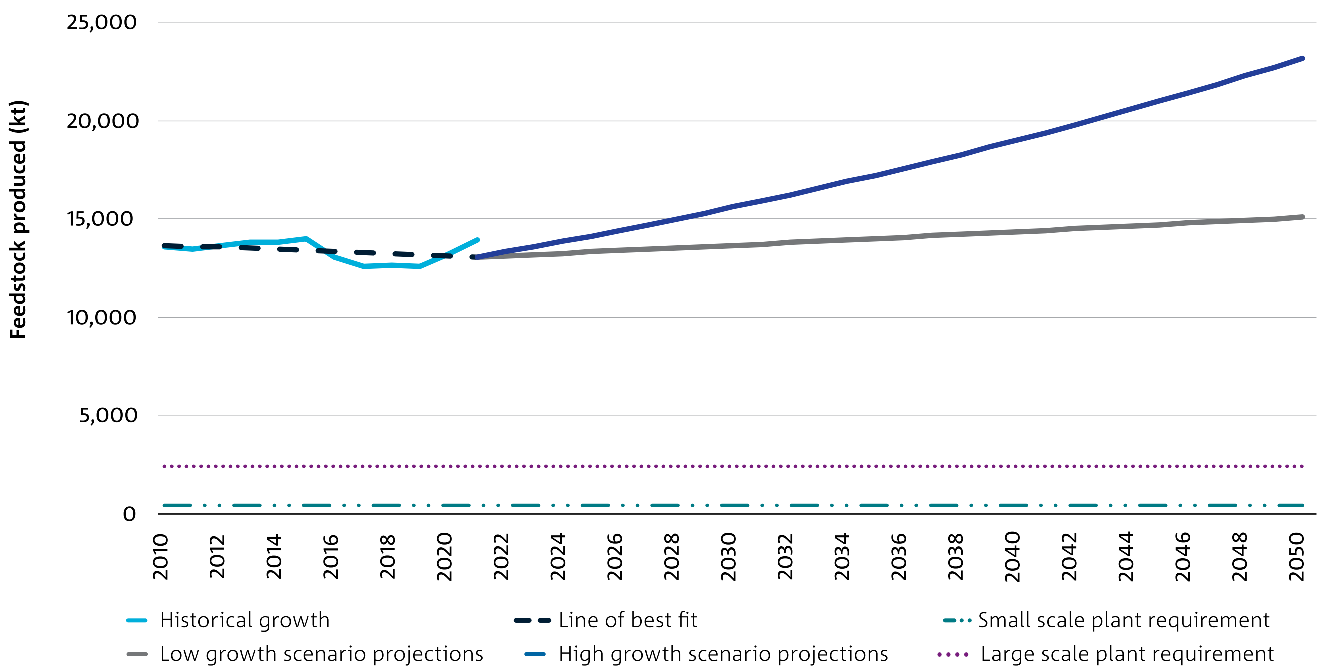
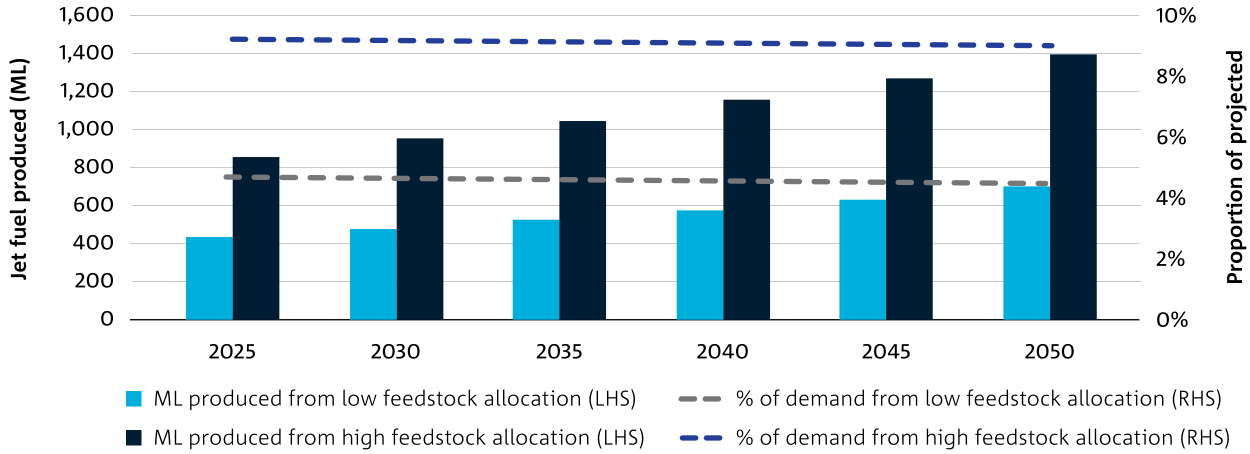


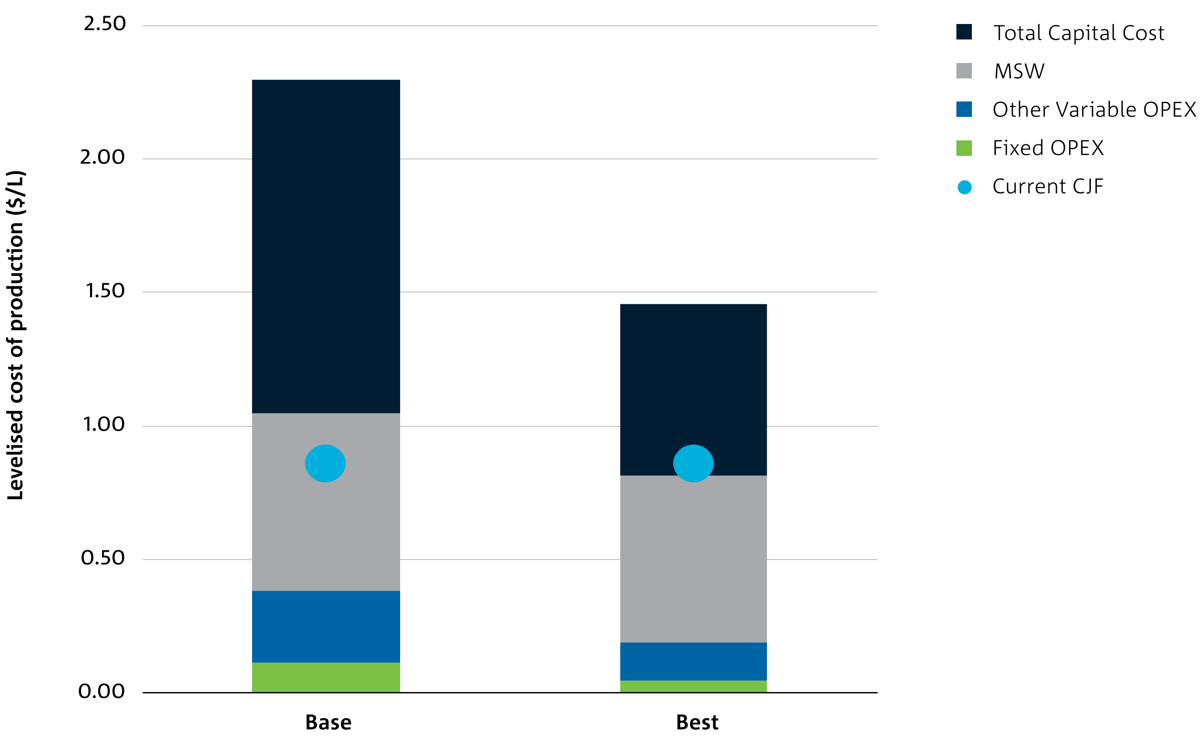
Figure 19. Potential SAF production from Australian tallow and MSW and contribution toward domestic fuel demand



As per most pathways, the cost of feedstock has a significant effect on the price of the SAF produced. When negotiating with councils, the cost of delivered MSW will be key to understanding the economic viability of fuel production. Feedstock costs are likely to differ depending on the plant size and collection model. The trade-off between aggregation and transport costs needed for a larger single facility, compared to smaller facilities with less transport needed is not captured in this model and will require deeper analysis for different use cases. Capital costs affect LCOP significantly, reflecting the capital-intensive nature of FT plants. This could be reduced with larger-scale plants.

The utilisation of MSW for conversion into SAF can provide a range of sustainability outcomes. As well as reducing the carbon intensity of the fuel by up to 94%, diverting MSW away from landfill can result in less harmful pollutants being released at landfills. This includes methane, a major GHG contributor, and other pollutants which can be released into nearby air and water.

Figure 20. Levelised production cost of jet fuel today and in 2050 – FT using MSW



Commercially, there may be issues with amalgamating waste products from several councils, all of whom may need to be negotiated with independently. These negotiations are likely to become more difficult as MSW shifts from being considered a waste to a sought-after product for bioenergy industries. Brisbane will provide the most straightforward MSW to SAF test bed, especially as a single local government area encompasses a significant portion of the metropolitan area with a population of approximately 1.2 million people.[82]

The heterogeneity of MSW can affect SAF yield and quality. The presence of fine contaminants for example can negatively affect the process and requires technologies to manage their emission. Additionally, as the make-up of MSW is likely to evolve over time as other uses are found, and waste management practices and legislation change, MSW consistency may impact processing requirements and create supply challenges. The use of feedstock hubs, where MSW is amalgamated with other waste and residue feedstocks can help to reduce the risk of supply interruptions.

Social impact challenges are likely, as can be seen in Australia's developing waste-to-energy sector. Public perceptions of the industry being dirty and harmful to the environment and public health, despite obtaining EPA approval and using proven technology, have delayed and led to the cancellation of some projects. Careful consideration of where these plants are located coupled with better community engagement on the sustainability benefits of MSW to SAF could help to overcome these issues.

Considering feedstock availability and co-benefits of processing MSW, it could support a number of SAF plants in Australia's major cities. The success of these plants will rely on ongoing access to supply, the economics of the process, council support and the social license to operate.

What next

IMMEDIATE TERM (2023-2025)	MEDIUM TERM (2025-2035)
• Secure MSW offtake agreements from councils. • Supply chain and facility design optimisation (e.g., capacity; co-location) to improve feedstock collection, pre-treatment, and waste recovery. • Demonstrate technologies to widen the acceptability of MSW compositions. • Calculate willingness to pay for local tallow supply given international incentives and explore domestic reservation policies as per natural gas industry.	• Implement biorefinery process improvements such as yield and cost optimisations.[83] • R&D to improve technologies and processes to manage contaminants from conversion of MSW to SAF.[84]

82 ABS (Australian Bureau of Statistics) (2021) 2021 Census. <https://abs.gov.au/census/find-census-data/quickstats/2021/LGA31000> (accessed 20 April 2023).

83 Meng F, Dornau A, Mason SJM, Thomas GH, Conradie A, McKechnie J (2021) Bioethanol from autoclaved municipal solid waste: Assessment of environmental and financial viability under policy contexts. Applied Energy 298. Manirethan V, Joy J, Varghese RT, Uddandarao P (2022) Municipal Solid Waste for Sustainable Production of Biofuels and Value-Added Products from Biorefinery. In Zero Waste Biorefinery. (Eds. YK Nandabalan, VK Garg, NK Labhsetwar, A Singh) 425-447. Springer, Singapore.

84 Lee SY, Sankaran R, Chew KW, Tan CH, Krishnamoorthy R, Chu D, Show P (2019) Waste to bioenergy: a review on the recent conversion technologies. BMC Energy 1, 4.

3.3 Residues

Residues is a term for biomass remains from agricultural and forestry practices. These include stalks, leaves, husks, or any other materials left over after crops are harvested, as well as wood chips, bark, branches and other parts of trees left over from harvest (also known as slash) or post-harvest. Residues are generally low-value products and are often left in the field to decompose, returning nutrients to the soil, or are burned. However, when managed sustainably, agricultural and sawmill residues can be an important source of renewable biomass for energy production or feedstock for SAF.

Forestry residues

The use of forestry harvest residues or slash as feedstock for other processes raises questions about its sustainability. Native forest harvest residues are unlikely to be considered an acceptable source of biomass due to their impact on biodiversity resulting from felling native forests. In contrast, the use of plantation forest harvest residues is more complex. The effects of removing these residues from plantations are challenging to quantify as they depend on many site-specific variables.

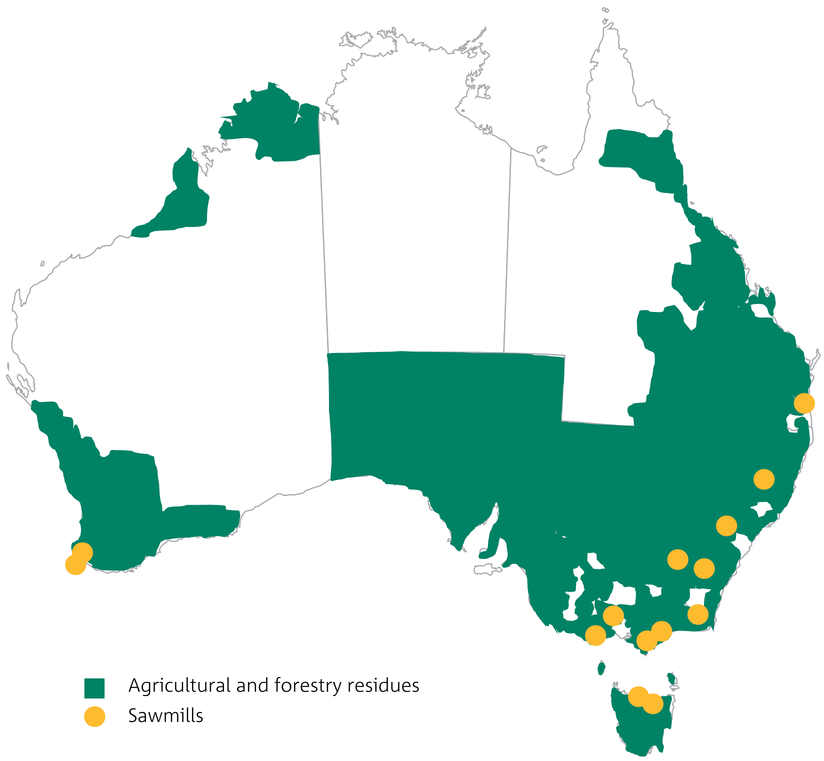
Leaving harvest residues in place offers several benefits, including improved carbon cycles and biodiversity. Additionally, reducing the demand for harvest residues could discourage the development of plantation forests for the purposes of new slash production, and instead, promote natural forestation. On the other hand, removing slash from plantations can reduce methane emissions, fire risk, and debris that can cause damage during storms.

By leveraging the prior research conducted by agencies like the Forest Industries Research Centre on processing, utilisation, harvest, and haulage, it is possible to enhance the assessment of the sustainability and suitability of forest residues to produce SAF.[85]

Crop residues

Crop residues are produced in massive quantities across Australian agriculture but lack collection and aggregation supply chains. Current uses include as animal feed and bioenergy. Oftentimes residues are burnt in the paddock to clear land for the next harvest. As a low-density feedstock, their collection and use are likely only to be economical in high-density farming areas to reduce the distance travelled or will need to rely on a distributed upgrading

Figure 21. Residue production, aggregation, and processing locations using local government areas[86]



85 University of the Sunshine Coast (n.d.) Forest Industries Research Centre. <https://www.usc.edu.au/research/forest-research-institute/forest-industries-research-centre> (accessed 17 May 2023)

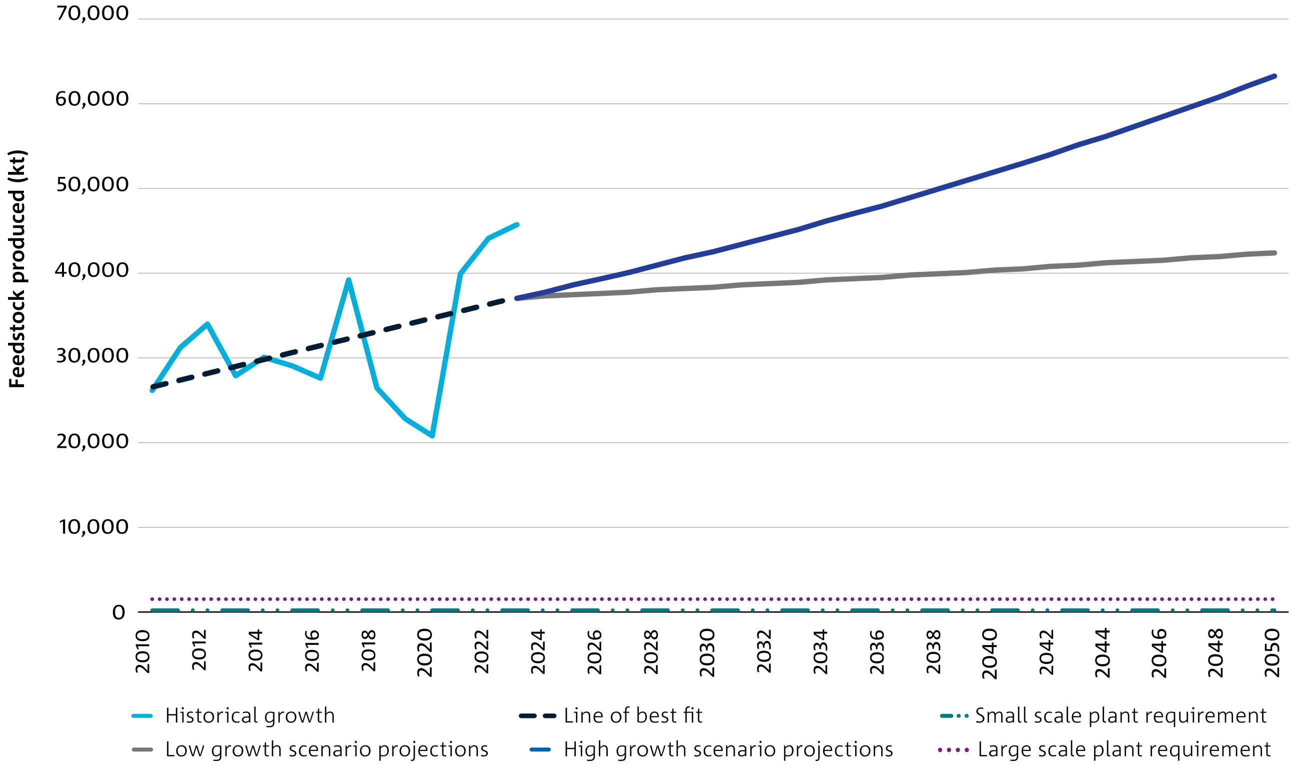
86 NationalMap (2023) Geoscience Australia <https://nationalmap.gov.au/renewables/> (accessed 12 February 2022); The Sawmill Database (2007) <https://www.sawmilldatabase.com/sawmills.php?countryid=32> (accessed 20 December 2022).

model to an intermediate, such as ethanol or bio-crude, which is then transported to a centralised fuel processing centre. Available crop residues are those considered to be in high-density farming areas and minus a portion left on field for soil erosion protection. Per Herr et. Al, 15% of total residues was considered unharvestable trash, and 1 t/ha in southern cropping regions and 1.5 t/ha in northern cropping regions was retained for soil erosion protection.[87]

Assuming a maximised SAF yield, a small-scale FT plant, capable of producing 50 ML of SAF per year would require 1% of Australia's projected 2025 available crop residues in high-density areas. A large-scale plant producing 300 ML per year would require 4% of available crop residues in 2025.

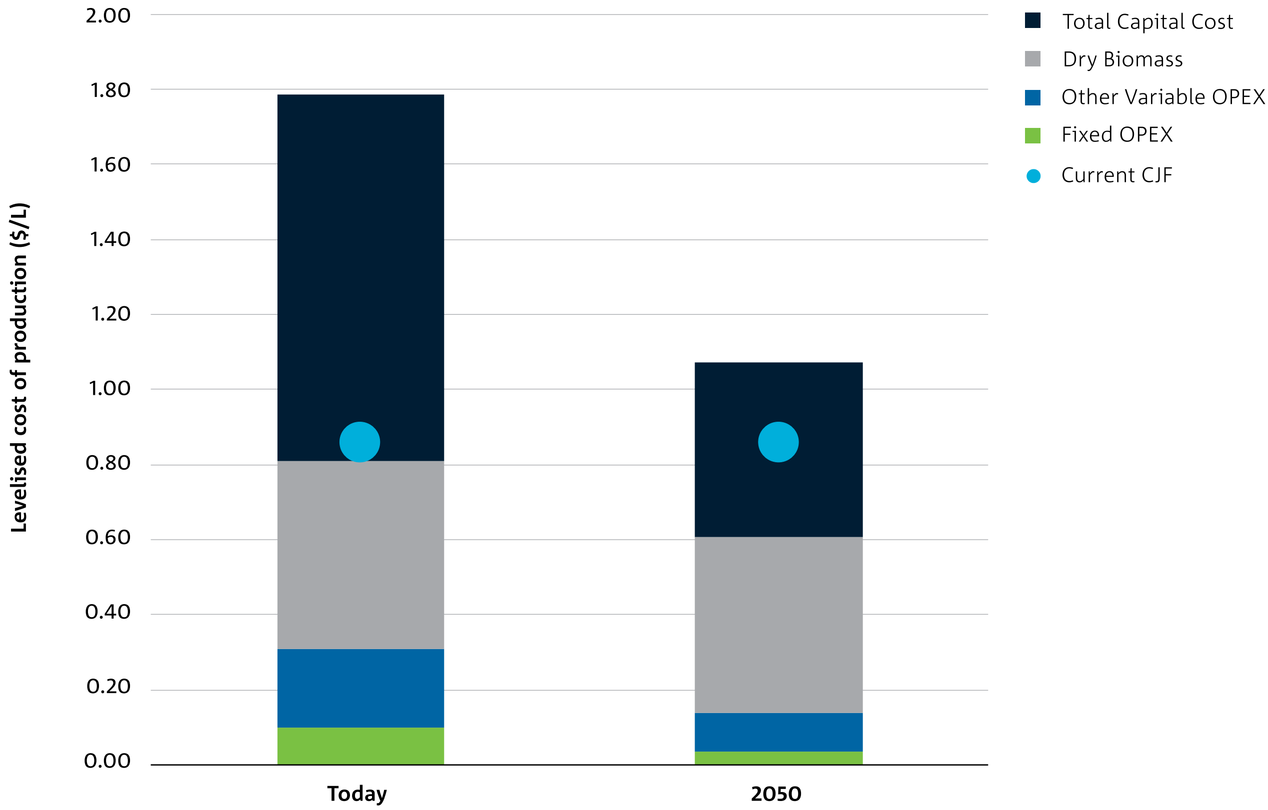
The two key cost drivers for converting crop residues into SAF via FT are capital costs and the cost of crop residues which is a function of collection and aggregation costs. Feedstock costs are likely to differ depending on the plant size and collection model. The trade-off between aggregation and transport costs needed for a larger single facility, compared to smaller facilities with less transport needed is not captured in this model and will require deeper analysis for different use cases. Capital costs of the FT plant component are assumed to decrease over time with larger-scale plants.

Figure 22. Australian crop residue growth projections and FT feedstock requirements based on plant size



87 Herr A, O'Connell D, Dunlop, M, Unkovich M, Poulton P and Poole M 2012, Second harvest – is there sufficient stubble for biofuel production in Australia? GCB Bioenergy, 4, 654–660. https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1757-1707.2012.01165.x

Figure 23. Levelised production cost of jet fuel today and in 2050 – FT using crop residues



Sawmill residues

Sawmill residues were also examined due to their partial aggregation at sawmills and lack of need in the forest ecosystem. Currently, sawmill residues are mostly exported as woodchips, but can also be used for onsite energy, other products or are left as waste.

Assuming a maximised SAF yield, a small-scale FT plant, capable of producing 50 ML of SAF per year would require 4% of Australia's projected sawmill residues in 2025. A large-scale plant producing 300 ML of SAF per year would require 24–25% of collected sawmill residues in 2025.

Residues could supply large quantities of jet fuel over time. As per figure 25, utilising 20% of crop and sawmill residues through to 2050 could produce 18% of fuel demand, whereas utilising 40% of projected available residues could produce 36–37% of fuel demand.

Beyond logistical challenges, a key consideration for crop residues is supply certainty, with climate variability significantly affecting crop residue availability from year to year. Stockpiling residues or co-locating with other biomass sources such as sawmill residues will help reduce biofuel plants' feedstock supply risk.

Figure 24. Australian sawmill residue growth projections and FT feedstock requirements based on plant size

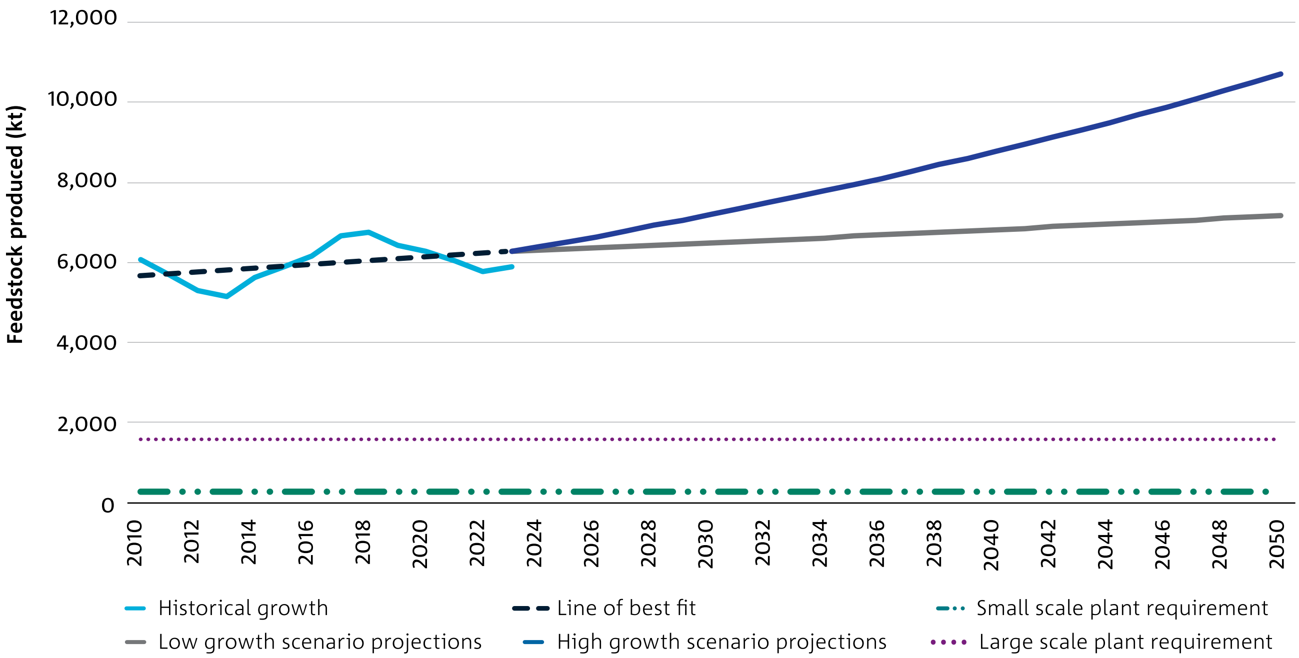
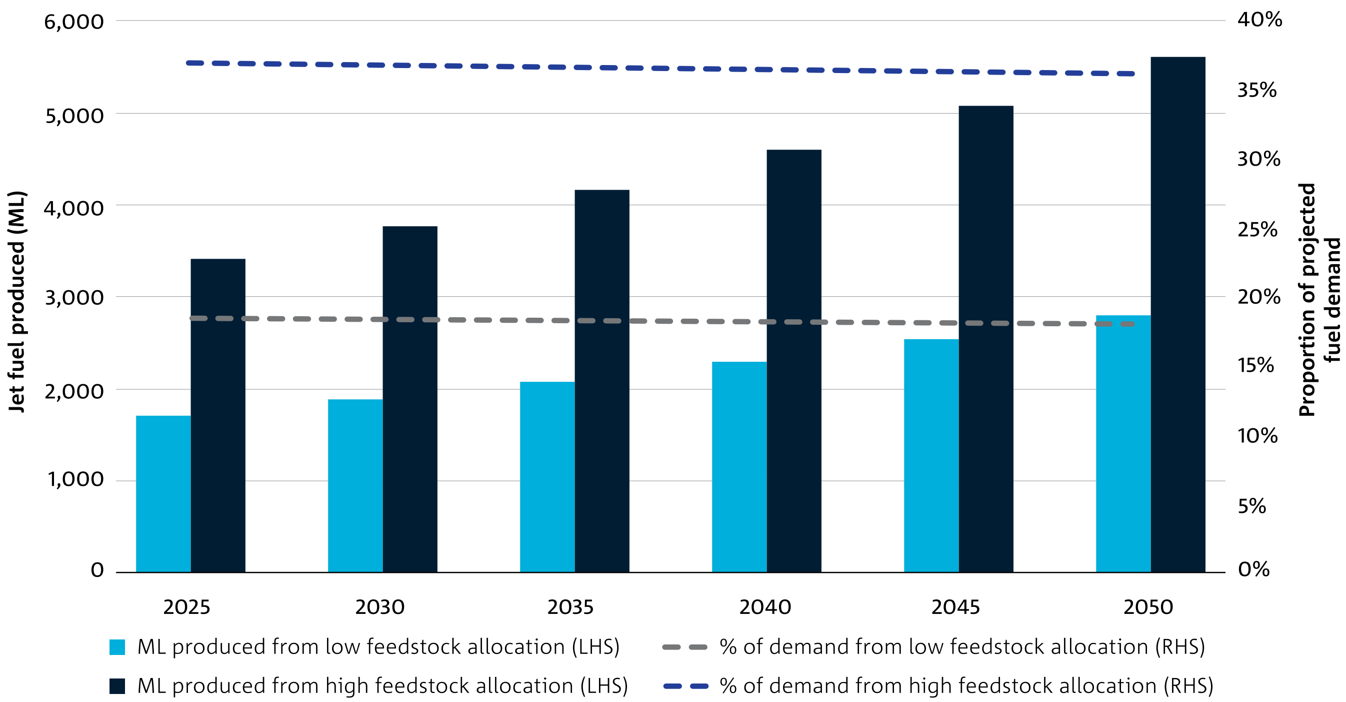


Figure 25. Potential SAF production from Australian crop and sawmill residues and contribution toward domestic fuel demand



Balancing the amount of crop residues left on the field is crucial for maintaining soil health and productivity. When left on field, crop residues can provide essential nutrients and organic matter to the soil, improve moisture retention, reduce erosion and control weed growth. However, too many residues left can pose problems for the sowing and emergence of the following crop, negatively affecting productivity. Current research recommends leaving between 30-50% of residues on the field to achieve the maximum benefits for the soil and crop growth.[88]

The longevity of sawmill residues as a feedstock will depend on overcoming potential social impact challenges and permitting policy. Logging of forests and plantations has historically been and continues to be a contentious issue. The use of sawmill residues could face public perception challenges being a by-product of the industry.

This is coupled with the potential for policy changes to overhaul the logging industry. Recent policy changes in Victoria aimed at halting native logging activity will have a direct impact on sawmill residue quantities in Victoria, and other jurisdictions may follow suit.

The opportunity for Australia to produce SAF from residues is significant, but much work needs to be done to economically collect, aggregate and upgrade them. To unlock this opportunity, more granular technoeconomics analysis is required to identify areas with high-density residues coupled with ideal supply chain analysis and technology analysis.

What next

IMMEDIATE TERM (2023-2025)	MEDIUM TERM (2025-2035)
• Conduct technoeconomic study on supply chain and technology configurations. • Engage agricultural centres with high-density residues to complete collection, aggregation, and upgrading trials. • Plan the location of the first large-scale SAF plant. • Invest in low TRL technologies capable of processing feedstock into energy dense intermediate.	• Build large-scale SAF plant using residue inputs. • Continue studies on the effects of crop residue removal on yield and soil health. • Explore cogeneration options for plants processing residues.[89] • Replicate supply chain, technology and business model informed from previous pilots.

88 Mirzaei M, Anari MG, Razavy-Toosi E, Asadi H, Moghiseh E, Saronjic N, Rodrigo-Comino J (2021) Preliminary effects of crop residue management on soil quality and crop production under different soil management regimes in corn-wheat rotation systems. Agronomy 11(2), 302; USDA (2006) Crop Residue Removal for Biomass Energy Production: Effects on Soils and Recommendations. Soil Quality National Technology Development Team.

89 Dudziec P, Stachowicz P, Stolarski MJ (2023) Diversity of properties of sawmill residues used as feedstock for energy generation. Renewable Energy 202, 822-833.

3.4 Oilseeds

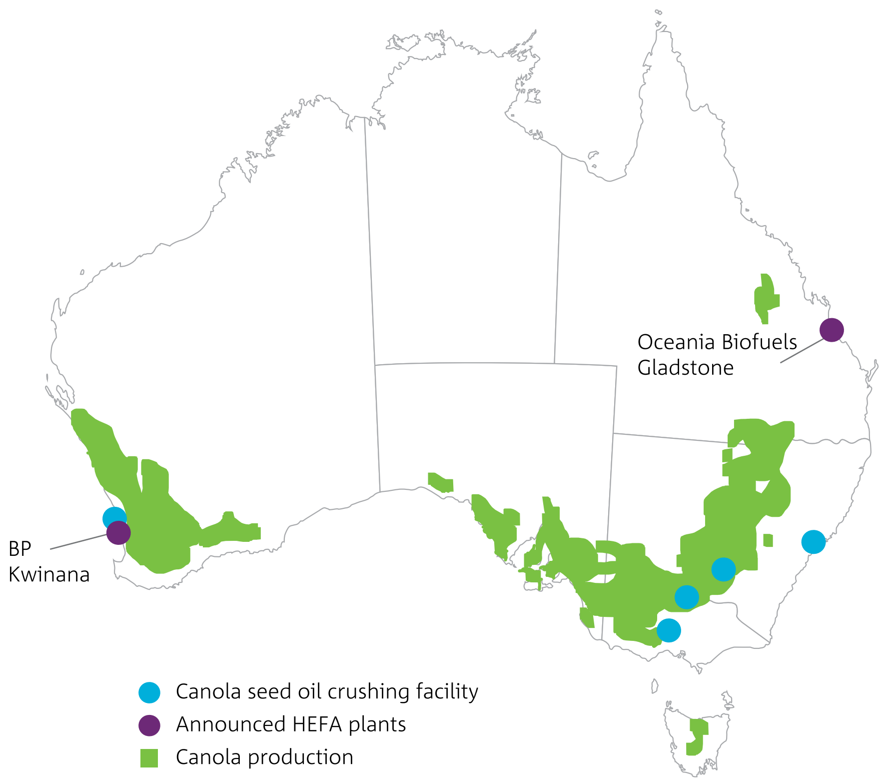
The cultivation of oilseeds is well-established, with their production, collection, and processing relying on mature technologies and supply chains that are widely used across Australia. Canola and cottonseed constitute 90% of Australia's total oilseed production. Oilseeds are upgraded via the HEFA pathway, which is commercially mature and the most common method globally for producing SAF, though no operational plants currently exist in Australia.

BP and Oceania Biofuels have announced plans to open HEFA plants in Perth and Brisbane respectively, with imported UCO as the primary input. As UCO is highly sought after for SAF production, Australia's oilseeds could be used as a supplementary feedstock in the case that producers face difficulties accessing supply or are faced with high feedstock prices in the medium to long term.

Australia could open additional HEFA plants by purchasing virgin vegetable oil destined for export. Assuming a maximised SAF yield, a small-scale plant, capable of producing 50 ML of SAF per year would require 3% of Australia's projected canola seed production in 2025 (0.2 Mt). A large-scale plant producing 300 ML per year would require 17% of canola seed production in 2025 (0.9 Mt). These amounts are lower than the volume of canola oilseeds that Australia exported to Europe's biodiesel market in 2016 (1.7 Mt).[90]

To meet a new demand for canola or seed oil, seed crushing capability would need to be increased as Australia's current capacity is only enough to meet the domestic demand for vegetable oil. It should also be noted that if oilseed production were to be significantly increased beyond historical peaks, it would likely be at the substitution of other crops or grazing land.

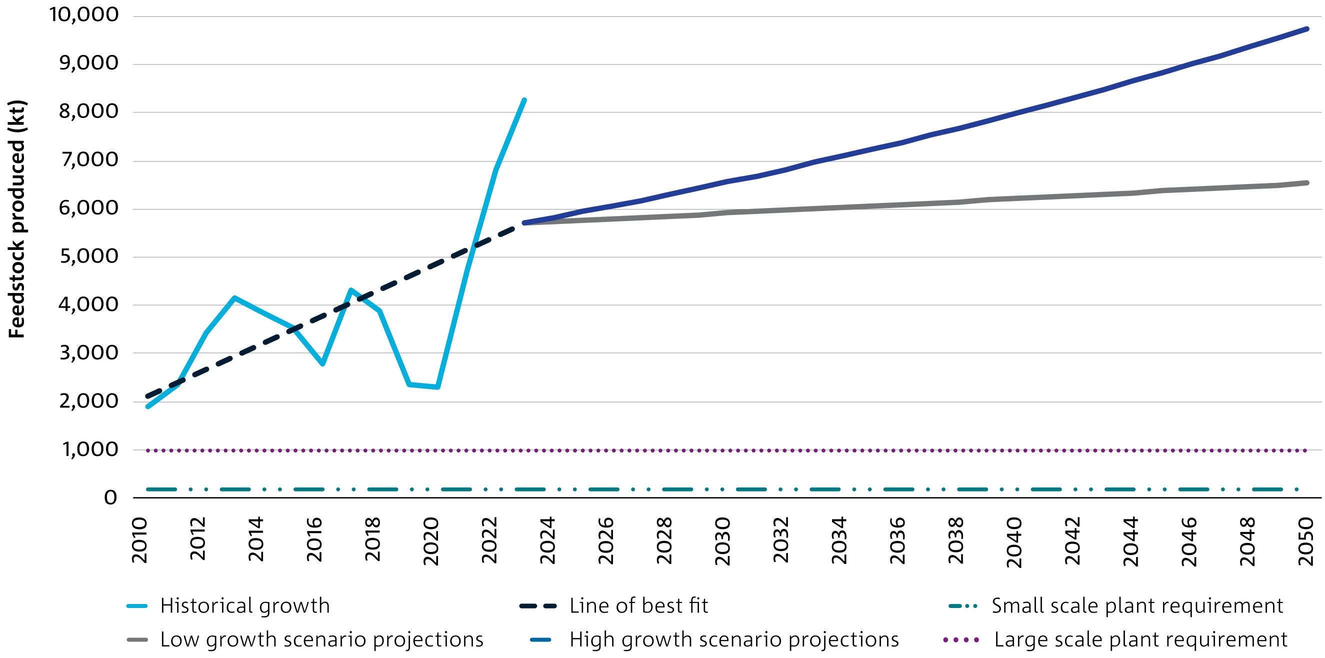
Figure 26. Oilseed production, aggregation and processing locations[91]



90 CSIRO (2019) Maintaining access to EU markets to Australian canola. CSIRO

91 Australian canola (2021) Australian Export Grains Innovation Centre <https://www.aegic.org.au/australian-grains/canola/> (accessed 5 November 2022); Cargill to upgrade three Australian crushing plants (2023) Grain Central <https://www.graincentral.com/news/cargill-to-upgrade-three-australian-crushing-plants/> (accessed 19 May 2023); bp plans for biorefinery at Kwinana energy hub reach new milestone (2023) <https://www.bp.com/en_au/australia/home/media/press-releases/biorefinery-plans-new-milestone.html> (accessed 19 May 2023); Oceania Biofuels (2022) <https://oceaniabiofuels.com.au/port-of-gladstone/> (accessed 12 January 2023).

Figure 27. Australian canola oilseed growth projections and HEFA feedstock requirements based on plant size



Canola and cottonseed could supply a small portion of Australia's fuel demand over time. As per figure 28 below, utilising 10% of projected oilseed production through to 2050 could produce enough SAF to meet approximately 2% of the fuel demand.

HEFA is currently one of the lowest cost methods to produce SAF. The primary cost driver is the price of feedstock which is unlikely to decrease over time as demand from food and biofuel users increases, significantly affecting the likelihood of canola oil being a long-term feedstock solution. Given its demand in the food industry, this places a proxy lower limit on how much canola prices can be reduced by. Improvements in the levelised cost of production will be the result of lower cost hydrogen input and overall capital expenditures improvements.

Figure 28. Potential SAF production from Australian oilseeds and contribution toward domestic fuel demand

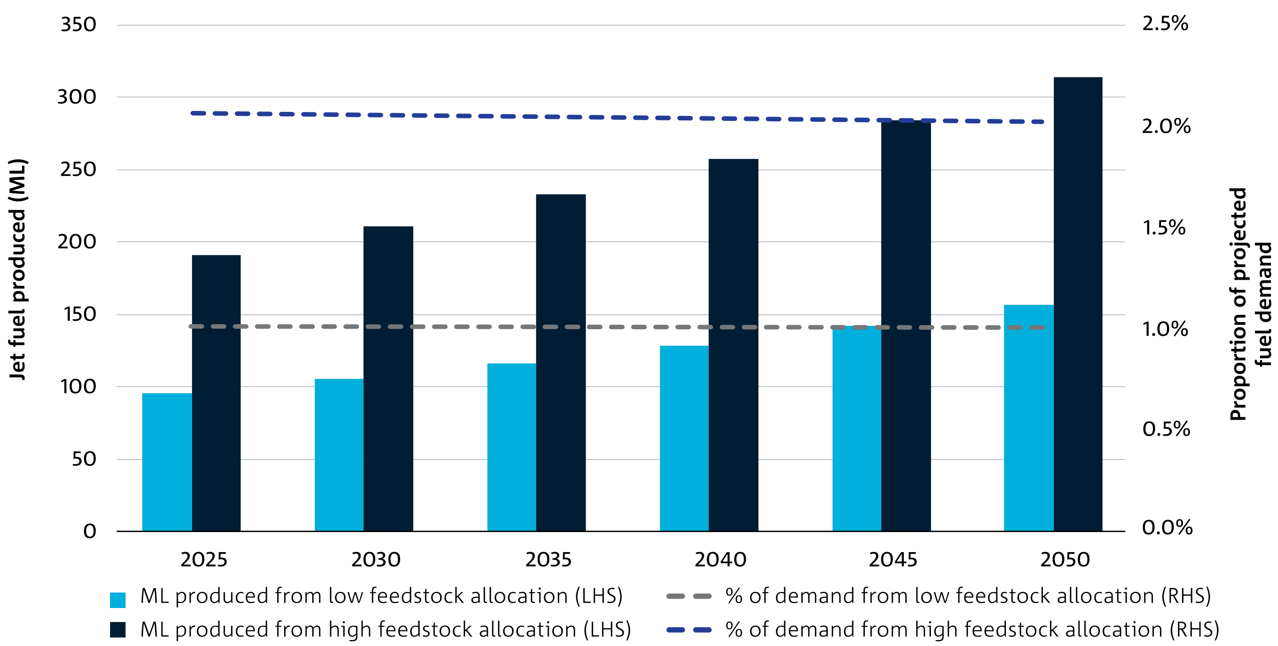
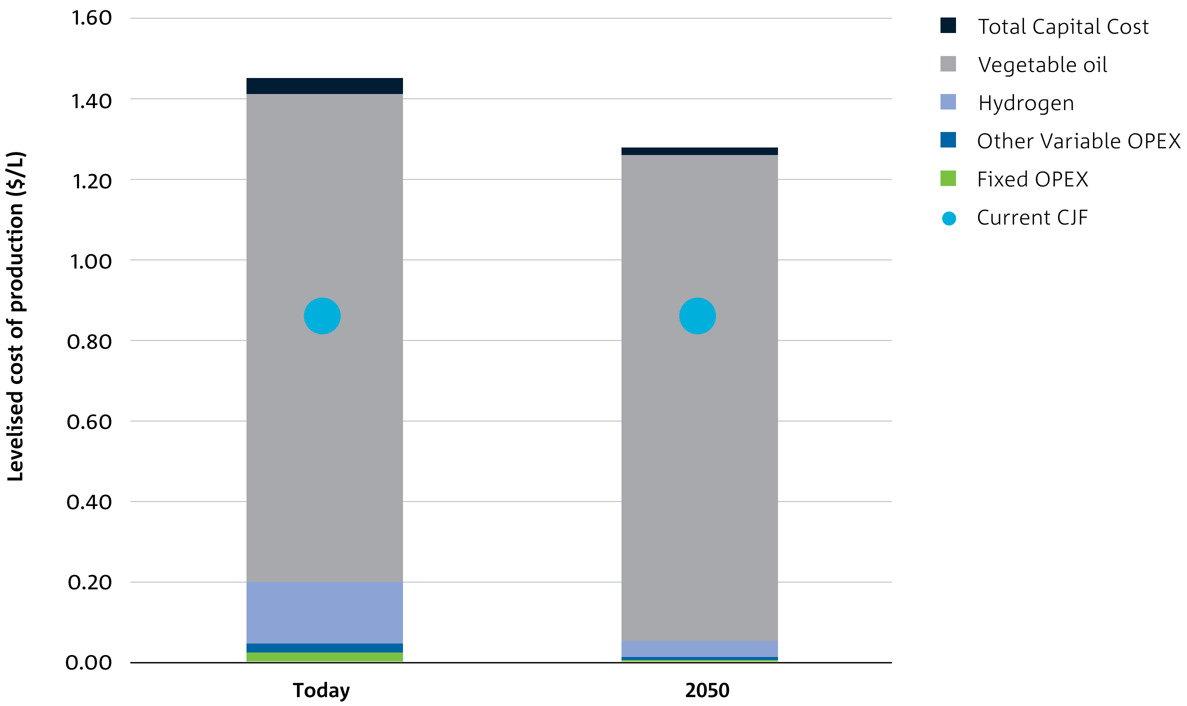


Figure 29. Base and best case levelised production cost of jet fuel – HEFA using vegetable oil



The biggest challenge with the adoption of oilseeds for SAF production is their competing use as food. Due to the constrained global supply of oilseeds, increased prices and food security concerns in some developing nations have reignited the debate on whether the priority for crops should be for human consumption over biofuel production. As a result of this, oilseed feedstocks for EU biofuels are already capped at 7% in relation to renewable energy targets. Furthermore, recently passed ReFuelEU regulations stipulate that from 2025 onwards, food and feed crops will be excluded from counting towards the mandate.[92] Any future use of oilseeds for SAF will depend entirely upon voluntary demand above the ReFuelEU targets. It is understood that virgin vegetable oils are not preferred feedstocks among aviation customers and since it is a global business, standards from the EU are likely to be incorporated in some form of international compliance.

From a sustainability perspective, there are also concerns that edible oilseeds such as canola do not significantly reduce the carbon intensity of SAF. This is largely due to attributed emissions from induced land use change when additional land is converted or subjected to intense cropping either from the feedstock itself, or other feedstocks that must compensate for the increased demand from displaced food crops. Though it is well established that Australian canola is relatively less carbon intensive than global competitors, clear standards on acceptable carbon reduction levels are needed from the government to ensure investments into SAF from oilseeds are best utilised.[93] Note that alternative non-edible oilseeds which do not encounter food vs. fuel challenges are explored in chapter 3.6.

92 European Commission (2023) European Green Deal: new law agreed to cut aviation emissions by promoting sustainable aviation fuels. <https://ec.europa.eu/commission/presscorner/detail/en/ip_23_2389> (accessed 17 May 2023).

93 CSIRO (2019) Maintaining access to EU markets for Australian canola. CSIRO.

Given the low hydrogen requirements of the HEFA process, it could act as an initial offtake for green hydrogen. Doing so would improve the carbon intensity of the fuel, match early hydrogen production forecasts and provide a test bed for the integration of green hydrogen into refinery processes.

Despite feedstock availability and technological maturity, edible oilseeds are unlikely to play a major role in SAF production. Their role is more likely to be as a supplementary feedstock in times of UCO and tallow shortages, as a liquid fuel security option for customers that do not require a large carbon emission reduction, or as a temporary measure until non-edible oilseeds can be scaled.

What next

IMMEDIATE TERM (2023-2025)	MEDIUM TERM (2025-2035)
• Engage canola farmers to understand their appetite to supply local industry. • Increase oilseed crushing capacity. • Engage environmental researchers and engineers to undertake detailed life cycle analyses to inform research into the improvement of land use management, the electrification of processes, machinery and transport, and the sourcing of hydrogen renewably to drive down CO_2 emissions across the process. • Support agricultural practices including intercropping for productivity increases and better soil health.	• Expand non-edible oilseed proliferation on marginal crop land. • Explore protected cropping options, such as vertical farming, greenhouses and modular farms for oilseeds.[94] • Develop and use fertiliser produced from green ammonia. • Explore genetic modification to improve oilseed yield and quality.[95] • Augment existing oilseed feedstocks supply with algal and microbial oil sources as discussed in Chapter 3.6.

94 O'Sullivan C, Bonnett G, McIntyre C, Hochman Z, Wasson AP (2019) Strategies to improve the productivity, product diversity and profitability of urban agriculture. Agricultural Systems 174, 133-144.

95 Savadi S, Lambani N, Kashyap PL, Bisht DS (2016) Genetic engineering approaches to enhance oil content in oilseed crops. Plant Growth Regulation 83, 207-222.

3.5 Power-to-liquids – CO_2 and H_2

Power-to-liquids (PtL) is a process that involves the production of jet fuel using non-biogenic (i.e., non-biological) feedstocks, such as hydrogen and carbon dioxide, along with renewable energy sources. The term “power-to-liquids” refers to the fact that renewable energy is a critical component of the production process.

Currently, the FT process is the only approved PtL pathway. However, unapproved pathways also have the potential to be adopted in the future, such as the production of eMethanol from water and CO_2 for upgrading into jet fuel, known as Methanol-to-Jet.

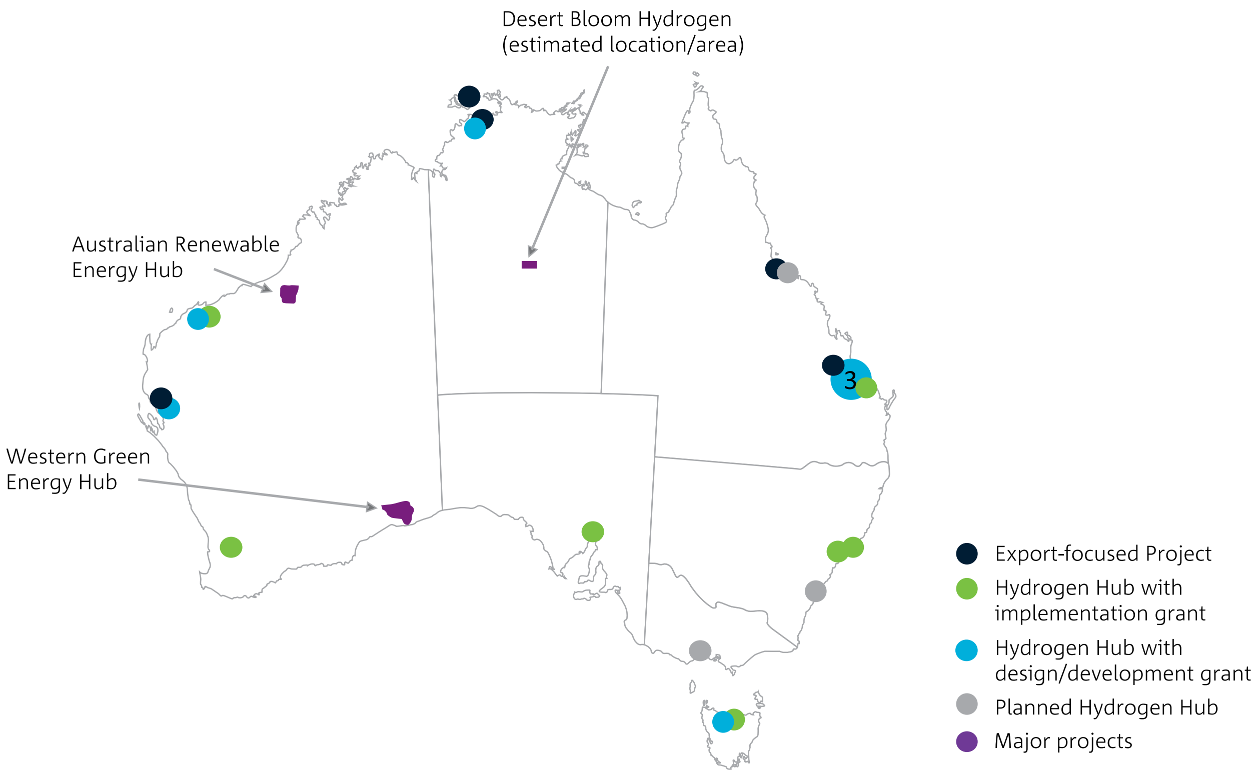
The development of a PtL capability will be heavily reliant on the availability of green hydrogen. As the limiting factor, the scale and growth of PtL will be closely tied to the development of a local hydrogen industry. Although Australia is slated to become a major hydrogen producer as set out by its National Hydrogen Strategy[96], the current production of green hydrogen is near zero, being limited to small-scale demonstration projects. This will need to increase manyfold before PtL is viable.

PtL will also require access to large quantities of CO_2. CO_2 can be sourced three ways, from industrial waste streams such as ammonia and ethanol production, by combusting biomass to produce biogenic CO_2 or directly from the air using Direct Air Capture (DAC) technologies. Given the availability of point-source CO_2, it should be targeted as the first source of CO_2 for cost-effective PtL fuels. Ammonia and ethanol plants provide the best concentrations and quantities of point sources. Following point sources, more sustainable biogenic CO_2 should be examined. Finally, DAC investments should begin to be scaled to gradually replace point-source CO_2.

There is no current activity in the production of PtL in Australia.

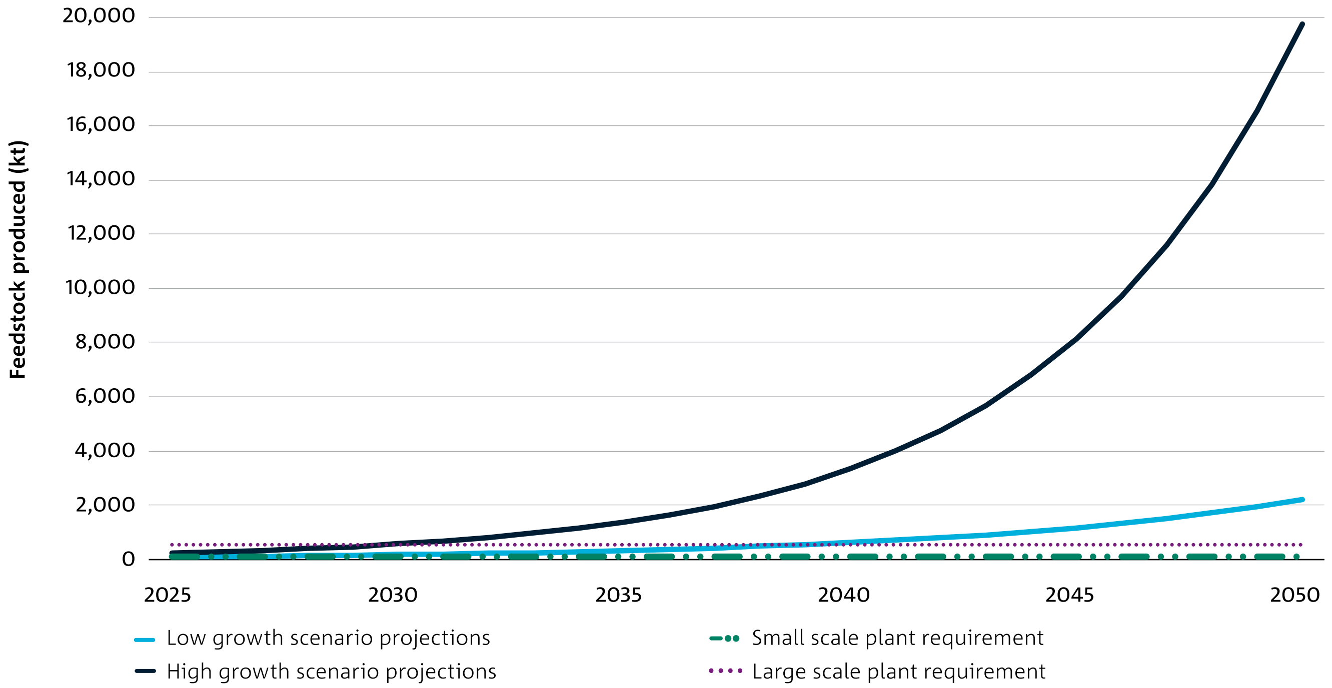
Assuming a maximised SAF yield, a small-scale FT plant, capable of producing 50 ML of SAF per year, would require 6% of Australia’s projected green hydrogen production in 2035 in the high growth scenario. A large-scale plant producing 300 ML per year, would require 38% of hydrogen production in 2035.

Figure 30. Green hydrogen project announcements and government-designated “hydrogen hubs”



96 Council of Australian Governments Energy Council (2019) Australia’s national hydrogen strategy. Commonwealth of Australia.

Figure 31. Australian hydrogen production projections and FT feedstock requirements based on plant size



The price of green hydrogen is a key cost driver for PtL. With green hydrogen prices currently high and a lack of large-scale manufacturing and economies of scale, there is an opportunity for commercial activity to help to reduce the cost of electrolysers. Developments in large-scale green hydrogen production and lower electricity prices can drive the cost of hydrogen down, reducing PtL production costs significantly.

Hydrogen could supply a growing portion of Australia's fuel demand over time. As per figure 33, utilising 25% of projected hydrogen production through to 2050 could produce enough SAF to meet approximately 32% of jet fuel demand.

Figure 32. Levelised production cost of jet fuel today and in 2050 – FT using H_2 and CO_2

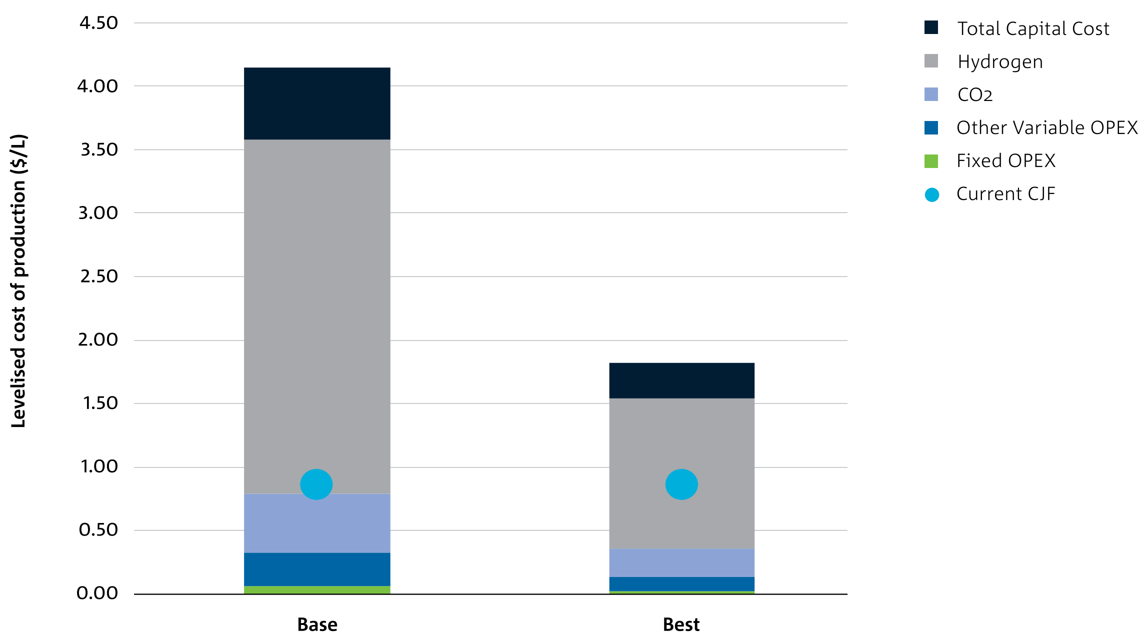
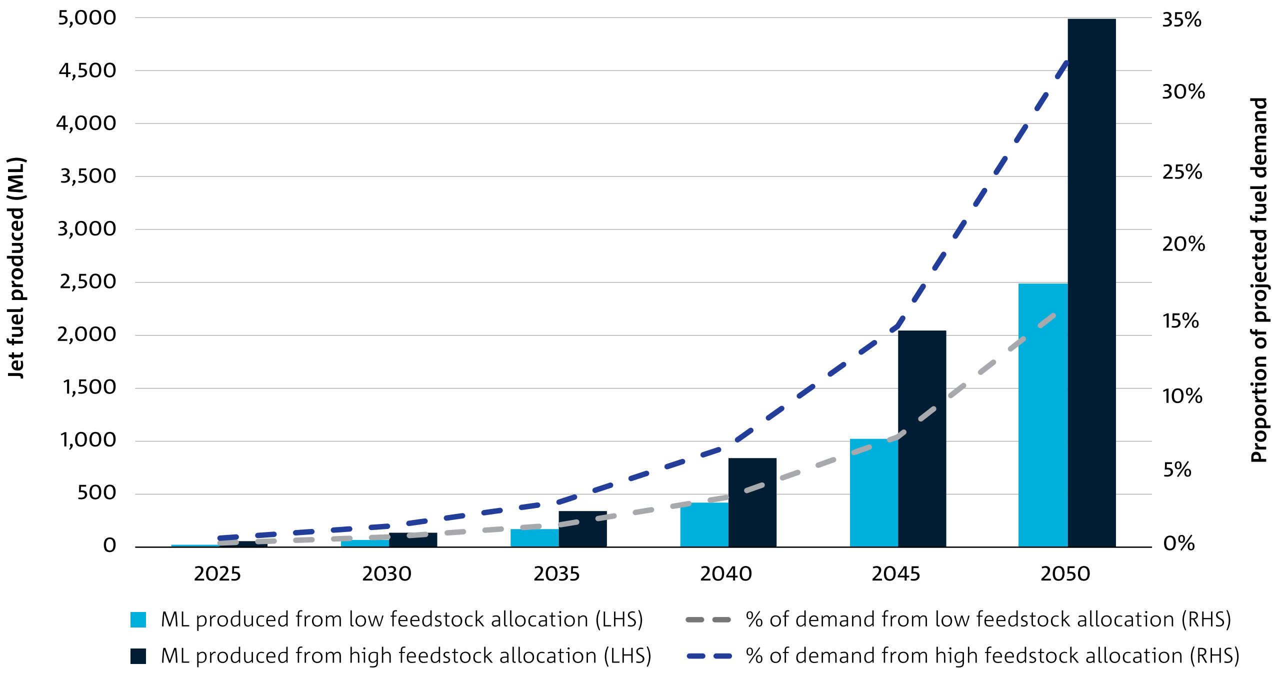


Figure 33. Potential SAF production from Australian green hydrogen and contribution toward domestic fuel demand



Scaling hydrogen production comes with many challenges, most notably, access to green electrons. With many industries relying on renewable energy to reach net zero goals, competition is likely to be high. Given electricity costs are a key cost driver for hydrogen (which in turn is the most significant cost factor for PtL), green electrons accessed must be low cost - much lower than they are today. States that should be targeted for PtL production are those that are aggressively pursuing hydrogen production strategies and can access large renewable energy projects.

Another key challenge will be access to CO_2. In the first instance, industrial point sources provide a high pressure and high purity source. However, these sources can come with social impact challenges as they are usually the result of fossil fuel processing. Biogenic CO_2, which is produced when biomass is combusted, can provide a medium-term solution for a CO_2 source. These sources can provide adequate CO_2 until DAC technologies are mature, scaled and cost effective. To ensure that DAC technologies receive investment and integration into PtL projects, assistance with overcoming the cost premium as well as research and development projects are required.

Although hydrogen production requires clean water as an input, the amount of water used is comparatively small compared to other industries. For example, if the government's aim of a $50b hydrogen industry was to be achieved, it would require 225,000 ML of water, which is only 4% of the water used for cropping in 2019-20.[97] However, the impact of this water usage depends on the context in which it is used; if the water is diverted from river or irrigation systems, it could impact other industries. Nevertheless, the majority of hydrogen projects and hubs are located on the coast, where access to water via desalination and wastewater is abundant.

With green hydrogen production almost non-existent and CO_2 utilisation rarely practiced, it is challenging to predict how access to green electrons and industry scale-up will play out. To ensure that the industry is properly analysed from a whole energy system point of view, additional research is required to understand how PtL could scale alongside other industries.

97 Lester R, Gunasekera D, Timms W, Downie D (2022) Water requirements for use in hydrogen production in Australia: Potential public policy and industry-related issues.

What next

IMMEDIATE TERM (2023-2025)	MEDIUM TERM (2025-2035)	LONG TERM (2035+)
• Establish a PtL demonstrator (100 L/day) to integrate with local renewables and hydrogen production. • Research public tolerance for point source and biogenic CO_2. • Conduct an assessment to identify the optimal location for the first large PtL plant considering the locations of potential hydrogen hubs. • Develop Roadmap aimed at a PtL industry in Australia, considering the evolution of CO_2 sources, the hydrogen industry, and renewable energy requirements. • Fund development of less mature hydrogen technologies such as high temperature electrolysis.	• Build consortium and initiate planning for large-scale plant • Guarantee supply of hydrogen and CO_2. • Implement pilot-scale projects for DAC technologies. • Industry involvement in demonstration projects for mature green hydrogen technologies to overcome 'first of kind' risk.	• Build the first large-scale PTL plant. • Focus on improving plant efficiencies and asset life.[98]

3.6 Other feedstocks

Some feedstocks were not included in the modelling portion due to insufficient data and a lack of commercial activity in Australia at present. These feedstocks warrant discussion and could contribute to biofuel production in the future. These feedstocks' technical and economic viability needs to be revisited over time as the energy transition continues to change our understanding of efficient land use, sustainability and cross-sectoral decarbonisation benefits.

3.6.1 Non-edible oilseeds

Non-edible oilseeds offer the opportunity of cultivating and utilising crops that do not have to compete with food markets and can use marginal or degraded land. Additionally, as a non-edible seed, the application of genetic modification to improve oil yield would face less barriers than applying GM to edible seeds. Although possible to use some non-edible seeds as cover crops overseas, this is not applicable in the Australian context due to rainfall levels.[99] Non-edible seeds can still be used in a crop rotation and would therefore have a similar CI to oilseeds such as canola. Using the HEFA process, non-edible oilseeds can be upgraded into SAF.

A strong candidate for the highest contributor is the carinata plant. It is a non-edible oilseed plant with high tolerance to various climates and growing conditions and high oil yield. Carinata is not commercially grown in Australia at present, however a 2018 trial plantation found that it produced grain yields similar to Australian canola varieties, with an average of 0.11–2.84 t/ha.[100] Developers of this seed type are looking to expand production in Australia and are seeking partners.

Another yet-to-be commercially grown candidate is pongamia, which is similar in yield and growth zones to the palm. Although pongamia does not suffer from the same historical social impact issues as palm, it will still encounter similar sustainability challenges such as being a monoculture that replaces native vegetation. More research is required, but early studies suggest they are a good candidate as fuel feedstock in northern Australia. Although drought tolerant, pongamia still requires rainfall, and irrigation will ensure better establishment. Like palms, the trees take three to four years to produce seeds.

98 Bruce S, Temminghoff M, Hayward J, Schmidt E, Munnings C, Palfreyman D, Hartley P (2018) National Hydrogen Roadmap. CSIRO, Australia.

99 Taheripour F, Sajedinia E, Karami O (2022) Oilseed cover crops for sustainable aviation fuels production and reduction in greenhouse gas emissions through land use savings. Front. Energy Res. 9; Prussi M, Lee U, Wang M, Malina R, Valin H, Taheripour F, Velarde C, Staples MD, Lonza L, Hileman JI (2021) CORSIA: The first internationally adopted approach to calculate life-cycle GHG emissions for aviation fuels. Renewable and Sustainable Energy Reviews 150.

100 Herwaarden A, Bennett R, Potter T, Lambrides C, Gororo N, Krakowski H, Arief V, Leveque W, Salisbury P (2022) The performance and feasibility of carinata in Australia. In Proceedings of the 20th Agronomy Australia Conference. 18–22 September, Toowoomba.

Their resilience to extreme weather events should be assessed to better understand their suitability. However, its long seed time and restricted growth zones are limiting, especially when considered against carinata.

Japanese fuel producers have expressed interest in pongamia for SAF. Japanese refiner Idemitsu, cooking oil producer J-Oil Mills and Australian non-profit Burnett Mary Regional will work together to start small-scale cultivation of pongamia trees in Queensland in 2023 to be scaled up to hundreds of hectares following a successful trial.[101]

To make oilseed production economical, by-products must be sold into other markets. Oilseeds such as canola sell their meal as animal feed due to the high protein content. Many non-edible seeds, however, including carinata and pongamia, contain flavonoids that make the meal unpalatable. This causes issues with making an economic case for the growth of some non-edible oilseeds. Continued R&D is required to improve the by-product use case.

3.6.2 Oil mallees (coppicing)

Australia has a long history of planting mallees as woody crops to harvest biomass for biofuel production. As of 2017, the total extent of area mallee planted was 213,000 ha, predominantly in South Australia and Western Australia where there are cool winters and hot, dry summers (semi-arid Mediterranean climate).[102] Three main species of mallee planted in WA are *Eucalyptus polybractea*, *Eucalyptus loxophleba* and *Eucalyptus kochii*.[103]

Mallee trees require six years of growing before it can be first harvested. After harvest (cutting at ground-level), mallee trees can regenerate by coppicing (sprouting) from the retained rootstocks, making it a sustainable supply of biomass feedstock. Subsequent harvests can recur every four years. In 2005, the potential annual mallee biomass supply was estimated to be 1.5–3 Mt, assuming a biomass yield of 14 tonnes per ha per year.[104]

Advanced biofuels can be produced from mallee biomass by combining pyrolysis and hydrotreatment technologies. A 2012 project funded by the Australian Renewable Energy Agency (ARENA) found that the cost of this production method can range between $0.49 to $0.60 per litre.[105] Further work is still needed to verify the harvesting logistics and the scalability of the production technologies.

The practice of growing and coppicing oil mallees can also aid with the soil health and natural capital of working farms, as well as provide an additional income source for landowners. To better quantify this opportunity, further research and more granular data are needed to understand current stocks of mallee and the potential for extra growth. This includes examining other potential species like the brigalow (*Acacia harpophylla*).

Inpex, ANZ and Qantas recently announced a memorandum of understanding to progress the evaluation of planting mallees in the Wheatbelt region of Western Australia to undertake a feasibility study into harvesting and processing native biomass crops and crop residues to produce biofuels.[106]

3.6.3 Microalgae

Microalgae is a microorganism that produces fatty acids that can be converted to SAF via the HEFA process or upgraded through pyrolysis or hydrothermal liquefaction.

Microalgae are of interest as they have no food value, high yields, high lipid content, little land requirement and low-cost requirements. They can also grow in various water types and bring co-benefits such as wastewater treatment.

Microalgae is a great candidate for SAF production as some species can grow at an annual rate of 91 tonnes per ha and have more than 50% of lipid content in its dry weight.[107] In 2015, the global potential of microalgae-derived jet fuels was estimated to range between 350 billion litres per year in a limited productivity scenario

101 Nakashima M (2023) Japan's Idemitsu eyes SAF production from pongamia oil. Argus. <https://www.argusmedia.com/en/news/2427110-japans-idemitsu-eyes-saf-production-from-pongamia-oil> (accessed 21 April 2023).

102 Department of Climate Change, Energy, the Environment and Water (DCCEEW) (2017) MVG 14 – Mallee woodlands and shrublands. <https://www.dcceew.gov.au/sites/default/files/documents/mvg14-nvis-mallee-woodlands-and-shrublands.pdf> (accessed 21 April 2023).

103 Brooksbank K, Goodwin A (2022) A model of coppice biomass recovery for mallee-form eucalypts. New Forests 53, 449-468.

104 Stucley C, Schuck S, Sims R, Bland J, Marino B, Borowitzka M, Abadi A, Bartle J, Giles R, Thomas Q (2012) Bioenergy in Australia: status and opportunities. Bioenergy Australia.

105 ARENA (2013) Project report: sustainable production of high-quality second-generation transport biofuels from mallee biomass by pyrolysis and biorefinery. ARENA.

106 Qantas (2022) INPEX, ANZ and Qantas announce carbon farming and renewable biofuels strategic collaboration. <https://www.qantasnewsroom.com.au/media-releases/inpex-anz-and-qantas-announce-carbon-farming-and-renewable-biofuels-strategic-collaboration/> (accessed 17 May 2023).

107 Stratton RW, Wong HM, Hileman JI (2010) Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels. Massachusetts Institute of Technology, Cambridge, Massachusetts; Rocca S, Agostini A, Giuntoli J, Marelli L (2015) Biofuels from algae: technology options, energy balance and GHG emissions. European Commission; Su Y, Song K, Zhang P, Su Y, Cheng J, Chen X (2017) Progress of microalgae biofuel's commercialization. Renewable and Sustainable Energy Reviews 74, 402-411.

and two trillion litres per year in a high productivity scenario.[108] CSIRO is currently researching potential green microalgae species of *Nannochloropsis*, *Tetraselmis* and *Botryococcus* for biofuel production.[109]

Despite their potential, there remain technological and logistical challenges. Although trials and pilot projects have been completed, there is yet to be large-scale commercial production of biofuels from microalgae globally. This is due to the inefficiency and capital- and resource-intensive nature of current cultivation, harvesting and oil extraction technologies.[110]

Growth and productivity rates differ greatly in the literature across various organisms and weather conditions. However, if high yields can be accomplished at a large scale and technological and logistical challenges can be overcome, Australia has the land required to commercially cultivate microalgae for biofuel production.

3.6.4 Macroalgae (seaweed)

Seaweed is an important aquaculture product with a global cultivation of 5.1 Mt in 2020, predominantly occurring in Asian countries.[111] While the seaweed industry in Australia is still in its early stage of development, some notable progress has been made. [112] For example, CH4 Global is growing and processing *Asparagopsis* seaweed to produce methane-reducing cattle feed in South Australia. In 2022, the company announced plans to expand its production which include building three large-scale Eco Parks in various locations of the state.[113]

A variety of species from three main categories of red, brown and green seaweeds have been trialled for biofuel production on a laboratory scale.[114] Seaweed feedstocks can be converted into biofuels via thermochemical conversion, anaerobic digestion and fermentation.[115] Other value-added products that can be produced from the fermented biomass include biogas, biofertiliser, bio-oil, syngas and biochar.[116]

Pre-treatment of the feedstock via chemical, mechanical, biological or thermal processing, or co-digestion can improve the product yield. However, these methods are currently restrained by cost and scalability. Other challenges with bioproduct manufacturing from seaweed include the recalcitrance of seaweeds, seasonal biomass variation, the presence of inhibitory compounds, and the expense of harvesting.[117]

3.6.5 Terpenes (leaf oils)

Terpenes are a class of hydrocarbons derived from the oil of plant leaves, mainly found in eucalyptus, pine and tea tree species. They contain a variety of subclass molecules which are comparable in hydrocarbon length to CJF.

To produce a hydrocarbon suitable for blending, steam distillation extracts plant oils from the leaves before undergoing hydroprocessing and minimal refining.

The challenge with commercial and cost-effective extraction and use of naturally derived terpenes is the low yield of specific terpenes in plants. Thus, conversion to low-value fuel products has been limited, with terpene use concentrated in the therapeutics, essential oils, flavourings and fragrance industries. However, the endemic growth of eucalyptus in Australian climates, alongside simple developments in plantation approaches can help to overcome these challenges.

108 Ames JL (2015) Microalgae-derived HEFA jet fuel: environmental and economic impacts of scaled/integrated growth facilities and global production potential. MS (thesis). Massachusetts Institute of Technology.

109 CSIRO (n.d.) Producing biofuels from algae. <https://www.csiro.au/en/research/plants/water-marine/algae-biofuels> (accessed 21 April 2023).

110 Doliente SS, Narayan A, Tapia JFD, Samsatli NJ, Zhao Y, Samsatli S (2020) Bio-aviation fuel: a comprehensive review and analysis of the supply chain components. Front. Energy Res. 8.

111 Food and Agriculture Organisation (FAO) (2022) The state of world fisheries and aquaculture 2022. <https://www.fao.org/3/cc0461en/online/sofia/2022/aquaculture-production.html#note-1_10> (accessed 21 April 2023).

112 Kelly J (2020) Australian seaweed industry blueprint. AgriFutures.

113 CH4 Global (2022) CH4 Global announces expansion plans in South Australia. <https://www.ch4global.com/2022/10/10/ch4-global-announces-expansion-plans-in-south-australia/> (accessed 28 April 2023).

114 Wang S, Zhao S, Cheng X, Qian L, Barati B, Gong X, Cao B, Yuan C (2021) Study on two-step hydrothermal liquefaction of macroalgae for improving bio-oil. Bioresource Technology 319.

115 Farghali M, Mohamed IMA, Osman AI, Rooney DW (2022) Seaweed for climate mitigation, wastewater treatment, bioenergy, bioplastic, biochar, food, pharmaceuticals, and cosmetics: a review. Environmental Chemistry Letters 21, 97-152.

116 Rajak RC, Jacob S, Kim BS (2020) A holistic zero waste biorefinery approach for macroalgal biomass utilization: a review. Science of The Total Environment 716.

117 Farghali M, Mohamed IMA, Osman AI, Rooney DW (2022) Seaweed for climate mitigation, wastewater treatment, bioenergy, bioplastic, biochar, food, pharmaceuticals, and cosmetics: a review. Environmental Chemistry Letters 21, 97-152.

3.6.6 Biogas

Biogas is produced through the anaerobic digestion of organic matter and consists of a range of chemicals, including methane, carbon dioxide and oxygen. Anaerobic digestion can use various feedstocks including food, biowaste, and other industrial wastes. It also occurs naturally in landfills. Biomethane is produced from biogas, usually through a catalytic process, requiring the addition of hydrogen. Biomethane can be treated like natural gas and upgraded into a variety of fuels via steam methane reforming then the Fischer-Tropsch process. Biomethane can be mixed with natural gas to ensure supply but will come at a sustainability and carbon emission cost.

Australia has a total estimated biogas potential of 16 PJ in 2020, growing to 364 PJ in 2050.[118] However, several barriers are remaining before this biogas can be utilised. These include a lack of biogas upgrading plants, industry experience, the financial viability of projects, distributed sources and the need for more favourable policy conditions. [119]

3.6.7 Biosolids

Sewerage sludge, the solid by-product of industrial and municipal waste, is a potential feedstock for SAF that is already collected and has no competing offtakers. Its utilisation would also help to eliminate a waste management issue. Biosolids contain lipids (2.9–2.3%) which can be extracted for upgrading or processed using thermochemical processing such as gasification or pyrolysis for further upgrading.[120] Biosolids are currently gasified for power production in Logan, Queensland.[121]

The major challenge for this feedstock is its moisture content, as biosolids are quite wet and cost-effectively managing this moisture in a thermal process is difficult. Gasification and hydrothermal liquefaction are potential solutions to this challenge.

3.6.8 Grasses

Several types of grass have been examined for biofuel production potential due to their high productivity and ability to be grown on marginal land. Of great focus is *Miscanthus* which is documented to have a productivity of 25 tonnes per hectare per year, greater than switchgrass.

Miscanthus can be fermented through advanced fermentation or processed using thermochemical processes.[122] A recent study has posited that planting 23.3 Mha of *Miscanthus* on marginal agricultural land could fulfill the US's 2040-projected fuel demand.[123]

Miscanthus is a summer-active grass and will be only suited to the northern half of Australia, however further work needs to be done to optimise grass selection and ideal locations. In some cases, the feedstock can save demand for additional cropland and generate "negative" induced land use change emission values, suggesting potentially lower CI than crops grown for primary production.

118 Kaparaju, P., Conde, E., Nghiem, L., Trianni, A., Cantley–Smith, R., Leak, J., Katic, M., Nguyen, L., Jacobs, B., Cunningham, R. (2023). Anaerobic digestion for electricity, transport and gas. Final report of Opportunity Assessment for research theme B5. Prepared for RACE for 2030 CRC.

119 Carlu E, Truong T, Kundevski M (2019) Biogas opportunities for Australia. ENEA.

120 Bashir MA, Lima S, Jahangiri H, Majewski AJ, Hofmann M, Hornung A, Ouadi M (2022) A step change towards sustainable aviation fuel from sewage sludge. Journal of Analytical and Applied Pyrolysis 163.

121 ARENA (2023) Logan City biosolids gasification project. <https://arena.gov.au/projects/logan-city-biosolids-gasification-project/> (accessed 21 April 2023).

122 Brosse N, Dufour A, Meng X, Sun Q, Ragauskas A (2012) Miscanthus: a fast- growing crop for biofuels and chemicals production. Biofrp 6(5), 580-598.

123 Aragon NZU, Parker NC, VanLoocke A, Bagley J, Wang M, Georgescu M (2022) Sustainable land use and viability of biojet fuels. Nature Sustainability 6, 158-168.

4 Technology overview

The major pathways to produce SAF can process feedstocks in various ways, each with different advantages and disadvantages, such as various by-products, logistical arrangements, capital versus operating costs, price structures, and technological maturity. To provide a snapshot of the fuel processing pathways, an assessment was conducted to show the advantages and disadvantages across a range of criteria as depicted in the table below.

CRITERIA	IMPORTANCE	LOW	MEDIUM	HIGH
Fuel readiness level (FRL)	Maturity of supporting technologies and process, coupled with the readiness to be used as an ASTM approved drop-in fuel.	FRL 1-3	FRL 4-6	FRL 7-9
Energy dense intermediate	The ability to increase the density of the feedstock is favourable as it reduces logistical burden and makes for more economical fuel.	Density is poor and cannot be economically improved.	Limited options to increase density.	Density is high by default or can be achieved through proven processes.
Feedstock flexibility	The ability to accept a range of feedstocks is favourable as it can reduce supply certainty risks.	Cannot accept different feedstocks.	Can process a limited number of feedstocks.	Can accept a wide range of feedstocks.
Potential for R&D improvements	Emerging processes have more scope to improve through the application of R&D, overcoming the challenges of other criteria.	Mature process with only minor continuous improvements possible.	Maturing process with improvements in efficiencies and logistics possible.	Step-change can be achieved through the application of R&D.
Waste management	Onsite waste and by-products can be hazardous to processes and personnel and needs to be minimised. These requirements are seen as unfavourable.	Significant or hazardous waste produced presenting range of difficulties in management.	Some waste or hazardous by-products but can be overcome with strict protocols.	Little waste and by-products produced, or safe protocols developed to manage.
Social acceptance	Projects that produce waste, odour or are not perceived to be sustainable may meet social opposition. Social impact concerns are unfavourable.	Project likely to be opposed by public.	Project likely to be accepted by public.	Project likely to be welcomed by public.

Assessment of fuel process pathways

PATHWAY	INTERMEDIATE	PROCESSING STEP(S)	FRL*	ENERGY DENSE INTERMEDIATE	FEEDSTOCK FLEXIBILITY	POTENTIAL FOR R&D IMPROVEMENTS	WASTE MANAGEMENT	SOCIAL ACCEPTANCE
HEFA	Oils and fats	Hydroprocessing	9	H	L	L	L	M
FT	Syngas	Gasification of non-fossil source	7	L	H	M	H	H
		Reverse-water-gas-shift of point source CO_2 with H_2	7	L	L	L	M	M
		Reverse-water-gas-shift of DAC CO_2 with H_2	3	L	L	H	M	L
Hydrotreating	Pyrolysis oil	Pyrolysis	5	M	H	M	H	M
	Bio-oil	Hydrothermal liquefaction	5	M	M	H	H	H
	Terpenes	Steam distillation of terpenes from biomass	7	H	L	L	H	M
ATJ	Ethanol	Gasification of non-fossil source, fermentation	5	M	H	M	H	M
		Gasification of non-fossil source, catalytic conversion	3	M	H	H	H	M
		Simple fermentation of sugars	7	M	L	L	H	H
		Advanced fermentation of lignocellulosic material	3	M	M	M	H	M
	Methanol	Hydrogenation of point source CO_2	7	L	L	M	L	M
		Hydrogenation of DAC CO_2	3	L	L	H	L	L
		Gasification of non-fossil source, catalytic conversion	7	M	M	M	H	M

*FRL relates to Fuel Readiness Level. This is based on the Technological readiness level framework but explicitly designed to reflect the risks affecting the development of fuels as opposed to equipment. It is accepted as a best practice communication tool of fuel technology maturity in the aviation industry. A more detailed breakdown of the CAAFI fuel readiness level scale and toll gates can be found in the appendix.

5 Roadmap

Australia produces several feedstocks that can be used to produce SAF. With the aid of supportive policies and concerted action, Australia can significantly reduce its reliance on fossil fuels with locally produced SAF, meeting a large portion of its domestic jet fuel demand by 2050. The contribution from individual feedstocks will evolve over time depending on availability, cost and location. More broadly, biogenic pathways provide a nearer, though naturally limited opportunity whilst power-to-liquids has much larger prospective supply but will take time to achieve scale.

Feedstock availability

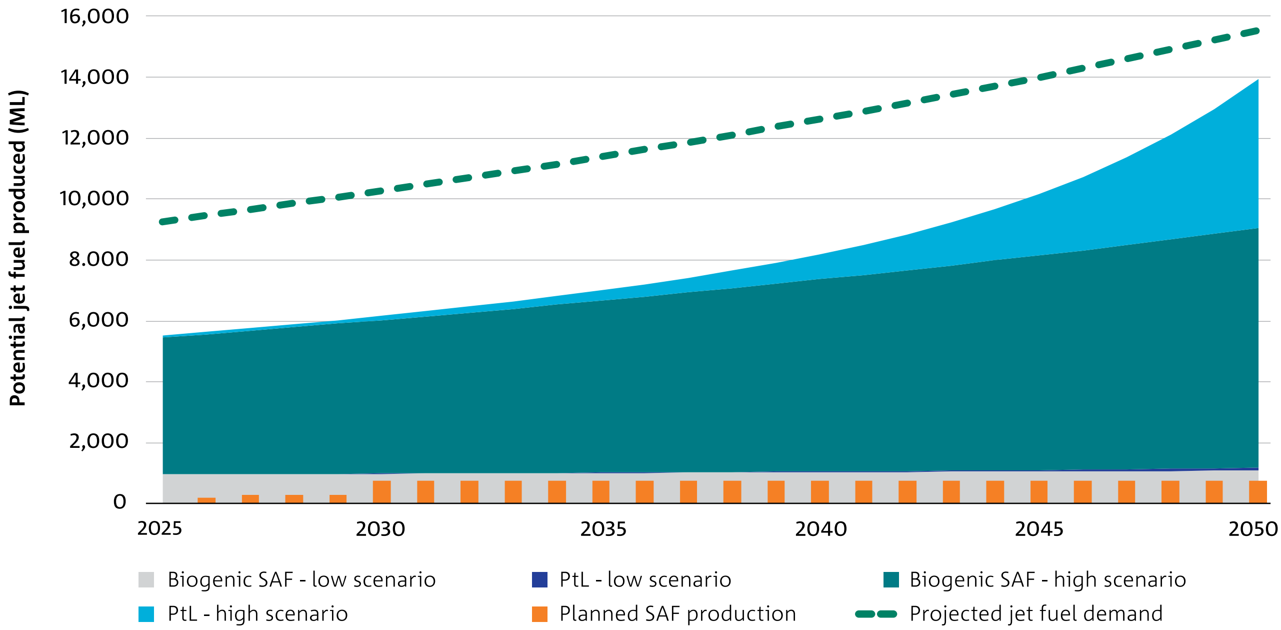
To understand how much SAF feedstock Australia produces and what that means in terms of potential sovereign fuel production, a stocktake of key feedstocks was conducted followed by projected growth modelling through to 2050. Two scenarios were produced, low and high, each considering three main variables:

1. Feedstock production rates – annual growth or production rate for each feedstock.
2. Biorefinery yields – the rate biorefineries select for SAF over other products.
3. Feedstock allocation – the proportion of feedstock allocated to SAF production.

To target the "high scenario", Australia would need to drive investment and create incentive to increase feedstock growth, prioritise SAF yield at biorefineries and actively allocate feedstocks towards SAF production. Without these actions, it is likely that a SAF industry in Australia would instead experience a "low scenario" and be unable to meet domestic fuel demand as show in figure 34.

VARIABLE	LOW SCENARIO	HIGH SCENARIO
Feedstock production rates	Increased climate variability and slow adoption of sustainable farming practices leads to poor yield and little productivity improvements. Hydrogen economy and DAC scale does not eventuate in line with optimistic scenarios. Lack of supportive policy does not incentivise feedstock collection and production.	New technology adoption such as new plant strains, improved farm management, better waste collection or sorting allows for improved production rates and counters the effects of a changing climate. Hydrogen economy is supported by large-scale renewables and collaborative action on distribution.
Yield at biorefineries	High demand from road transport drives demand for renewable diesel, leading biorefineries to deprioritise SAF.	Pooled demand from several stakeholders and clear offtake commitments for SAF leads biorefineries to prioritise SAF yields.
Feedstock allocation	High competition for other uses such as food, recycling, bioenergy, animal feed restricts allocation of feedstocks to SAF production. High international activity continues trend of feedstocks being exported, leaving little available for domestic use.	Economic incentive encourages feedstock producers to sell their product to local SAF producers in large numbers.

Figure 34. Potential fuel production from projected feedstock production



Biogenic includes carbohydrates, MSW, tallow, crop and sawmill residues and oilseeds. Projected jet fuel demand is derived from CSIRO transport modelling that takes into consideration a range of economic, infrastructure and policy drivers over time.[124]

Today there is sufficient feedstock to supply approximately 5 billion litres of SAF production, but Australia is currently constrained by refining potential. Even with planned SAF production coming online from 2026 onwards, a large opportunity remains to produce SAF from Australian feedstocks. By utilising the feedstock and technoeconomic modelling from the report's analysis, this opportunity equates to $10 billion worth of fuel in 2025 and $19 billion by 2050. Without acting to liberate and refine these resources, Australia risks losing them to offshore processors.

As well as refining capability, new technologies and supply chains will be required to liberate and process feedstocks. Improvements in how feedstocks are collected, sorted and processed into energy dense intermediates or transported directly to centralised locations for upgrading into SAF are vital.

Economics of SAF production

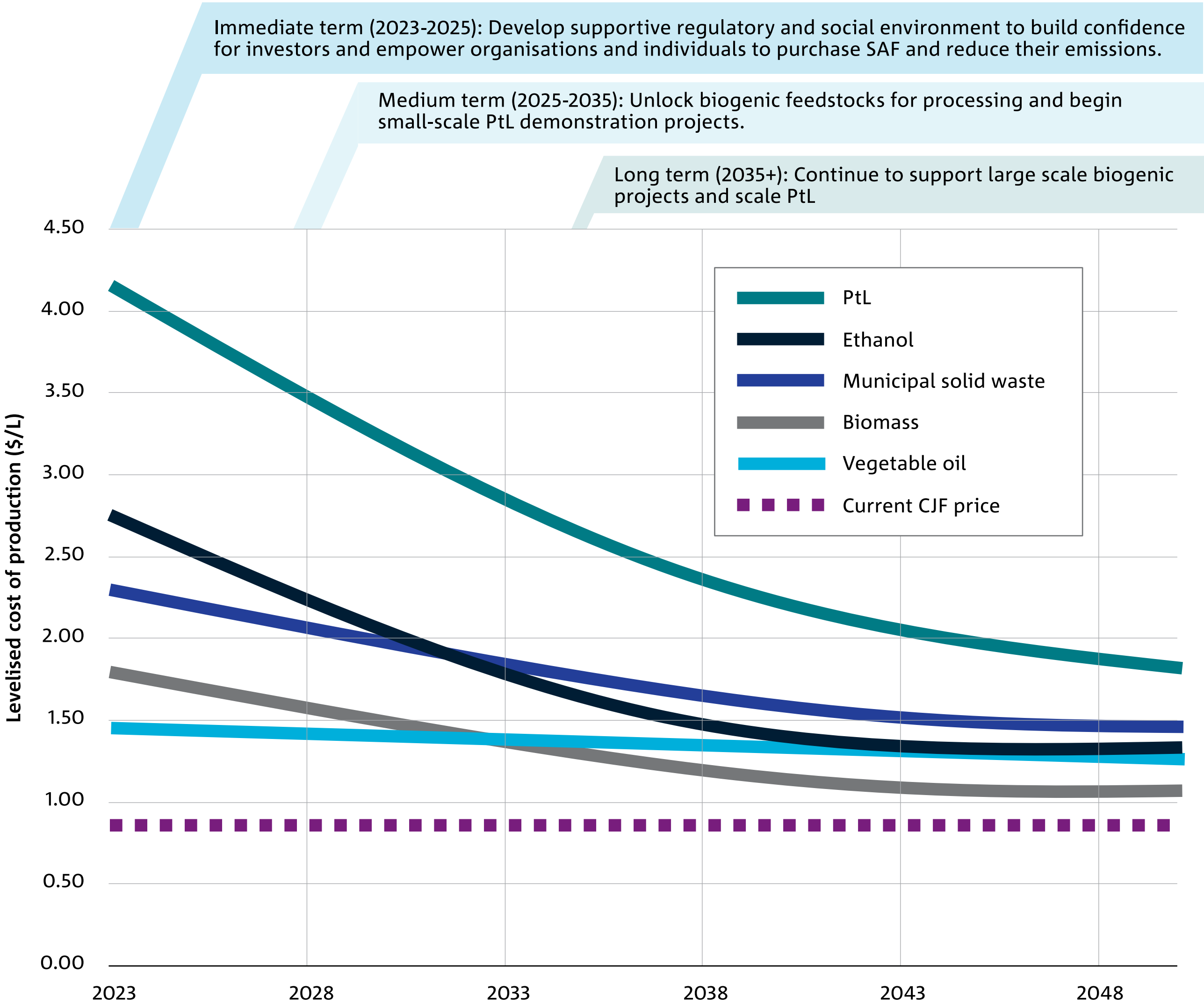
Each SAF pathway comes with a green premium due to feedstock costs, additional processing steps and lack of economies of scale, with the severity of the premium differing across pathways. The production costs of SAF pathways will be a major influencer on feedstock choice and technology deployment over time.

Biogenic pathways provide the most economic choice in the immediate to medium term. In the longer term, there are risks of cost increases as competition for feedstocks increases and supply reaches a natural limit, such is the case with used cooking oil, animal fats and edible oilseeds. Other biogenic feedstock price increases could be mitigated, such as production costs of ethanol through a step-change reduction in the price because of advanced fermentation technologies. Decreasing capital costs associated with increased scale and ongoing R&D improvements, as well as reduced operating costs such as energy and hydrogen, will also help to drive down production costs.

PtL pathways begin with a greater green premium than biogenic but fall as the hydrogen economy grows and drives significant reductions in hydrogen production costs. The cost of DAC will also influence the cost of PtL and is projected to fall as the technology matures and scales. Resource availability is almost infinite for PtL, so input costs are unlikely to experience a rebound in the long term. As with biogenic, decreasing capital costs as plant scale increases, as well as falling operating costs will also contribute to lower production costs.

124 Graham, P. 2022, Electric vehicle projections 2022. CSIRO, Australia.

Figure 35. Projected levelised cost of production for five key SAF feedstocks[125]



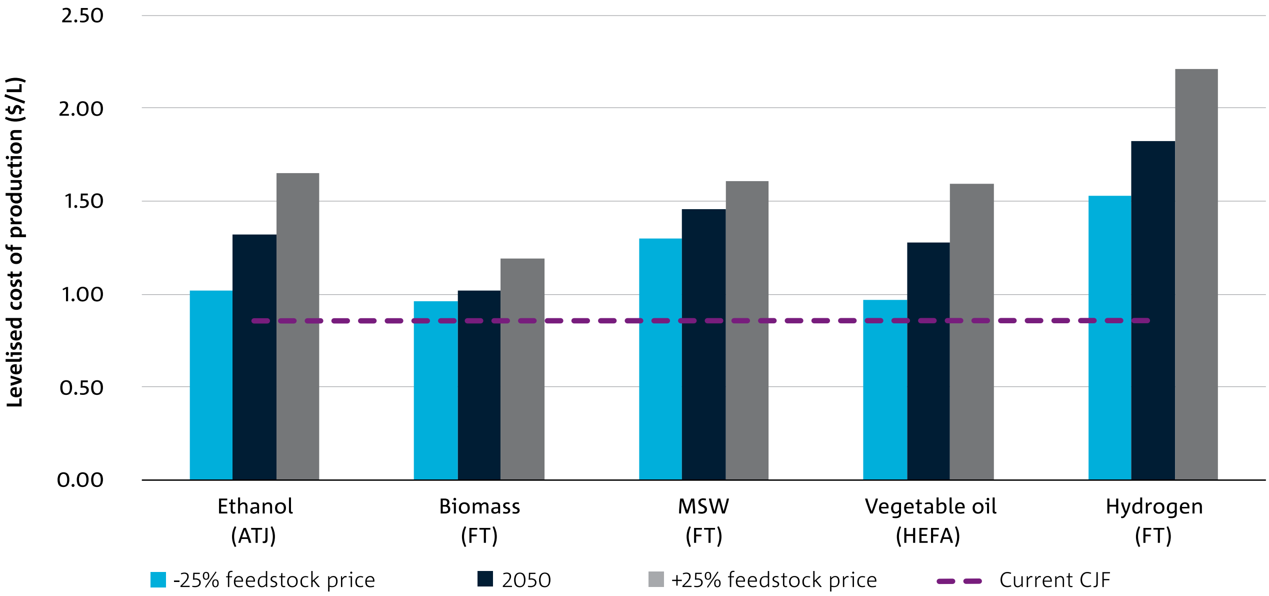
CJF prices are difficult to forecast and have undergone a range of fluctuations over time. In the previous 5 years, CJF prices fell to $0.14/L in 2020 and then rose to $1.66/L in 2022.[126] As well as general market fluctuations, CJF could experience upwards price pressure due to carbon prices, geopolitical events and demand shortfalls for other oil refinery products which can in turn cause higher jet fuel prices.

Long term feedstock prices are difficult to forecast and can have substantial effects on the levelised cost of production for various SAF pathways. The following figure explores how changes in feedstock prices assumed for 2050 can change the levelised cost of production. Maintaining low feedstock prices and shielding against price fluctuations will be vital for each production pathway.

125 The levelised cost of production describes the average cost of producing a unit of fuel over the lifetime of a production process, considering all costs associated with producing the product, as well as the expected amount of product that will be produced. The calculation considers the initial capital costs of the production process, the ongoing operating and maintenance costs, and the expected lifetime of the process. Additionally, the cost of raw materials, labour, energy, and any other inputs required for the production process are factored in. Profit margins are not included in the final figures. Although LCOP can inform analysis of cost drivers and allow a comparison across pathways, LCOP calculations have limitations and their real-world applicability is limited by available data, assumptions and the need to account for numerous products. In this case, each product of the biorefining process, such as diesel and naphtha, must be assigned the same value as the SAF produced, which is not reflective of market pricing at refineries.

126 IATA (2023) Jet fuel price monitor. <https://www.iata.org/en/publications/economics/fuel-monitor/> (accessed 19 May 2023).

Figure 36. Sensitivity of feedstock price to 2050 levelised cost of production of SAF



Although some pathways may look to be close to parity with CJF, other factors are preventing these cases from being practicable, such as the ability to liberate and deliver feedstock to a site, reliance on technology not yet demonstrated at scale or supply chains that are yet to be established. These projected costs are intended to provide an indicative comparison of the different pathways and their feedstocks overtime, and will differ from use case to use case, considering local conditions and policy.

Immediate term (2023-2025)

To achieve the high scenario, the focus for the immediate term is developing a supportive regulatory and social environment that supports the planned plants in Perth, Brisbane and Gladstone and builds confidence for investment in the next generation of biorefineries. This groundwork also needs to enable organisations and individuals to purchase SAF and claim emissions reductions. The decisions made in the coming 18 months need to begin to address the most pressing challenges facing the industry today.

MAJOR CHALLENGES	
	• Balancing supply and demand • Assuring certification and provenance • Carbon accounting and reporting • Building SAF literacy • Access to capital

Through literature reviews and stakeholder consultations across industry, government and research institutions, the following recommendations were developed to inform the development of an Australian SAF industry.

Recommendation 1: Consider policy frameworks and tools that support domestic distribution and use of certified SAF with clear long-term support strategy for industry.

Actions

- Develop and communicate long term Australian SAF strategy and policy approach through the Jet Zero council, taking into consideration state and territory advantages and international policy.
- Examine subsidy and tax credit options to incentivise SAF production.
- Align certification methodologies to global standards and marketplace for sustainability verification of SAF production.
- Explore standardised mechanisms for carbon accounting and reporting of SAF use to claim Scope 1 and Scope 3 emissions reductions for airlines and their customers, such as book-and-claim and SAFc.
- Allow SAF investment proposals as part of the Clean Energy Finance Corporation, Powering the Regions Fund, National Reconstruction Fund and the Northern Australia Development Program.

Recommendation 2: Encourage the signalling of local demand for SAF across government, commercial and defence users, giving investors certainty to establish new plants.

Actions

- Pool demand from multiple stakeholders to accumulate sufficient offtake for new plants, considering the green premiums. By doing so across Government, commercial and defence stakeholders, the potential will be greater and economies of scale can be realised.
- Establish national program to enable consumers to voluntarily purchase SAF for flights.

Recommendation 3: Educate consumers on the role and benefits of SAF, building social license for investment and demand for fuels.

Actions

- Conduct focus groups to gain a better understanding of the current level of knowledge and misconceptions among consumers and identify the most sensitive issues. Utilise the findings from the focus groups to develop targeted campaigns that increase understanding of SAF and encourage their purchasing.
- Develop and launch public media campaigns following the Roadmap launch and continued advocacy by airlines and peak bodies such as the Sustainable Aviation Fuels Alliance of Australia and New Zealand to inform both public and business consumers about SAF.
- Use SAF at public aerial events such as the Avalon Airshow, Brisbane's Riverfire festival and the Australian Grand Prix to engage public interest and awareness.

Recommendation 4: Invest in R&D to support emerging technologies and improve feedstock availability and sustainability understanding.

Actions

- Improve data granularity for feedstock sources by updating Australian Biomass for Bioenergy Assessment.
- Expand development of alternative oilseeds projects.
- Explore options to develop a centralised body to provide advice on feedstock production or into an existing body such as Grains Research and Development Corporation.
- Provide funding to developing technologies and near-commercial projects through the ARENA.
- Conduct LCA assessments for Australian specific feedstock and proposed supply chains.

Recommendation 5: Scale-up of biogenic SAF production in appropriate locations, increasing market supply and driving cost reductions.

Actions

- Evaluate the feasibility of establishing an additional HEFA plant in Australia, considering the need to compete in the spot market for feedstocks and potential cost increases.
- Conduct feasibility studies examining the utilisation of second-generation feedstocks such as bagasse and other residues to determine the most economical resource to use and identifying ways to optimise their collection.
- Engage agribusiness such as sugar millers to communicate the challenges and opportunities of a biogenic SAF supply chain.
- Purchase SAF from international producers to test supply chain and airport fuel infrastructure.

Medium term (2025-2035)

With low cost and available feedstocks captured by the immediate term opportunities, the medium term will likely need to focus on unlocking the next available biogenic feedstocks, whilst beginning small-scale demonstration projects in PtL and taking stock of future feedstock possibilities. Despite action in the immediate term, some challenges, such as green premium will remain, and new challenges that reflect the evolving attitudes to feedstock sustainability will begin to emerge.

MAJOR CHALLENGES

- Overcoming green premium
- Competing feedstock uses
- Economic collection and processing of low-density feedstocks
- Securing feedstock supply

Recommendation 6: Scale-up second-generation biogenic feedstock collection and processing.	
Actions	• Design gasification feedstock hubs to take a range of biogenic and MSW feedstocks to provide scaled syngas production for FT processing. • Boost production at operational and idle ethanol facilities to provide feedstock for the establishment of ATJ capability in Queensland. • Develop better collection, sorting and processing of waste products such as biosolids and MSW to unlock additional second-generation opportunities.
Recommendation 7: Invest in R&D to reduce the costs and logistical hurdles for biogenic supply chains and continue scaling up of PtL demonstrations.	
Actions	• Study emerging technologies that could provide intermediate solutions to produce high-density biocrudes for processing at a centralised location. • Improve efficiencies of lignocellulosic feedstock processing. Better fermentation technologies will enable distributed, low-cost ethanol production to lower ATJ costs • Re-evaluate economic and environmental viability of emerging feedstocks such as algae, energy grasses and bio-wastes.

Long term (2035+)

In the longer term, biogenic feedstocks will approach full allocation and further increases in potential biogenic SAF production depend on productivity improvements and maximised yields in biorefineries. The large opportunity remaining is now PtL.

By this time, PtL costs will have begun to fall with larger-scale, lower-cost hydrogen and CO_2 collection and aggregation. Building on demonstration investments in preceding years, PtL output can be maximised.

MAJOR CHALLENGES

- Lowering production cost and increasing availability of green hydrogen
- Guaranteeing supply of CO_2
- Competing for green electrons

Recommendation 8: Develop large-scale production of power-to-liquids at several locations across Australia.	
Actions	• Co-locate PtL plants with established hydrogen and CO_2 supply hubs. • Scale direct air capture to integrate with existing CO_2 supply.

6 International activity overview

Australia's key APAC neighbours were assessed to understand their current or likely role in a regional SAF production zone. Comprehensive assessments for each country can be found in the supplementary report *Sustainable Aviation Fuel Roadmap: International Activity*. Four key indicators were used to assess SAF development in each country.

- **Other biofuels experience**: does the country have experience in other biofuels?
- **Government SAF policy**: what measures are their government taking to encourage SAF or feedstock production?
- **Feedstock activity and plans**: are there plans to allocate or import feedstocks for SAF?
- **SAF activity and plans**: are there plans to begin SAF production?

Three rankings are provided for each criterion:

RANKING	STATUS	DESCRIPTION
●	Developed	• Established and operational, supported by strategy, investment, and outputs.
◐	Developing	• Activity is planned or under construction.
○	Undeveloped	• No to little action taken with no strategy in place.

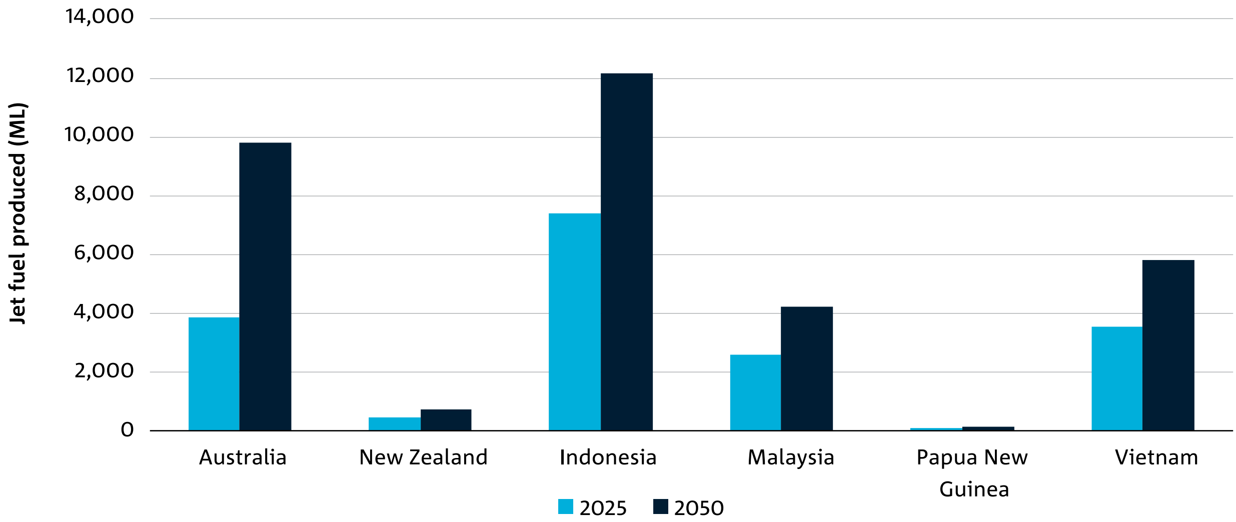
Activity summary

COUNTRY	OTHER BIOFUELS	SAF POLICY	FEEDSTOCK ACTIVITY	SAF ACTIVITY	LIKELY FEEDSTOCKS
New Zealand	◐	◐	◐	◐	Sawmill residues, tallow
China	●	◐	◐	◐	UCO, animal fat, ethanol
Fiji	◐	○	○	○	Bagasse, sawmill residues, coconut oil
India	◐	◐	◐	○	Ethanol
Indonesia	◐	◐	◐	◐	Palm oil
Japan	◐	◐	◐	◐	Ethanol from MSW, imported UCO.
Malaysia	●	◐	○	◐	Palm oil, UCO
Philippines	◐	○	○	◐	MSW, ethanol
Papua New Guinea	○	○	○	○	Palm oil, agricultural residues, MSW
Singapore	●	◐	●	●	Imported UCO, animal fats
South Korea	◐	○	○	◐	Import UCO
Thailand	●	○	○	◐	Palm oil, UCO and ethanol
Vietnam	◐	○	○	○	Ethanol, agricultural residues

Feedstock potential summary

To better understand the feedstock potential of some countries of the APAC region, a high-level modelling exercise was undertaken to provide an indication of their feedstock production compared to Australia's. The countries in the figure below were chosen due to a combination of factors including likelihood to be a feedstock producer, proximity to Australia and availability of relevant data. Further research is required to better quantify the SAF potential of the whole APAC region.

Figure 37. Potential SAF production from each country's top two feedstocks (high scenario)[127]



127 CSIRO (2023) Sustainable Aviation Fuel Roadmap: International Activity. CSIRO. The top two feedstocks for SAF production in Australia by 2025 are agricultural residues (from barley, corn (maize), grain sorghum, oats, rice, triticale, and wheat crops), and the combination of sugarcane and bagasse. By 2050, the two most potential feedstocks for SAF production come from the PtL process and agricultural residues. The two primary feedstocks available for SAF production in New Zealand up to 2050 are sawmill residues and tallow. For Indonesia, they are palm fruit and sugarcane and bagasse combined. The two most potential feedstocks for SAF production in Vietnam are agricultural residues and sugarcane and bagasse combined. For Malaysia, they are palm fruit and agricultural residues. For PNG, they are palm fruit and coconut.

6.1 New Zealand

Snapshot

CRITERIA	ASSESSMENT	DESCRIPTION
Other biofuels	◑	• Small biofuel industry for bioethanol and biodiesel (< 0.1% of transport fuels) hindered by lack of domestic production and previous policy support.
SAF policy	◑	• SAF mandate is under development, but no policy announcements have been made yet.
Feedstock activity	◑	• Forestry products and residues are the primary feedstock candidate with a history of projects evaluating the production of biofuels from them. • Exports of tallow.
SAF activity	◑	• 1.2 ML shipment of SAF imported in 2022. • Airline commitment to reach 10% SAF by 2030.

Other biofuels experience

Biofuel use in New Zealand is minimal and lacks domestic refining capacity.[128] With three processing plants, Lactanol supplies approximately 15 ML of bioethanol from whey, a dairy industry by-product, annually.[129] 0.6 ML of biodiesel was also produced in 2015, but the aim of increasing biodiesel production through Z Energy has not been realised.[130] The 20 ML per annum biodiesel plant was permanently closed due to rising tallow prices and high capital costs involved in its scaling.[131] Overall, liquid biofuels contribute less than 0.1% of total fuel sales.[132]

The Sustainable Biofuels Obligation was expected to contribute to future road transport fuel targets and strategies. However, this has recently been scrapped due to concerns over the cost-of-living and the sustainability of imported biofuels.[133]

Government SAF policy

In 2021, Cabinet agreed that a separate SAF mandate would be developed to address aviation, following the Sustainable Biofuels Obligation. Policy is under development, after facing delays from extended consultations on the Obligation. Progress is now being made on the SAF mandate, but timing has not yet been determined.

Additionally, New Zealand operates an Emissions Trading Scheme (ETS), putting a price on emissions to incentivise technology investment and improve practices to reduce them. This provides benefits to forestry participants for CO_2 removal through tree plantings and opportunities to trade emission units. To date, this has had little effect on transport fuel use as prices for emission units have been very low.

128 NZ Ministry of Business, Innovation & Employment (2022) Biofuels and the sustainable biofuel obligation <https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-generation-and-markets/liquid-fuel-market/biofuels/> (accessed 19 May 2023).

129 Lactanol (n.d.) Lactanol - Sustainable New Zealand Ethanol. <https://www.lactanol.com/content/dam/lactanol/Lactanol%20Brochure.pdf> (accessed 19 May 2023).

130 Scion NZ (2018) New Zealand Biofuels Roadmap Summary Report. <https://www.scionresearch.com/__data/assets/pdf_file/0005/63293/Biofuels_summary_report.pdf> (accessed 19 May 2023).

131 Z (2022) Z confirms closure of Te Kora Hou biofuels plant. <https://www.z.co.nz/about-z/news/z-confirms-closure-of-te-kora-hou-biofuels-plant/> (accessed 19 May 2023).

132 Scion NZ (2018) New Zealand Biofuels Roadmap Summary Report. <https://www.scionresearch.com/__data/assets/pdf_file/0005/63293/Biofuels_summary_report.pdf> (accessed 19 May 2023).

133 Autocar NZ Magazine (2023) Government announces end to biofuels mandate. <https://www.autocar.co.nz/government-announces-end-to-biofuels-mandate/> (accessed 19 May 2023).

NZ Ministry of Business, Innovation & Employment (2022) Biofuels and the sustainable biofuel obligation <https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-generation-and-markets/liquid-fuel-market/biofuels/> (accessed 19 May 2023).

Feedstock activity and plans

Woody biomass

The New Zealand Biofuels Roadmap has identified forestry products and residues as the leading feedstock candidates, with the potential to account for 2.3 BL fuel annually by 2050 and thereby meet all South Island's demand.[134] The advantage of using forestry products from plantation forests in New Zealand is centred around the profitability and productivity of feedstock produced on lower quality, non-arable land. This includes land types that are rolling and steep, which is unsuitable for agriculture. Furthermore, the flexibility with growing practices as well as harvest schedules, and the range of forestry products offered are also significant.

However, contention exists over the sustainability of harvesting forestry products and residues for bioenergy, given the complexity of forest ecosystems and limited site-specific data. Key arguments include carbon sequestration being favourable compared to atmospheric emissions from biomass combustion, the perception that forestry activities accounting and reporting is not transparent and leads to biodiversity loss.

Conversely, there are also benefits to residue removal from forestry plantations such as reducing methane emissions, less fire risk and minimising infrastructure destruction caused by debris during storms. A Ministerial inquiry is being held to investigate land use practices and the impact of woody debris including forestry residues on the local environments following cyclone events.[135]

Forest harvest and wood processing residues are likely to provide an initial source of biofuel feedstocks based on previous availability assessments. Projections based on the National Exotic Forest Description (NEFD) data showed a consistent 10-12 million cubic metres of woody biomass produced annually from combined forest residues and pulp logs.[136] Additional residues would be produced in sawmills.

There is an opportunity to convert residues and low-cost products like small, exported pulp logs to higher-value products like SAF. This could increase the price paid for residues, improving the viability of sawmills and existing wood processing plants, while also displacing fossil carbon and generating greater liquid fuel security for New Zealand.

The Biofuels Roadmap contented that considerations which are thought to limit their feedstock potential for large-scale biofuel application are the low available volumes compared to expected fuel demand, high costs from competing existing uses and lacking technical or economic feasibility to collect geographically dispersed forest residues. Therefore, the ability to secure woody biomass will be driven by its location and SAF producers' willingness to pay. Based on this, New Zealand's forestry industry, starting with sawmill residues, is the most promising feedstocks for domestic SAF production.

Sawmill residues

As per the approach of Australian feedstocks, sawmill residues were assessed to understand the potential for New Zealand. Firstly, historical data was used to calculate average growth since 2010. Using this trajectory, two growth scenarios (low and high) were applied to forecast production through 2050. It was assumed that residues would be converted to SAF using gasification and FT.

Assuming a maximised SAF yield, a small-scale FT plant, capable of producing 50 ML of SAF per year would require 5% of New Zealand's projected sawmill residues in 2025. A large-scale plant producing 300 ML of SAF per year would require 31% of collected sawmill residues in 2025.

To understand how feedstock allocation can impact fuel production, the proportion of annual feedstock production was varied (20% and 40%), assuming high growth projections and high SAF yields. Sawmill residues could supply large quantities of jet fuel over time. As per figure 39, utilising 20% of residues through to 2050 could meet 10-12% of fuel demand, whereas utilising 40% of projected available residues could produce 21-24% of fuel demand.

134 Scion NZ (2018) New Zealand Biofuels Roadmap Summary Report. <https://www.scionresearch.com/__data/assets/pdf_file/0005/63293/Biofuels_summary_report.pdf> (accessed 19 May 2023).

135 NZ Government (2023) Inquiry to investigate forestry slash and land use after cyclone. <https://www.beehive.govt.nz/release/inquiry-investigate-forestry-slash-and-land-use-after-cyclone> (accessed 19 May 2023).

136 Bio Pacific Partners (2020) Wood Fibre Futures. <https://mpi.govt.nz/dmsdocument/41824/direct> (accessed 19 May 2023).

Figure 38. New Zealand sawmill residue growth projections and FT feedstock requirements based on plant size

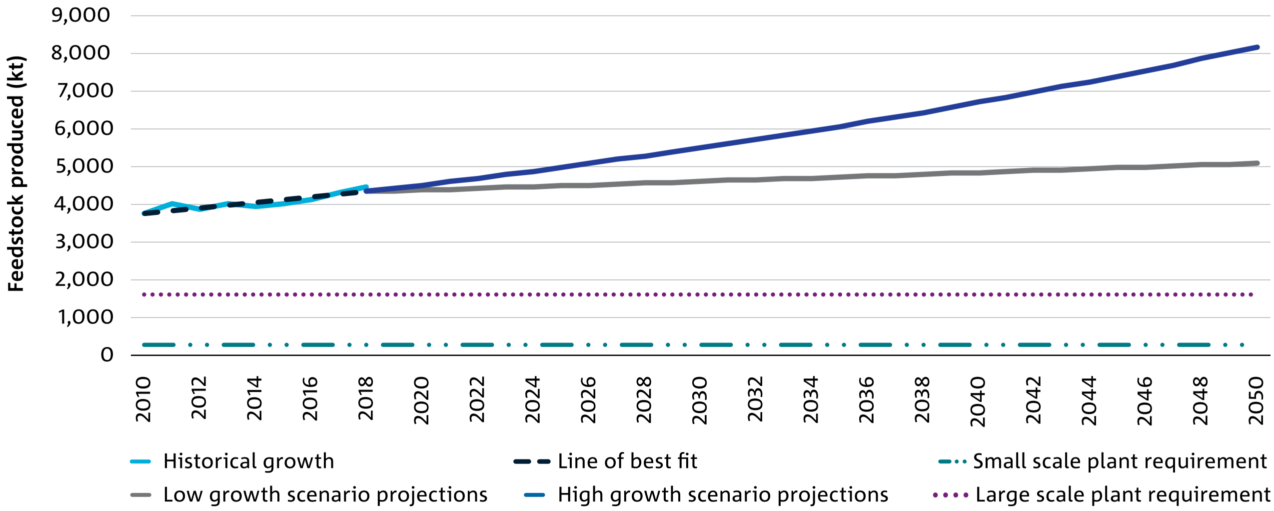
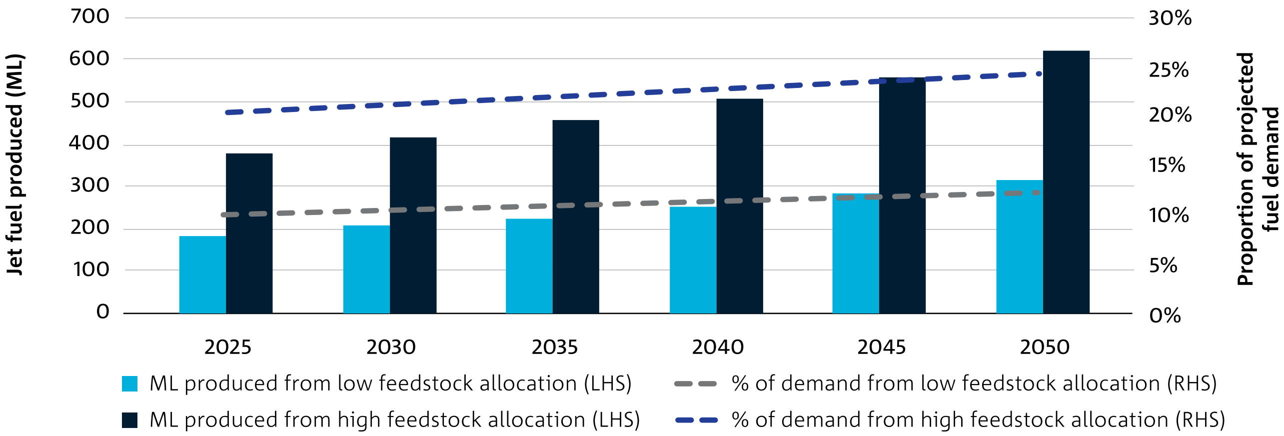


Figure 39. Potential SAF production from New Zealand sawmill residues and contribution toward domestic fuel demand



Tallow

New Zealand produces around 150 kt of tallow per year. A large volume of this is currently exported while the remaining 20% is consumed in domestic markets for animal feed, soap and margarine.[137] The NZ Biofuels Roadmap outlined the competition for existing use and tallow often being too costly as a factor limiting their potential as a feedstock.[138] This is supported by the closure of Z Energy's biodiesel plant.

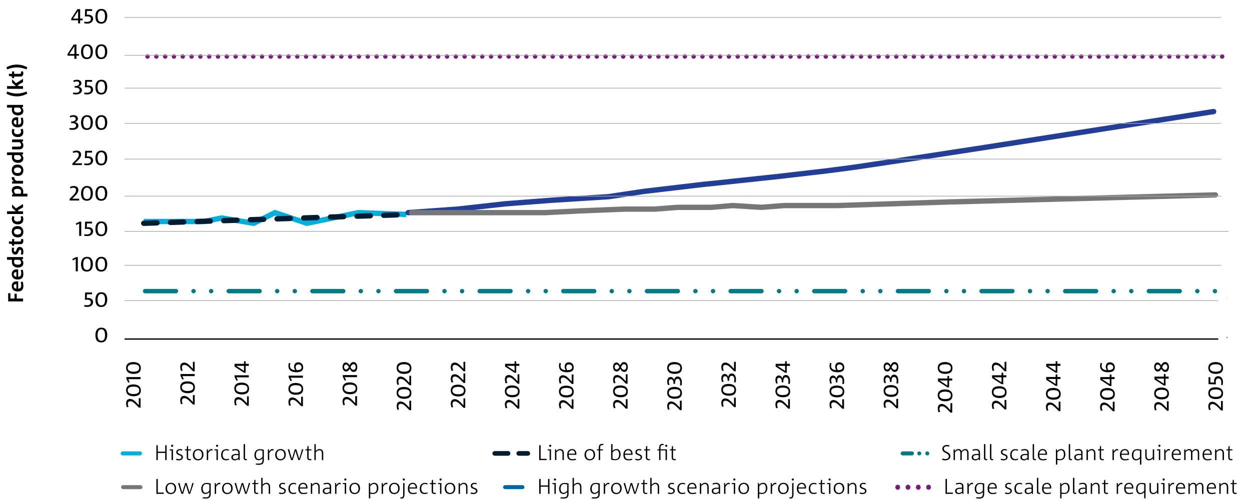
Assuming a maximised SAF yield a small-scale HEFA plant, capable of producing 50 ML of SAF per year, would require 34% of New Zealand's projected tallow production in 2025. Whereas a a large-scale plant producing 300 ML of SAF per year could not be sufficiently supplied by tallow alone. This shows that tallow is unlikely to be a suitable feedstock for SAF in New Zealand.

SAF activity and plans

Currently, there is no SAF available in New Zealand. However, this has not deterred Air New Zealand from SAF-related activity. In 2008, a successful test flight was conducted using a 50% SAF blend in a Boeing 747.[139] More recently, the first SAF import was received into New Zealand fuel infrastructure for use in commercial flights. The 1.2 ML of UCO-derived SAF was purchased and delivered in 2022 and is equivalent to fuelling 400 flights between Auckland and Wellington, operating at 100% SAF.[140]

As a member of the Clean Skies for Tomorrow Coalition, Air New Zealand has committed to helping accelerate the supply and use of SAF to reach the goal of 10% by 2030. Despite there being no more local refining, the airline and the Ministry of Business, Innovation and Employment issued a request for proposal for feasibility demonstrations of operating commercial SAF plants in New Zealand.[141] The study is still underway.

Figure 40. New Zealand tallow growth projections and HEFA feedstock requirements based on plant size



137 Bioenergy NZ (2015) What and how much is being made in New Zealand? <https://www.liquidbiofuels.org.nz/documents/resource/WLB01_LiquidBiofuels-biodiesel-bioethanol-sources-details.pdf

138 Scion NZ (2018) New Zealand Biofuels Roadmap Summary Report. <https://www.scionresearch.com/__data/assets/pdf_file/0005/63293/Biofuels_summary_report.pdf> (accessed 19 May 2023)

139 Air New Zealand (2023) Sustainable Aviation Fuel. <https://flightnz0.airnewzealand.co.nz/initiatives/sustainable-aviation-fuel> (accessed May 19 2023).

140 Neste (2022) Air New Zealand welcomes first shipment of Neste MY Sustainable Aviation Fuel into New Zealand. <https://www.neste.com/releases-and-news/renewable-solutions/air-new-zealand-welcomes-first-shipment-neste-my-sustainable-aviation-fuel-new-zealand> (accessed May 19 2023).

Air New Zealand (2022) Air New Zealand to welcome first shipment of Sustainable Aviation Fuel into Aotearoa. <https://www.airnewzealand.com/press-release-2022-airnz-air-new-zealand-to-welcome-first-shipment-of-sustainable-aviation-fuel-into-nz> (accessed May 19 2023).

141 Air New Zealand (2023) Sustainable Aviation Fuel. <https://flightnz0.airnewzealand.co.nz/initiatives/sustainable-aviation-fuel> (accessed May 19 2023).

RNZ (2021) Refining NZ confirms Marsden Point switch to import-only terminal from April 2022. <https://www.rnz.co.nz/news/business/456277/refining-nz-confirms-marsden-point-switch-to-import-only-terminal-from-april-2022> (accessed May 19 2023).

7 Appendices and supplementary information

7.1 Stakeholder Engagement List

Advisory Group

- A*Star
- Airlines 4 ANZ
- Australian Bureau of Agricultural and Resource Economics (ABARES)
- Australian Farm Institute
- Bioenergy Australia
- Bioenergy Association (NZ)
- Boeing
- BP
- Commercial Aviation Alternative Fuels Initiative (CAAFI)
- Department of Infrastructure, Transport, Regional Development, Communications and the Arts
- Griffith University
- Lanzajet
- Neste
- Qantas
- Roundtable of Sustainable Biomaterials (RSB)
- Royal Australia Air Force (RAAF)
- Scaling Green Hydrogen CRC
- Scion Research
- The University of Queensland (UQ)
- Virgin Australia

Consultations

- Australian Council of Recycling (ACOR)
- Adelaide Airport
- AgriFutures Australia
- Air New Zealand
- Ampol
- Australian Renewable Energy Agency (ARENA)
- Australian Oilseed Federation
- Biofutures Qld
- Future Fuels CRC
- Highly Innovative Fuels Global (HIF Global)
- INPEX
- Invest South Australia
- Jet Zero Australia
- Licella
- NZ Ministry of Transport
- Oil Mallee Association
- Queensland University of Technology (QUT)
- SkyNRG
- Sydney Airport
- Sugar Milling Council
- Sugar Research Australia
- Wagners Corporation

CSIRO

- Deborah Lau
- Justine Lacey
- Peter Thorburn
- Randall Donohue
- Stuart Whitten
- Brett Molony
- Michael Battaglia
- Warren Flentje

7.2 Additional feedstock analysis

7.2.1 Carbohydrates

Fundamentally carbohydrates are sugar molecules, ranging from simple sucrose found in sugarcane to complex longer-chain starches in maize and sorghum. Fermentation of these sugars can produce ethanol, an alcohol intermediate suited for upgrading to SAF.

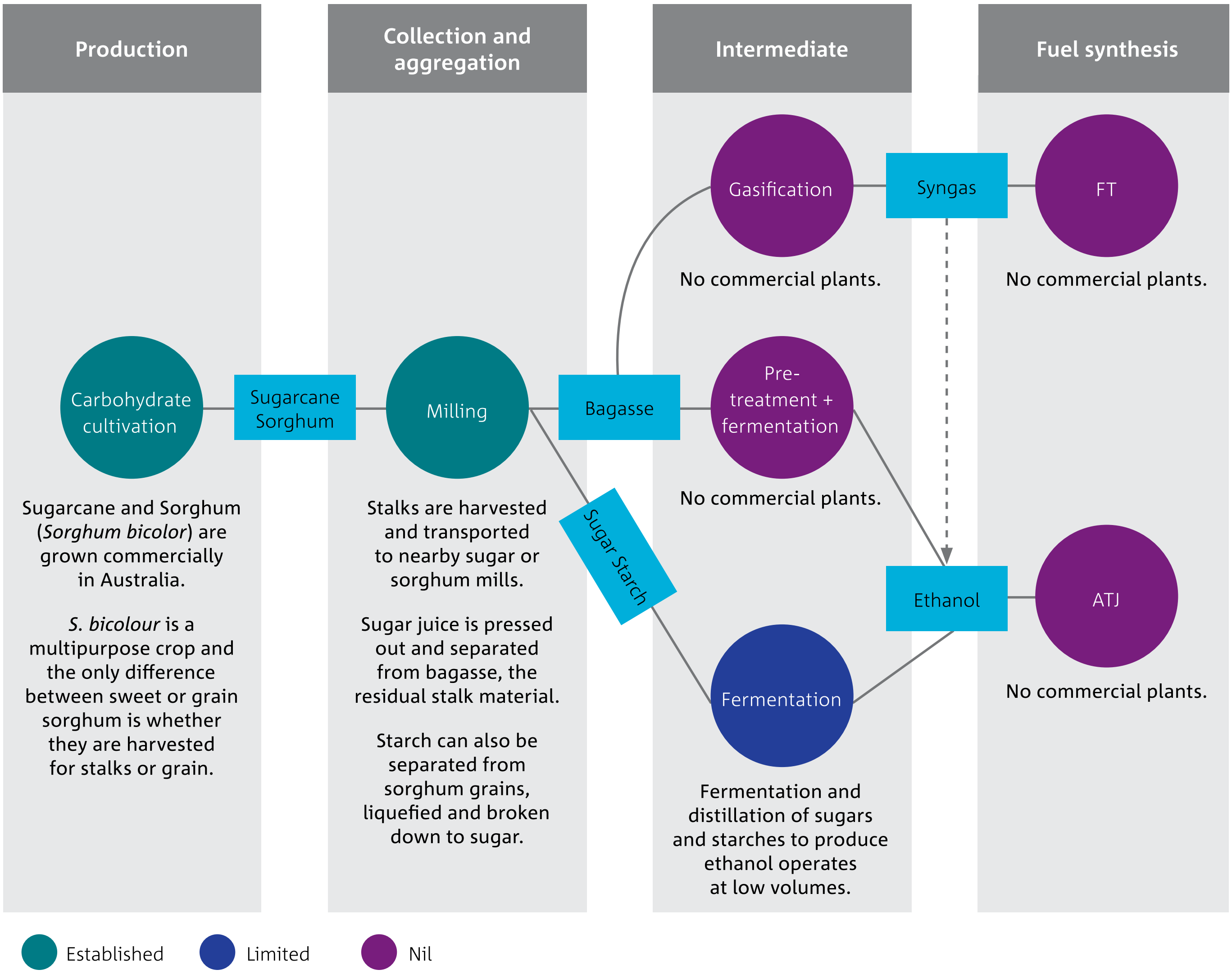
The cultivation of sugar provides additional biomass resources. As well as residues from sugarcane harvesting on farms, sugarcane bagasse is a fibrous by-product from milling. In most cases, this is combusted to produce steam and electricity, but could be liberated for conversion into fuels.

Australia is a significant producer and exporter of sugarcane and sorghum, whereas most maize is used in domestic markets. Due to low production and use in domestic markets, maize was excluded as a potential feedstock. 95% of Australian sugarcane is grown along Queensland's east coast's tropical and subtropical regions and processed into raw sugar with sufficient capability.[142] Sorghum is grown as a summer grain crop in the central QLD and NSW zones.

As a long-established industry, an existing supply chain for collection and aggregation of sugarcane and sorghum is in place, which can be leveraged for SAF production.

142 Sugar (2023) Department of Agriculture, Fisheries and Forestry. <https://www.agriculture.gov.au/agriculture-land/farm-food-drought/crops/sugar> (accessed 26 April 2023).

Figure 41. Current state of Australia's carbohydrate to SAF supply chain



Apart from the infrastructure needed for fuel synthesis, there are additional challenges in the supply chain that need to be addressed. These include finding ways to free up bagasse from its current use in power and steam generation at mills, as well as developing methods for transporting low-density bagasse to a centralised plant. Another approach could be to convert the low-density bagasse into a more energy-dense intermediate, such as ethanol, before transporting it to a centralised plant for further upgrading.

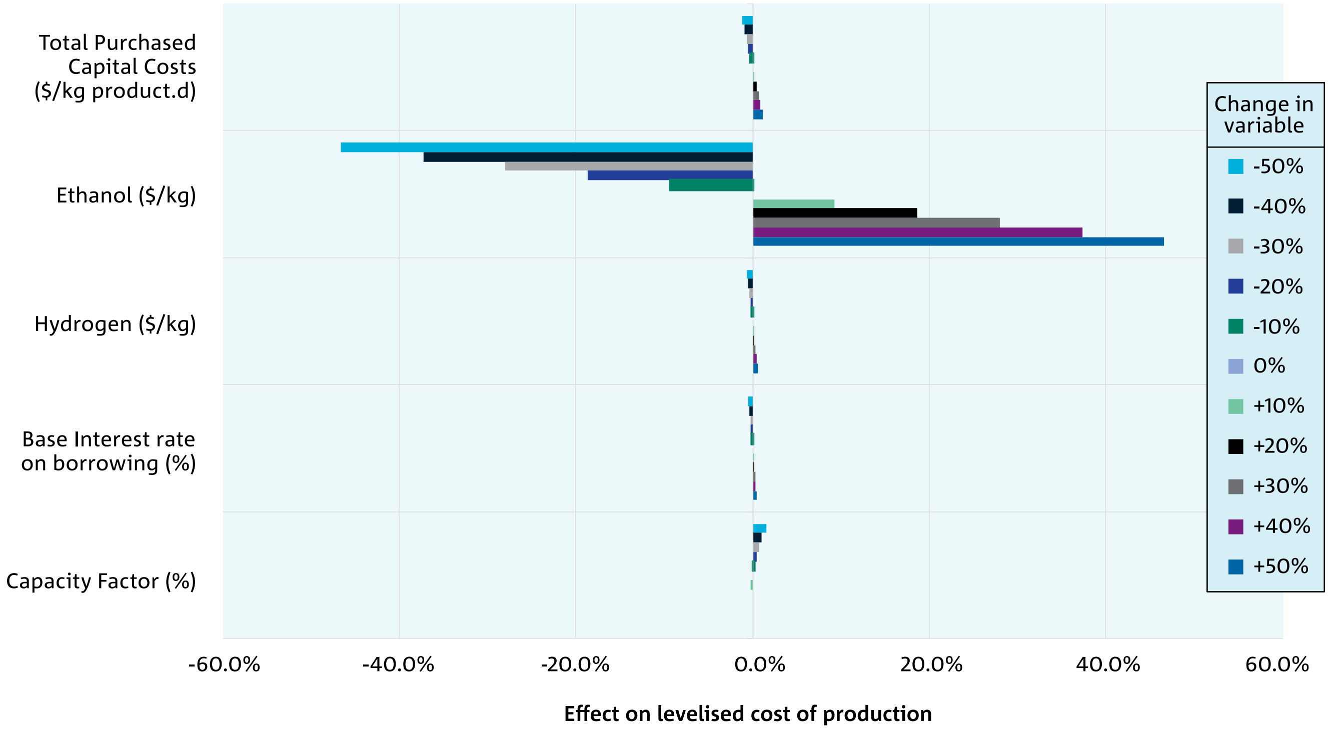
There are currently two plants in Australia that produce ethanol from waste starch and molasses derived from wheat. However, despite having a combined annual capacity of 360 ML, these plants are not being fully utilised and only operated at 57% capacity in 2022.[143] Additionally, there is a previously decommissioned ethanol plant located in Dalby, which could add another 80 ML to the total capacity. Increasing the capacity of the existing plants and reopening the Dalby refinery presents a promising opportunity to boost local ethanol production for ATJ facilities in the near term.

143 Kelly A (2022) Ethanol fuel production in Australia. IBISWorld.

Technoeconomic analysis and key cost drivers

A sensitivity analysis was performed to understand the key cost drivers of producing SAF from ethanol. Using these results, methods to reduce fuel costs and their limitations can be considered.

Table 5: Sensitivity on key cost inputs – Ethanol to jet



Ethanol price: In the ethanol-to-jet pathway, such as with HEFA, the price of the feedstock is the main factor driving costs. To achieve significant cost reductions for SAF produced through ATJ, it is necessary to lower the process costs associated with ethanol production. This can be accomplished through the development of alternative methods for ethanol production and the reduction in demand for ethanol in road transportation as electric vehicle adoption increases. By implementing these strategies, it may be possible to decrease the price of ethanol and, in turn, lower the cost of ATJ-derived SAF.

Considerations and challenges for carbohydrates

Economic

Liberating bagasse from current use: Bagasse is combusted on site to produce heat and steam. Given it is a waste product that requires disposal, this process is deliberately inefficient to ensure no bagasse remains. Accessing large quantities of bagasse will be dependent on finding alternative, economically viable renewable energy solutions for sugar millers that do not disrupt current operations adversely. More efficient boilers, alternative energy sources such as solar and batteries, and financial incentives may be necessary.

Case study – Utilising bagasse at sugar mills

The sugarcane industry has a long history of utilising sugarcane waste or residues like bagasse to produce heat and renewable electricity to power the mills and export surplus electricity to the grid. Current capacity amounts to over 1 million megawatt hours of cogenerated electricity annually, 56% of which are used to power onsite operations. This equates to 27% of Queensland's renewable electricity supply and estimated GHG emissions reductions of 1.5 Mt.

However, bagasse derived power generation systems achieve a net efficiency of approximately 20%.[144] In comparison, global averages for electricity production from fossil fuels are between 34-40% and wind energy efficiency reaches almost 60%.[145] Often, inefficiencies are incurred intentionally during bagasse combustion to maximise disposal volumes.

One solution is the co-production of ethanol and electricity from sugarcane bagasse at existing mills. International examples have shown an increased process energy efficiency during techno-economic analysis.[146] Furthermore, ethanol production is more desirable than electricity generation from bagasse, when considering the avoided CO2 emissions.[147]

Industry views that 5 Mt, approximately half of the bagasse, can be freed up for alternate uses if investments in energy efficient infrastructure were made.[148] These include electrification of steam turbines, developing high voltage networks and bagasse drying processes.[149]

Despite the obvious sustainability benefits, capital is required to liberate the sugarcane bagasse. Stakeholder consultations suggest investment upwards of $20 million is likely needed to upgrade the energy infrastructure at each mill. Some would require even more investment, depending on the efficiency and state of their milling technologies.

Biosecurity risks: Like many industries, biosecurity and pests concern the sugarcane industry. Queensland's proximity to Southeast Asia increases the risk. The introduction of sugarcane smut, the whitefly or yellow leaf virus, could significantly affect the industry's output. Various biosecurity measures include crop monitoring and quarantine protocols to protect the industry. Continued vigilance and implementation of these measures are critical to safeguarding the industry.

The desire for growth and new markets: The sugar industry is keen to increase output and explore new markets and customers to position the sector as part of Australia's bioeconomy for the long term.[150] Much work has already been completed or is underway that examines the product potential for sugarcane and waste, including using ATJ or FT to produce SAF. This interest and knowledge base make Queensland and its surroundings a key candidate for early deployment of ATJ and FT.

Ethanol production is limited: Low local ethanol production could limit early deployment of ATJ plants or force reliance on imported ethanol in the shorter term. Australia has two remaining operational ethanol production facilities in Nowra, NSW and Sarina, QLD. Australia's potential ethanol production is approximately 360 million litres per year and relies on the fermentation of waste starch and molasses. If the Dalby refinery were re-commissioned, an additional 80 million litres of ethanol annually would be available for jet fuel conversion.

New ethanol production comes with challenges such as high capital investment requirements and higher labour and energy costs than competing countries. To mitigate investment risk, strong local demand signals would be needed.

Competing land use: As sugarcane farmers face the challenge of price volatility in the sugar market, some are considering diversifying into other crops such as macadamia trees, avocados, citrus, and berries. While this may provide an alternative revenue source, it could also lead to increased competition for land and negatively impact growth projections for sugarcane. However,

144 https://www.tandfonline.com/doi/pdf/10.1080/15453660909595148

145 https://www.planete-energies.com/en/media/article/energy-efficiency-power-and-measurement; https://iea.blob.core.windows.net/assets/acaecb98-4430-4395-a4fa-d1a4d5ccb3d3/EnergyEfficiencyIndicatorsforPublicElectricityProductionfromFossilFuels.pdf

146 https://biotechnologyforbiofuels.biomedcentral.com/articles/10.1186/1754-6834-7-105

147 https://onlinelibrary.wiley.com/doi/full/10.1002/bbb.1662; https://www.sciencedirect.com/science/article/pii/S0306261913002778?via%3Dihub#b0185

148 https://asmc.com.au/industry-welcomes-recognition-of-the-sugar-industrys-renewable-energy-potential-28-september-2022/

149 https://www.diva-portal.org/smash/get/diva2:905929/FULLTEXT02.pdf

150 Sugar Research Australia (2022) Sugar Plus – Fuelling the Future of Food, Energy and Fabrication

with market signals indicating a greater demand for sugarcane, farmers may be swayed back to cultivating it. It is therefore important to strike a balance between diversification and maintaining sugarcane production to ensure the long-term sustainability of the industry.

Sustainability

The sugarcane industry is targeting improved measurable performance. The industry has developed a national sustainability framework that outlines crucial environmental, social, and economic sustainability goals and indicators. CSIRO has been involved with sugar mills and cane farmers to reduce nitrogen loss through precision application of fertilisers and developing new generation fertilisers.[151] Other initiatives focus on reducing water use and enhancing biodiversity and crop resilience.

The industry has also implemented Great Barrier Reef (GBR) protection measures that aim to protect the reef by reducing agricultural run-off, including retaining nitrogen, phosphorus and sediment to improve water quality.[152] Continued commitments and enactment of initiatives will help to maintain good environmental outcomes and water quality targets for the industry. However, there is concern that expanding the sugarcane industry would lead to increased runoff and reverse the progress made towards improved GBR water quality.

R&D

Selecting sugarcane for biofuel characteristics: Growing "energy cane", a variety of sugarcane with a higher fibre content, could provide more biomass for conversion into SAF. Historically, sugarcane has been bred to minimise fibre and maximise sugar content, and bagasse has been seen as a waste product.[153] However, with a new market for bagasse, a shift to energy cane could increase the available biomass. Further research is needed to determine the amount of extra bagasse that could be produced and its potential impact on sugar output and export markets in Australia.

Conclusion

Sugarcane is an established industry in Queensland with a mature supply chain that provides carbohydrates for sugar production. By-products such as bagasse are used onsite to generate heat and steam.

Sugar and residues can be upgraded into fuel either via fermentation followed by ATJ, or through hydrothermal processes like gasification followed by FT. Although fermentation is practiced commercially in Australia, its upgrading into SAF via ATJ is not, neither is FT.

The sugar industry primarily produces sugar for export and is looking to diversify its customer base. The industry is actively considering new industries that they can supply sugar into to disconnect from global sugar prices, so convincing farmers to sell their sugarcane to a jet fuel producer could be straight forward provided the business case is sound. This business interest still needs to be balanced with the potential social impact challenges that come with shifting food into fuel production.

If ATJ is to be pursued, Australia would need to increase ethanol production significantly. Re-opening the Dalby refinery and exploring options for new centralised and distributed ethanol plants will be necessary.

In relation to upgrading bagasse, supply chains need to be designed to minimise bagasse transport. Therefore, technology choice is likely to favour a distributed upgrading model to an intermediate, such as ethanol or bio-crude, which is then transported to a centralised fuel processing centre.

Both sugar and bagasse were modelled to understand potential feedstock production and potential jet fuel production. By converting 10% of Australian sugar and 25% of bagasse into jet fuel, there is the potential to produce 988 ML of jet fuel in 2025 comprising 11% of Australia's projected jet fuel consumption.

With the sugarcane industry implementing a range of sustainability initiatives to reduce water use, pesticide use, and enhance biodiversity, continued research and monitoring of sustainable farming practices will need to continue to manage healthy ecosystems.

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151 CSIRO Submission 19/683: Identification of leading practices in ensuring evidence-based regulation of farm practices that impact water quality outcomes in the Great Barrier Reef

152 Queensland Government (2023) Requirements for sugarcane growers. https://www.qld.gov.au/environment/agriculture/sustainable-farming/reef/reef-regulations/sugarcane

153 Matsuoka et al (2014) Energy Cane: Its Concept, Development, Characteristics, and Prospects. Advances in Botany

The opportunity for Queensland to produce SAF from sugar and bagasse is significant. Established supply chains, willing feedstock producers and mature technology options make ATJ an attractive option for SAF production in the immediate to medium term if sugar and bagasse can be liberated from current uses.

7.2.2 Waste

Waste feedstocks refer to organic materials or biomass discarded after primary use. Of interest are the following:

- municipal solid waste (MSW),
- used cooking oil (UCO) and
- tallow.

Households and other non-industrial sources, including a mixture of food scraps, plastics, paper, textiles, glass and metals generate MSW. This is collected by local authorities and processed in landfill or recycled.

UCO is the remaining oil from cooking food generated by food service establishments like restaurants and households. As disposal is problematic for the sewage system and environment, UCO is either recycled to animal feed or converted to biofuels.

Tallow is a type of fatty by-product resulting from the meat rendering of beef and mutton. It has various applications in food products, soap and candles, and biofuel. Australia is one of the largest producers of tallow worldwide and a major exporter.

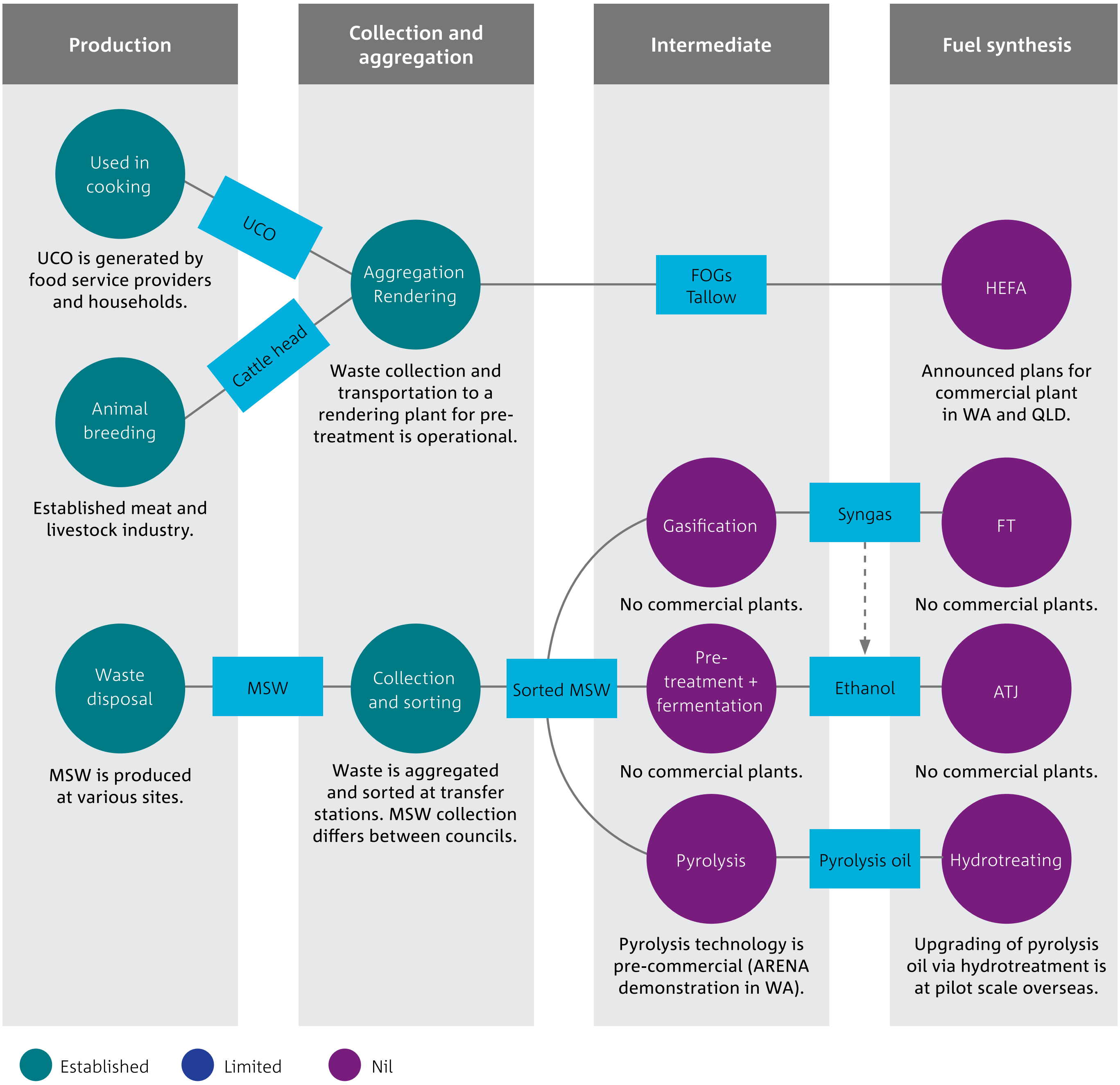
UCO is concentrated around densely populated urban areas, as it is generated in various locations such as households, restaurants, food service outlets and manufacturing plants. Collection and rendering is available through waste management services in every major city.

Queensland produces around 45% of all cattle in Australia, with Victoria and New South Wales making up another 33%. Tallow processing facilities, abattoirs and rendering plants, are located down the entire east coast, central Victoria and found near each state's capital.

MSW is collected through household kerbside waste and recycling stations within local councils. Numerous waste and resource recovery facilities are distributed across Australia.

Waste feedstock production, collection, and aggregation benefit from mature supply chains. Although challenges remain for the efficient, cooperative and cost-effective collection and transport of wastes, feedstocks are relatively concentrated within urban areas, and current infrastructure has sufficient capacity to divert waste from disposal. Supply chains to produce waste intermediates and synthesise SAF do not exist within Australia and require several solutions, such as technology development, regulatory approval and capability demonstrations.

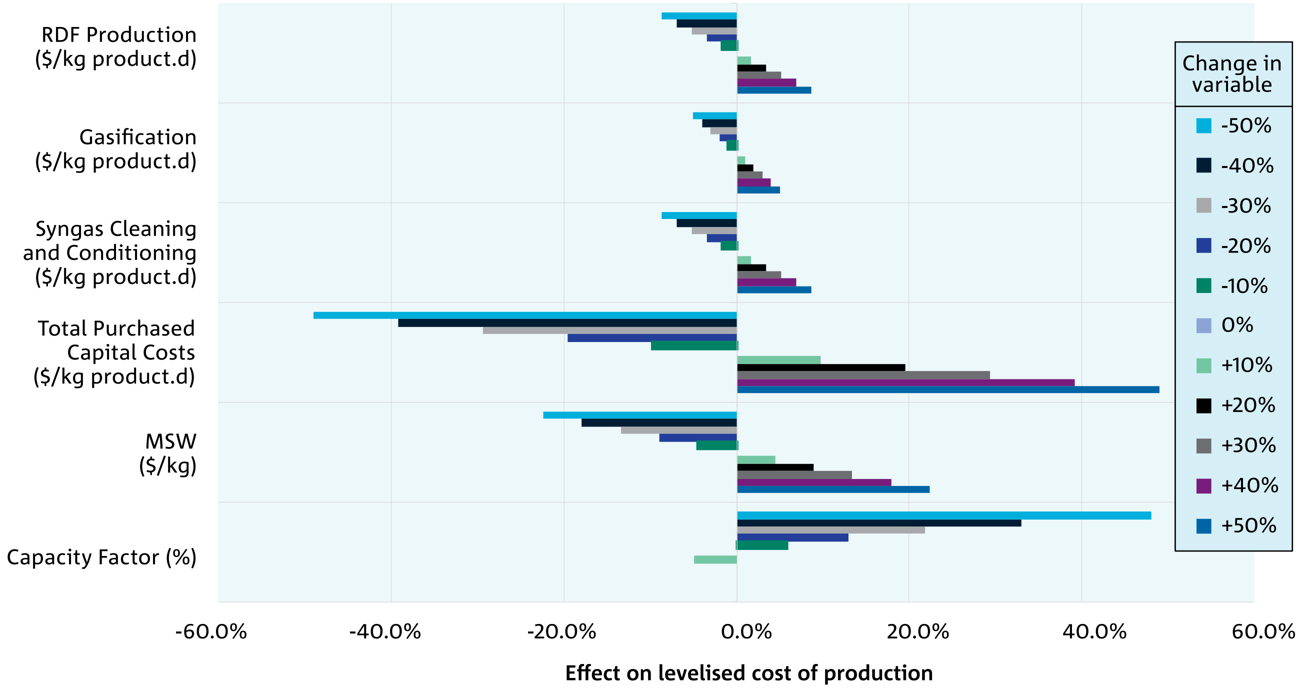
Figure 42. Current state of Australia's waste to SAF supply chain



Technoeconomic analysis and key cost drivers

A sensitivity analysis was performed to understand the key cost drivers of producing SAF from MSW using gasification and FT. Using these results, methods to reduce fuel costs and their limitations can be considered.

Table 6: Sensitivity analysis of the impact of key cost inputs on levelised cost - FT-SPK from MSW



Capacity factor: Lowering the capacity factor of the plant (the time in which it is operational and processing feedstocks) can significantly affect the cost of production. This means that feedstock supply needs to be adequate to eliminate any downtime that may be incurred by delayed delivery or sorting, or supply shortages.

Capital costs: Capital costs affect levelised cost of production significantly, reflecting the capital-intensive nature of FT plants. This could reduce overtime if FT plants become more common as large-scale plants are currently rare.

MSW price: As per most pathways, the cost of feedstock has a significant effect on the price of the SAF produced. When negotiating with councils, the price of MSW will be key to understanding the economic viability of fuel production.

Considerations and opportunities for wastes

Economic

Mixed and evolving nature of MSW: The heterogeneity of MSW can affect SAF yield and quality. Different input materials yield different volumes, and many materials have high moisture and ash content and low heating value which can decrease the thermochemical conversion rate.[154] The presence of fine contaminants in MSW such as soil, dust or aluminium foil can deactivate the catalysts required for the pyrolysis and decrease the favourable properties of the final product.[155] As a result, MSW typically requires pre-treatment including sorting, cleaning and drying which adds extra costs to the production. As the make-up of MSW is likely to evolve overtime as other uses are found, and waste management practices and legislation change, MSW consistency may impact processing requirements and create supply challenges.

154 https://www.sciencedirect.com/science/article/pii/S1364032122006980
155 https://www.sciencedirect.com/science/article/pii/S0378382017318064?via%3Dihub
156 https://www.euractiv.com/section/agriculture-food/news/new-fraud-investigation-casts-doubt-over-used-cooking-oil-origins/
157 https://www.euractiv.com/section/alternative-renewable-fuels/news/proposed-eu-green-jet-fuel-mandate-risks-incentivising-fraud-mep-warns/
158 https://theicct.org/wp-content/uploads/2022/09/refueleu-definitions-trilogue-sep22.pdf
159 2021 Australian census.
160 https://www.gtlaw.com.au/knowledge/energy-waste-load-rubbish-or-viable-solution-landfill

Waste fraud: The increasing global demand for UCO and tallow as SAF feedstock may encourage harmful practices and fraudulent activities would could have negative effects on the credibility of SAF producers and users. For example, a Dutch company illegally collected animal fat and mixed it with UCO to trade it as a raw material for sustainable biofuel.[156] Additionally, many feedstock exporting countries such as Indonesia, Malaysia and China were suspected to have sold virgin palm oil as UCO to take advantage of the higher prices.[157] The tampered feedstocks in both examples were found to have significant GHG intensity, even worse than fossil fuels. To mitigate fraudulent activities in the EU, the International Council on Clean Transportation recommends introducing a cap (1.7%) to the proportion of waste-based feedstock in total SAF production.[158] In Australia, regulatory developments and technological investments will be needed to build a transparent supply chain.

Multi-party negotiations: Obtaining a sufficient supply of MSW for SAF production may require enlisting multiple councils, which can be challenging due to the need for several agreements to ensure ongoing feedstock supply. Protracted negotiations may lead to a shortfall in supply or high feedstock prices that could impact production capacity. It is important to establish strong relationships with councils and stakeholders and have a clear plan for securing adequate feedstock supply to ensure the success and sustainability of the SAF production process.

Brisbane will provide the most straightforward MSW to SAF test bed as the City of Brisbane council encompasses a significant portion of the Brisbane metropolitan area, with a population of approximately 1.2 million people, compared to Melbourne and Sydney where councils are smaller in size and more numerous.[159]

Shift from waste to product: The sustainability movement's focus on circular economies and product life cycles is creating a new perception of waste as a valuable resource. As a result, waste and residues are increasingly sought after for recycling, upcycling, and energy production, which can drive up their market value. This shift is already underway, with stakeholders reporting rising demand for waste-derived feedstocks like tallow and UCO for the production of SAF. As more companies enter this market, the competition for feedstocks may intensify, potentially leading to higher prices and new challenges for sourcing adequate quantities of waste materials.

Landfill levy competition: Each state except the Northern Territory imposes a landfill or waste levy. These are not consistent across different jurisdictions and effectively determine whether waste-to-energy is a viable economic alternative to landfill. If the waste levy is substantially lower than the cost of waste-to-energy solution, then there is no financial incentive for councils to divert waste from landfill disposal to alternative treatment of waste, such as SAF production.[160]

Table 7: Waste levies (2022-23) of Australian states ($ per tonne waste)[161]

ACT	NSW	QLD	SA	TAS	VIC	WA
$105.25	$151.60	$95	$149	$20	$125.90	$105 per m^3

Note: Waste levy collected for metropolitan areas. Different fees apply for different materials and sources.
Eg. Category 1 and Category 2 waste and commercial waste fees are higher, whereas lower fees are encountered in rural or regional landfill areas.

Sustainability

Minimising landfill drives sustainability outcomes: The production of SAF from MSW can have environmental benefits by reducing the amount of waste sent to landfills. Landfills that lack proper methane capture mechanisms can release large amounts of methane into the atmosphere, contributing to GHG emissions and climate change. Additionally, harmful pollutants can be released into the surrounding air and water, posing a threat to public health and the environment. By diverting MSW from landfills to be converted into SAF, these issues can be mitigated, making it an effective strategy to drive sustainability outcomes.

Sustainable waste management: To achieve good sustainability outcomes, it is crucial to recycle and reuse components of MSW. For instance, recycling plastics not only reduces the demand for fossil fuel-derived plastics but also helps keep CO_2 locked in a solid form instead of being released into the atmosphere as fuels. It is essential to consider the sustainability implications of including specific waste and identify opportunities for reuse and recycling before processing MSW into fuel.

Social impact

Negative perceptions toward burning waste: Australia's bioenergy industry has faced significant challenges in gaining social acceptance due to public perceptions of the industry being dirty and harmful to the environment and public health, despite obtaining EPA approval and using proven technology. This negative perception is exemplified by the Cleanaway waste-to-energy plant proposal in western Sydney, which received 630 submissions from the public, with 600 objecting to the project.[162] The NSW government has changed the planning system to ban thermal energy development from waste facilities, with limited exceptions.[163] This attitude could extend to the production of SAF from MSW, making it crucial to carefully address concerns about location selection, EPA guidelines, and public education to alleviate any concerns and build trust in the technology. Failure to do so could lead to significant difficulties in securing the necessary public and regulatory support for this industry to grow and realise its full potential as a sustainable energy solution.

Policy

Price parity for alternative waste solutions: Stakeholders noted a significant price disconnect between landfill waste disposal and alternative waste solutions such as waste-to-energy. This differs between Australian states, as well as across metropolitan and regional areas, making it challenging to develop coordinated and consistent SAF production processes. In Europe, the waste pricing issue has been overcome through government policy settings like using landfill levy pricing to achieve parity with alternative waste treatment and incentivise waste-to-energy technologies.[164] Potential producers in Australia are calling for a similar manner of policy support.

161 https://nre.tas.gov.au/environmental-management/waste-and-resource-recovery/landfill-levy-faqs, https://www.epa.vic.gov.au/waste-levy, https://www.epa.nsw.gov.au/your-environment/waste/waste-levy/levy-regulated-area-and-levy-rates, https://www.der.wa.gov.au/your-environment/waste/151-landfill-levy, https://www.epa.sa.gov.au/business_and_industry/waste-levy, https://www.qld.gov.au/environment/management/waste/recovery/disposal-levy/about/levy-rates, https://www.cityservices.act.gov.au/about-us/fees_and_charges

162 Skatssoon J (2020) Sydney energy from waste plant faces pushback. Government News. https://www.governmentnews.com.au/western-sydney-energy-from-waste-plant-faces-pushback/

163 NSW Government (2022) Energy from waste. https://www.planning.nsw.gov.au/Assess-and-Regulate/State-Significant-Projects/Energy-from-waste

164 https://www.gtlaw.com.au/knowledge/energy-waste-load-rubbish-or-viable-solution-landfill

Tallow exports for SAF production

Australia's largest market for tallow is in Singapore, with over 223,000t of tallow exported in 2021/22 for biofuel production.[165] Neste Singapore refinery uses animal fats to produce biofuels with an expansion into SAF by the end of the first quarter of 2023.[166] It hopes to add an annual capacity of up to 1 million tonnes of SAF in addition to its 1.3 million tonne renewable diesel capacity, requiring more waste feedstock like tallow.[167] As of 2021/22, around 156,000t of Australian tallow is exported to the US, up from 7,500t five years previously, according to ABS records.[168] This recent growth could continue with the Inflation Reduction Act 2022 includes numerous incentives for SAF production, such as a US$1.25/gal blending credit which aim to meet the annual domestic production goal of 3 billion gallons set by the Biden administration.[169] The U.S. Department of Energy highlighted that SAF production from lipids would be the major process until 2030, which could expand demand for waste fats like tallow from international markets.[170]

7.2.3 Residues

Residues is a term for biomass remains from agricultural and forestry practices. These include stalks, leaves, husks, or any other materials left over after crops are harvested, as well as wood chips, bark, branches and other parts of trees left over post-harvest. Residues are generally low-value products, called waste, and are left in the field to decompose or are burned. However, when managed sustainably, agricultural and sawmill residues can be an important source of renewable biomass for energy production or feedstock for SAF.

Australia's primary residues consist of straw, bagasse, gin trash, sawmill, and logging. Coppiced mallee also provides another unique opportunity for sustainable biomass generation by adopting the practice of repeatedly cutting down multi-stemmed eucalyptus trees to ground level and promoting new growth from the base of the tree.

Agricultural and sawmill residues are widely distributed across Australia, depending on specific crops grown and harvest management styles.

Western Australia residues consist mainly of cereal straw, fruit, and vegetable residues, and some limited plantation sawmill residues and oil mallee stems.

Victoria and Tasmania residues are derived from cereals straw and chaff, as well as native and plantation forestry harvest and wood processing.

South Australia mainly produces straw, hay, and silage residues.

North-eastern region, including NSW and Queensland, gives access to residues such as cotton gin trash, straws from cereal, wheat and sorghum, forestry harvest, wood processing and sawmill activities. Additionally, sugarcane bagasse is a unique resource found in QLD.

Existing supply chains for collecting and processing residues are limited to sugarcane bagasse. Overcoming challenges, such as the efficient and cost-effective collection and transport of residues or mallee biomass due to geographic dispersion and lack of infrastructure for harvesting, storage, and processing are crucial to establishing a supply chain for SAF production.

165 Tallow: ABS 2007, Information Consultancy Services, cat. no. 9920.0, Canberra. Assumes tallow exports ≈ tallow production given data availability. Excludes foreign (re-exports). Tallow exports = AHECC codes 15020041, 15020051, 15020059, 15020060, 15021000, 15021001, 15021002, 15021003, 15021041, 15021049, 15021060, 15021061, 15021062, 15021063, 15030000.

166 Neste (n.d) *A wide variety of renewable raw materials.* <https://www.neste.com/products/all-products/raw-materials/renewable-raw-materials#ac9017e0> (Accessed 22nd December 2022).

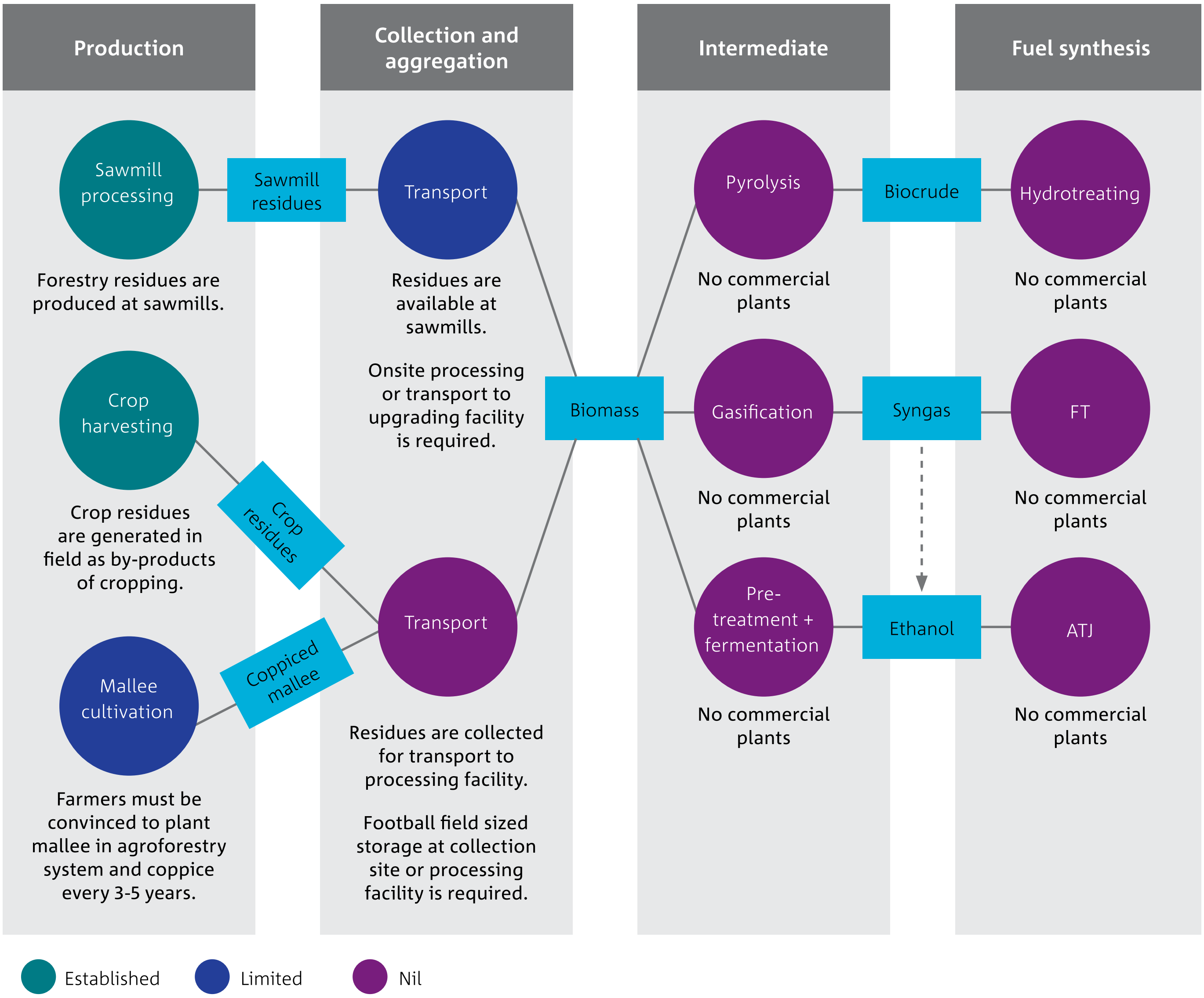
167 Samanta K (2022) *Neste to start Singapore sustainable aviation fuel plant by Q1 2023 – executive.* <https://www.reuters.com/business/sustainable-business/neste-start-singapore-sustainable-aviation-fuel-plant-by-q1-2023-executive-2022-02-16/> (Accessed 22nd December 2022); Neste (n.d) *Singapore.* <https://www.neste.com/about-neste/who-we-are/production/singapore#ac9017e0> (Accessed 22nd December 2022).

168 Tallow: ABS 2007, Information Consultancy Services, cat. no. 9920.0, Canberra.

169 Lavinsky C (2022) *Inflation Reduction Act charts a new course for US biofuels industry*. <https://www.spglobal.com/commodityinsights/en/market-insights/blogs/agriculture/090822-ira-inflation-reduction-act-us-biofuels> (Accessed 22nd December 2022); The White House (2021) *Fact Sheet: Biden Administration Advances the Future of Sustainable Fuels in American Aviation.* <https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/> (Accessed 22nd December 2022).

170 Golner W et al. (2022) *SAF Grand Challenge Roadmap*. Prepared by the USDE, USDT and USDA, Washington, D.C.

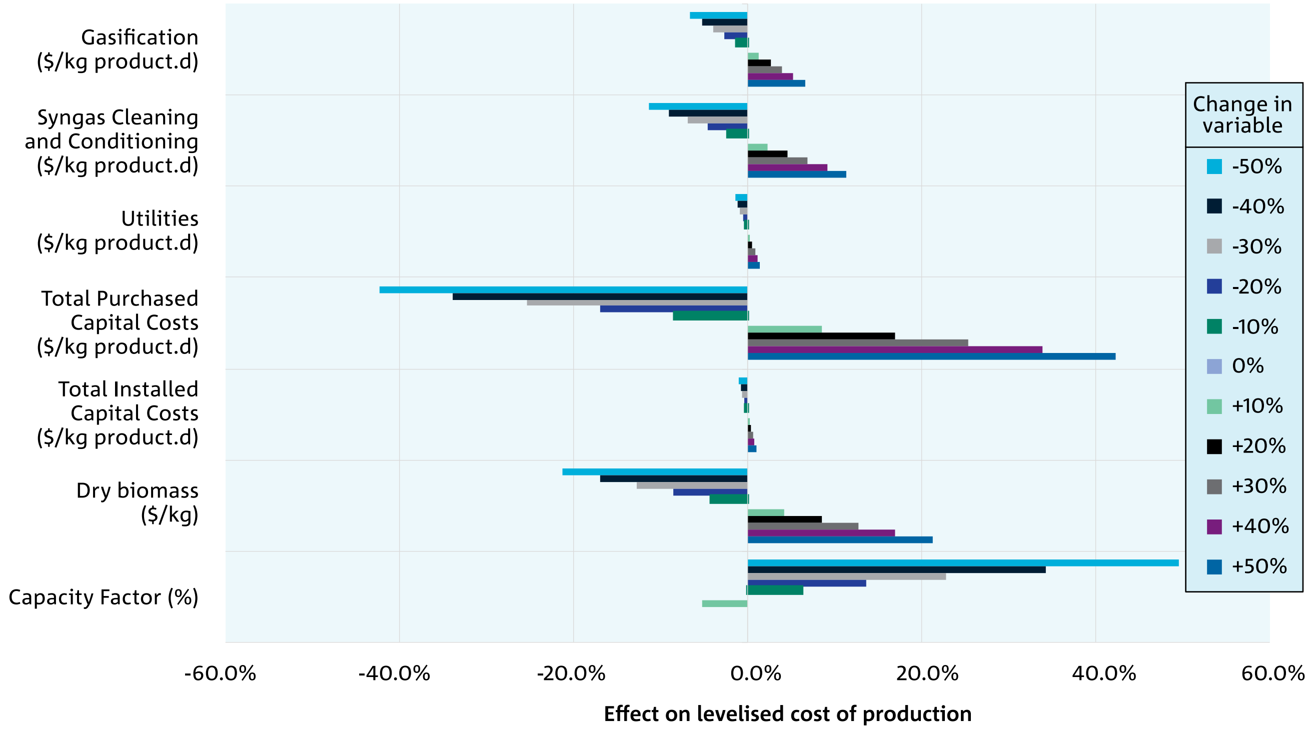
Figure 43. Current state of Australia's residue and coppiced mallee to SAF supply chain



Technoeconomic analysis and key cost drivers

A sensitivity analysis was performed to understand the key cost drivers of producing SAF from residues. Using these results, methods to reduce fuel costs and their limitations can be considered. As a feedstock, bagasse was used as it has a similar chemical composition to forestry and agricultural residues.

Table 8: Sensitivity analysis on key cost inputs - FT with gasification of crop residues



Capacity factor: Lowering the capacity factor of the plant (the time in which it is operational and processing feedstocks) can significantly affect the cost of production. This means that the feedstock supply needs to be adequate to eliminate any downtime incurred by delayed delivery or sorting or supply shortages.

Capital cost: Capital costs affect the levelised cost of production significantly, reflecting the capital-intensive nature of FT plants. This could reduce over time if FT plants become more common as large-scale plants are rare.

Feedstock input: As per most pathways, the cost of feedstock significantly affects the price of the SAF produced. The final cost of delivered residues will be a critical factor in assessing the economic viability of a residue supply chain. Fuel production may become unfeasible if collection and transport costs are too great.

Considerations and challenges for residues

Economic

Collection and aggregation economics: As crop residues are not collected in many instances, a shift to utilisation may require a change in how harvesting is conducted, for example by having to run a baler behind a harvester which could increase costs. Additionally, due to the low density of these residues, transport of the biomass should be minimised. Stakeholder consults imply that transport distances over 100 km lead to uneconomic supply chains. Alternatively, modular technologies such as pyrolysis and advanced fermentation could enable the production of higher density intermediates which could increase the economic transport distance.

Similarly, for sawmill residues, although these are collected at sawmill locations, it will take aggregation of several mills to supply a biofuel refinery. Further studies are needed to understand the economic challenges of supplying adequate residues to a plant constantly.

Sustainability

Crop residue balance: Balancing the amount of crop residues left on the field is crucial for maintaining soil health and productivity. When left on field, crop residues can provide essential nutrients and organic matter to the soil, improve moisture retention, reduce erosion and control weed growth. However too many residues left can pose problems for the sowing and emergence of the following crop, negatively affecting productivity. The optimal amount of residues left on the field varies according to factors such as crop type, climate, and soil type. While it is common practice to leave some residues on the field, studies have shown that leaving too many residues can result in diminishing returns. Current research recommends leaving between 30-50% of residues on the field to achieve the maximum benefits for the soil and crop growth.[171]

Sources of woody biomass: Using forestry residues for bioenergy or biofuel purposes is a controversial issue, as it can have sustainability implications. Despite being labelled by some as wastes or residues, these materials play a crucial role in maintaining the health and integrity of forest ecosystems by sustaining carbon-nutrient-water stocks and flows. Their removal could deplete carbon stock, accelerate the time before CO_2 is released into the atmosphere, and lead to significant areas of forests being harvested to meet the demand for these residues.[172]

Sawmill residue utilisation may intensify the demand for low-grade wood for the purposes of producing more sawmill residues, leading to unsustainable harvesting practices. It is essential to consider these sustainability concerns and ensure that the use of sawmill residues is done in a way that does not harm the environment or jeopardise the integrity of forest ecosystems.

Social impact

Links to forestry industry: Logging of forests and plantations has historically been and continues to be a contentious issue. The use of sawmill residues could face public perception challenges being a by-product of the industry.

Policy

Changing policy landscape: Sawmill residues depend on the forestry industry. Recent policy changes in Victoria that cease native logging activity will reduce the potential for sawmill residues in Victoria. With biorefineries likely to have long asset lives, long term assurance that its feedstock can be produced is vital and there is a chance other jurisdictions may follow suit.

R&D

Improved field verification: Further spatial analysis to quantify and monitor annual variability in cropping and residues will help to quantify availability better and inform optimal biofuel plant location.

171 Mirzaei et al (2021) Preliminary Effects of Crop Residue Management on Soil Quality and Crop Production under Different Soil Management Regimes in Corn-Wheat Rotation Systems. Agronomy USDA (2006) Crop Residue Removal for Biomass Energy Production: Effects on Soils and Recommendations. Soil Quality National Technology Development Team.

172 Mackey, BG, Lindenmayer DB (2022) Burning Forestry Biomass for energy; Not a clean source of energy and harmful to forest ecosystem integrity Griffith University.

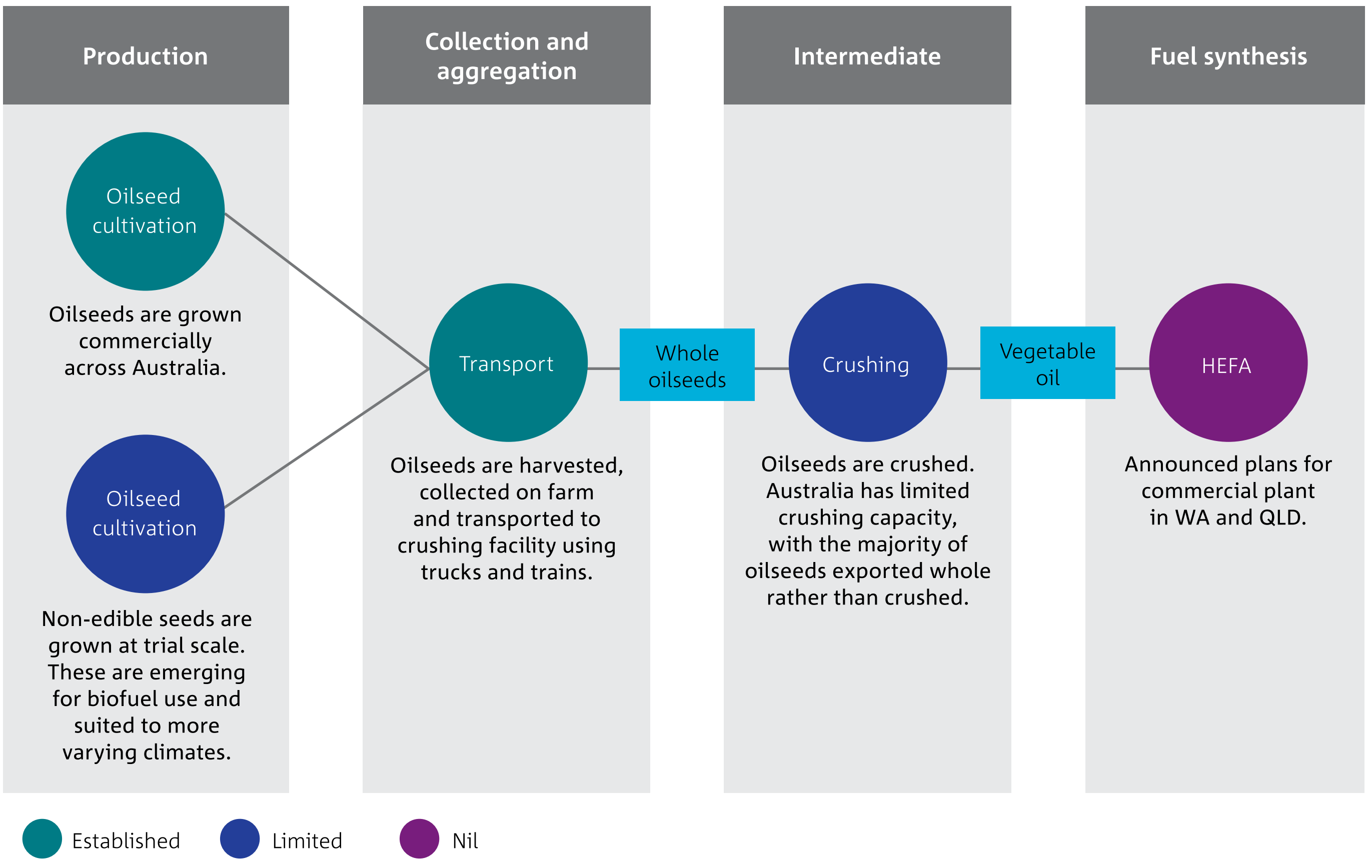
7.2.4 Oilseeds

Oilseeds refer to a range of seeds cultivated primarily to produce vegetable oil. These seeds are classified into two types: edible oilseeds and non-edible oilseeds or energy crops. In Australia, canola and cottonseed are the major oilseed crops. Other oilseeds grown in the country include soybean, sunflower, safflower, peanut, and linseed.

Australia is divided into three broadacre cropping zones that determine oilseed growth based on different climates, cropping, and market conditions. Canola is primarily grown in the Western Australia wheatbelt, and along the east coast, which features other oilseeds too given temperate and subtropical climates, fertile soil, and higher rainfall. While other oilseeds like pongamia and carinata have the potential to be grown in different climates, they are not yet commercially grown in Australia.

Australia has cultivated oilseeds for many years and has an established supply chain for their collection, aggregation, and export. However, domestic processing and consumption are constrained due to population size. This existing infrastructure lays the foundation for an oilseed to SAF supply chain, the current state of which is shown below.

Figure 44. Current state of Australia's oilseed to SAF supply chain

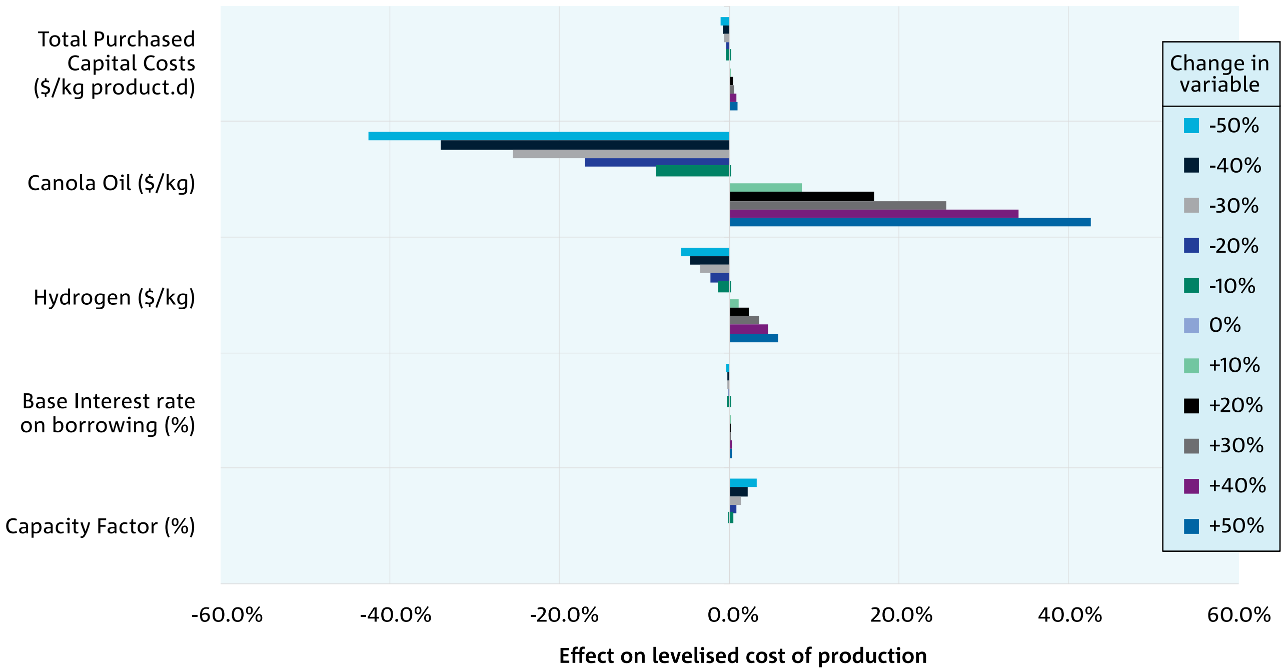


The development of a functional supply chain for SAF requires overcoming some challenges. Currently, Australia's crushing capacity is only enough to meet the domestic demand for vegetable oil. In 2022, 1.3 million tonnes of oilseed were crushed, which represents only 20% of the total harvest of 6.8 million tonnes. Therefore, if oilseed were to be used for SAF production, additional crushing capacity would be required.

Technoeconomic analysis and key cost drivers

A sensitivity analysis was performed to understand the key cost drivers of producing SAF from vegetable oil. Using these results, methods to reduce fuel costs and their limitations can be considered.

Table 9: Sensitivity analysis on key cost inputs – HEFA from vegetable oil



Vegetable oil input: To produce HEFA-derived SAF, the cost of vegetable oil is the primary factor influencing the overall cost of the process. Since vegetable oil is a mature agricultural product, it is unlikely that any innovations will significantly reduce its cost. The cost projections of HEFA-derived SAF will closely follow the price of vegetable oil, and as demand for vegetable oil increases due to population growth, its price is expected to rise. As a result, the cost of HEFA fuels is limited in how much it can be reduced.

Hydrogen cost: The cost of hydrogen is not a major cost driver for HEFA production, but it still plays a role. Currently, green hydrogen prices are high due to limited large-scale manufacturing and economies of scale, as well as a lack of available and affordable green electrons. However, there is an opportunity for commercial activity to help bring down the cost of electrolysers. As large-scale green hydrogen production develops and electricity prices decrease, the cost of hydrogen is expected to decrease, leading to a slight reduction in HEFA production costs.

There is an opportunity for commercial activity to help bring down the cost of producing hydrogen by improving the efficiency and scalability of electrolysis, as well as increasing the availability of renewable energy sources. It is important to note that feedstock costs have a significant impact on production costs, and without reductions in feedstock costs, the levelised cost of HEFA fuel production can only improve up to a certain point.

Considerations and challenges for oilseeds

Economic

Land management: Australia is currently utilising all available arable land for agriculture and grazing, meaning that there are limited options to significantly increase oilseed production without impacting other existing land uses. Continuous improvement through productivity gains is achievable through a mix of genetic modification, fertiliser usage and better farm management.

If oilseed production were to be significantly increased, it would likely be at the substitution of other crops or grazing land. Alternatively, the development and proliferation of new oilseeds such as carinata and pongamia provide an opportunity to utilise marginal cropland.[173]

173 https://agrifutures.com.au/wp-content/uploads/2021/08/21-085.pdf

Oil seed crushing by-products: Increasing local oilseed crushing can reduce reliance on meal imports and even provide an export opportunity to neighbouring countries. Crushing oilseeds produces a product known as a meal, which is high in proteins and is used in animal feed. Despite having limited local crushing capacity, there is still a gap in the local supply of meal, which is currently filled by imports. By increasing local oilseed crushing, a new meal supply could be created, reducing reliance on meal imports. This would provide an opportunity to meet local demand, and even provide an export opportunity to neighbouring countries. With increasing demand for high-quality protein in the Asia-Pacific region, there is potential to tap into this market by developing an export supply chain for local meal production.

Sustainability

Effects of cropping on the environment and natural capital: Long-term agricultural practices can adversely affect the environment. Monoculture cropping can lead to low biodiversity, changing the purpose of the land can disrupt natural processes, and water use and management require constant vigilance. The increasing use of fertiliser to generate higher crop yields leads to greater nitrogen oxide emissions from the soil. This however needs to be balanced in terms of the resulting higher soil organic carbon. Further research is required to understand the GHG balance of these two effects.

Solutions such as intercropping, where different species are grown during the same season, are not used widely in Australia due to additional labour requirements and increased complexity in farm management, harvesting and handling products. However, productivity, environmental and resource efficiency gains are needed to increase crop diversity.[174] Additional research is required to understand long-term benefits, complexity-productivity benefits, and ideal crop variety selections. Other potential solutions include agroforestry and silvopasture. Agroforestry and silvopasture enhance farming sustainability by integrating trees and livestock into agricultural systems, which helps conserve soil, enhance biodiversity, mitigate climate change through carbon sequestration, provide shade and shelter for livestock, and diversify income streams for farmers.

Social impact

Food versus fuel: Using canola and other edible oilseeds for SAF production may raise questions about using available land to grow food versus fuel, and this may deter consumers from accepting SAF made from these crops. Due to the constrained global supply of oilseeds, increased prices and food security concerns, the debate on whether the priority for crops should be for human consumption over biofuel production is in focus in regions such as the EU. Internationally this pressure translates into policy, such as the 7% cap on the consumption of crop-based biofuels, including vegetable oils, in the EU.

R&D

Genetic modification: Although European markets have historically preferred non-GM crops, this trend is starting to shift as the benefits of genetic modification become more widely recognised.[175] By pursuing genetic modification to enhance the yield of oil and specific carbon length oil, researchers can improve the efficiency and sustainability of vegetable oil production for jet fuel. These modifications can also increase crop resilience to environmental stressors, reducing the need for harmful pesticides and fertilisers.

Policy

Evolving international legislation: The EU biodiesel market has historically been a significant and valuable export destination for Australian canola oilseeds. Over the past ten years, volumes have averaged almost 1.7 Mt or 75% of total exports.[176] Australia's competitive advantage lies in the sustainability certification of its canola crop, relatively low GHG emissions intensity compared to other canola-producing nations and the offering of non-GM varieties. However, Australia's future as a significant supplier of canola seed to the EU biodiesel market is likely to be subject to changes in biofuel mandates due to food security pressures and the ongoing transition to EVs. This could provide the opportunity to redirect much of Australia's canola export to local demand and maintain customers for Australian farmers.

174 Fletcher et al (2016) Prospects to utilise intercrops and crop variety mixtures in mechanised, rain-fed, temperate cropping systems.

175 https://food.ec.europa.eu/plants/genetically-modified-organisms_en

176 CSIRO (2019) Maintaining access to EU markets for Australian canola.

7.2.5 Power-to-liquids

Power-to-liquids (PtL) is a process that involves the production of jet fuel using non-biogenic (i.e., non-biological) feedstocks, such as hydrogen and carbon dioxide, along with renewable energy sources. The term "power-to-liquids" refers to the fact that renewable energy is a critical component of the production process.

Currently, the Fischer-Tropsch process is the only approved PtL pathway. However, unapproved pathways also have the potential to be adopted in the future, such as the production of methanol from water and CO_2 for upgrading into jet fuel, known as Methanol to Jet (MTJ). The methanol pathway produces shorter chain hydrocarbons and therefore enables a more targeted fuel production process that requires significantly less feedstock when compared to an equivalent volume of fuel produced via FT. Future strategies for PtL scale should consider both FT and MTJ pathways.

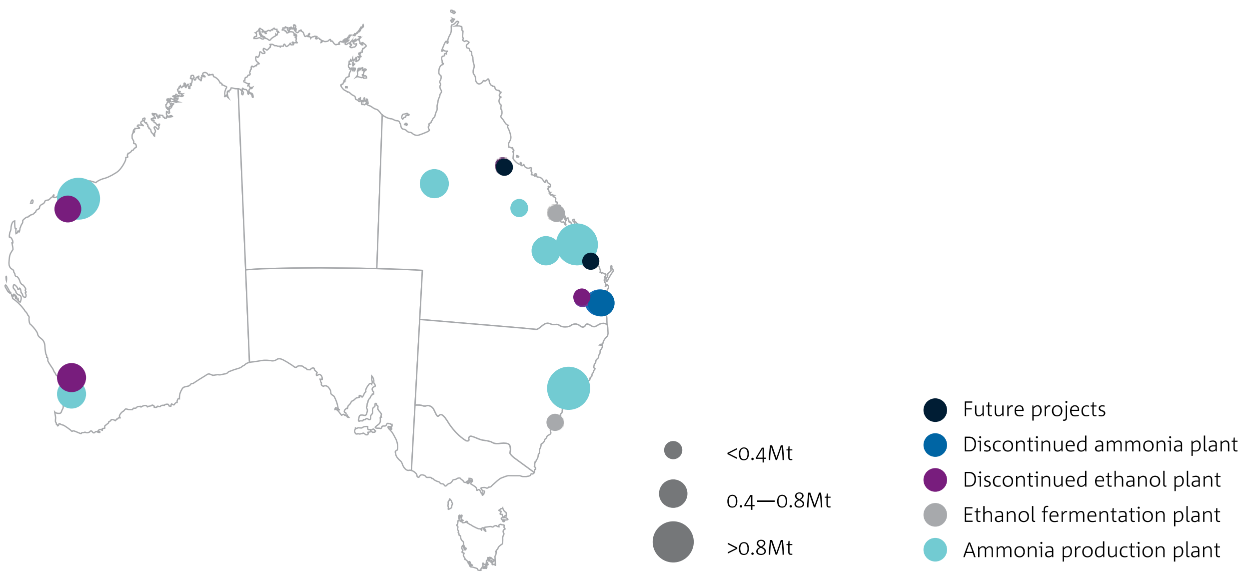
Hydrogen can be produced through various industrial processes, including Steam-Methane Reforming (SMR), which involves breaking down natural gas into hydrogen and CO_2. However, this report solely focuses on the use of green hydrogen as a feedstock for SAF. This is because processes like SMR are not carbon-neutral, which reduces the potential carbon offset of the resulting SAF. Green hydrogen, on the other hand, is produced through a process called electrolysis that uses renewable electricity to split water into hydrogen and oxygen. The carbon footprint of green hydrogen is determined by the carbon intensity of the electricity source used in the electrolysis process.

Currently, only limited quantities of green hydrogen are being produced in Australia. However, there are numerous planned projects throughout the country, some of which are highlighted below. These projects include the establishment of "hydrogen hubs", which are designated by the government as regions where industrial, transport, and energy hydrogen users are situated near one another. This allows for the sharing of infrastructure and a reduction in the cost of hydrogen production.

CO_2 is a waste stream generated from many industrial processes, such as the combustion of fossil fuels for power generation, ammonia production as a by-product of hydrogen production, and ethanol production as a by-product of fermentation. Australia produces CO_2 at several sites including power plants, cement kilns and natural gas reservoirs, mostly vented into the atmosphere. CO_2 is captured in small volumes, mostly from ethanol and ammonia plants for markets such as food and beverage and agriculture.

Operational ammonia plants are shown in the figure below. They are concentrated in industrial zones in Queensland, NSW and WA. The combined CO_2 production of these ammonia plants is 2.9–3.8 Mt annually.

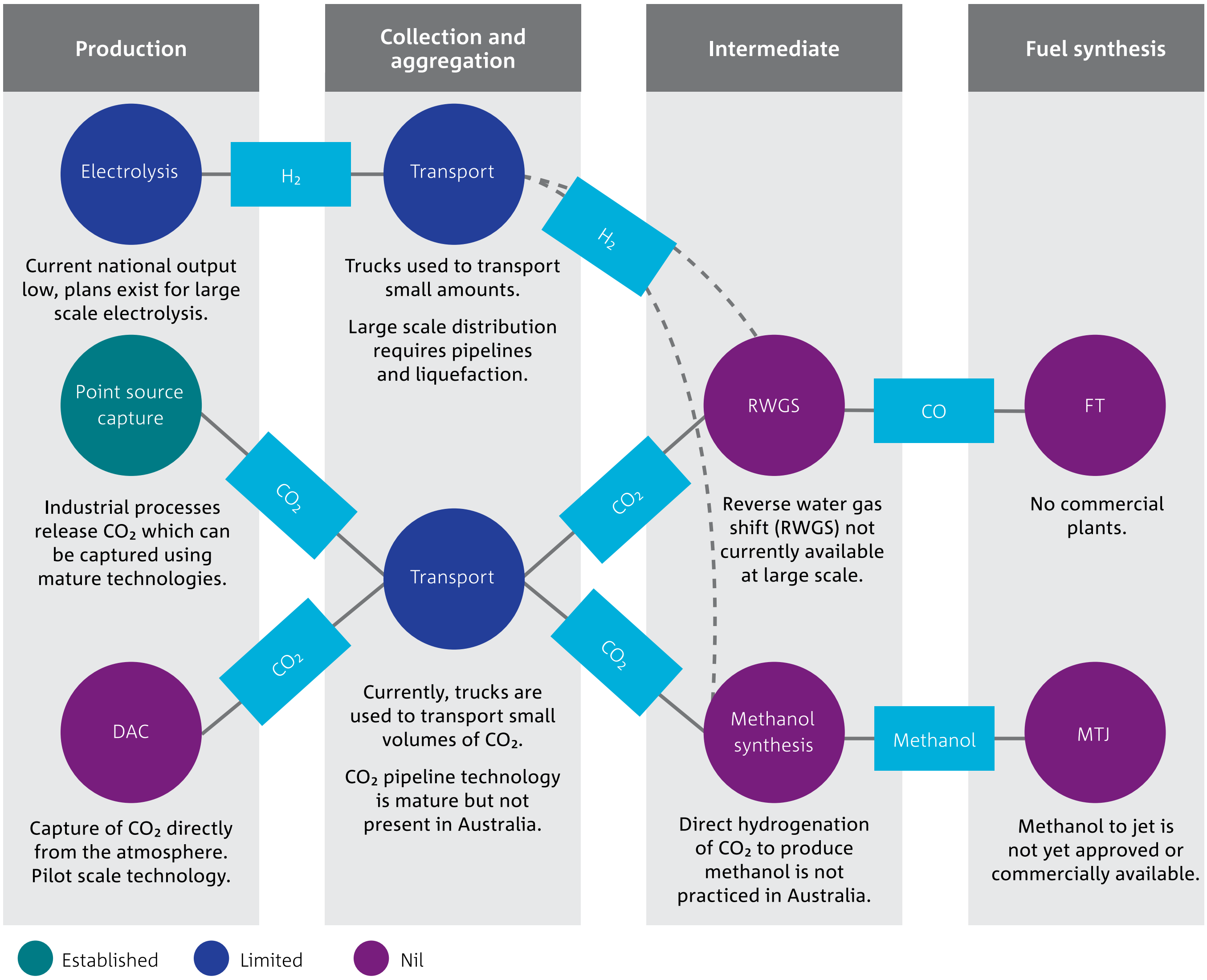
Figure 45. CO_2 emissions from past, present and future point sources at full capacity[177]



177 Kelly A (2022) Ethanol fuel production in Australia. IBISWorld; Peacock B (2021) *'Carbon negative' hydrogen & ammonia hub plan partially unveiled for Bundaberg*. <https://www.pv-magazine-australia.com/2021/10/06/carbon-negative-hydrogen-ammonia-hub-plan-part-unveiled-for-bundaberg/> (Accessed 13th December 2022); Environmental Protection Authority (2021) *Perdaman urea project.* Environmental Protection Authority prepared for Western Australian and Commonwealth Ministers for Environment, Perth; Shine R (2021) *Woodside Petroleum unveils plans for $1 billion hydrogen and ammonia plant in Kwinana*. <https://www.abc.net.au/news/2021-10-25/woodside-unveils-plans-for-hydrogen-plant-in-kwinana/100565502> (Accessed 27th January 2023); Yara (2022) *Yara Pilbara Fertilisers.* <https://www.yara.com.au/about-yara/about-yara-australia/pilbara/yara-pilbara-fertilisers/> (Accessed 13th December 2022); Orica (n.d) *Kooragang Island Operations.* <https://www.orica.com/Locations/Asia-Pacific/Australia/Kooragang-Island/Operations#.Y8DXEXZBw2w> (Accessed 27th January 2023); information provided by industry stakeholders.

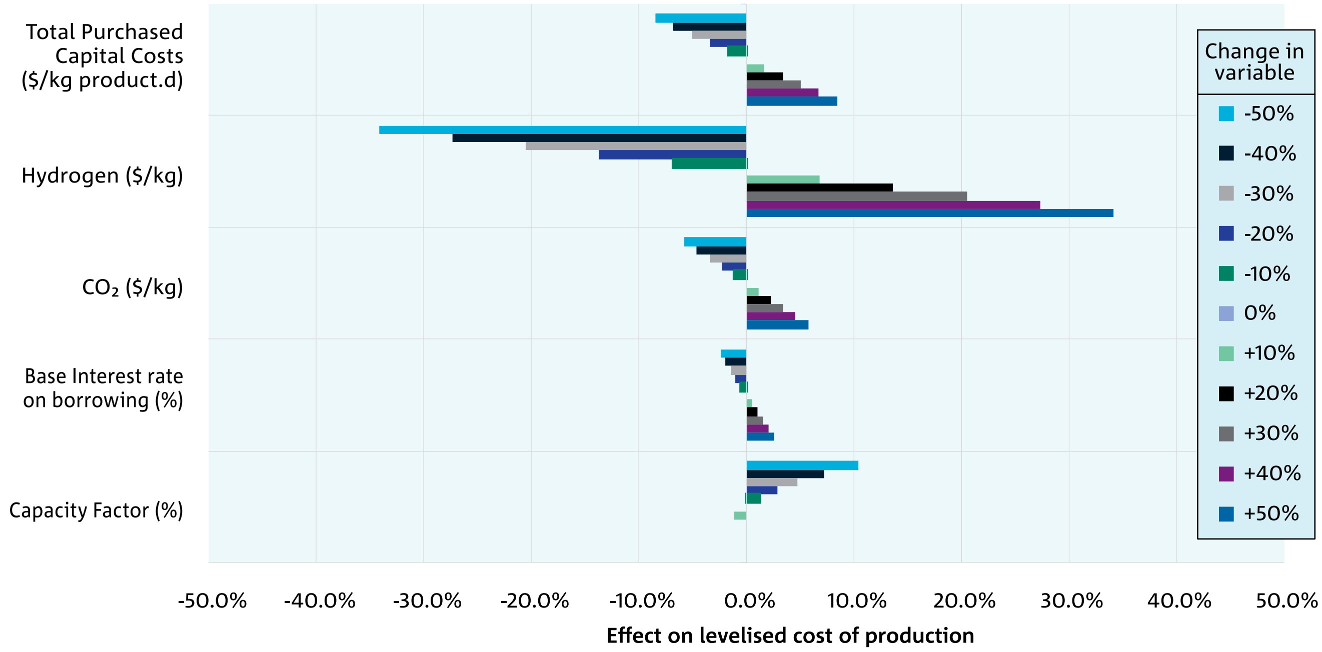
The power-to-liquid supply chain is in its infancy as seen below.

Figure 46. Current state of Australia's power-to-liquid supply chain



Technoeconomic analysis and key cost drivers

Figure 47. Sensitivity analysis on key cost inputs – PtL via FT



Hydrogen cost: The price of green hydrogen is a key cost driver for PtL. With green hydrogen prices currently high with a lack of large-scale manufacturing and economies of scale, there is an opportunity for commercial activity to help to reduce the cost of electrolysers. Developments in large-scale green hydrogen production and lower electricity prices can drive the cost of hydrogen down, reducing PtL production costs significantly.

Considerations and opportunities for hydrogen and CO_2

Commercial

Guaranteeing supply of CO_2: CO_2 point sources may become inactive due to plant shutdowns, depletion of natural resources, or changes in emissions targets.[178] Losing a significant CO_2 source could have major consequences for SAF plant operations. For instance, the ammonia plant at Gibson Island Incitec Pivot Ltd. is set to cease using natural gas and convert to green hydrogen.[179] Some ammonia producers are also considering shifting from natural gas to green hydrogen for hydrogen production in the long term, which would almost eliminate emissions. To minimise the risk of CO_2 supply, plans for CO_2 source redundancy, along with ongoing investments in DAC, can be helpful.

Increasing the scale of DAC: Previous studies have demonstrated that as the scale of DAC technology increases, the cost of CO_2 capture decreases.[180] Therefore, scaling up DAC will be essential for future projects to provide CO_2 at a reduced price. While it may take time for DAC to become a major source of CO_2, it can supplement point sources in the meantime, and its scale can gradually increase over time.

Competition for green electrons: The production of green hydrogen relies on renewable electricity, which can either come from the grid or be generated on-site through renewable sources such as wind and solar. However, generating electricity through these sources requires significant capital costs and land area. In Australia's most optimistic hydrogen production scenario in 2050, Deloitte estimates that 912TWh of renewable electricity will be required every year, equivalent to 9,290km^2 of solar panels or 60,154km^2 of wind farms.[181] For comparison, this is five times larger than Greater Sydney. [182] As a result, the high cost of acquiring large amounts of land and installing capital on it will be a significant barrier to building hydrogen production facilities. Furthermore, using electricity from renewable sources introduces energy variability that is not present in the grid, which lowers the capacity factor. This can be addressed by utilising energy

178 CO_2 Roadmap

179 Incitec Pivot Limited (2021) *FFI and IPL Progress Green Conversion of Gibson Island Ammonia Facility*. <https://www.incitecpivot.com.au/about-us/about-incitec-pivot-limited/media/2022-10-07-ffi-and-ipl-progress-green-conversion-of-gibson-island-ammonia-facilitys> (Accessed 2nd May 2023).

180 CO_2 Roadmap

181 Deloitte (2019) *Australian and Global Hydrogen Demand Growth Scenario Analysis.* Deloitte prepared for the COAG Energy Council National Hydrogen Strategy Taskforce.

182 City of Sydney (2020) The city at a glance. <https://www.cityofsydney.nsw.gov.au/guides/city-at-a-glance> (Accessed 20th January 2023).

storage technology in conjunction with renewables. The great demand for renewables may impact hydrogen production due to the significant capital costs and land area required for renewable electricity generation, as well as the energy variability introduced by using renewable sources.

Manufacturing limitations: The current global manufacturing capacity for electrolysers is significantly less than what will be needed for a large global green hydrogen market. The world's most prominent historical manufacturer of electrolysers, Nel, has indicated that there are significant short-term supply constraints at present, arising from a shortage of robotic components, including semiconductors and microchips.[183]

The global capacity of electrolysers used for hydrogen production in 2022 was 0.5GW, with 0.2GW installed that year.[184] However, this is significantly less than what the hydrogen industry needs in the near future. If all scheduled projects are completed by 2030, global capacity from hydrogen electrolysers could range from 134–280GW.[185]

In Australia, Fortescue Future Industries began building a hydrogen equipment manufacturing facility in Gladstone in early 2022.[186] It is expected to finish in 2023 and have an initial manufacturing electrolyser capacity of 2GW per year.[187]

Sustainability

CO_2 Source: To achieve carbon neutrality, it is essential to capture CO_2 from the air through DAC. However, this process is currently expensive and not yet widely available on the scale required for SAF production. As an alternative, point source capture can be used to capture CO_2 from concentrated streams emitted by industrial processes. This approach is more mature, available, and cheaper than DAC. By using point source capture, large amounts of concentrated CO_2 that would otherwise be released into the atmosphere can be used twice and displace fossil fuel derived fuel, leading to a lower carbon intensity of the fuel. Another potential source with better sustainability credentials is the use of biogenic CO_2 which can be sourced from combusting biomass. This process still comes with the issues of biomass collection and aggregation challenges but provides a more sustainable CO_2 source than industrial sources in lieu of scaled DAC.

Social impact

CO_2 origin: Sourcing CO_2 from point sources rather than directly from the air can raise social impact concerns since it still allows CO_2 to enter the atmosphere. This can be perceived as a way to delay the reduction of CO_2 emissions from these point sources. However, it is important to communicate that using point sources is a necessary step before DAC technologies can produce sufficient CO_2. Additionally, sourcing CO_2 from point sources displaces the demand for fossil fuels and offsets the amount of CO_2 that would have been released if CJF had been used. Therefore, while there may be some social impact challenges associated with using point sources for CO_2, it is a crucial step towards achieving carbon neutrality and reducing the overall carbon intensity of aviation fuel.

Policy

Bridging the DAC price gap: DAC of CO_2 is currently more expensive than capturing CO_2 from point sources, which makes it less competitive and negatively affects its demand. To address this issue, two potential solutions are proposed. Firstly, generating demand for DAC CO_2 by setting a future requirement for carbon capture and utilisation projects to incorporate a certain proportion of its CO_2 from DAC. This policy would help increase demand for DAC CO_2 and create a market for it, which could make it more competitive with point source capture over time. Secondly, offsetting the price differential between DAC CO_2 and lower-cost CO_2 offered from point sources would help DAC producers compete with point source capture on a more level playing field, which could also increase demand for DAC CO_2. Overall, bridging the price gap between DAC CO_2 and point source CO_2 would help increase demand for DAC CO_2 and make it more competitive with point source capture, either through policy or market mechanisms.

183 Ker P (2022) *Big hydrogen warns newcomers that electrolyser dreams won't come easy.* <https://www.afr.com/companies/energy/big-hydrogen-warns-newcomers-that-electrolyser-dreams-won-t-come-easy-20221021-p5brv5> (Accessed 20th January 2023).

184 International Energy Agency (2022a).

185 International Energy Agency (2022a).

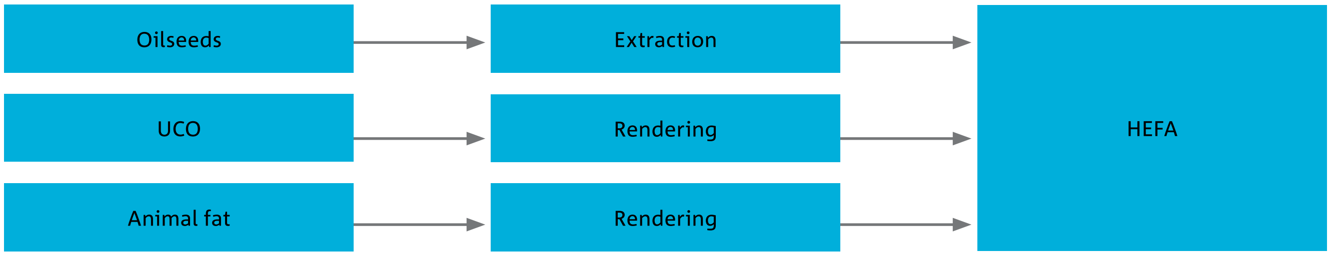
186 Queensland Government (2021) *One of the world's largest hydrogen equipment manufacturing hubs set for Gladstone.* <https://statements.qld.gov.au/statements/93470> (Accessed 20th January 2023); Beavan K (2022) *Andrew Forrest begins work on green hydrogen hub in Gladstone, confirms $3b for renewables farm.* <https://www.abc.net.au/news/2022-02-28/andrew-forrest-begins-work-on-green-hydrogen-hub-in-gladstone/100865988> (Accessed 20th January 2023).

187 Queensland Treasury (2022) Fortescue Future Industries. <https://www.treasury.qld.gov.au/investment/success-stories/fortescue-future-industries/> (Accessed 20th January 2023); Queensland Government (2021).

7.3 Additional technology analysis

7.3.1 Hydroprocessing of esters and fatty acids

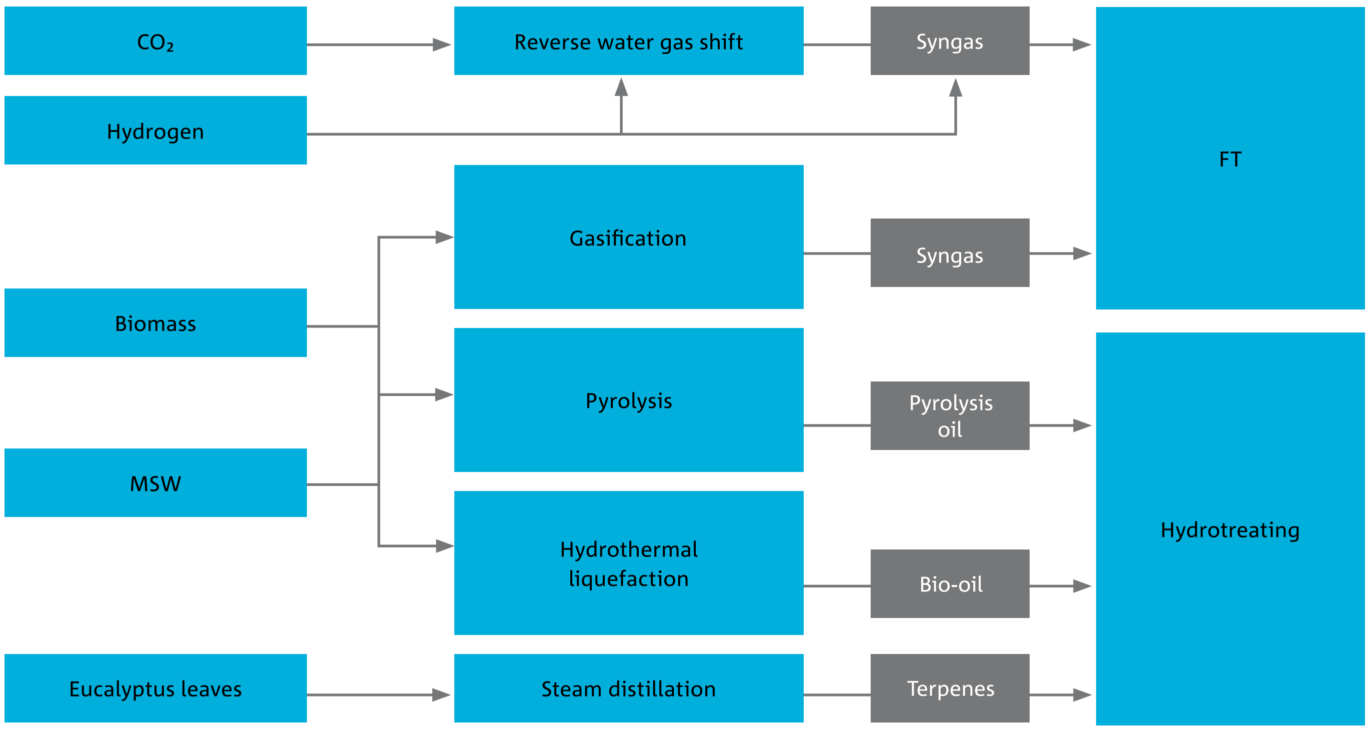
Figure 48. Processing pathways for hydroprocessing of esters and fatty acids



HYDROPROCESSING	
Process	Feedstock is hydrogenated and isomerised to produce long-chain hydrocarbons. Additional hydroprocessing is used to produce aviation fuel.
Feedstocks	Vegetable oils, palm oil, animal fats, used cooking oil
Advantages	• Mature process at large-scale commercial maturity. • Can use waste products like UCO and tallow.
Challenges	• Mature and commercial process leaves less room for step-change improvements in process and production cost. • Feedstocks are limited and highly sought after. • Co-produces lower molecular weight hydrocarbons that require management

7.3.2 Fischer-Tropsch and hydrotreating

Figure 49. Processing pathways for FT and hydrotreating



GASIFICATION OF NON-FOSSIL SOURCE, FISCHER-TROPSCH	
Process	After drying and grinding, biomass or MSW undergoes thermochemical processing to produce syngas (CO and H_2) which is then upgraded in an FT Reactor to synthetic crude.
Feedstocks	Biomass (forestry and agricultural residues including bagasse), MSW
Advantages	• Precedent in coal gasification to FT fuels (industrially practiced). • Range of feedstocks can be pooled together at feedstock hubs for gasification to better achieve scale and diversify feedstock supply.
Challenges	• Must be centralised processing as there is no economically viable way of transporting syngas. • Consistency of feedstock can be an issue; - Upstream processing of feedstocks can be very different, e.g., crop residues vs forestry residues require different approaches to handling and grinding. - Weather dependent, e.g., wet feedstock needs to be dried - Post-gasification clean up can be complex and expensive – removing microcontaminants, and particulates, as well as balancing the syngas and other gas ratio to be suitable for FT synthesis

REVERSE-WATER-GAS-SHIFT OF CO_2 WITH H_2, FISCHER-TROPSCH	
Process	The 'reverse water gas shift' reaction produces CO from CO_2 and H_2, which is combined with additional H_2 to provide a syngas ratio with the required composition. The syngas is then fed into an FT reactor to produce longer-chain hydrocarbons.
Feedstocks	CO_2 (sourced from MSW or biomass combustion, point sources or DAC), green H_2
Advantages	• Can produce a net zero fuel with DAC or biogenic CO_2 • Upstream can be progressively upgraded to more sustainable CO_2 sources whilst maintaining FT and downstream refining.
Challenges	• Overall process is low TRL • RWGS at scale with renewable heat requires R&D • Although mature, FT is costly, with large capex. • Feedstock challenges: DAC is long term, and green hydrogen is currently expensive and sparse

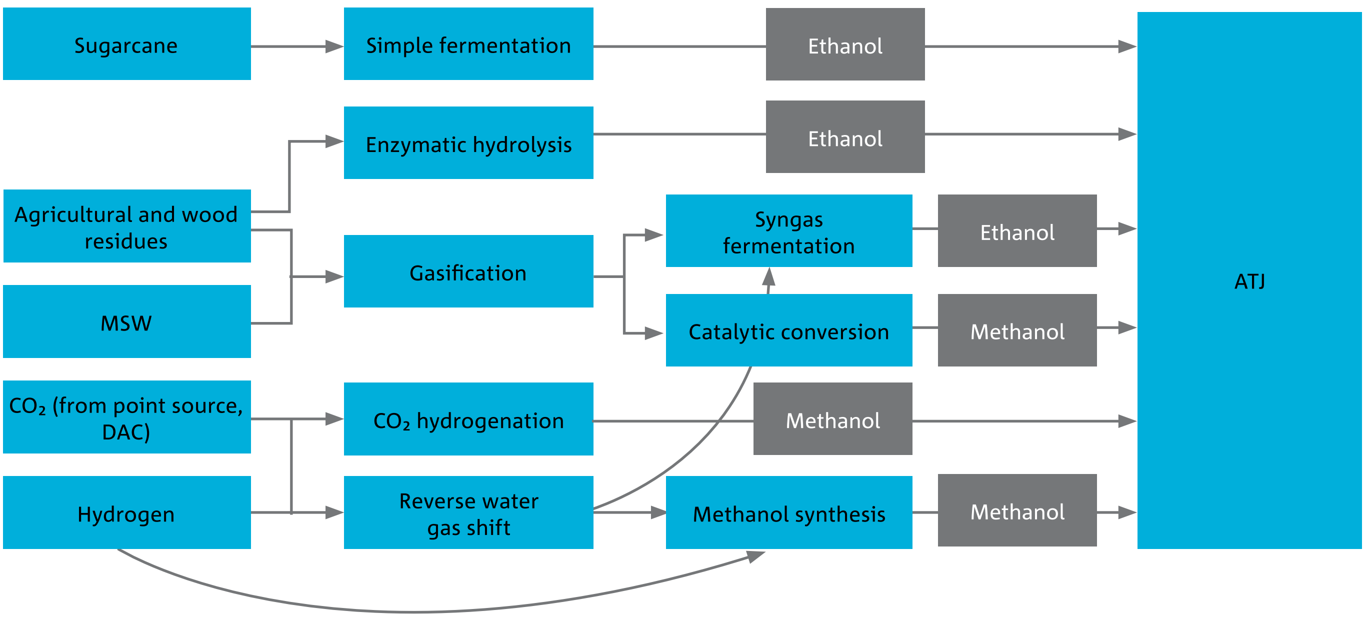
PYROLYSIS, HYDROTREATING	
Process	After drying and grinding, biomass is heated to high temperatures in the absence of oxygen, producing pyrolysis gas, oil, and biochar. Hydrotreating is then required to remove oxygen.
Feedstocks	Biomass (forestry and agricultural residues including bagasse), MSW
Advantages	• Can be used in distributed manner to produce a concentrated intermediate, removing need to transport low density feedstock.
Challenges	• Process can produce odours and smoke. • Pyrolysis bio-oil has undesirable fuel properties such as high acidity, high viscosity, poor stability, and low calorific value. • Requires certification. • Complex outputs may be challenging to control and upgrade. • Primary pyrolysis output is reactive, requires stabilisation before transport and may require specially designed vehicles. • Difficult processes to commercialise due to odour, pollutants, and other waste by-products.

HYDROTHERMAL LIQUEFACTION, HYDROTREATING	
Process	High temperatures, and pressurised water convert the feedstock to a bio-crude. Hydrotreating is needed to remove oxygen and suited to liquid biomasses such as algae and manures.
Feedstocks	Biomass (forestry and agricultural residues including bagasse), MSW, algae, biosolids
Advantages	• Can be used in distributed manner to produce a concentrated intermediate, removing the need to transport low-density feedstock.
Challenges	• Dirty process that produces odours and smoke. • Requires certification. • Complex outputs that are challenging to control and upgrade. • Primary pyrolysis output is reactive, requires stabilisation before transport, and may require special transport vehicles. • Low TRL

TERPENES, HYDROTREATING	
Process	Terpenes are extracted from eucalyptus via steam distillation and then hydrotreated.
Feedstocks	Terpenes such as cineole (from Eucalyptus or pine oil) and hydrogen
Advantages	• Abundant, local feedstock • Straightforward process • Precedence of terpene approval (farnesane)
Challenges	• Feedstock is low density and requires collection.

7.3.3 Alcohol-to-Jet

Figure 50. Processing pathways for alcohol to jet



GASIFICATION OF NON-FOSSIL SOURCE, FERMENTATION (ETHANOL)	
Process	Feedstock is gasified to produce syngas which is fed to a fermenter to produce ethanol.
Feedstocks	MSW, biomass (Grass, wood, and crop residue), captured CO_2
Advantages	• Range of feedstocks can be pooled together at feedstock hubs for gasification to better achieve scale and diversify feedstock supply.
Challenges	• Low TRL • Numerous process steps

GASIFICATION OF NON-FOSSIL SOURCE, CATALYTIC CONVERSION (ETHANOL)	
Process	Feedstock is gasified to produce a syngas passed over a catalyst to produce ethanol.
Feedstocks	MSW, biomass (Grass, wood, and crop residue)
Advantages	• Range of feedstocks can be pooled together at feedstock hubs for gasification to better achieve scale and diversify feedstock supply.
Challenges	• Numerous process steps • Ethanol from the syngas market is almost non-existent as it is cheaper to ferment.

SIMPLE FERMENTATION OF SUGARS (ETHANOL)	
Process	Simple sugars are fermented with yeast into ethanol, which undergoes ATJ.
Feedstocks	Sugar, molasses, wheat starch, bagasse, sorghum
Advantages	• Simple fermentation is a mature process. • Large global market for ethanol. • Could be used in distributed model.
Challenges	• Feedstock price is linked to food.

ADVANCED FERMENTATION OF LIGNOCELLULOSIC MATERIAL (ETHANOL)	
Process	Lignocellulosic material is biochemically pre-treated to release and break complex plant sugars into simple sugars before fermentation to ethanol. Alternatively, biomass can undergo thermochemical conversion to syngas, which is then catalytically reformed to ethanol. ATJ process follows once ethanol is obtained.
Feedstocks	Biomass (Grass, wood, and crop residue)
Advantages	• Uses second-generation (non-food) feedstocks
Challenges	• Complex process, added pre-treatment step required

HYDROGENATION OF CO_2 (METHANOL)	
Process	CO_2 and H_2 are passed over multi-component catalysts to produce methanol.
Feedstocks	CO_2 (sourced from MSW or biomass combustion, point sources or DAC), green H_2
Advantages	• Can produce a net zero fuel with biogenic and DAC CO_2 • Upstream can be progressively upgraded to more sustainable CO_2 sources whilst maintaining methanol to jet downstream plant.
Challenges	• Yet to be approved (currently under assessment).

GASIFICATION OF NON-FOSSIL SOURCE, CATALYTIC CONVERSION (METHANOL)	
Process	Feedstock is gasified to produce a syngas passed over a catalyst to produce methanol.
Feedstocks	MSW, biomass (Grass, wood, and crop residue)
Advantages	• Processes mature, methanol to olefins and aromatics. Methanol to gasoline technology (Exxon) can be modified to go to a jet. • Range of feedstocks can be pooled together at feedstock hubs for gasification to better achieve scale and diversify feedstock supply.
Challenges	• Favours centralised models. • Difficulties in managing varieties of feedstock. • Yet to be approved by ASTM (currently under assessment).

7.4 Feedstock modelling for Australia

7.4.1 This analysis

Economic analysis of feedstock availability for SAF was undertaken by CSIRO Futures to assess the commercial opportunity for SAF in Australia by 2050. While a broad range of feedstocks can be used to produce SAF, only feedstocks with current production at commercially significant quantities were modelled for Australia. This Appendix summarises the parameters, methodology and results of this modelling for each feedstock, developed in consultation and used to produce the estimates presented in this Roadmap.

7.4.2 Parameters

Feedstock production data

- Historical data going as far back as 2010 was sourced for each feedstock to ensure projections reflected trends rather than a single year (such as the most recent year of production).
- Feedstock production was forecast out to 2050 from the most recent data point for production estimates, using the two feedstock growth rates described below.
- For feedstocks where historical data was unavailable or limited (e.g. residues), data was modelled via correlations to related data sources.
- A line of best fit was calculated for historical feedstock production data using a least squares approach. Forecasts were then calculated based on the current production estimate from the trend line using feedstock growth rates. This was preferred to starting forecasts from the final year's production data to consider production trends in prior years.

Feedstock growth rates

- Two feedstock growth scenarios were explored through a 0.5% and 2% annual feedstock production growth rate. These figures were chosen because they are within the range of historical growth rates, they remain plausible out to 2050, and they can be consistently applied across all feedstocks.
- In the 0.5% scenario, it was assumed that global feedstock prices are low, discouraging their production, and climate disruptions further limit production growth.
- In the 2% scenario, it was assumed that global feedstock prices are high, encouraging their production, and climate disruptions are minimal.

Feedstock allocated to jet fuel

- Two feedstock allocation scenarios were explored through a low and high percentage of feedstock allocated to jet fuel production.
- These figures were chosen because they are within the range of historical allocations to biofuels, they remain plausible out to 2050 based on the properties of the feedstock categories, and they allow the reader to create their own calculations through multipliers of the percentage.
- These figures were chosen to consider competing demands for these feedstocks for alternative uses through to 2050. As such, a low scenario of 5% allocated and high scenario of 10% allocated were chosen for feedstocks also used for food, a low scenario of 12.5% allocated and a high scenario of 25% allocated were chosen for hydrogen, and a low 20% and high 40% allocation for all other feedstocks as it was assumed that displacement would have minimal effect on human health.

Jet fuel yield

- Two jet fuel yield scenarios were explored through low and high percentages of jet fuel yield from each feedstock type.
- These percentages were chosen for each technology pathway (e.g., the same percentages across multiple feedstocks that use a HEFA, ATJ, G+FT, or RWGS+FT pathway).
- In the low scenario, it was assumed that there are minimal technology and efficiency improvements of the SAF production pathway to 2050, and the process may be optimised for biodiesel rather than jet fuel outputs.
- In the high scenario, it was assumed that there are some technology and efficiency improvements of the SAF production pathway to 2050, and the process may be optimised for jet fuel rather than biodiesel outputs.

Jet fuel demand production data

- Projections of Australian total jet fuel demand from 2025–2050 were obtained from CSIRO's transport demand model.
- These projections were used to calculate the percentage of fuel demand that SAF projections represented for context, allowing comparison across feedstocks and across time.

Table 10: Projected Australian jet fuel demand to 2050[188]

YEAR	PROJECTED JET FUEL DEMAND
2025	9,257 ML
2030	10,272 ML
2035	11,382 ML
2040	12,618 ML
2045	13,996 ML
2050	15,536 ML

Table 11: Planned Australian SAF production to 2050[189]

YEAR	PLANNED SAF PRODUCTION
2025	0 ML
2026	186 ML
2027	286 ML
2028	286 ML
2029	286 ML
2030+	750 ML

Plant scale

- Feedstock requirements for small scale plant production of 50 ML/year and large-scale plant production of 300 ML/year were calculated for a high jet fuel yield scenario to represent a typical commercially sized plant.
- These feedstock requirements are shown against feedstock growth projections to provide context of quantity needed for SAF production versus projected quantity available.

Planned SAF production

- Data on planned Australian SAF production quantities was obtained from publicly available announcements. This data was used for context to compare to broader potential SAF production from available feedstock quantities.

188 CSIRO 2022, Electric vehicle projections 2022. https://publications.csiro.au/publications/publication/PIcsiro:EP2023-0235

See Section 2.1.4 for description of how the model is constructed. See Section 3 for a definition of the Step Change scenario underpinning the jet fuel demand projections used. A ratio of 34.7 MJ/L of jet fuel is used.

189 Argus Media 2022, Australia's Oceania Biofuels plans Gladstone SAF plant, 13 April 2022, https://www.argusmedia.com/en/news/2321511-australias-oceania-biofuels-plans-gladstone-saf-plant

Airport Technology 2023, Construction of Australia's first ATJ SAF production plant to start in 2024, 30 March 2023, https://www.airport-technology.com/news/saf-queensland-qantas-lanzajet/

Oil & Gas Journal 2023, bp Australia targets 2026 start of Kwinana biofuels production, 21 February 2023, https://www.ogj.com/energy-transition/article/14290018/bp-australia-targets-2026-start-of-kwinana-biofuels-production

A ratio of 1 barrel = 159ML was used to convert production quantities.

A 20% SAF yield from total fuels was assumed based on industry consultations.

A three-year construction period prior to production was assumed where start production year was not reported.

7.4.3 Carbohydrates

Calculations (sugarcane bagasse)

(1)	Potential domestic feedstock production by 2023 (t)	= A x 1,000 x B
	Potential domestic feedstock production by 2050 (t)	= A x 1,000 x B x $(1+C)^{27}$
(2)	Potential domestic SAF production (ML)	= [(1) x E x F]/1,000,000
(3)	Potential SAF production as portion of projected fuel demand (%)	= [(2)/G] x 100

Calculations (sugar, sorghum)

(1)	Potential domestic feedstock production by 2023 (t)	= A x 1,000 x B
	Potential domestic feedstock production by 2050 (t)	= A x 1,000 x B x $(1+C)^{27}$
(2)	Potential ethanol production (L)	= (1) x D
(3)	Potential domestic SAF production (ML)	= [(2) x E]/1,000,000
(4)	Potential SAF production as portion of projected fuel demand (%)	= [(3)/G] x 100

Assumptions

<table>
<tr><th colspan="3">PARAMETERS</th><th>SUGARCANE BAGASSE</th><th>SUGAR</th><th>SORGHUM</th></tr>
<tr><td>A</td><td colspan="2">Current estimate of domestic feedstock production based on historical trends (2023)[190]</td><td>10,117 kt</td><td>4,603 kt</td><td>1,663 kt</td></tr>
<tr><td rowspan="2">B</td><td rowspan="2">Feedstock portion allocated to jet fuel</td><td>Low</td><td>20%</td><td colspan="2">5%</td></tr>
<tr><td>High</td><td>40%</td><td colspan="2">10%</td></tr>
<tr><td rowspan="2">C</td><td rowspan="2">Forecast annual growth in feedstock production</td><td>Low</td><td colspan="3">0.5%</td></tr>
<tr><td>High</td><td colspan="3">2%</td></tr>
<tr><td>D</td><td colspan="2">Ethanol yield from feedstock[191]</td><td></td><td>513 L/t</td><td>420 L/t</td></tr>
<tr><td rowspan="2">E</td><td rowspan="2">Jet fuel yield[192]</td><td>Low</td><td>5% (G+FT)</td><td colspan="2">20% (ATJ)</td></tr>
<tr><td>High</td><td>15% (G+FT)</td><td colspan="2">60% (ATJ)</td></tr>
<tr><td>F</td><td colspan="2">Jet fuel density[193]</td><td colspan="3">1,263L/t</td></tr>
<tr><td>G</td><td colspan="2">Projected jet fuel demand</td><td colspan="3">See Table 1</td></tr>
<tr><td rowspan="2">H</td><td rowspan="2">Plant requirement</td><td>Small scale</td><td>264 kt (G+FT)</td><td>122 kt (ATJ)</td><td>149 kt (ATJ)</td></tr>
<tr><td>Large scale</td><td>1,584 kt (G+FT)</td><td>731 kt (ATJ)</td><td>893 kt (ATJ)</td></tr>
</table>

190 Sugarcane bagasse: ABARES 2023, Agricultural commodities: March quarter 2023, Statistical tables - data tables, Table 12, Australian Bureau of Agricultural and Resource Economics and Sciences. https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/data

Queensland Government 2018, Queensland technical methods – cropping (sugarcane), Australian Biomass for Bioenergy Assessment.

A reported ratio of 1t sugarcane = 0.3t sugarcane bagasse was applied to sugarcane production data to estimate bagasse production.

Sugarcane: ABARES 2022, Agricultural Commodity Statistics, Rural commodities – Sugar XLSX, AG526, Australian Bureau of Agricultural and Resource Economics and Sciences. https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/data

ABARES 2023, Agricultural commodities: March quarter 2023, Outlook tables – data tables, Sugar, Australian Bureau of Agricultural and Resource Economics and Sciences. https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/data

Sorghum: ABARES 2023, Australian crop report: March 2023, Table 12, Australian Bureau of Agricultural and Resource Economics and Sciences. https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/data

A historical trend line was calculated from 2010–2023 feedstock production data reported, and then applied to obtain a 2023 current estimate to use for forecasts.

191 USDA 2006, The economic feasibility of ethanol production from sugar in the United States. https://www.fsa.usda.gov/Internet/FSA_File/ethanol_fromsugar_july06.pdf

Department of Agriculture and Food, Western Australia 2006, Ethanol production from grain. Department of Primary Industries and Regional Development, Western Australia, Perth. https://library.dpird.wa.gov.au/cgi/viewcontent.cgi?article=1031&context=pubns

192 Low and high jet fuel yield figures were chosen based on what is feasible for Australia, obtained via literature review and industry stakeholder consultations.

ATJ:

Diederichs GW 2015, Techno-economic assessment of processes that produce jet fuel from plant-derived sources, university thesis. https://core.ac.uk/download/pdf/37440495.pdf

Geleynse S, Brandt K, Garcia-Perez M, Wolcott M, Zhang X 2018, The alcohol-to-jet conversion pathway for drop-in biofuels: techno-economic evaluation, Chemistry-Sustainability-Energy-Materials, 11(21), 3728–3741. https://chemistry-europe.onlinelibrary.wiley.com/doi/10.1002/cssc.201801690

G+FT:

Diederichs GW 2015, Techno-economic assessment of processes that produce jet fuel from plant-derived sources, university thesis. https://core.ac.uk/download/pdf/37440495.pdf

Bressanin JM et al. 2020, Techno-economic and environmental assessment of biomass gasification and Fischer-Tropsch synthesis integrated to sugarcane biorefineries, Energies, 13(17). https://www.mdpi.com/1996-1073/13/17/4576

193 Department of Climate Change, Energy, the Environment and Water 2023, Australian Petroleum Statistics – Data Extract December 2022 [XLSX]. https://www.energy.gov.au/publications/australian-petroleum-statistics-2022

Results

The lowest estimates (from our low feedstock portion allocated to jet fuel, low forecast annual growth rate, and low jet fuel yield scenario) and highest plausible estimates (from our high feedstock portion allocated to jet fuel, high forecast annual growth rate, and high jet fuel yield scenario) are summarised here. Discrepancies in summations are due to differences in rounding.

LOW SCENARIO		SUGARCANE BAGASSE	SUGAR	SORGHUM	TOTAL CARBOHYDRATES
Potential domestic SAF production	2025	129.06 ML	23.85 ML	7.06 ML	159.97 ML
	2050	146.20 ML	27.02 ML	7.99 ML	181.21 ML
Potential SAF production as portion of projected fuel demand	2025	1.39%	0.26%	0.08%	1.73%
	2050	0.94%	0.17%	0.05%	1.17%

HIGH SCENARIO		SUGARCANE BAGASSE	SUGAR	SORGHUM	TOTAL CARBOHYDRATES
Potential domestic SAF production	2025	797.64 ML	147.41 ML	43.60 ML	988.66 ML
	2050	1,308.62 ML	241.84 ML	71.54 ML	1,622.00 ML
Potential SAF production as portion of projected fuel demand	2025	8.62%	1.59%	0.47%	10.68%
	2050	8.42%	1.56%	0.46%	10.44%

Figure 51. Australian sugarcane bagasse growth projections and FT feedstock requirements based on plant size

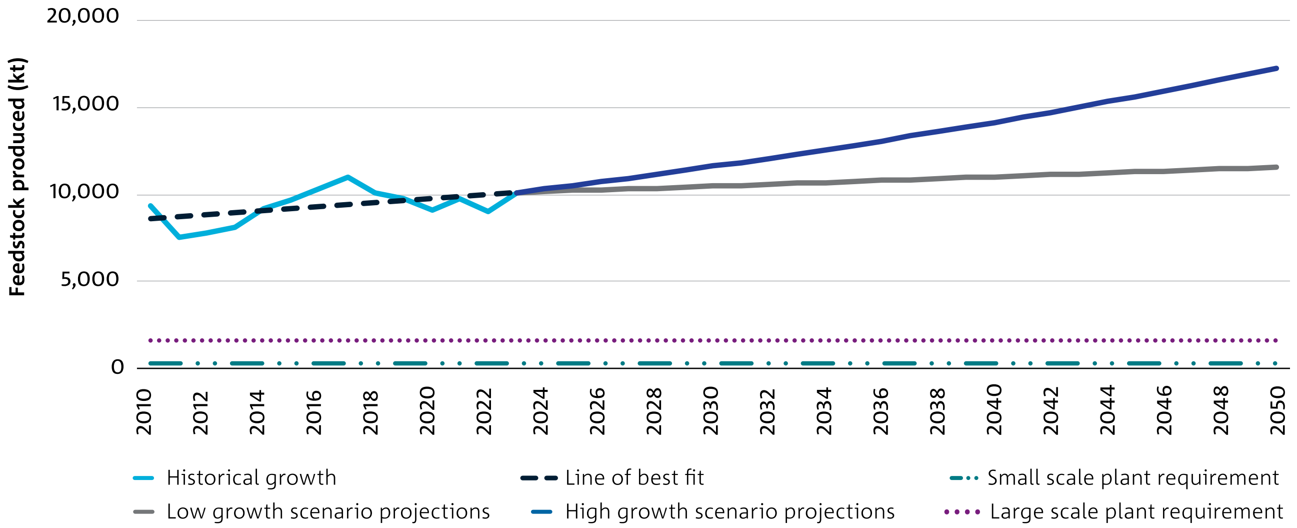


Figure 52. Potential SAF production from Australian sugarcane bagasse and contribution toward domestic jet fuel demand (high feedstock growth rate, high jet fuel yield scenario)

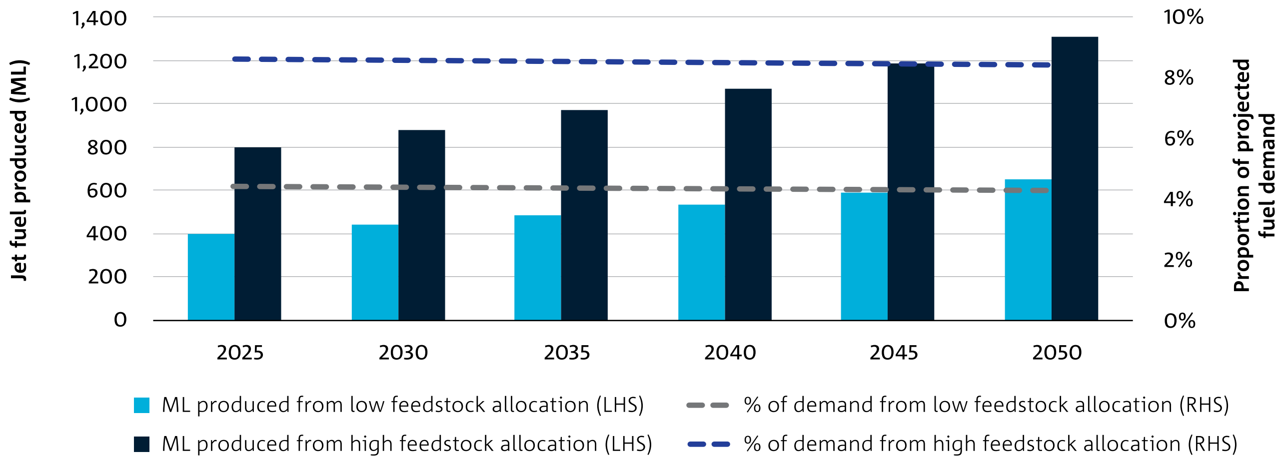


Figure 53. Australian raw sugar growth projections and ATJ feedstock requirements based on plant size

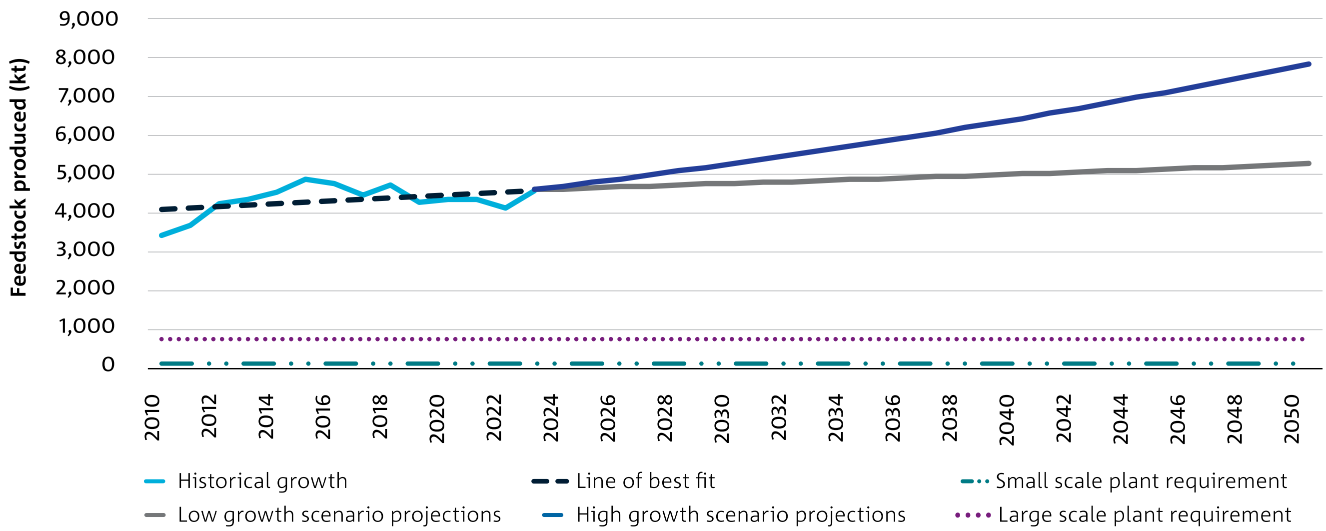


Figure 54. Potential SAF production from Australian sugar and contribution toward domestic jet fuel demand (high feedstock growth rate, high jet fuel yield scenario)

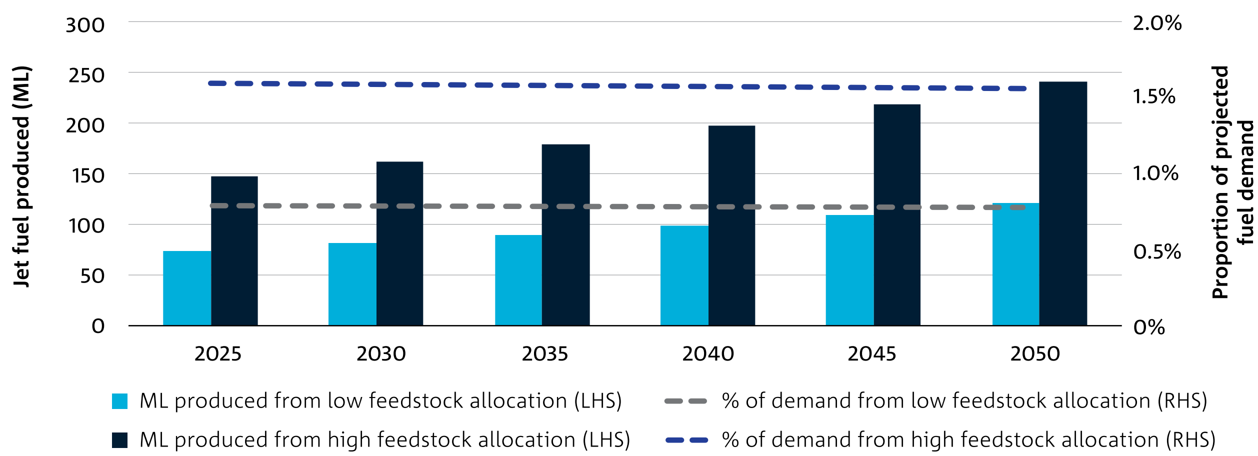


Figure 55. Australian sorghum growth projections and ATJ feedstock requirements based on plant size

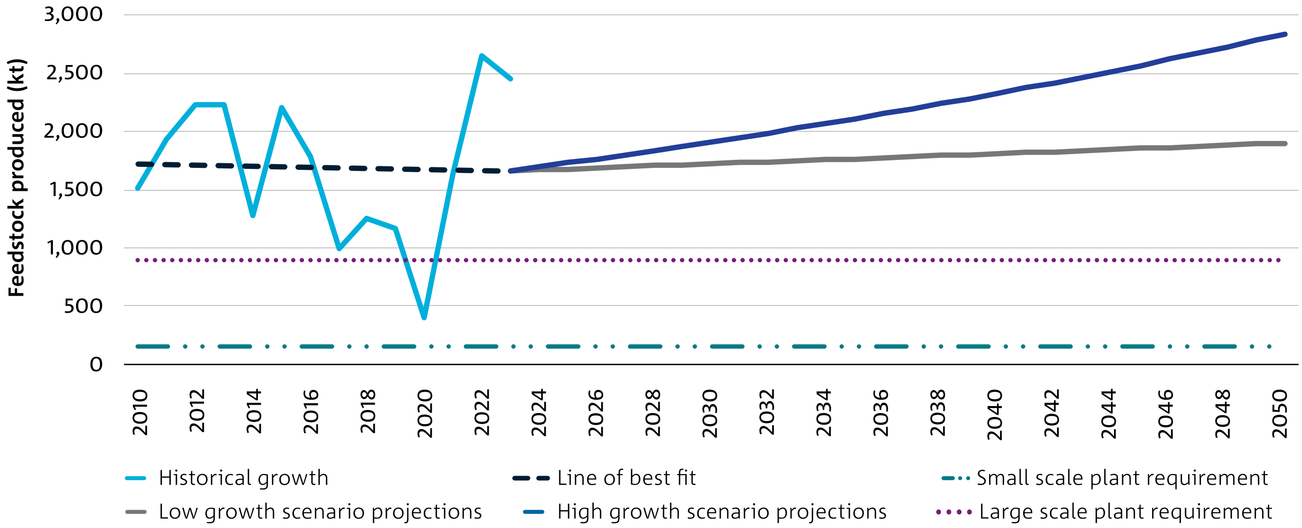


Figure 56. Potential SAF production from Australian sorghum and contribution toward domestic jet fuel demand (high feedstock growth rate, high jet fuel yield scenario)

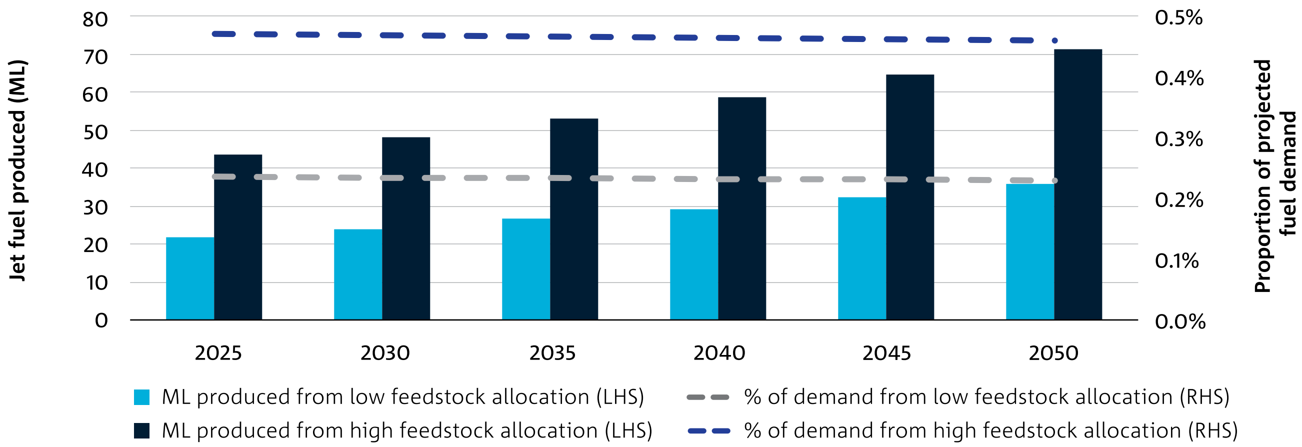
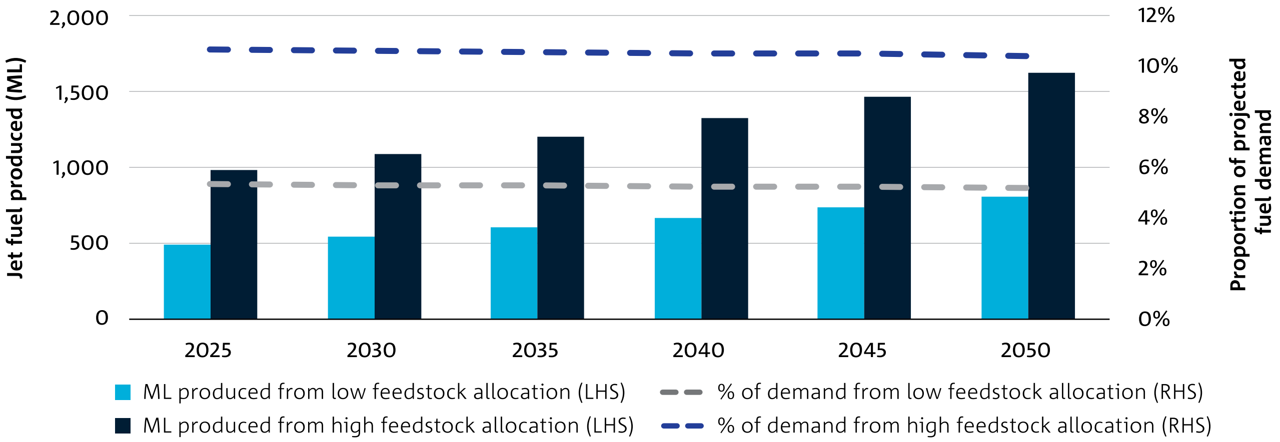


Figure 57. Potential SAF production from Australian carbohydrates and contribution toward domestic jet fuel demand (high feedstock growth rate, high jet fuel yield scenario)



7.4.4 Waste

Calculations

(1)	Potential current domestic feedstock production (t)	= A x 1,000 x B
	Potential domestic feedstock production by 2050 (t): tallow	= A x 1,000 x B x $(1+C)^{28}$
	Potential domestic feedstock production by 2050 (t): MSW	= A x 1,000 x B x $(1+C)^{29}$
(2)	Potential domestic SAF production (ML)	= [(1) x D x E]/1,000,000
(3)	Potential SAF production as portion of projected fuel demand (%)	= [(2)/F] x 100

Assumptions

PARAMETERS			TALLOW	MUNICIPAL SOLID WASTE
A	Current estimate of domestic feedstock production based on historical trends[194]		434 kt (2022)	13,046 kt (2021)
B	Feedstock portion allocated to jet fuel (%)	Low	20%	
		High	40%	
C	Forecast annual growth in feedstock production	Low	0.5%	
		High	2%	
D	Jet fuel yield[195]	Low	30% (HEFA)	5% (G+FT)
		High	60% (HEFA)	10% (G+FT)
E	Jet fuel density[196]		1,263 L/t	
F	Projected jet fuel demand		*See Table 1*	
G	Plant requirement	Small scale	66 kt (HEFA)	396 kt (G+FT)
		Large scale	396 kt (HEFA)	2,375 kt (G+FT)

194 Tallow: ABS 2007, Information Consultancy Services, cat. no. 9920.0, Canberra.

Assumes tallow exports ≈ tallow production given data availability. Excludes foreign (re-exports).

Tallow exports = AHECC codes 15020041, 15020051, 15020059, 15020060, 15021000, 15021001, 15021002, 15021003, 15021041, 15021049, 15021060, 15021061, 15021062, 15021063, 15030000.

Municipal solid waste: Department of Climate Change, Energy, the Environment and Water, National Waste Report 2022, Australian Government, Canberra. https://www.dcceew.gov.au/environment/protection/waste/national-waste-reports/2022

Data was imputed for missing years of 2012 and 2013 by using the difference between the 2011 and 2014 data points.

A historical trend line was calculated from 2010 to current production year for feedstock data reported, and then applied to obtain a current estimate to use for forecasts.

195 Low and high jet fuel yield figures were chosen based on what is feasible for Australia, obtained via literature review and industry stakeholder consultations.

HEFA:

Diederichs GW 2015, Techno-economic assessment of processes that produce jet fuel from plant-derived sources, university thesis. https://core.ac.uk/download/pdf/37440495.pdf

Han J, Elgowainy A, Cai H and Wang MQ 2013, Life-cycle analysis of bio-based aviation fuels, Bioresource Technology, 150, 447–456. https://www.sciencedirect.com/science/article/pii/S0960852413012297?via%3Dihub

Martinez-Hernandez E, Ramirez-Verduzco LF, Amezcua-Allieri MA and Aburto-J 2019, Process simulation and techno-economic analysis of bio-jet fuel and green diesel production – minimum selling prices, Chemical Engineering Research and Design, 146, 60–70. https://www.sciencedirect.com/science/article/pii/S0263876219301534?via%3Dihub

Pearlson M, Wollersheim C and Hileman J 2013, A techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production, Biofuels, Bioproducts and Biorefining, 7(1), 89–96. https://onlinelibrary.wiley.com/doi/full/10.1002/bbb.1378

Tao L, Milbrandt A, Zhang Y and Wang WC 2017, Techno-economic and resource analysis of hydroprocessed renewable jet fuel, Biotechnology for Biofuels, 10(261). https://biotechnologyforbiofuels.biomedcentral.com/articles/10.1186/s13068-017-0945-3

G+FT for MSW:

Codignole Luz F et al. 2015, Techno-economic analysis of municipal solid waste gasification for electricity generation in Brazil, Energy Conversion and Management, 105, 321–327. https://www.sciencedirect.com/science/article/pii/S0196890415006226?via%3Dihub

Jones SB, Zhu Y and Valkenburg C 2009, Municipal solid waste (MSW) to liquid fuels synthesis, volume 2: a techno-economic evaluation of the production of mixed alcohols, prepared for the US Department of Energy. https://www.pnnl.gov/main/publications/external/technical_reports/pnnl-18482.pdf

Niziolek AM, Onel O, Hasan MMF and Floudas CA 2015, Municipal solid waste to liquid transportation fuels – part II: process synthesis and global optimization strategies, Computers & Chemical Engineering, 74, 184–203. https://www.sciencedirect.com/science/article/pii/S0098135414003020?via%3Dihub

Niziolek AM, Onel O and Floudas CA 2017, Municipal solid waste to liquid transportation fuels, olefins, and aromatics: process synthesis and deterministic global optimization, Computers & Chemical Engineering, 102, 169–187. https://www.sciencedirect.com/science/article/pii/S0098135416302447?via%3Dihub

196 Department of Climate Change, Energy, the Environment and Water 2023, Australian Petroleum Statistics – Data Extract December 2022 [XLSX]. https://www.energy.gov.au/publications/australian-petroleum-statistics-2022

Results

The lowest estimates (from our low feedstock portion allocated to jet fuel, low forecast annual growth rate, and low jet fuel yield scenario) and highest plausible estimates (from our high feedstock portion allocated to jet fuel, high forecast annual growth rate, and high jet fuel yield scenario) are summarised here. Discrepancies in summations are due to differences in rounding.

LOW SCENARIO		TALLOW	MUNICIPAL SOLID WASTE	TOTAL WASTE
Potential domestic SAF production	2025	33.37 ML	168.10 ML	201.47 ML
	2050	37.80 ML	190.42 ML	228.22 ML
Potential SAF production as portion of projected fuel demand	2025	0.36%	1.82%	2.18%
	2050	0.24%	1.23%	1.47%

HIGH SCENARIO		TALLOW	MUNICIPAL SOLID WASTE	TOTAL WASTE
Potential domestic SAF production	2025	139.55 ML	713.43 ML	852.98 ML
	2050	228.95 ML	1,170.46 ML	1,399.41 ML
Potential SAF production as portion of projected fuel demand	2025	1.51%	7.71%	9.21%
	2050	1.47%	7.53%	9.01%

Figure 58. Australian tallow growth projections and HEFA feedstock requirements based on plant size

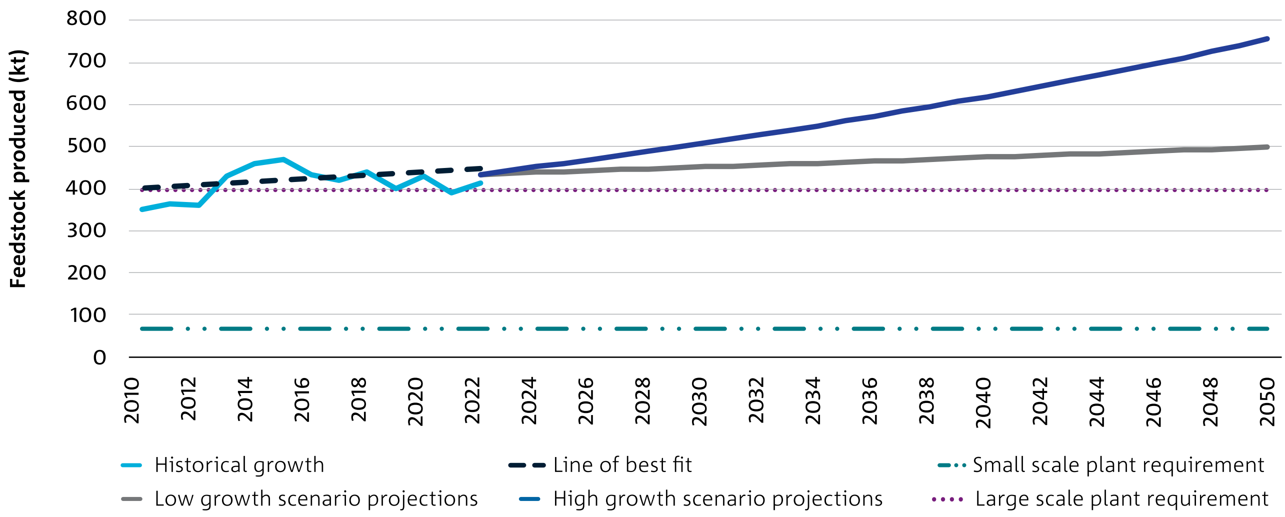


Figure 59. Potential SAF production from Australian tallow and contribution toward domestic jet fuel demand (high feedstock growth rate, high jet fuel yield scenario)

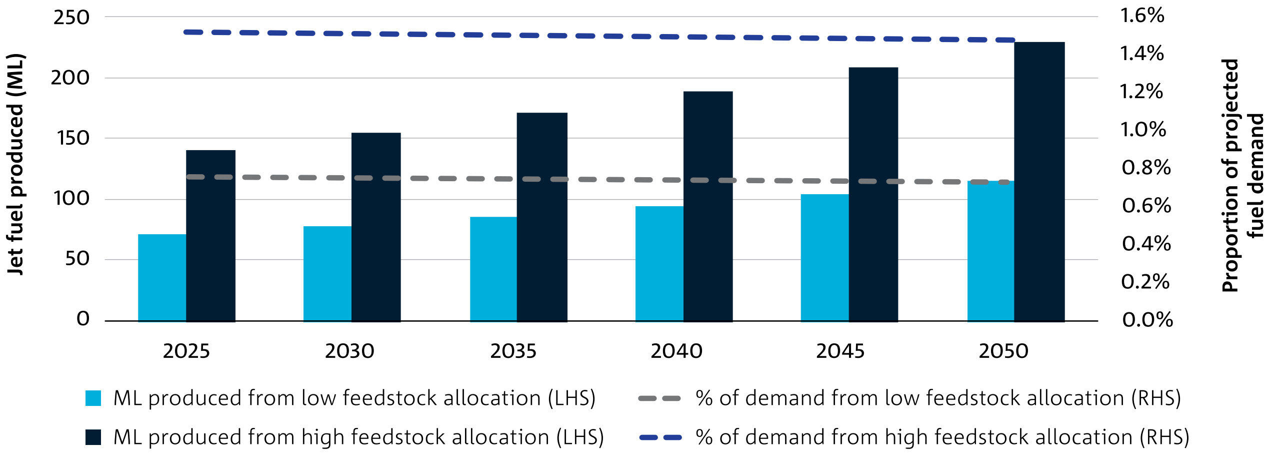


Figure 60. Australian MSW growth projections and FT feedstock requirements based on plant size

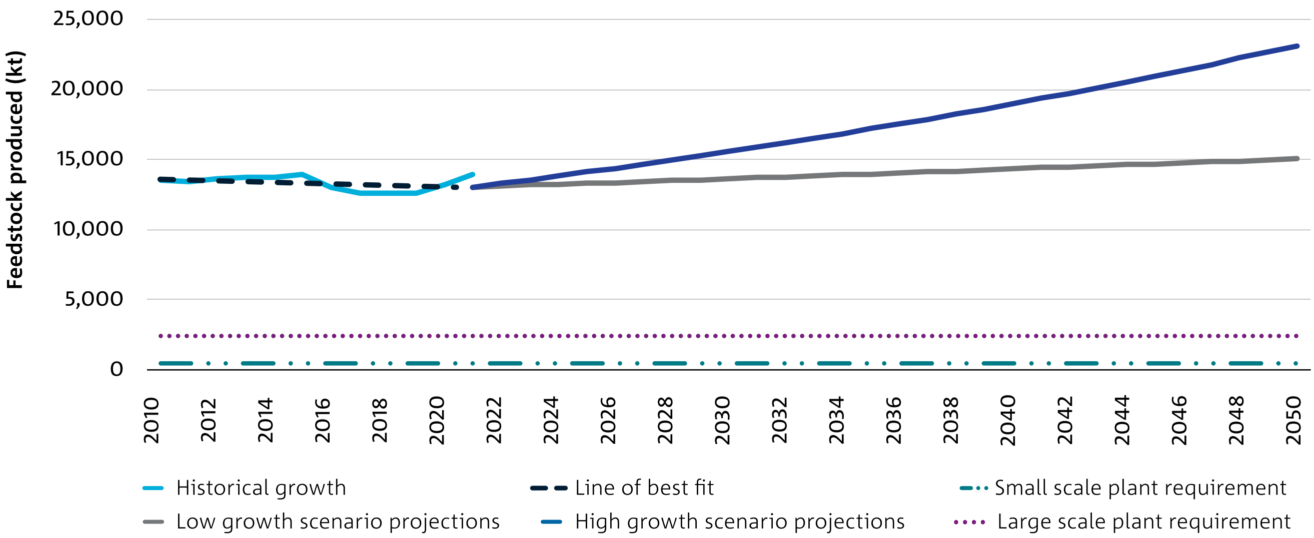


Figure 61. Potential SAF production from Australian MSW and contribution toward domestic jet fuel demand (high feedstock growth rate, high jet fuel yield scenario)

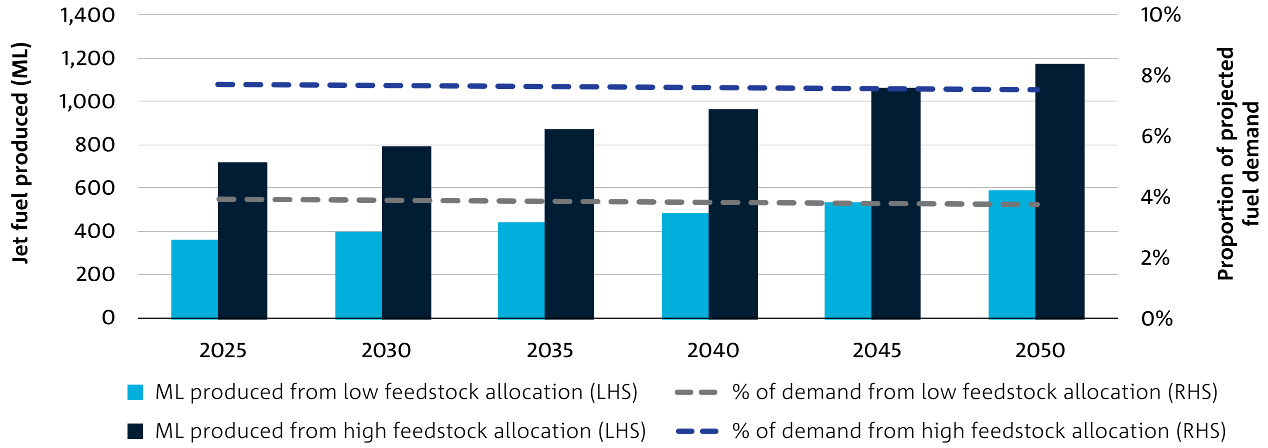
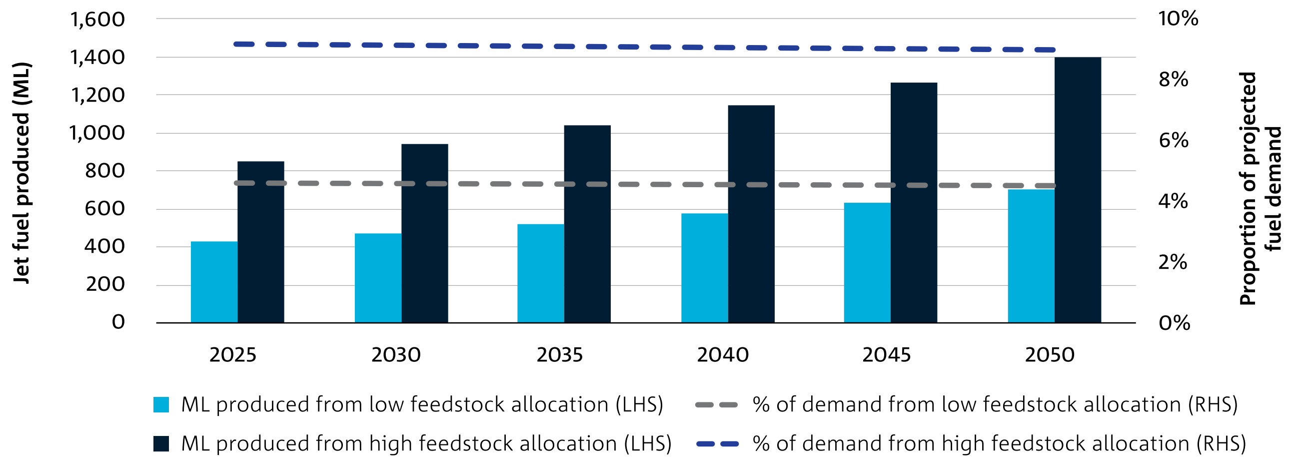


Figure 62. Potential SAF production from Australian waste and contribution toward domestic jet fuel demand (high feedstock growth rate, high jet fuel yield scenario)



7.4.5 Residues

Calculations

(1) Potential domestic feedstock production by 2023 (t)	= A x 1,000 x B
Potential domestic feedstock production by 2050 (t)	= A x 1,000 x B x $(1+C)^{27}$
(2) Potential domestic SAF production (ML)	= [(1) x D x E]/1,000,000
(3) Potential SAF production as portion of projected fuel demand (%)	= [(2)/F] x 100

Assumptions

PARAMETERS			AGRICULTURAL RESIDUES	SAWMILL RESIDUES
A	Current estimate of domestic feedstock production based on historical trends (2023)[197]		37,109 kt	6,266 kt
B	Feedstock portion allocated to jet fuel (%)	Low	20%	
		High	40%	
C	Forecast annual growth in feedstock production	Low	0.5%	
		High	2%	
D	G+FT jet fuel yield[198]	Low	5%	
		High	15%	
E	Jet fuel density[199]		1,263 L/t	
F	Projected jet fuel demand		*See Table 1*	
G	G+FT plant requirement	Small scale	264 kt	
		Large scale	1,584 kt	

197 ABARES 2023, Agricultural commodities: March quarter 2023, Statistical tables - data tables, Table 12, Australian Bureau of Agricultural and Resource Economics and Sciences. https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/data

Agricultural residues: Grain production defined as sum of barley, corn (maize), grain sorghum, oats, rice, triticale, and wheat production.

Herr A, O'Connell D, Dunlop, M, Unkovich M, Poulton P and Poole M 2012, Second harvest – is there sufficient stubble for biofuel production in Australia? GCB Bioenergy, 4, 654–660. https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1757-1707.2012.01165.x

A ratio of stubble potentially available for harvest with grain production (0.8) was calculated for Australian 1986–2005 data and applied to grain production data for 2010–2023 to estimate available stubble.

Sawmill residues: ABARES 2022, Australian forest and wood products statistics, Dashboard data tables - Plantation area and log production: AFWPS: Mar – Jun quarters 2022, Volume of production, Australian Bureau of Agricultural and Resource Economics and Sciences. https://www.agriculture.gov.au/abares/research-topics/forests/forest-economics/forest-wood-products-statistics#download-the-overview-report-and-datasets

ABARES 2018, Future opportunities for using forest and sawmill residues in Australia, Australian Bureau of Agricultural and Resource Economics and Sciences. https://www.agriculture.gov.au/abares/research-topics/forests/forest-economics/forest-economic-research/forest-sawmill-residues-report

A reported ratio of 1m3 sawlogs = 0.5t sawmill residues was applied to sawlog production data to estimate available sawmill residues.

A historical trend line was calculated from 2010–2023 feedstock production data reported, and then applied to obtain a 2023 current estimate to use for forecasts.

198 Low and high G+FT jet fuel yield figures were chosen based on what is feasible for Australia, obtained via literature review and industry stakeholder consultations.

Diederichs GW 2015, Techno-economic assessment of processes that produce jet fuel from plant-derived sources, university thesis. https://core.ac.uk/download/pdf/37440495.pdf

Bressanin JM et al. 2020, Techno-economic and environmental assessment of biomass gasification and Fischer-Tropsch synthesis integrated to sugarcane biorefineries, Energies, 13(17). https://www.mdpi.com/1996-1073/13/17/4576

199 Department of Climate Change, Energy, the Environment and Water 2023, Australian Petroleum Statistics – Data Extract December 2022 [XLSX]. https://www.energy.gov.au/publications/australian-petroleum-statistics-2022

Results

The lowest estimates (from our low feedstock portion allocated to jet fuel, low forecast annual growth rate, and low jet fuel yield scenario) and highest plausible estimates (from our high feedstock portion allocated to jet fuel, high forecast annual growth rate, and high jet fuel yield scenario) are summarised here. Discrepancies in summations are due to differences in rounding.

LOW SCENARIO		AGRICULTURAL RESIDUES	SAWMILL RESIDUES	TOTAL RESIDUES
Potential domestic SAF production	2025	473.38 ML	79.93 ML	553.32 ML
	2050	536.25 ML	90.55 ML	626.80 ML
Potential SAF production as portion of projected fuel demand	2025	5.11%	0.86%	5.98%
	2050	3.45%	0.58%	4.03%

HIGH SCENARIO		AGRICULTURAL RESIDUES	SAWMILL RESIDUES	TOTAL RESIDUES
Potential domestic SAF production	2025	2,925.72 ML	494.02 ML	3,352.69 ML
	2050	4,799.96 ML	810.49 ML	5,610.45 ML
Potential SAF production as portion of projected fuel demand	2025	31.61%	5.34%	36.94%
	2050	30.90%	5.22%	36.11%

Figure 63. Australian agricultural residues growth projections and FT feedstock requirements based on plant size

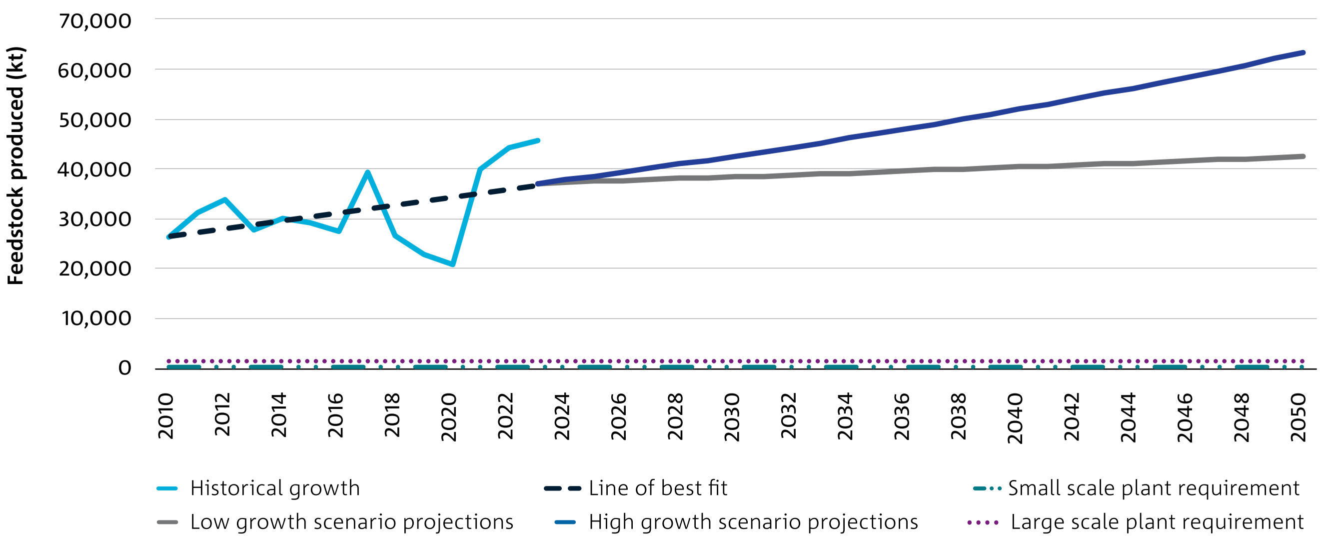


Figure 64. Potential SAF production from Australian agricultural residues and contribution toward domestic jet fuel demand (high feedstock growth rate, high jet fuel yield scenario)

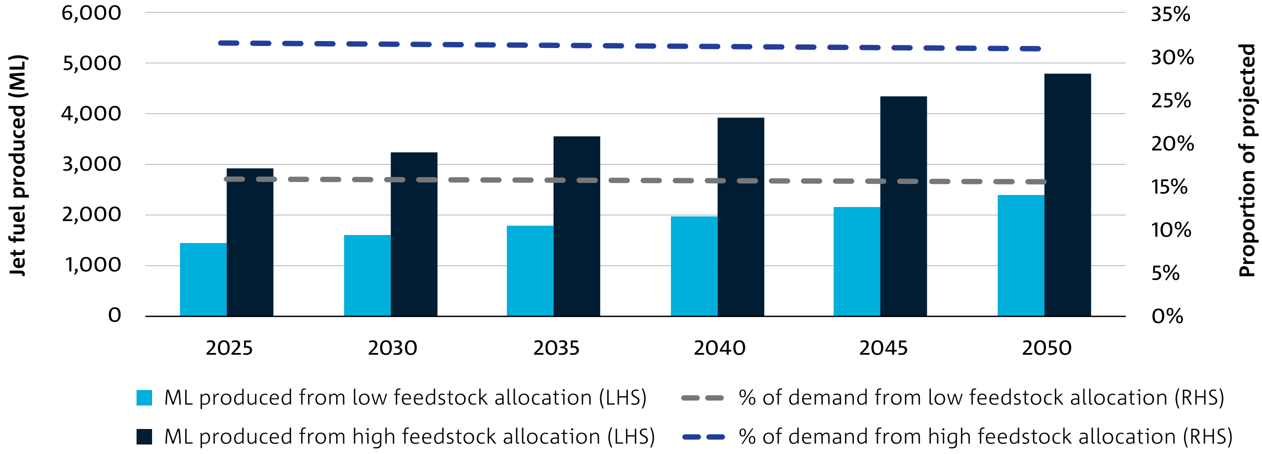


Figure 65. Australian sawmill residues growth projections and FT feedstock requirements based on plant size

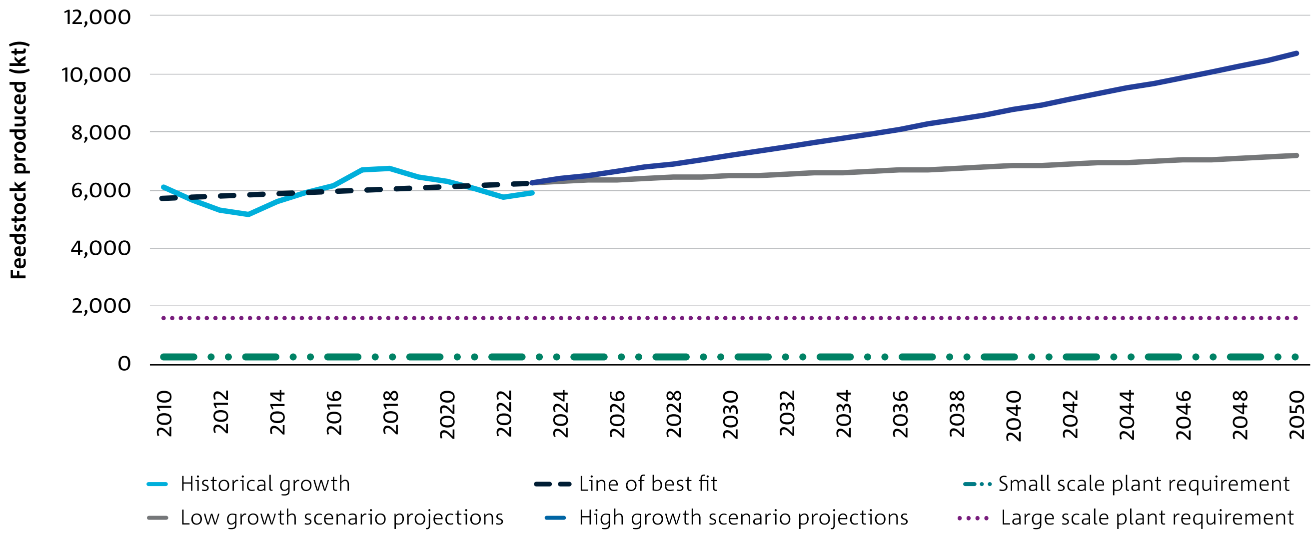


Figure 66. Potential SAF production from Australian sawmill residues and contribution toward domestic jet fuel demand (high feedstock growth rate, high jet fuel yield scenario)

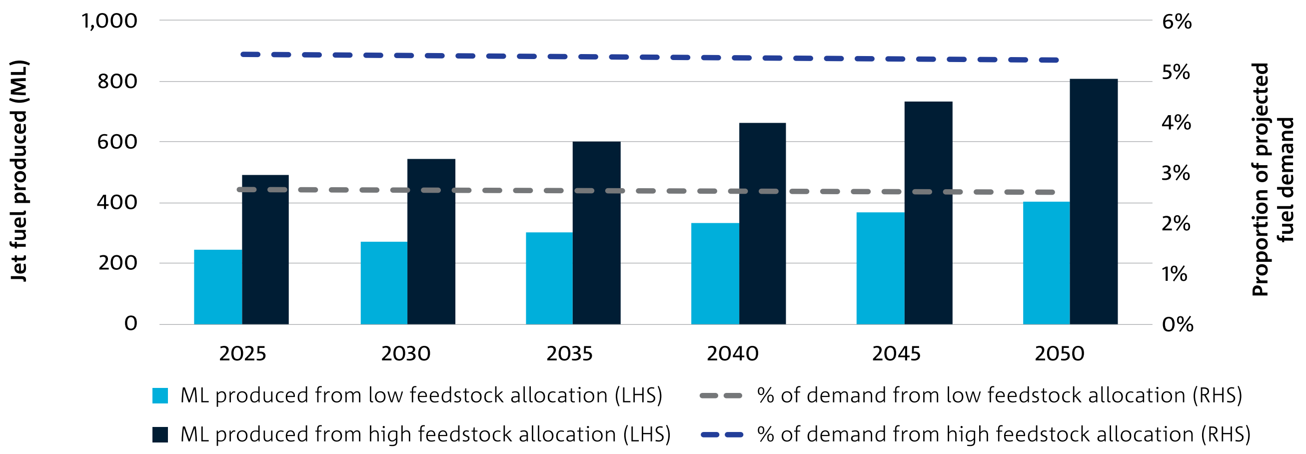
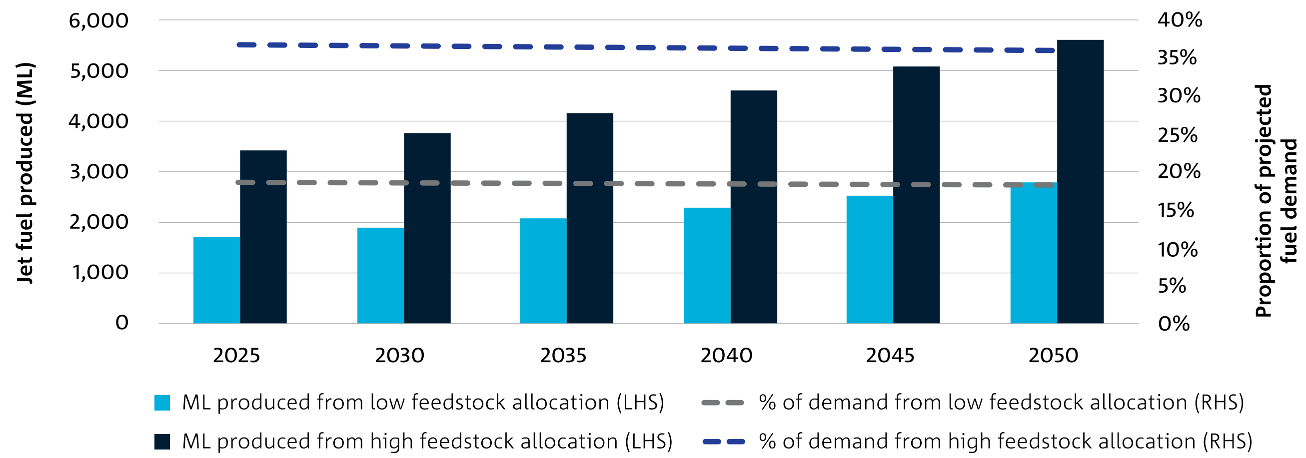


Figure 67. Potential SAF production from Australian residues and contribution toward domestic jet fuel demand (high feedstock growth rate, high jet fuel yield scenario)



7.4.6 Oilseeds

Calculations

(1) Potential domestic feedstock production by 2023 (t)	= A x 1,000 x B
Potential domestic feedstock production by 2050 (t)	= A x 1,000 x B x $(1+C)^{27}$
(2) Potential domestic oil production (t)	= (1) x D
(3) Potential domestic SAF production (ML)	= [(2) x E x F]/1,000,000
(4) Potential SAF production as portion of projected fuel demand (%)	= [(3)/G] x 100

Assumptions

PARAMETERS			CANOLA	COTTONSEED
A	Current estimate of domestic feedstock production based on historical trends (2023)[200]		5,709 kt	954 kt
B	Feedstock portion allocated to jet fuel (%)	Low	5%	
		High	10%	
C	Forecast annual growth in feedstock production	Low	0.5%	
		High	2%	
D	Feedstock oil content[201]		40%	15%
E	HEFA jet fuel yield[202]	Low	30%	
		High	60%	
F	Jet fuel density[203]		1,263L/t	
G	Projected jet fuel demand		*See Table 1*	
H	HEFA plant requirement	Small scale	165 kt	440 kt
		Large scale	990 kt	2,639 kt

200 ABARES 2023, Australian crop report: March 2023, Tables 11 – 12, Australian Bureau of Agricultural and Resource Economics and Sciences. https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/data#agricultural-commodities

A historical trend line was calculated from 2010–2023 feedstock production data reported, and then applied to obtain a 2023 current estimate to use for forecasts.

201 Canola: GRDC 2017, GRDC Canola GrowNotes, Grains Research and Development Corporation. https://grdc.com.au/resources-and-publications/grownotes

Cottonseed: Sekhar SC and Rao B 2011, Cottonseed oil as health oil, Pertanika Journal of Tropical Agricultural Science, 34(1), 17–24. https://www.researchgate.net/profile/Savanam-Chandra-Sekhar/publication/290537659_Cottonseed_oil_as_health_oil/links/6144660df4a9f76511635af1/Cottonseed-oil-as-health-oil.pdf

202 Low and high HEFA jet fuel yield figures were chosen based on what is feasible for Australia, obtained via literature review and industry stakeholder consultations.

Diederichs GW 2015, Techno-economic assessment of processes that produce jet fuel from plant-derived sources, university thesis. https://core.ac.uk/download/pdf/37440495.pdf

Han J, Elgowainy A, Cai H and Wang MQ 2013, Life-cycle analysis of bio-based aviation fuels, Bioresource Technology, 150, 447–456. https://www.sciencedirect.com/science/article/pii/S0960852413012297?via%3Dihub

Martinez-Hernandez E, Ramirez-Verduzco LF, Amezcua-Allieri MA and Aburto-J 2019, Process simulation and techno-economic analysis of bio-jet fuel and green diesel production – minimum selling prices, Chemical Engineering Research and Design, 146, 60–70. https://www.sciencedirect.com/science/article/pii/S0263876219301534?via%3Dihub

Pearlson M, Wollersheim C and Hileman J 2013, A techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production, Biofuels, Bioproducts and Biorefining, 7(1), 89–96. https://onlinelibrary.wiley.com/doi/full/10.1002/bbb.1378

Tao L, Milbrandt A, Zhang Y and Wang WC 2017, Techno-economic and resource analysis of hydroprocessed renewable jet fuel, Biotechnology for Biofuels, 10(261). https://biotechnologyforbiofuels.biomedcentral.com/articles/10.1186/s13068-017-0945-3

203 Department of Climate Change, Energy, the Environment and Water 2023, Australian Petroleum Statistics – Data Extract December 2022 [XLSX]. https://www.energy.gov.au/publications/australian-petroleum-statistics-2022

Results

The lowest estimates (from our low feedstock portion allocated to jet fuel, low forecast annual growth rate, and low jet fuel yield scenario) and highest plausible estimates (from our high feedstock portion allocated to jet fuel, high forecast annual growth rate, and high jet fuel yield scenario) are summarised here. Discrepancies in summations are due to differences in rounding.

LOW SCENARIO		CANOLA	COTTONSEED	TOTAL OILSEEDS
Potential domestic SAF production	2025	43.70 ML	2.74 ML	46.44 ML
	2050	49.50 ML	3.10 ML	52.60 ML
Potential SAF production as portion of projected fuel demand	2025	0.47%	0.03%	0.50%
	2050	0.32%	0.02%	0.34%

HIGH SCENARIO		CANOLA	COTTONSEED	TOTAL OILSEEDS
Potential domestic SAF production	2025	180.06 ML	11.28 ML	191.34 ML
	2050	295.40 ML	18.50 ML	313.91 ML
Potential SAF production as portion of projected fuel demand	2025	1.95%	0.12%	2.07%
	2050	1.90%	0.12%	2.02%

Figure 68. Australian canola seed growth projections and HEFA feedstock requirements based on plant size

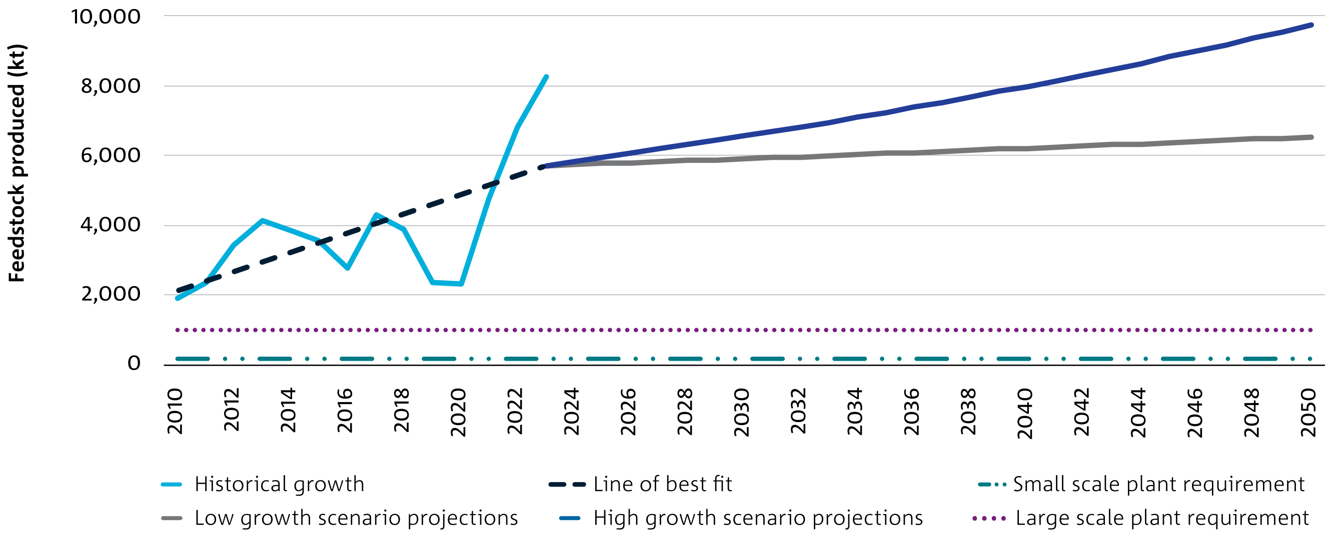


Figure 69. Potential SAF production from Australian canola and contribution toward domestic jet fuel demand (high feedstock growth rate, high jet fuel yield scenario)

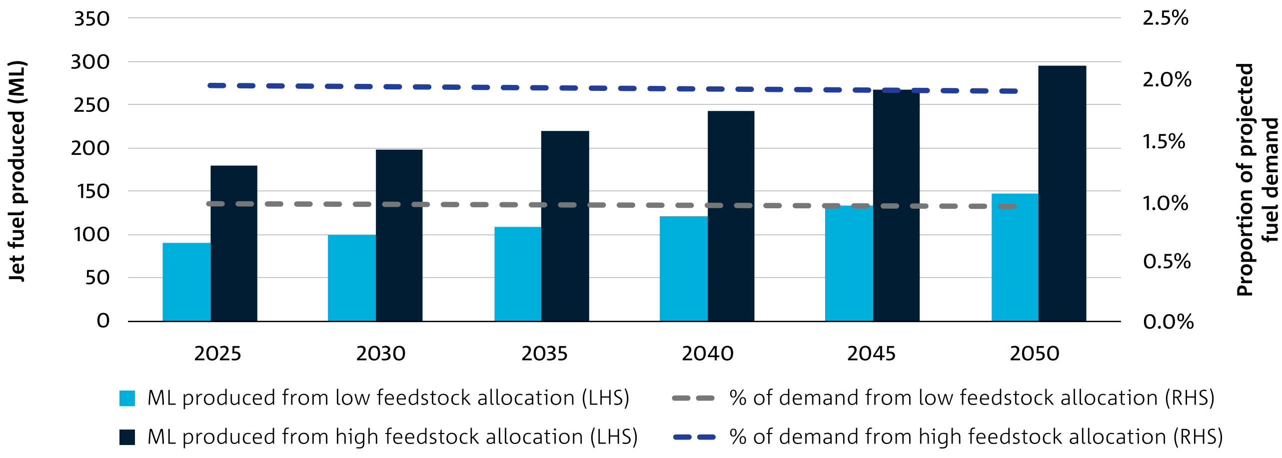


Figure 70. Australian cottonseed growth projections and HEFA feedstock requirements based on plant size

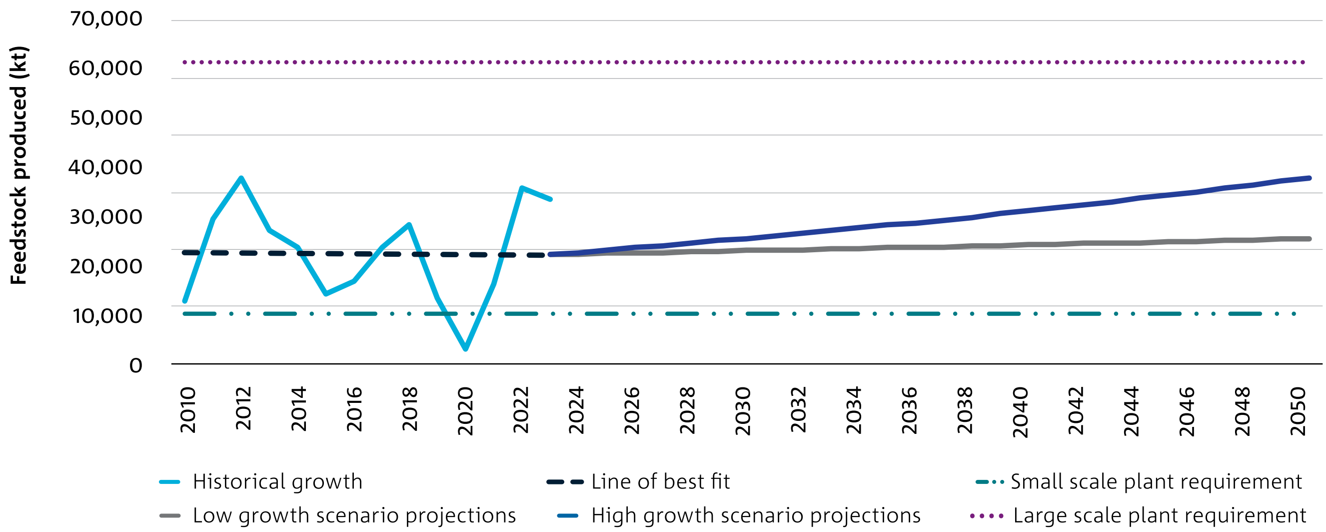


Figure 71. Potential SAF production from Australian cottonseed and contribution toward domestic jet fuel demand (high feedstock growth rate, high jet fuel yield scenario)

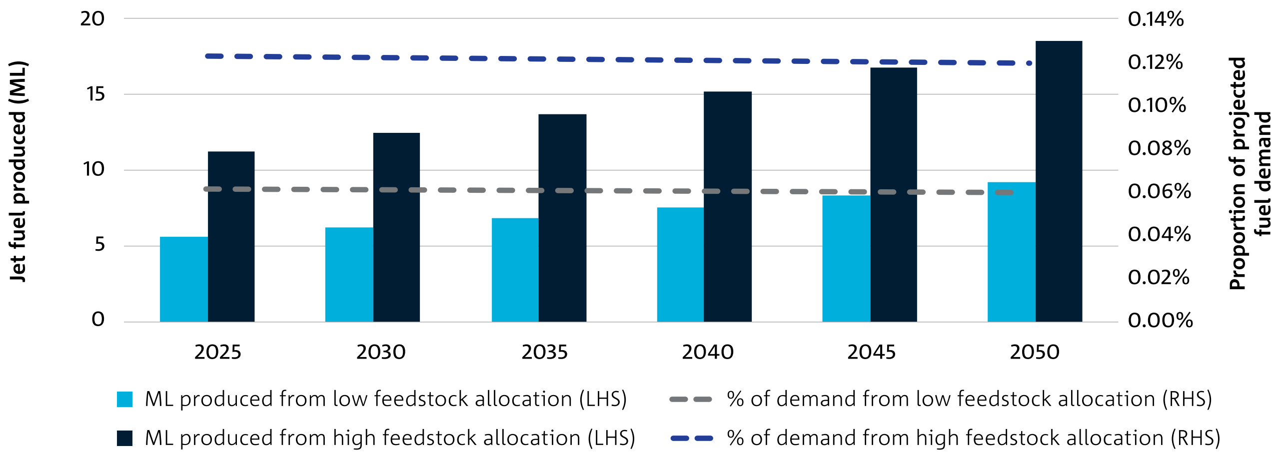
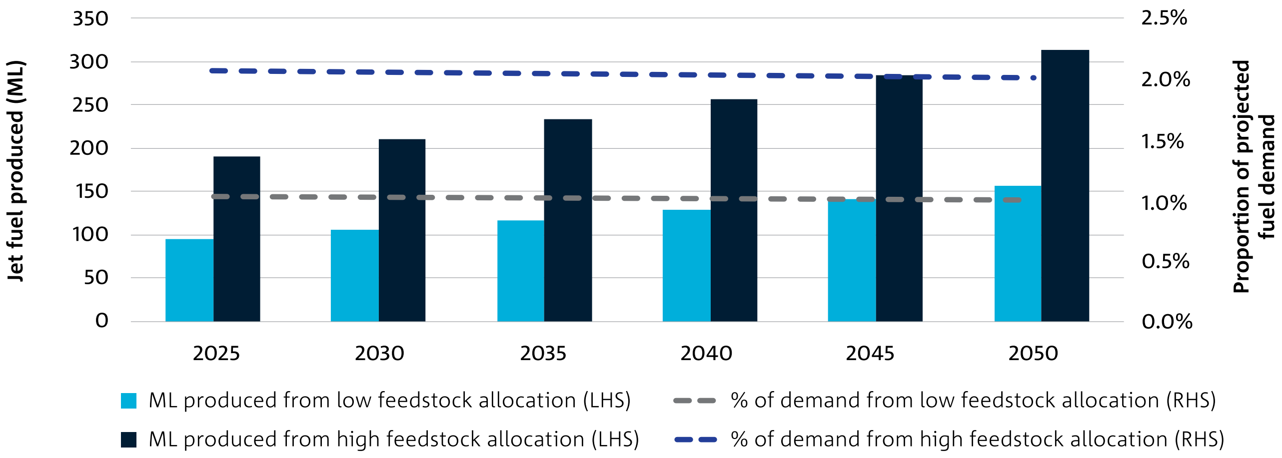


Figure 72. Potential SAF production from Australian oilseeds and contribution toward domestic jet fuel demand (high feedstock growth rate, high jet fuel yield scenario)



7.4.7 Power-to-liquids (PtL)

Calculations

(1) Potential domestic feedstock production by 2025 (t)	= A x 1,000 x B
Potential domestic feedstock production by 2050 (t)	= 1,000,000 x B x C
(2) Potential domestic SAF production (ML)	= [(1) x D x E]/1,000,000
(3) Potential SAF production as portion of projected fuel demand (%)	= [(2)/F] x 100

Assumptions

PARAMETERS			HYDROGEN
A	Projection of domestic feedstock production (2025)[204]	Low	91 kt
		High	232 kt
B	Feedstock portion allocated to jet fuel (%)	Low	12.5%
		High	25%
C	Forecast annual growth in feedstock production[205]	Low	Hydrogen (Mt) = 3E-114e^(0.1279*year)
		High	Hydrogen (Mt) = 1E-157e^(0.1778*year)
D	RWGS+FT jet fuel yield[206]	Low	25%
		High	80%
E	Jet fuel density[207]		1,263 L/t
F	Projected jet fuel demand		*See Table 1*
G	PtL plant requirement	Small scale	88 kt
		Large scale	528 kt

204 Deloitte 2020, Erratum: Australian and global hydrogen demand growth scenario analysis, COAG Energy Council – National Hydrogen Strategy Taskforce. https://www.dcceew.gov.au/sites/default/files/documents/erratum-coag-report.pdf

Australian hydrogen projections were obtained by summing global hydrogen demand for Australia and international demand captured by Australia for 2025, 2030, 2040 and 2050. Year-on-year hydrogen projections were then estimated from 2025–2050 by applying an exponential trendline to these data points and using the associated equation to solve for the years in between.

205 E.g., year = 2050.

206 Low and high RWGS+FT jet fuel yield figures were chosen based on what is feasible for Australia, obtained via literature review and industry stakeholder consultations.

Klerk A 2011, Fischer-Tropsch fuels refinery design, Energy & Environmental Science, 4, 1177–1205. https://pubs.rsc.org/en/content/articlelanding/2011/ee/c0ee00692k

Zang G et al. 2021, Performance and cost analysis of liquid fuel production from H2 and CO2 based on the Fischer-Tropsch process, Journal of CO2 Utilisation, 46, https://www.sciencedirect.com/science/article/pii/S2212982021000263

207 Department of Climate Change, Energy, the Environment and Water 2023, Australian Petroleum Statistics – Data Extract December 2022 [XLSX]. https://www.energy.gov.au/publications/australian-petroleum-statistics-2022

Results

The lowest estimates (from our low feedstock portion allocated to jet fuel, low forecast annual growth rate, and low jet fuel yield scenario) and highest plausible estimates (from our high feedstock portion allocated to jet fuel, high forecast annual growth rate, and high jet fuel yield scenario) are summarised here. Discrepancies in summations are due to differences in rounding.

LOW SCENARIO		TOTAL POWER-TO-LIQUIDS
Potential domestic SAF production	2025	3.59 ML
	2050	87.74 ML
Potential SAF production as portion of projected fuel demand	2025	0.04%
	2050	0.56%

HIGH SCENARIO		TOTAL POWER-TO-LIQUIDS
Potential domestic SAF production	2025	58.61 ML
	2050	4,993.78 ML
Potential SAF production as portion of projected fuel demand	2025	0.63%
	2050	32.14%

Figure 73. Australian hydrogen growth projections and FT feedstock requirements based on plant size

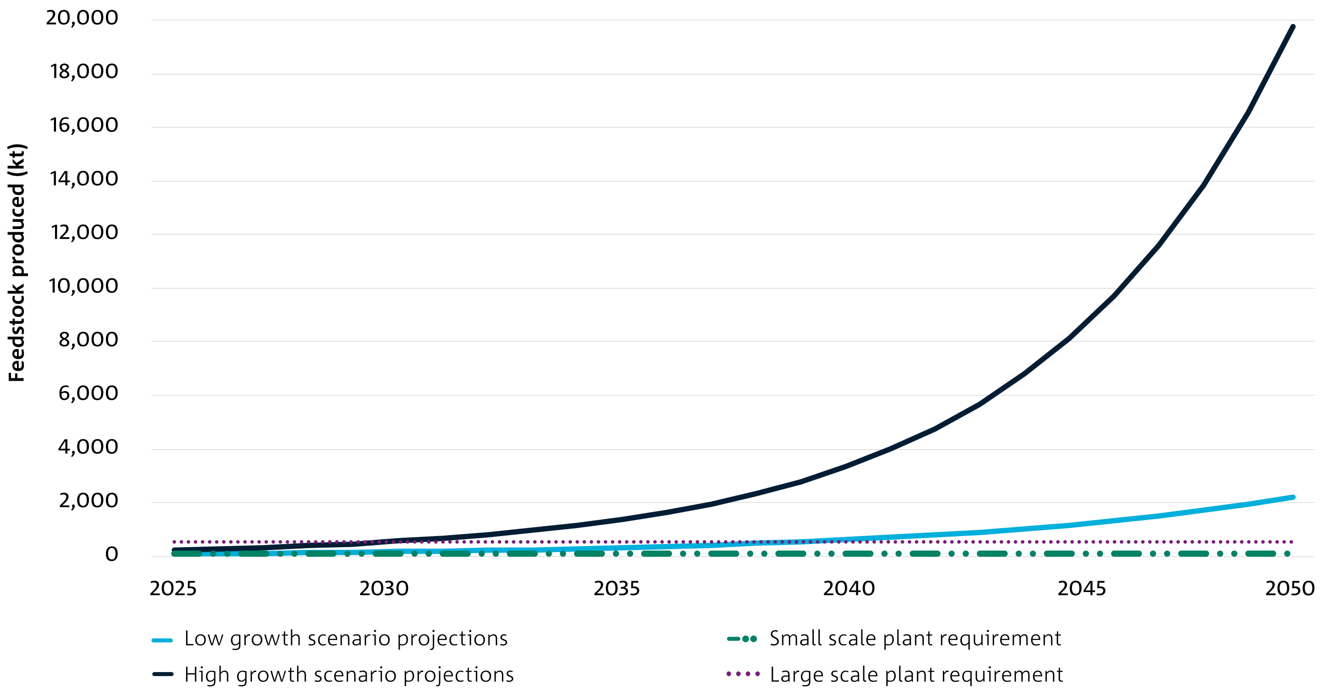
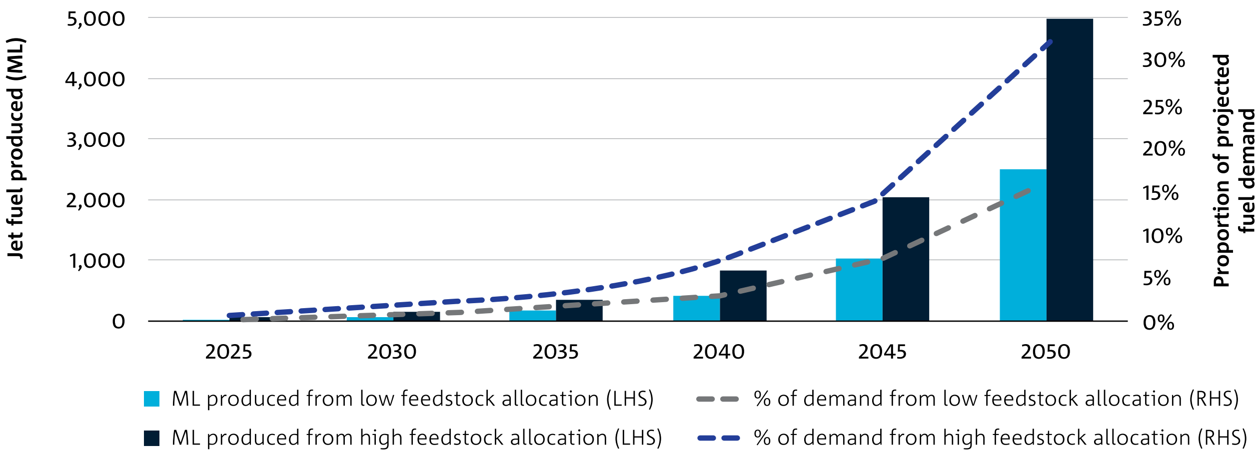


Figure 74. Potential SAF production from Australian PtL and contribution toward domestic jet fuel demand (high feedstock growth rate, high jet fuel yield scenario)



7.4.8 Total SAF

Results

The lowest estimates (from our low feedstock portion allocated to jet fuel, low forecast annual growth rate, and low jet fuel yield scenario) and highest plausible estimates (from our high feedstock portion allocated to jet fuel, high forecast annual growth rate, and high jet fuel yield scenario) are summarised here. Discrepancies in summations are due to differences in rounding.

LOW SCENARIO		TOTAL SAF
Potential domestic SAF production	2025	964.77 ML
	2050	1,176.57 ML
Potential SAF production as portion of projected fuel demand	2025	10.42%
	2050	7.57%

HIGH SCENARIO		TOTAL SAF
Potential domestic SAF production	2025	5,511.33 ML
	2050	13,939.54 ML
Potential SAF production as portion of projected fuel demand	2025	59.54%
	2050	89.72%

Figure 75. Potential Australian total SAF production and contribution toward domestic jet fuel demand (high feedstock growth rate, high jet fuel yield scenario)

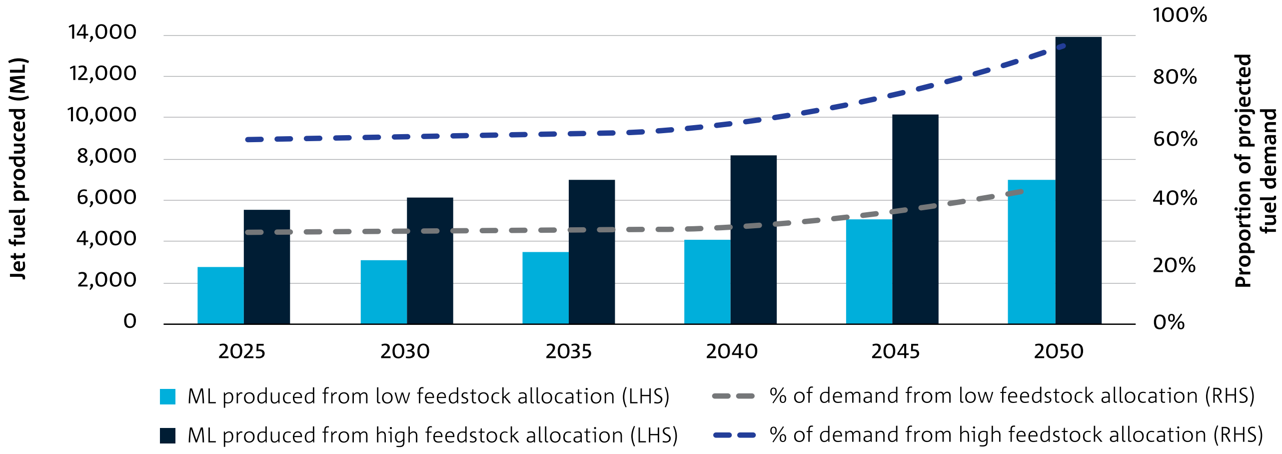


Figure 76. Australian feedstock availability converted to SAF across low and high scenario

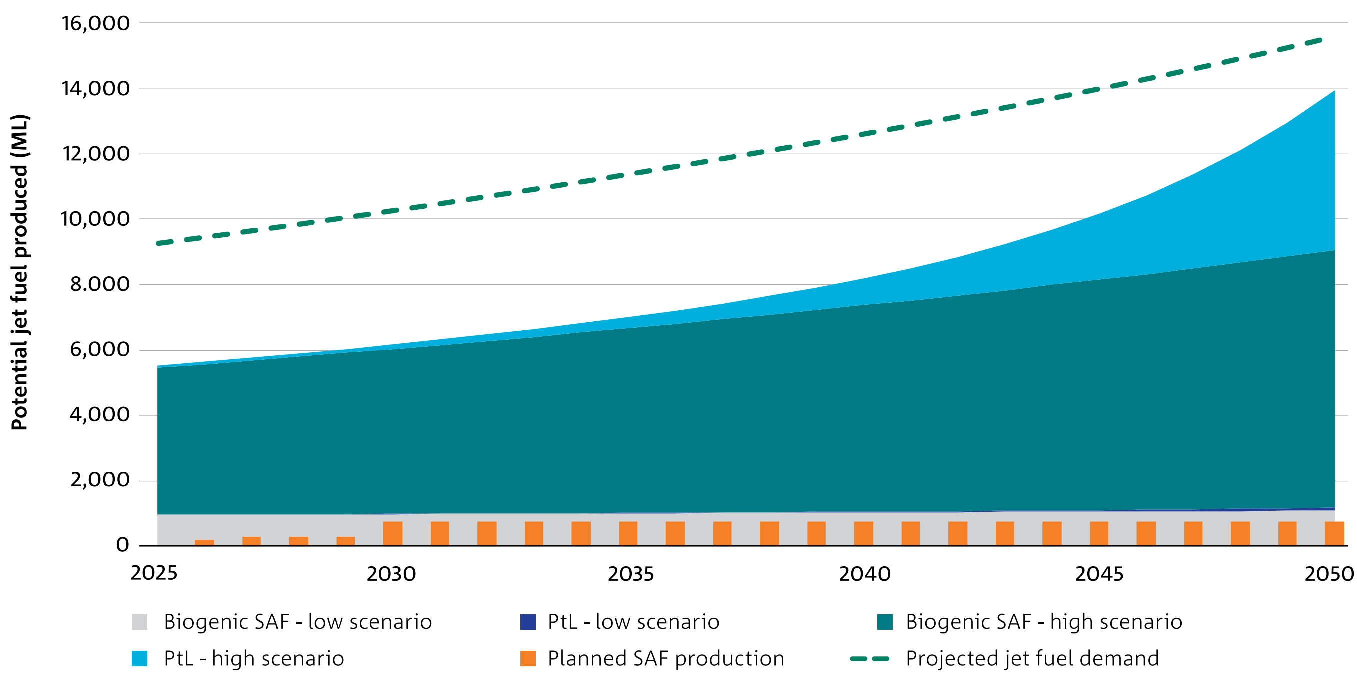
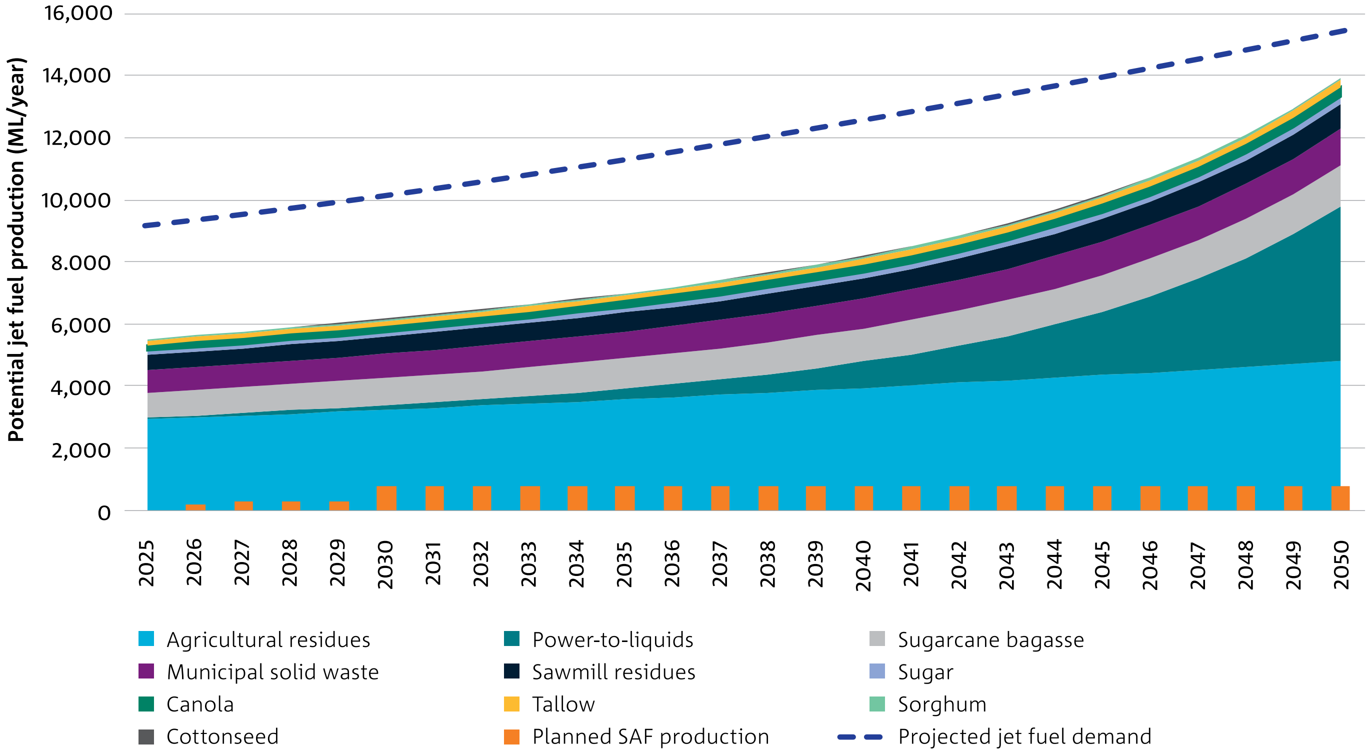


Figure 77. Australian feedstock availability converted to SAF for high scenario



7.5 Feedstock modelling for New Zealand

7.5.1 This analysis

Economic analysis of feedstock availability for SAF was undertaken by CSIRO Futures to assess the commercial opportunity for SAF in New Zealand by 2050. Sawmill residues and tallow were selected for analysis due to the commercial maturity of their production. Other woody biomass was excluded from this modelling exercise due to the contention over their use in biofuels as per chapter 3.3. As such, this Appendix summarises the parameters, methodology and results of this modelling, developed in consultation and used to produce the estimates presented in this Roadmap.

7.5.2 Parameters

Jet fuel demand

Projections of New Zealand's total jet fuel demand from 2025–2050 were obtained from its 2018 Biofuels Roadmap.

These projections were used to calculate the percentage of fuel demand that SAF projections represented for context, allowing comparison across feedstocks and across time.

Table 11: Projected New Zealand jet fuel demand to 2050[208]

YEAR	PROJECTED JET FUEL DEMAND
2025	1,842 ML
2030	1,982 ML
2035	2,121 ML
2040	2,260 ML
2045	2,399 ML
2050	2,539 ML

Other parameters

All other parameters are assumed to be the same as for Australia, as defined in Section 7.4.2.

208 Business NZ Energy Council 2018, BEC Energy Scenarios: BEC2050 (MARKEL), 2050 dataset, https://bec.org.nz/tools/scenarios/bec2050-energy-scenarios-markel/

Estimates for aviation TFC (PJ/y) for 2010, 2020, 2030, 2040, 2050 for the low use and high use scenario were used. The average estimates for the two scenarios were calculated and converted to ML/y using a ratio of 34.7 MJ/L of jet fuel. Jet fuel demand was estimated for 2025–2050 by applying a linear line of best fit with a least squares approach.

7.5.3 Sawmill residues

Calculations

(1)	Potential domestic feedstock production by 2018 (t)	= A x 1,000 x B
	Potential domestic feedstock production by 2050 (t)	= A x 1,000 x B x (1+C)^32
(2)	Potential domestic SAF production (ML)	= [(1) x D x E]/1,000,000
(3)	Potential SAF production as portion of projected fuel demand (%)	= [(2)/F] x 100

Assumptions

PARAMETERS			SAWMILL RESIDUES
A	Current estimate of domestic feedstock production based on historical trends (2018)[209]		4,342 kt
B	Feedstock portion allocated to jet fuel (%)	Low	20%
		High	40%
C	Forecast annual growth in feedstock production	Low	0.5%
		High	2%
D	G+FT jet fuel yield[210]	Low	5%
		High	15%
E	Jet fuel density[211]		1,263 L/t
F	Projected jet fuel demand		*See Table 3*
G	G+FT plant requirement	Small scale	264 kt
		Large scale	1,584 kt

209 New Zealand Ministry for Primary Industries 2019, Production of sawn timber, 1970 to most recent [XLSX, 21 KB]. https://www.mpi.govt.nz/forestry/forest-industry-and-workforce/forestry-wood-processing-data/wood-processing-data/

ABARES 2018, Future opportunities for using forest and sawmill residues in Australia, Australian Bureau of Agricultural and Resource Economics and Sciences. https://www.agriculture.gov.au/abares/research-topics/forests/forest-economics/forest-economic-research/forest-sawmill-residues-report

A reported ratio of 1m3 sawlogs = 0.5t sawmill residues was applied to sawn timber production data to estimate available sawmill residues. Calculation assumes sawlog = sawn timber + sawmill residues, and therefore 1m3 sawn timber = 1t sawmill residues.

A historical trend line was calculated from 2010–2018 feedstock production data reported, and then applied to obtain a 2018 current estimate to use for forecasts.

210 Low and high G+FT jet fuel yield figures were chosen based on what is feasible for Australia, obtained via literature review and industry stakeholder consultations.

Diederichs GW 2015, Techno-economic assessment of processes that produce jet fuel from plant-derived sources, university thesis. https://core.ac.uk/download/pdf/37440495.pdf

Bressanin JM et al. 2020, Techno-economic and environmental assessment of biomass gasification and Fischer-Tropsch synthesis integrated to sugarcane biorefineries, Energies, 13(17). https://www.mdpi.com/1996-1073/13/17/4576

211 Department of Climate Change, Energy, the Environment and Water 2023, Australian Petroleum Statistics – Data Extract December 2022 [XLSX]. https://www.energy.gov.au/publications/australian-petroleum-statistics-2022

Results

The lowest estimates (from our low feedstock portion allocated to jet fuel, low forecast annual growth rate, and low jet fuel yield scenario) and highest plausible estimates (from our high feedstock portion allocated to jet fuel, high forecast annual growth rate, and high jet fuel yield scenario) are summarised here. Discrepancies in summations are due to differences in rounding.

LOW SCENARIO		SAWMILL RESIDUES
Potential domestic SAF production	2025	56.79 ML
	2050	64.33 ML
Potential SAF production as portion of projected fuel demand	2025	3.08%
	2050	2.53%

HIGH SCENARIO		SAWMILL RESIDUES
Potential domestic SAF production	2025	377.98 ML
	2050	620.12 ML
Potential SAF production as portion of projected fuel demand	2025	20.52%
	2050	24.43%

Figure 78. New Zealand sawmill residues growth projections and FT feedstock requirements based on plant size

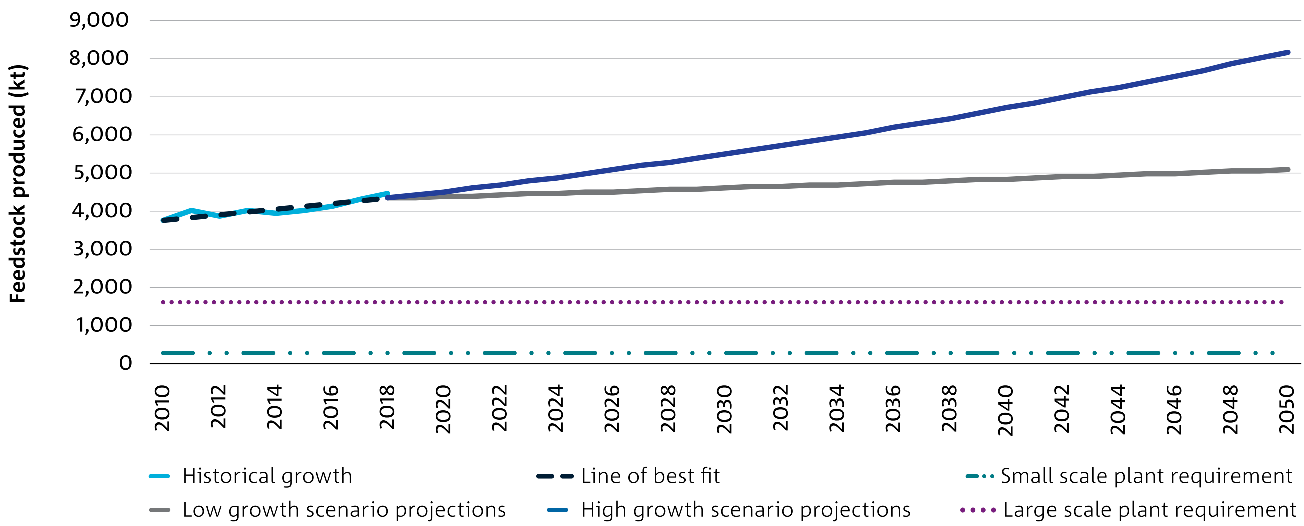
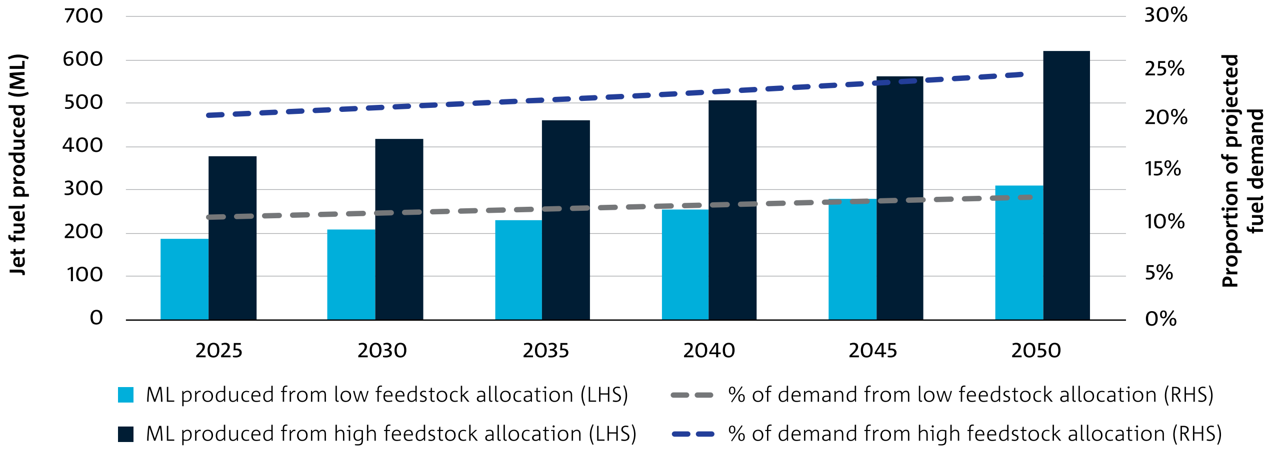


Figure 79. Potential SAF production from New Zealand sawmill residues and contribution toward domestic jet fuel demand (high feedstock growth rate, high jet fuel yield scenario)



7.5.4 Tallow

Calculations

(1)	Potential domestic feedstock production by 2020 (t)	= A x 1,000 x B
	Potential domestic feedstock production by 2050 (t)	= A x 1,000 x B x (1+C)^30
(2)	Potential domestic SAF production (ML)	= [(1) x D x E]/1,000,000
(3)	Potential SAF production as portion of projected fuel demand (%)	= [(2)/F] x 100

Assumptions

PARAMETERS			TALLOW
A	Current estimate of domestic feedstock production based on historical trends (2020)[212]		177 kt
B	Feedstock portion allocated to jet fuel (%)	Low	20%
		High	40%
C	Forecast annual growth in feedstock production	Low	0.5%
		High	2%
D	HEFA jet fuel yield[213]	Low	30%
		High	60%
E	Jet fuel density[214]		1,263L/t
F	Projected jet fuel demand		*See Table 3*
G	HEFA plant requirement	Small scale	66 kt
		Large scale	396 kt

212 Food and Agriculture Organization of the United Nations 2023, New Zealand tallow production quantity. https://www.fao.org/faostat/en/#data/QCL

A historical trend line was calculated from 2010–2020 feedstock production data reported, and then applied to obtain a 2020 current estimate to use for forecasts.

213 Low and high HEFA jet fuel yield figures were chosen based on what is feasible for Australia, obtained via literature review and industry stakeholder consultations.

Diederichs GW 2015, Techno-economic assessment of processes that produce jet fuel from plant-derived sources, university thesis. https://core.ac.uk/download/pdf/37440495.pdf

Han J, Elgowainy A, Cai H and Wang MQ 2013, Life-cycle analysis of bio-based aviation fuels, Bioresource Technology, 150, 447–456. https://www.sciencedirect.com/science/article/pii/S0960852413012297?via%3Dihub

Martinez-Hernandez E, Ramirez-Verduzco LF, Amezcua-Allieri MA and Aburto-J 2019, Process simulation and techno-economic analysis of bio-jet fuel and green diesel production – minimum selling prices, Chemical Engineering Research and Design, 146, 60–70. https://www.sciencedirect.com/science/article/pii/S0263876219301534?via%3Dihub

Pearlson M, Wollersheim C and Hileman J 2013, A techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production, Biofuels, Bioproducts and Biorefining, 7(1), 89–96. https://onlinelibrary.wiley.com/doi/full/10.1002/bbb.1378

Tao L, Milbrandt A, Zhang Y and Wang WC 2017, Techno-economic and resource analysis of hydroprocessed renewable jet fuel, Biotechnology for Biofuels, 10(261). https://biotechnologyforbiofuels.biomedcentral.com/articles/10.1186/s13068-017-0945-3

214 Department of Climate Change, Energy, the Environment and Water 2023, Australian Petroleum Statistics – Data Extract December 2022 [XLSX]. https://www.energy.gov.au/publications/australian-petroleum-statistics-2022

Results

The lowest estimates (from our low feedstock portion allocated to jet fuel, low forecast annual growth rate, and low jet fuel yield scenario) and highest plausible estimates (from our high feedstock portion allocated to jet fuel, high forecast annual growth rate, and high jet fuel yield scenario) are summarised here. Discrepancies in summations are due to differences in rounding.

LOW SCENARIO		TALLOW
Potential domestic SAF production	2025	13.72 ML
	2050	15.54 ML
Potential SAF production as portion of projected fuel demand	2025	0.74%
	2050	0.61%

HIGH SCENARIO		TALLOW
Potential domestic SAF production	2025	59.08 ML
	2050	96.92 ML
Potential SAF production as portion of projected fuel demand	2025	3.21%
	2050	3.82%

Figure 80. New Zealand tallow growth projections and HEFA feedstock requirements based on plant size

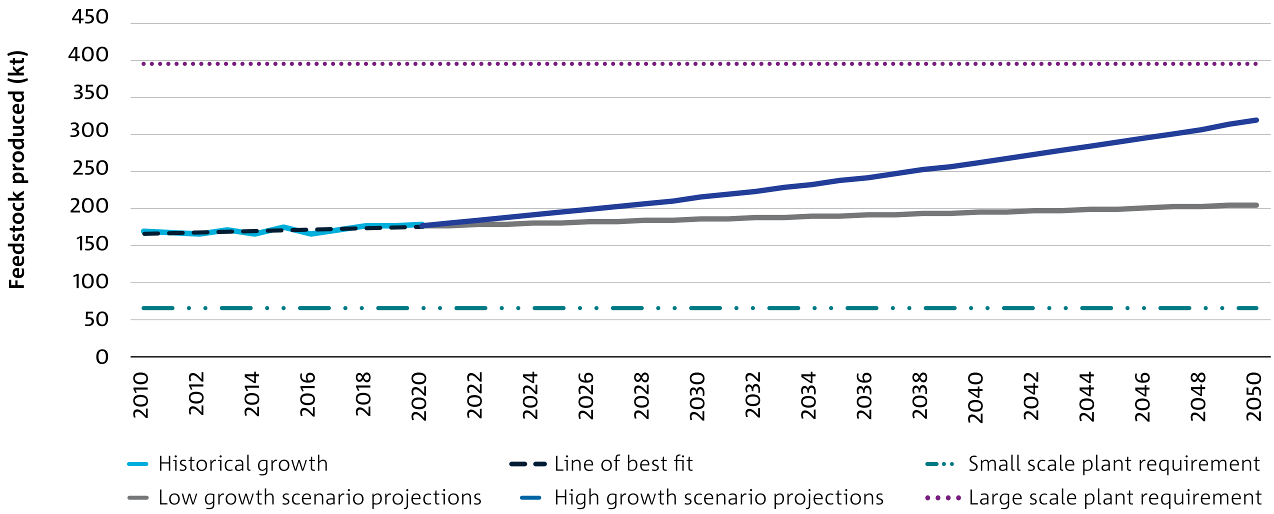
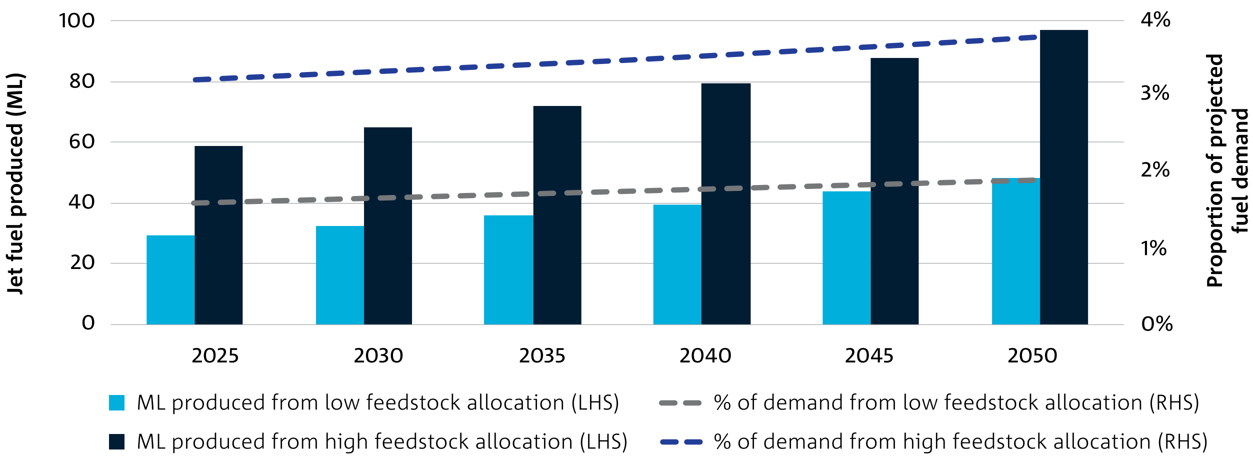


Figure 81. Potential SAF production from New Zealand tallow and contribution toward domestic jet fuel demand (high feedstock growth rate, high jet fuel yield scenario)



7.6 Feedstock modelling country summary

7.6.1 Summary

Results

The lowest estimates (from our low feedstock portion allocated to jet fuel, low forecast annual growth rate, and low jet fuel yield scenario) and highest plausible estimates (from our high feedstock portion allocated to jet fuel, high forecast annual growth rate, and high jet fuel yield scenario) are summarised here for potential jet fuel produced (ML) from each country's top two highest potential feedstocks. Discrepancies in summations are due to differences in rounding.

The top two feedstocks for SAF production in Australia by 2025 are agricultural residues (from barley, corn (maize), grain sorghum, oats, rice, triticale, and wheat crops), and the combination of sugarcane and bagasse. By 2050, the two most potential feedstocks for SAF production come from the PtL process and agricultural residues. The two primary feedstocks available for SAF production in New Zealand up to 2050 are sawmill residues and tallow. For Indonesia, they are palm fruit and sugarcane and bagasse combined. The two most potential feedstocks for SAF production in Vietnam are agricultural residues and sugarcane and bagasse combined. For Malaysia, they are palm fruit and agricultural residues. For PNG, they are palm fruit and coconut.

LOW SCENARIO		AUSTRALIA	NEW ZEALAND	INDONESIA	VIETNAM	MALAYSIA	PNG
Potential domestic SAF production	2025	626 ML	71 ML	1,675 ML	556 ML	593 ML	21 ML
	2050	624 ML	80 ML	1,897 ML	629 ML	672 ML	24 ML

HIGH SCENARIO		AUSTRALIA	NEW ZEALAND	INDONESIA	VIETNAM	MALAYSIA	PNG
Potential domestic SAF production	2025	3,871 ML	437 ML	7,399 ML	3,537 ML	2,573 ML	90 ML
	2050	9,794 ML	717 ML	12,139 ML	5,803 ML	4,221 ML	148 ML

Figure 82. Potential SAF production from each country's top two feedstocks (low scenario)

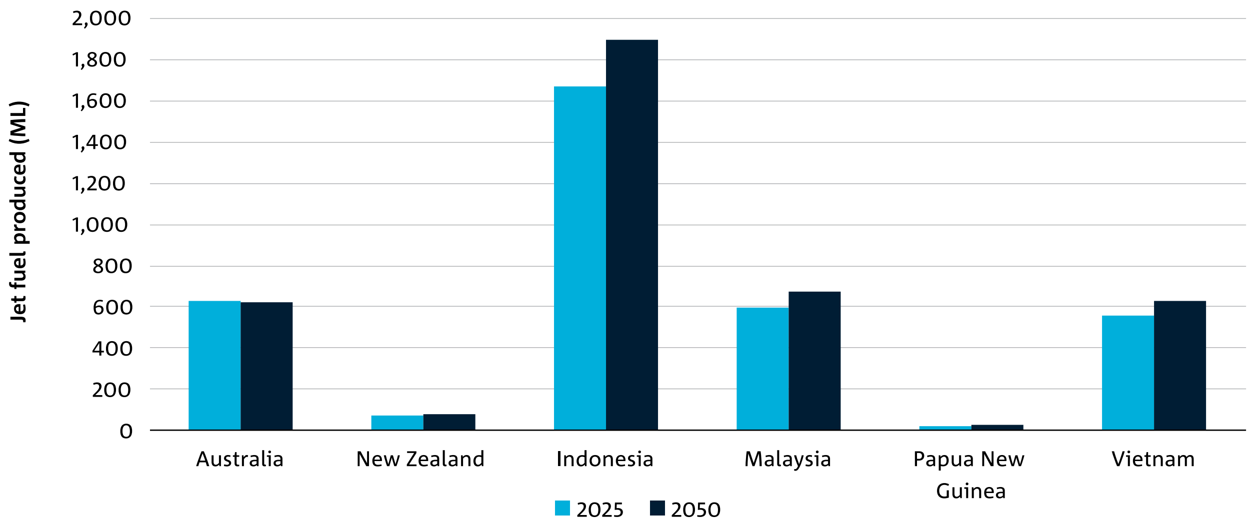
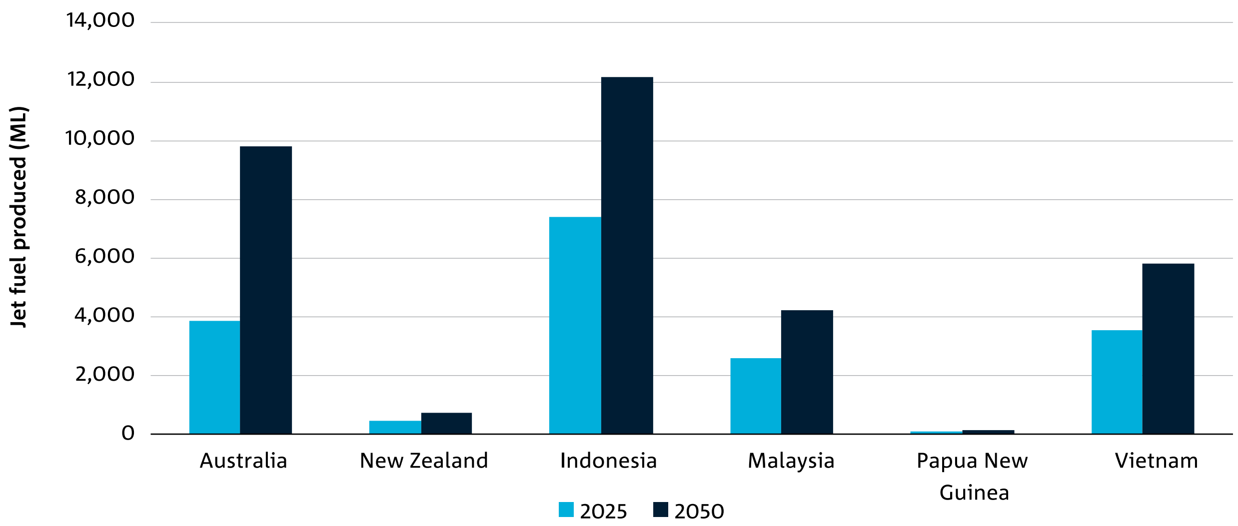


Figure 83. Potential SAF production from each country's top two feedstocks (high scenario)



7.7 Technoeconomic appendix

Overarching assumptions

The tables below provide a summary of the key financial and model parameters used for the analysis of all SAF pathways. It is assumed that each project would run for 20 years. It was also assumed that these projects were funded by 100% debt financing.

Small scale plants were standardised across pathways to produce 50 ML of SAF, in addition to other outputs such as diesel and LPG.

Large scale plants were standardised across pathways to produce 300 ML of SAF, in addition to other outputs such as diesel and LPG.

Cost assumptions used in this report were informed by desktop analysis and project consultations undertaken for the CSIRO CO_2 Utilisation Roadmap, the CSIRO National Hydrogen Roadmap and CSIRO Opportunities for Hydrogen in Commercial Aviation report. They are designed to reflect estimates of the costs that could be achieved for different scale projects at the time of writing. All assumptions are in real terms for 2023. These costs can be expected to reduce as the industry grows in scale.

Financial assumptions[215,216]

VARIABLES	UNIT	BASE CASE	BEST CASE
Interest rate (real)	%	6	6
Debt financing ratio	%	100	100
Length of loan	Years	20	20
Plant life	Years	20	20
Electricity	c/kWh	6.00	4.00
Hydrogen	$/kg	5.47	2.62
Conventional jet fuel	$/L	86[217]	86
AUD:USD Exchange Rate	USD	0.70	0.70
AUD:EUR Exchange Rate	EUR	0.64	0.64
AUD:CNY Exchange Rate	CNY	5.56	5.56

215 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO2 Utilisation Roadmap*. CSIRO.

216 Bruce et al (2018) National Hydrogen Roadmap. CSIRO.

217 IATA (2023) Jet Fuel Price Monitor. https://www.iata.org/en/publications/economics/fuel-monitor/ (Accessed May 3 2023). Asia and Oceania price of $USD90.85/bbl

Alcohol-to-Jet (From ethanol)

Plant assumptions and inputs[218]

VARIABLES	UNITS	TODAY	2050
Capacity factor	%	90	90
Ethanol input	L/year	123,875,913	743,225,477
Hydrogen input	t/year	421	2,533
Ethanol cost	$/L	1.49[219]	0.72[220]

Plant outputs[221]

VARIABLES	UNITS	TODAY	2050
ATJ-SPK output	L/year	50,000,000	300,000,000
Gasoline	L/year	7,956,968	47,741,810
Diesel	L/year	13,863,560	83,181,358
Total	**L/year**	**71,820,528**	**430,923,168**

Levelised cost of production

VARIABLE	TODAY ($/L)	2050 ($/L)	TODAY ($/t)	2050 ($/t)
Capital cost	0.06	0.03	75	37
Feedstock	2.57	1.24	3147	1514
Hydrogen	0.03	0.01	42	7
Other variable opex	0.07	0.05	82	59
Fixed opex	0.03	0.01	38	11
Levelised cost of production	**2.76**	**1.33**	**3,385**	**1,627**

Feedstock cost sensitivity

EFFECT ON 2050 ETHANOL PRICE	ETHANOL PRICE IN 2050 ($/L)	LEVELISED COST OF PRODUCTION IN 2050 ($/L)
-25%	0.54	1.02
No change	0.72	1.32
+25%	0.90	1.65

218 Geleynse S et al. (2018) The Alcohol-to-Jet Conversion Pathway for Drop-In Biofuels: Techno-Economic Evaluation.

219 Independent Pricing and Regulatory Tribunal NSW (2021) Wholesale price for fuel ethanol 2022. https://www.ipart.nsw.gov.au/sites/default/files/cm9_documents/Fact-Sheet-Wholesale-Price-for-Fuel-Ethanol-2022-December-2021.PDF

220 Junqueira T et al. (2017) Techno-economic analysis and climate change impacts of sugarcane biorefineries considering different time horizons.

Junqueira et al. shows a decrease 52% decrease in ethanol price from today's 1G ethanol to a long-term 2G ethanol price. This decrease was applied to the NSW 2022 average wholesale ethanol price to arrive at $0.72/L.

221 Geleynse S et al. (2018) The Alcohol-to-Jet Conversion Pathway for Drop-In Biofuels: Techno-Economic Evaluation.

Fischer-Tropsch (from MSW)

Plant assumptions and inputs[222,223,224]

VARIABLES	UNITS	TODAY	2050
Capacity factor	%	90	90
MSW input	t/year	965,751	5,794,508
MSW cost[225]	$/t	100	100

Plant outputs

VARIABLES	UNITS	TODAY	2050
FT-SPK output	L/year	50,000,000	300,000,000
Gasoline	L/year	64,328,116	385,968,699
Diesel	L/year	31,051,012	186,306,069
Total	**L/year**	**145,379,128**	**872,274,768**

Levelised cost of production

VARIABLE	TODAY ($/L)	2050 ($/L)	TODAY ($/t)	2050 ($/t)
Capital cost	1.25	0.64	1,587	815
Feedstock	0.66	0.63	842	794
Hydrogen	-	-	-	-
Other variable opex	0.27	0.14	342	180
Fixed opex	0.11	0.04	143	56
Levelised cost of production	**2.30**	**1.46**	**2,914**	**1,845**

Feedstock cost sensitivity

EFFECT ON 2050 MSW PRICE	MSW PRICE IN 2050 ($/t)	LEVELISED COST OF PRODUCTION IN 2050 ($/L)
-25%	75	1.30
No change	100	1.46
+25%	125	1.61

222 Jones et al. (2009) Municipal Solid Waste (MSW) to Liquid Fuels Synthesis, Volume 2: A Techno-economic Evaluation of the Production of Mixed Alcohols

223 Bressanin J et al. (2020) Techno-Economic and Environmental Assessment of Biomass Gasification and Fischer–Tropsch Synthesis Integrated to Sugarcane Biorefineries

224 Niziolek et al. (2017) Municipal solid waste to liquid transportation fuels, olefins, and aromatics: Process synthesis and deterministic global optimization

225 Assumption based on desktop research and stakeholder consultations

Fischer-Tropsch (from biomass)

Plant assumptions and inputs[226]

VARIABLES	UNITS	TODAY	2050
Capacity factor	%	90	90
Biomass input	t/year	724,313	4,345,878
Biomass cost[227]	$/t	100	100

Plant outputs[228]

VARIABLES	UNITS	TODAY	2050
FT-SPK output	L/year	50,000,000	300,000,000
Gasoline	L/year	64,328,116	385,968,699
Diesel	L/year	31,051,012	186,306,069
Total	**L/year**	**145,379,128**	**872,274,768**

Levelised cost of production

VARIABLE	TODAY ($/L)	2050 ($/L)	TODAY ($/t)	2050 ($/t)
Capital cost	0.98	0.47	1,239	590
Feedstock	0.50	0.47	631	596
Hydrogen	-	-	-	-
Other variable opex	0.21	0.10	267	130
Fixed opex	0.10	0.04	126	45
Levelised cost of production	**1.79**	**1.07**	**2,264**	**1,361**

Feedstock cost sensitivity

EFFECT ON 2050 BIOMASS PRICE	BIOMASS PRICE IN 2050 ($/t)	LEVELISED COST OF PRODUCTION IN 2050 ($/L)
-25%	75	0.96
No change	100	1.02
+25%	125	1.19

226 Bressanin J et al. (2020) Techno-Economic and Environmental Assessment of Biomass Gasification and Fischer–Tropsch Synthesis Integrated to Sugarcane Biorefineries

227 Assumption based on desktop research and stakeholder consultations

228 Bressanin J et al. (2020) Techno-Economic and Environmental Assessment of Biomass Gasification and Fischer–Tropsch Synthesis Integrated to Sugarcane Biorefineries

Hydroprocessed Esters and Fatty Acids (from vegetable oil)

Plant assumptions and inputs[229]

VARIABLES	UNITS	TODAY	2050
Capacity factor	%	96	96
Canola oil input	t/year	86,421	518,526
Hydrogen input	t/year	2,583	15,508
Canola oil cost	$/kg	1.36[230]	1.36

Plant outputs[231]

VARIABLES	UNITS	TODAY	2050
HEFA-SPK output	L/year	50,000,000	300,000,000
Propane	L/year	7,008,195	42,049,168
LPG	L/year	9,284,600	55,707,597
Naptha	L/year	8,023,175	48,139,048
Diesel	L/year	22,886,099	137,316,593
Total product	**L/year**	**97,202,068**	**583,212,407**

Levelised cost of production

VARIABLE	TODAY ($/L)	2050 ($/L)	TODAY ($/t)	2050 ($/t)
Capital cost	0.04	0.02	51	25
Feedstock	1.21	1.21	1,573	1,573
Hydrogen	0.15	0.04	201	47
Other variable pex	0.02	0.01	28	10
Fixed opex	0.02	0.01	32	9
Levelised cost of production	**1.45**	**1.28**	**1,886**	**1,664**

229 Technoeconomic analysis of biojet fuel production from camelina at commercial scale: Case of Canadian Prairies.
230 https://www.neste.com/investors/market-data/palm-and-rapeseed-oil-prices. Accessed 5 May 2023.
231 Technoeconomic analysis of biojet fuel production from camelina at commercial scale: Case of Canadian Prairies.

Feedstock cost sensitivity

EFFECT ON 2050 CANOLA OIL PRICE	CANOLA PRICE IN 2050 ($/KG)	LEVELISED COST OF PRODUCTION IN 2050 ($/L)
-25%	1.02	0.97
No change	1.36	1.28
+25%	1.70	1.59

Power-to-liquids (Fischer-Tropsch from CO_2 and H_2) input assumptions

Plant assumptions and inputs[232]

VARIABLES	UNITS	TODAY	2050
Capacity factor	%	90	90
Hydrogen input	t/year	55,846	335,078
Carbon dioxide input	t/year	597,778	3,586,682
CO_2 cost[233]	$/t	85.78	46.13

Plant outputs

VARIABLES	UNITS	TODAY	2050
FT-SPK output	L/year	50,000,000	300,000,000
Naphtha	L/year	31,038,322	186,229,934
Diesel	L/year	28,780,987	172,685,923
Total	**L/year**	**109,819,310**	**658,915,858**

Levelised cost of production

VARIABLE	TODAY ($/L)	2050 ($/L)	TODAY ($/t)	2050 ($/t)
Capital cost	0.57	0.28	713	348
Hydrogen	2.78	1.19	3,475	1,481
CO_2	0.47	0.22	583	279
Other variable opex	0.26	0.11	329	140
Fixed opex	0.06	0.02	81	27
Levelised cost of production	**4.15**	**1.82**	**5,181**	**2,276**

232 Zang et al. (2021) Performance and cost analysis of liquid fuel production from H2 and CO2 based on the Fischer-Tropsch process

233 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO2 Utilisation Roadmap*. CSIRO.

Feedstock cost sensitivity

EFFECT ON 2050 HYDROGEN PRICE	HYDROGEN PRICE IN 2050 ($/KG)	LEVELISED COST OF PRODUCTION IN 2050 ($/L)
-25%	1.97	1.53
No change	2.62	1.82
+25%	3.28	2.12

HYDROGEN		CARBON DIOXIDE		
BEST CASE MODEL (2.62/KG)	GOVT. STRETCH GOAL ($2.00/KG)	POINT SOURCE ($46/t)	DAC ($203/t)	LEVELISED COST OF PRODUCTION (2050) ($/L)
X		X		1.82
X			X	2.59
	X	X		1.54
	X		X	2.30

7.8 Fuel readiness levels

LEVEL	FRL DESCRIPTION	TOLL GATE
1	Basic principles	• Feedstock & process basic principles identified
2	Technology concept formulated	• Feedstock & complete process identified
3	Proof of concept	• Lab-scale fuel sample produced from realistic feedstock • Energy balance analysis conducted for initial environmental assessment • Basic fuel properties validated
4	Preliminary technical evaluation	• System performance and integration studies • Specification properties evaluated
5	Process validation	• Scaling from laboratory to pilot plant
6	Full-scale technical evaluation	• ASTM certification tests conducted: fit-for-purpose properties evaluated, turbine hot section testing, components, and testing
7	Certification/fuel approval	• Fuel listed in international standards
8	Commercialisation	• Business model validated for production • Airline purchase agreements secured • Plant-specific independent GHG assessment conducted in line with internationally accepted methodology
9	Production capability established	• Full-scale plant operational

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