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Opportunities and Priorities for a Low Carbon Liquid Fuel Industry in Australia

CSIRO Towards Net Zero mission
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Contents

List of acronyms

ABARES	Australian Bureau of Agricultural and Resource Economics
ABS	Australian Bureau of Statistics
ARA	Australian Renderers Association
ASTM	American Society for Testing and Materials International
ATJ	Alcohol to Jet
CI	Carbon Intensity
CLEEN	Continuous Lower Energy, Emissions and Noise
CO_2	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DAC	Direct Air Capture
DAFF	Department of Agriculture, Fisheries and Forestry
DCCEEW	Department of Climate Change, Energy, Environment and Water
EU	European Union
EU ETS	European Union’s Emissions Trading System
FAO	Food and Agriculture Organization of the United Nations
FIAL	Food Innovation Australia
GFT	Gasification Fischer-Tropsch process
GHG	Greenhouse Gas
GJ	Gigajoule
GLOBIOM	Global Biosphere Management Model
GREET	Greenhouse Gases, Regulated Emissions and Energy use in Transportation
GWh	Gigawatt-hour
H_2	Hydrogen
ha	Hectares
HEFA	Hydro-processed Esters and Fatty Acids
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
ILUC	Indirect Land Use Change

IRA	Inflation Reduction Act, 2022 (US)
ISCC	International Sustainability and Carbon Certification
JZA	Jet Zero Australia
kW	kilowatts
kWh	kilowatt-hour
LCA	Life Cycle Assessment
LCLS	California’s Low Carbon Fuel Standard
LCLF	Low Carbon Liquid Fuel
Mha	Million hectares
MJ	Megajoule
ML	Million litres
MSW	Municipal Solid Waste
Mt	Million tonnes
MW	Megawatts
MWh	Megawatt-hour
NSW	New South Wales
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
PJ	Petajoule
PtL	Power-to-Liquids
PBtL	Power-and-Biomass-to-Liquids
RD	Renewable Diesel
RED	Europe’s Renewable Energy Directive
RFS	Renewable Fuel Standard (US)
RPP	Australia’s Refinery Production Payment
RSB	Roundtable of Sustainable Biomaterials
SAF	Sustainable Aviation Fuel
SAFAANZ	Sustainable Aviation Fuel Alliance of Australia and New Zealand
SRT	Short Rotation Trees
TRL	Technology Readiness Level
UCO	Used Cooking Oil
US DA	United Stated Department of Agriculture
US DOE	United States Department of Energy

US DOT	United States Department of Treasury
WA	Western Australia

Conversion tables

Energy units

	Multiply by	
GW to MW	1,000.00	*ARENA Australia's Bioenergy Roadmap*
GW to kW	1,000,000.00	*ARENA Australia's Bioenergy Roadmap*
MW to kW	1,000.00	*ARENA Australia's Bioenergy Roadmap*
GWh to MWh	1,000.00	*ARENA Australia's Bioenergy Roadmap*
GWh to kWh	1,000,000.00	*ARENA Australia's Bioenergy Roadmap*
MWh to kWh	1,000.00	*ARENA Australia's Bioenergy Roadmap*
GWh to GJ	3,600.00	*ARENA Australia's Bioenergy Roadmap*
MWh to GJ	3.60	*ARENA Australia's Bioenergy Roadmap*
kWh to GJ	0.0036	*ARENA Australia's Bioenergy Roadmap*
PJ to MJ	1,000,000,000.00	*ARENA Australia's Bioenergy Roadmap*
PJ to GJ	1,000,000.00	*ARENA Australia's Bioenergy Roadmap*
GJ to MJ	1,000.00	*ARENA Australia's Bioenergy Roadmap*

Other conversions

	Multiply by	
Tonne to Kilogram	1,000	*ARENA Australia's Bioenergy Roadmap*
Million (mega) litre to Litres	1,000,000	*ARENA Australia's Bioenergy Roadmap*
Barrel of oil (US) to Litres	158.987	*Statistical Review of World Energy Report*
Billion	1,000,000,000	*ARENA Australia's Bioenergy Roadmap*
Billion to Millions	1,000	*ARENA Australia's Bioenergy Roadmap*
1 tonne jet fuel to Litre	1,263	*CSIRO-Boeing SAF Roadmap* *Standard density (kg/L) used in conversion is 0.792, based on Australian Petroleum Statistics Dec 2022*

Executive Summary

The global low carbon liquid fuel (LCLF) industry is undergoing a transformative shift, driven by national commitments to decarbonisation, growing fuel security demands, and the declining cost of LCLF technologies. This presents Australia with a unique and timely opportunity to harness our abundant biomass resources and renewable energy potential to build a robust domestic LCLF industry. By doing so, Australia can not only meet its decarbonisation and fuel security goals but also lay the groundwork for a globally competitive synthetic fuel export industry.

Why Australia? Why Now?

As Australia progresses towards net zero, the focus is shifting to decarbonising hard-to-abate sectors, including long-distance transport, aviation, mining, and construction—industries that rely on high-energy, drop-in fuels compatible with existing infrastructure. Recent advances in renewable diesel (RD) and sustainable aviation fuel (SAF) have paved the way for LCLFs to replace fossil fuels without compromising performance.

By capitalising on this momentum, Australia can build demand for green hydrogen and provide a transition path to new Net Zero global export markets – see more in Section 5 of this report.

Abatement Potential and Pathways

The potential climate and economic benefits are substantial. Developing new feedstocks and innovative processing routes has the theoretical potential to enable Australia to realise over 33 MtCO2-e per year in emissions abatement by 2035, supplying the entire transport sector and paving the way to net zero.

Australia's competitive edge lies in our vast supply of second-generation feedstocks, including agricultural and forestry residues, and emerging technologies such as pyrolysis-biocrude and gasification Fischer-Tropsch processes. Additionally, third and fourth-generation feedstocks, like algae and power-to-liquids, offer future growth potential with continued R&D investment.

Economic Potential and Regional Growth

Australia has an opportunity to develop an LCLF industry which delivers regional economic growth while meeting decarbonisation and fuel security goals. An LCLF industry could contribute between AUD $6 billion to $12 billion annually in direct economic benefits, with greater gains from regional co-benefits, including:

- Diversified income streams for farmers and regional communities
- Enhanced biodiversity and natural capital
- Carbon sequestration in soils and biomass
- Strengthened resilience and productivity in agricultural landscapes

Investing in novel crops, low carbon farming practices, and integrated agroforestry can significantly expand feedstock production, unlocking opportunities in both prime and marginal agricultural regions.

Addressing Industry Barriers

To capitalise on this opportunity, strategic industry settings and targeted support are essential. The primary investment barrier is the cost gap between fossil fuels and renewable alternatives, compounded by secondary challenges such as:

- Certification requirements for market access
- Infrastructure limitations and feedstock supply uncertainties
- High capital costs for new refining technologies

A balanced approach involving both supply and demand-side measures is crucial. This includes developing feedstocks, supporting pilot facilities to de-risk new technologies, and conducting life cycle assessments tailored to Australian conditions.

Navigating Competing Uses and Growing the Balance Sheet

Australia's LCLF feedstocks currently compete in existing markets, underscoring the need for detailed material flow analyses to determine true availability and inform economic modelling. However, by transitioning farming systems through novel crops, agroforestry, and regenerative practices, Australia can significantly increase feedstock volumes without compromising food production or environmental sustainability.

Australia stands at a pivotal moment to position itself within the global LCLF market while enhancing energy security, stimulating regional economies, and achieving substantial emissions reductions.

For detailed analysis of market opportunities, abatement pathways, and strategic recommendations, refer to Sections 2, 3, 5, 6, and 7 of this report.

Estimated production potential

Australia has significant potential for existing and new biomass production to refine through a variety of conversion pathways to LCLFs.

Estimates of biomass production depend on numerous assumptions and constraints – both explicit and hidden. Using published national analyses and CSIRO modelling, this report provides the latest estimates of national production potential.

			2030				2050			
Feedstock category	Feedstock type	Production pathway (conversion efficiency)	Estimated annual feedstock production volume (Mtpa)	Estimated annual LCLF production volumes (MLpa)	% of domestic LCLF demand met	Abatement potential (MtCO2-e)	Estimated annual feedstock production volume (Mtpa)	Estimated annual LCLF production volumes (MLpa)	% of domestic LCLF demand met (high)	Abatement potential (MtCO2-e)
			LOW				HIGH			
Carbohydrates										
	Sugar cane bagasse	GFT (10%)	10	505	10	1.20	20	1010	19	2.40
	Sugar	ATJ (60%)	5	1516	29	3.71	10	3031	56	7.41
	Sorghum	ATJ (60%)	2	606	12	1.48	3	909	17	2.22
Waste										
	Tallow	HEFA (60%)	0.5	152	3	0.38	1	303	6	0.76
	Used cooking oil (UCO)	HEFA (60%)	0.1	30	1	0.08	0.3	91	2	0.24
	MSW	GFT (10%)	13	657	13	2.02	20	1010	19	3.10
Lignocellulosic										
	Agricultural residues	GFT (10%)	37	1869	36	5.58	60	3031	56	9.05
	Sawmill waste	GFT (10%)	6	303	6	0.90	12	606	11	1.80
	Short Rotation Trees (SRT)	GFT (10%)	14	707	14	1.81	30	1516	28	3.87
Oilseeds										
	Canola	HEFA (60%)	7	849	16	1.41	10	1212	22	2.02
	Cottonseed	HEFA (60%)	1	45	1	0.08	2	91	2	0.15
Power-to-liquids				3				5000*	92	+4750*
Total (estimated)			**96**	**7243**	**141**	**19**	**168**	**17812**	**327**	**33**

Table 1 Estimated potential biomass and liquid fuel production *Production volumes and abatement potential from Power-to-Liquids pathways are highly dependent on technology development and incentives

Note: *Data in Table 1 is drawn from a range of sources which are referenced throughout Section 3.*

This report finds that by 2050, Australia has sufficient biomass production capacity to produce over 12 GL of LCLF per year – roughly equivalent to our current domestic fuel industry (14.6GL in 2023) and around a quarter of total fuel demand. This is more than enough to meet the projected LCLF demand and abatement targets but is almost entirely dependent on appropriate price signals. Projected demand for LCLFs is based on modelling of sectoral fuel growth rates and share of biofuels uptake by sector in the Net Zero Emissions Scenario using data released by the International Energy Agency. Note that, while the term LCLFs is understood to encompass hydrogen and power-to-liquids (efuels), this analysis focusses on supply of feedstocks for fuels requiring biogenic inputs. Biomass and fuel production estimates are highly sensitive to a number of assumptions, notably:

- allocation rates (biomass collected and allocated to fuel production – assumed to be 40% in this analysis)
- mass conversion rates (ratio of biomass to mass of fuel – published here; note these are distinct from carbon efficiency)
- production growth rates

- exclusion of development of emerging and experimental feedstocks that could increase feedstock and fuel production volumes

Changes in these assumptions have a major impact on projected fuel production and resulting carbon abatement. This analysis seeks to use appropriate assumptions as much as possible.

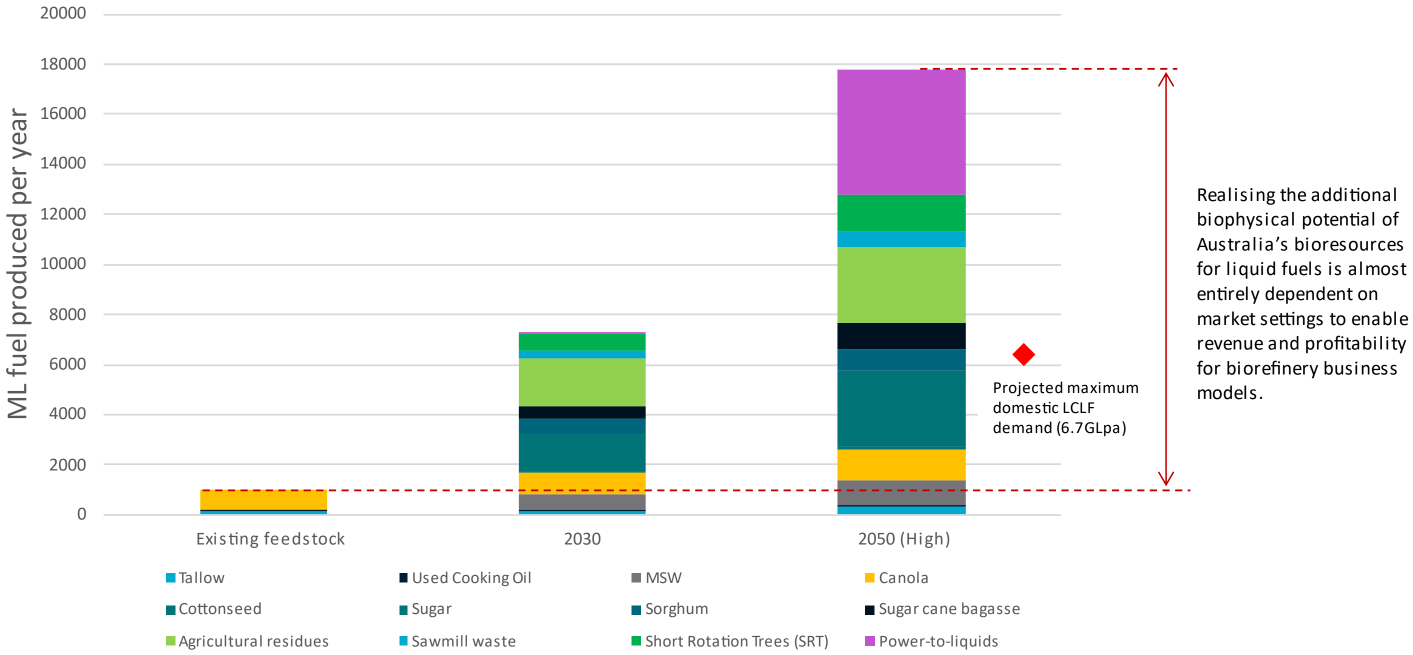

Chart 1 Potential for LCLF production volumes by different feedstocks.
Producing and diverting sufficient biomass feedstock for LCLFs production is almost entirely dependent on market settings and consequent price signals.

Existing feedstocks for liquid fuels include canola, waste fats and oils and municipal solid waste. These sources can be accessed by current international fuel markets which will impact both demand and pricing. There remains a much greater potential for LCLF production from carbohydrates and lignocellulosic sources, and potential for synthetic fuel production from power-to-liquids (PtL) and power-and-biomass-to-liquids (PBtL). However, any allocation of these resources to fuels will require new, additional price signals resulting from changed market settings. There are also various experimental feedstock sources such as arid zone and salt tolerant plants, alternative oilseeds, algae, leaf oils, and precision fermentation which may increase feedstock supplies in future but are not included in Table 1 as they are currently considered non-commercial.

Further increases in production are available by improving conversion efficiencies – including through the use of green hydrogen in thermochemical processes. This not only increases fuel yield from the same amount of biomass, but also enables a pathway for Australia to embed solar and wind renewables into liquid fuels and establish a major market for green hydrogen. See section 3.4 for a discussion on blending green hydrogen for increased carbon efficiency and yield.

1 Australia's fuel industry

A domestic LCLF industry will support national net zero emissions goals, along with ensuring a stable, sovereign fuel supply for Australia. Transport sector emissions are growing and will soon become the highest component of total national emissions. Diesel is the largest single source of energy demand in Australia today but is largely imported. The megatrend of increasing decarbonisation and strategic importance of a sovereign capability presents an opportunity to build a new industry in Australia, starting with biogenic fuels and growing to incorporate an internationally competitive synthetic fuels industry.

Fuel refining in Australia

Australia's fuel refining industry has been declining following a series of refinery closures (Ibis World 2023). In 2023 the two remaining large-scale refineries produced less than 15 billion litres of fuel, or 24% of domestic petroleum product sales[1]. This followed government assistance in the form of the Fuel Security Package and Refinery Production Payment (RPP) designed to ensure ongoing fuel security with combined payments totalling AUD 52.5m from 2020 to 2022. However, domestic production meets only around 22% of demand, the remainder supplied by imported fuels. Imports of petroleum products are dominated by diesel. In 2023, Australia imported over 52 billion litres of refined petroleum products, around 60% of which was diesel (30.9 billion litres). Existing fuel stocks cover only around 25 days of consumption (Australian Energy Statistics, 2024).

Australia's two large refineries generated AUD 13.5 billion in revenue in 2022-23 largely from the sale of automotive petroleum (38%), followed by diesel (35%) and aviation turbine fuel (6%) (Ibis World 2023). This follows a steady decline of around 6.9% p.a. over the past five years, but yielded an increased profit of AUD 406.1 million, or 3% margin in 2023, driven by the post-pandemic global demand growth, but supply remains constrained. As a result, in 2022-23 no payments were made under the government's support measures.

Today, Australian refineries face competition from larger, newer and more sophisticated refineries from the Asia-Pacific region, which are now producing fuels closer to Australian standards. The growing fuel import industry has created opportunities for small-scale specialised refineries upgrading imported fuels to Australian specifications, providing specialised blends and value-added processing for niche fuels.

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[1] Petroleum products include regular fuel, premium fuel, ethanol-blended, diesel oil, aviation turbine fuel, LPG (automotive and non-automotive), aviation gasoline, fuel oil, lubricating oils & greases, and other products, as defined by Australian Petroleum Statistics Dec 2023.

Opportunity through low carbon liquid fuels

With governments and major industry customers increasingly committing to emissions reduction and renewable energy procurement, existing refineries operated by Ampol and Viva as well as newer ventures such as BP-Kwinana and Jet Zero Australia (JZA) have announced intentions to invest in LCLF production.

In March 2023, Ampol, operating the Lytton refinery in the Port of Brisbane, announced a partnership with Japan’s largest oil company, ENEOS to jointly explore the feasibility of delivering an advanced biofuels manufacturing facility with the capacity to generate up to 500 million litres (ML) per year of sustainable aviation fuel (SAF) and renewable diesel (RD).

As modelled in the recent ICF report, both BP-Kwinana and Ampol-Lytton refineries are likely to favour the Hydro-processed Esters and Fatty Acids (HEFA) technology, which converts oil feedstocks from oilseeds such as canola and soy into hydrocarbon fuel. Presently, HEFA is the most mature pathway for producing petroleum and diesel from biogenic feedstocks and is more compatible with existing refineries compared to the ethanol fermentation or thermochemical routes for fuel production. However, new domestic refining capacity approaching 1000 ML p.a. will establish a long-term demand for locally grown canola and other oilseeds that already experience high demand in overseas markets.

The other large-scale operating refinery in Australia is the Viva facility in Geelong, Victoria, having changed ownership from Shell to international oil company Vitol. The Viva refinery is also in the process of evaluating biofuel production options. Viva have invested in pyrolysis-based processing with partners, such as Cleanaway, and are setting up a small-scale green hydrogen production unit and refuelling station.

Another notable refinery project under development is from Jet Zero Australia (JZA), based on Lanzajet’s alcohol-to-jet (ATJ) process. JZA has proposed a >100 ML p.a. ATJ refinery in Townsville, Queensland, by converting ethanol to jet fuel, with offtake by Qantas Airways. Through the Project Winton partnership, Qantas and Airbus have invested equity capital into the JZA project.

2 Global trends in low carbon liquid fuels

Leveraging global advances and increasing transition to low carbon liquid fuels, Australia may have an opportunity to develop a sovereign low carbon liquid fuel industry. Variable growing conditions, vast distances and highly dispersed biomass and historically high costs have so far reduced the attractiveness of investing in a domestic LCLF industry. Today, the convergence of several global trends has improved the prospects of this industry, but a significant cost gap remains to be bridged. New technologies for producing high-quality drop-in fuels from a broader range of feedstocks have been demonstrated, bringing a reduction in costs.

Evolution of the biofuels industry across countries

Since 2005, the global renewable fuels market has grown at a dramatic rate, driven primarily by the United States and Brazil, and notable expansion in Germany. Around two-thirds of future growth is expected to come from emerging economies like India, Brazil and Indonesia. The International Energy Agency (IEA) forecasts biofuel demand to grow by another 11% in 2024 (IEA 2023), equivalent to 18 billion litres, in response to policies increasingly shaped by energy security concerns.

In advanced economies, renewable diesel is driving most of the new capacity, while ethanol and biodiesel dominate in emerging economies. Existing policies in the United States (Renewable Fuel Standard, Inflation Reduction Act, California LCFS) and in Europe (Renewable Energy Directive) are driving new capacity in transport fuels. The 2023 US SAF Grand Challenge established under the IRA aims to re-prioritise aviation fuel to achieve production of 3 billion gallons by 2030, and 35 billion gallons or 100% of sustainable jet fuel, by 2050. Singapore has recently announced a mandate for SAF blending on all flights beginning with 1% in 2026 and rising to 3-5% by 2030.

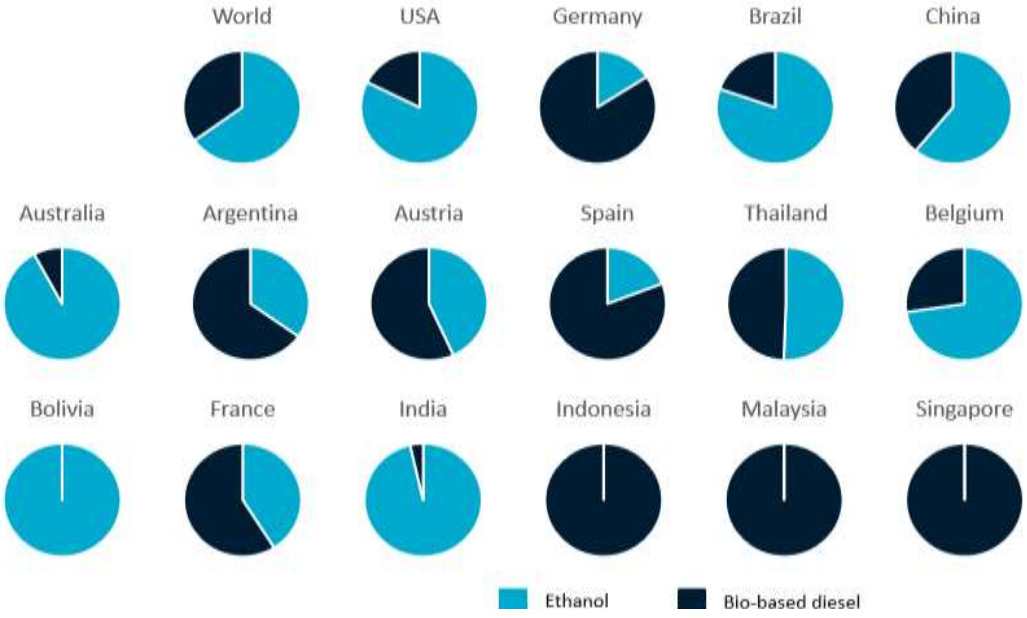


Figure 1: Prioritisation of ethanol and bio-based diesel in various countries

Among emerging economies, Indonesia increased its biodiesel blending mandate to 35% in 2023 and has published an Ethanol for Energy Security Strategy. Brazil has a biodiesel blending target of 15% and is considering a 2.5% increase to its mandatory ethanol blending requirement. India has committed to 20% ethanol blending by 2025.

Prevailing feedstock availability, demand preferences, and policy settings determine the fuel split between countries. Among the largest biofuels producers, the US has historically developed ethanol production capacity, driven by low-cost cornstarch feedstock. More recently, renewable diesel has been prioritised, before a move to SAF since the introduction of the IRA. This is similar to Brazil where sugar-derived ethanol dominates but contrasts sharply with Germany which prioritises diesel fuel, along with Singapore, Malaysia and Indonesia where abundant low-cost palm oil is available (US Energy Information Administration, 2024).

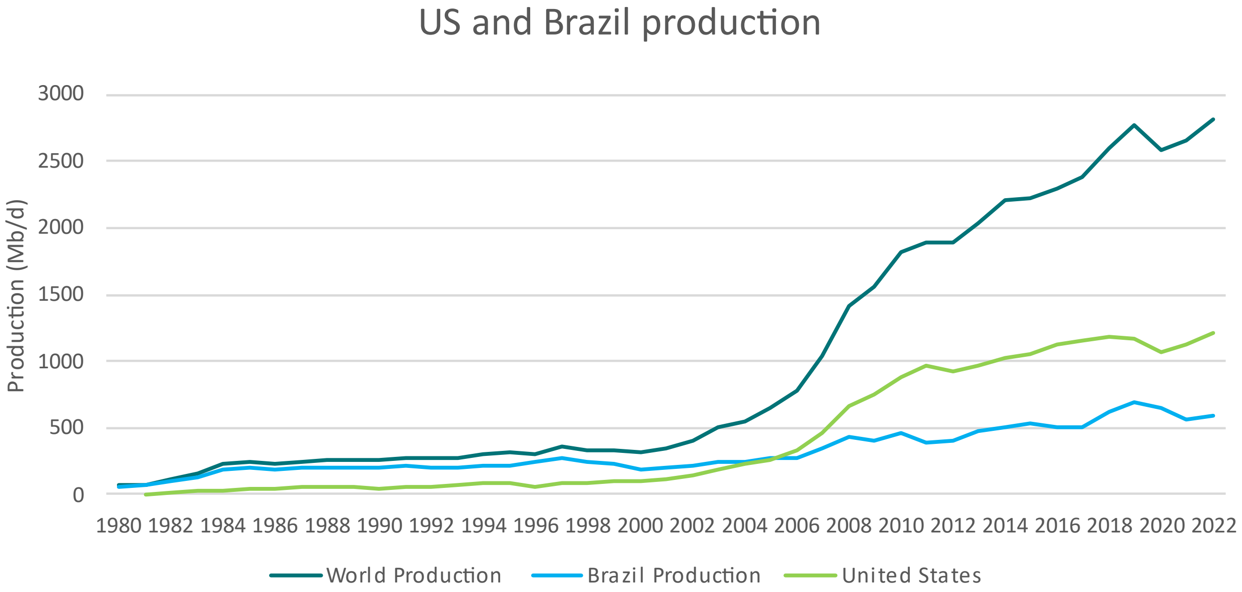


Figure 2: Historical biofuel production in the US and Brazil, and world production

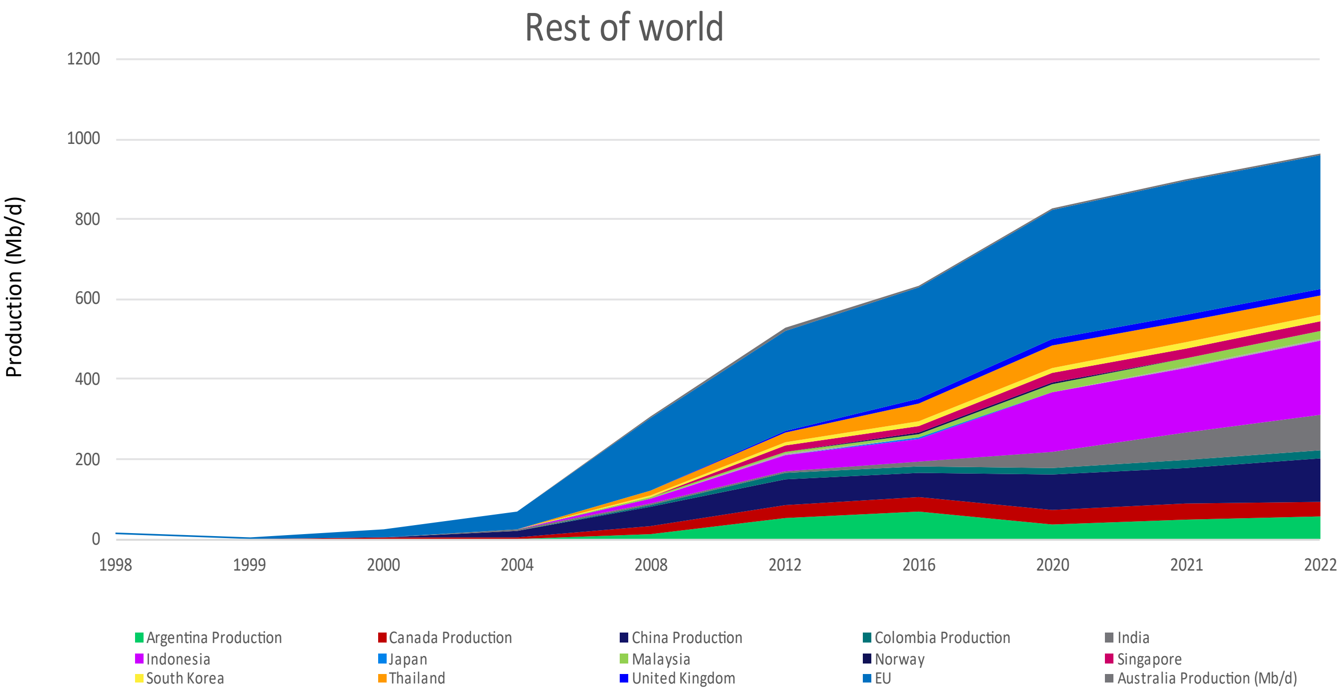


Figure 3: Historical production of LCLFs in rest of the world

Varying emissions profile across biofuels, technologies and regions

The global increase in biofuel production since the turn of the century has been accompanied by the development of a larger number of energy technologies for converting biomass to fuel.

In its early stages, the biofuel industry focused on production of first-generation ethanol from fermentation of simple sugars, predominantly from sugar cane and corn, and on biodiesel from trans-esterification of oils from oilseeds and waste. Ethanol and biodiesel are low-cost and relatively easy to produce, both from rudimentary and very mature processes, but are not ideal replacements for fossil fuels as blending is constrained to low concentrations for use in traditional internal combustion engines or require engine modification to run at 100%. To address this, direct biomass-derived drop-in fuels for different applications were developed including jet fuel.

Key technologies are introduced in **Figure 7**. Each feedstock-technology combination results in a different overall emissions profile. This makes it necessary to conduct a Life Cycle Assessment (LCA) to properly evaluate the net emissions savings of displacing fossil fuels in any application with a biofuel alternative. Targeted LCAs for specific use cases can provide highly accurate quantification of emissions profile, thus improving comparability. This can also be done for specific projects, if they are materially different from common industry practice.

Previously conducted LCAs indicate that significant climate as well as economic impact is available by developing new feedstocks and processing routes to service all end-use sectors, instead of prioritising biofuel use in one end-use sector over others. Differences in emissions profile exist between applications, but the differences between feedstocks and technologies are much greater.

For example, the use of ethanol to replace fuel might reduce net emissions of petrol by 78% (US DOE), or ethanol-derived jet fuel by 73%. But the use of pyrolysis-derived bio-oil from lignocellulosic feedstock might reduce net emissions of petrol by 88% and jet fuel by 92% (Zupko 2019). This illustration draws on LCA of ethanol from corn starch in the US (refined simple sugar and first-generation fermentation process analogous to the use of sugar in Australia) and bio-oil from catalytic fast pyrolysis of forestry residues (thermochemical conversion of lignocellulosic feedstock analogous to the use of waste residues or coppiced short rotation trees in Australia).

The variance in emissions profile between end-use sectors and between feedstock-technology routes are illustrated in **Figure 4**. These are based on selected published LCAs and are used only to illustrate that abatement resulting from switching between feedstocks and routes is greater than switching between end-use sectors.

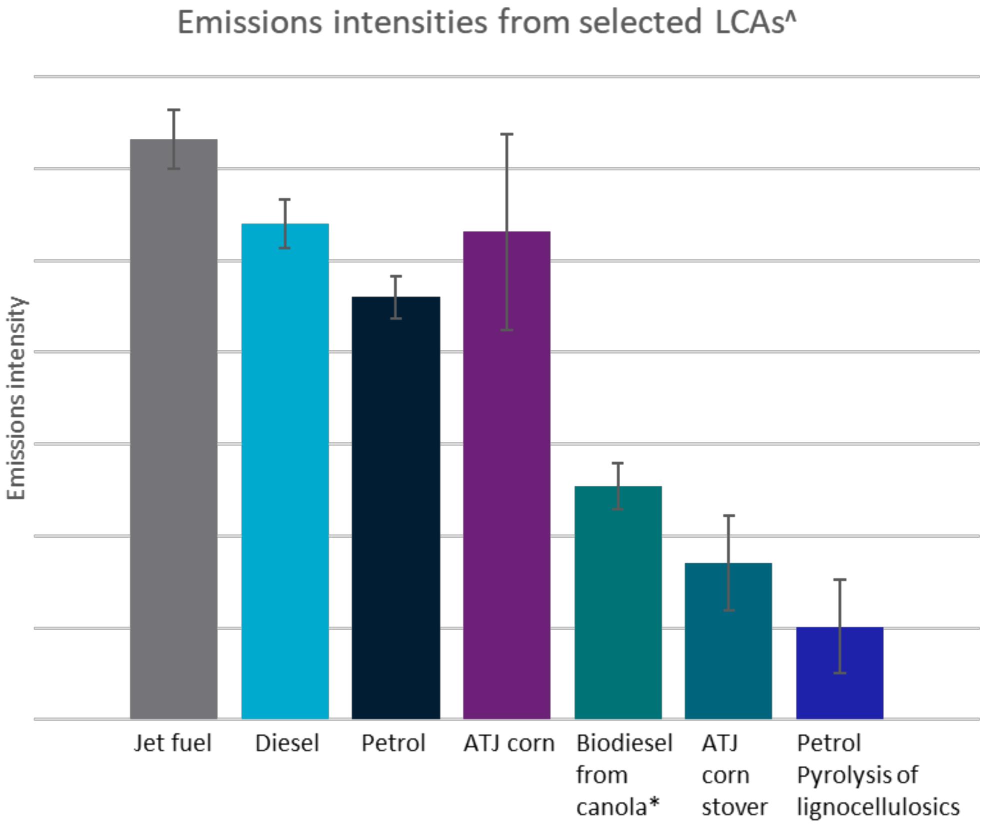


Figure 4: Comparison between emissions intensities of bio-based liquid fuels and fossil fuels (kg CO_2e/L)
Source: CSIRO, Towards Net Zero 2024

Impact of international market regulations and certifications

The rate of adoption of LCLFs by industry is also determined by their acceptability and alignment with various market regulations, standards and certifications of new pathways. Development of LCLFs – particularly bio-based fuels – needs to be closely regulated to ensure climate and economic impacts are maximised while maintaining sustainability and avoiding adverse impacts.

International markets for these fuels are subject to different levels of regulation. These regulations can impose a barrier to entry which can slow or prohibit the growth of that market for Australian fuels. This barrier can limit the abatement potential for different end-use sectors. Therefore, to maximise the climate and economic impact of LCLFs and maximise the rate of development of the sector, it is advisable to consider the regulatory barriers and prioritise staged development of different fuel products. Specific examples and cases are discussed below.

Regulations specific for aviation fuel

Aviation fuel is not only subject to specific jurisdictional regulations (some of which are discussed in Section 8), but also to international standards committed to by the major airlines. The International Civil Aviation Organization (ICAO) has established a framework for certifying fuel sustainability credentials and is becoming increasingly accepted as the international benchmark for SAF. ICAO’s Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) aims to harmonise emissions reduction options for the aviation sector, including the use of SAF. CORSIA sustainability metrics are based on the use of approved recognised models for LCA and certified through third party sustainability schemes – the International Sustainability and Carbon Certification group (ISCC) and the Roundtable on Sustainable Biomaterials (RSB).

CORSIA certification is accepted by most airlines and national regulatory bodies as a standard for SAF around the world, and feedstocks or fuels sold in Australia to either the domestic or international sector or exported will be required to meet CORSIA guidelines to gain market acceptance.

In addition to compliance with CORSIA guidelines for market access, aviation fuels must meet strict standards set by ASTM International to be certified for use in commercial aircraft. ASTM stipulates accepted fuel products based on rigorous testing, and feedstock-technology combinations that are not explicitly certified by ASTM are not available to the aviation sector.

As of July 2023, 11 conversion processes were approved by ASTM with 11 more under evaluation (ICAO 2023). See Table 2.

ASTM Reference	Conversion process	Abbreviation	Possible feedstocks	Maximum Blend Ratio
ASTM D7566 Annex A1	Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene	FT	Coal, natural gas, biomass	50%
ASTM D7566 Annex A2	Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids	HEFA	Vegetable oils, animal fats, used cooking oils	50%
ASTM D7566 Annex A3	Synthesized iso-paraffins from hydroprocessed fermented sugars	SIP	Biomass used for sugar production	10%
ASTM D7566 Annex A4	Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources	FT-SKA	Coal, natural gas, biomass	50%
ASTM D7566 Annex A5	Alcohol to jet synthetic paraffinic kerosene	ATJ-SPK	Ethanol, isobutanol and isobutene from biomass	50%
ASTM D7566 Annex A6	Catalytic hydrothermolysis jet fuel	CHJ	Vegetable oils, animal fats, used cooking oils	50%
ASTM D7566 Annex A7	Synthesized paraffinic kerosene from hydrocarbon - hydroprocessed esters and fatty acids	HC-HEFA-SPK	Algae	10%
ASTM D7566 Annex A8	Synthetic Paraffinic Kerosene with Aromatics	ATJ-SKA	C2-C5 alcohols from biomass’	
ASTM D1655 Annex A1	co-hydroprocessing of esters and fatty acids in a conventional petroleum refinery		Vegetable oils, animal fats, used cooking oils from biomass processed with petroleum’	5%
ASTM D1655 Annex A1	co-hydroprocessing of Fischer-Tropsch hydrocarbons in a conventional petroleum refinery		Fischer-Tropsch hydrocarbons co-processed with petroleum	5%
ASTM D1655 Annex A1	Co-Processing of HEFA	Hydroprocessed esters/fatty acids from biomass		10%

Table 2: Various ASTM approved pathways, associated feedstocks and blending ratios

Biodiesel and Renewable Diesel into Europe

A further example of the tightening regulations impacting market access for Australian feedstocks and fuels into international markets is the Renewable Energy Directive (RED) regulations in Europe. RED has been in place under European Commission legislation since 2009, with progressive tightening of standards in 2018 (REDII) and again in 2023 (REDIII) as part of the European Fit for 55 Package.

The RED regulations include strict rules for bio-based fuels sold in Europe. This impacts Australian feedstocks significantly as approximately 65% of Australia's canola crop is sold to Europe for conversion to diesel fuel (ABARES 2024). RED requires fuels sold in Europe to contribute at least 50% life cycle emissions reduction over fossil alternatives, and the LCA assessment of the fuels includes accounting for factors such as Induced Land Use Change (ILUC) which imposes a significant requirement on fuel producers to provide historical land use data attributable to feedstocks. Feedstocks with higher ILUC scores are likely to be prohibited for use to produce fuels.

The RED regulations also outline potential measures to check against adversely affecting food production by prohibiting fuel feedstocks from crops used for human consumption. However, the impact of these conditions on prevailing feedstocks like canola, which also Australia's major export to EU for biofuel production, is unclear and will emerge over time.

Californian Low Carbon Fuel Standard (LCFS)

Like the REDIII scheme, the Californian LCFS requires fuels to meet carbon intensity thresholds which are heavily affected by ILUC. The carbon intensity scores for each fuel are compared to a declining benchmark each year. Low carbon fuels below the benchmark generate credits, while fuels above the CI benchmark generate deficits (CARB 2024). Similar requirements are being adopted in jurisdictions throughout the US and will affect Australian feedstocks and export fuels.

Aviation fuel produced and sold in Australia or exported, and LCLF feedstock or fuel exported for road transport internationally, will be increasingly subjected to tightening regulations, creating a barrier to the rate of growth of the industry or market access. By contrast, transport sectors in Australia, particularly the diesel market, represent a lower-risk growth market because the development of regulations is wholly within the control of the Australian Federal and State governments. Developing regulation for a domestic market can consider the unique features of Australian biomass production as well as industry needs and barriers.

In this case, a focus on renewable diesel, particularly for mining and heavy haulage allows the Australian government to plan for the initial development of the LCLF industry by focusing on domestic demand, thereby avoiding the constraints to growth and ultimate scale imposed by foreign regulatory risk. The long-term goal would be the development of regulatory structures that are inter-operable with international policies and regulations to enable trade of fuels and feedstocks globally as the industry scales.

3 Australia's biomass supply

Although Australian growing conditions are among the harshest and most variable in the world, we have an abundant supply of low-input bioresources for conversion to fuels. The opportunity to integrate with food production and repurposing wastes can deliver important co-benefits including economic value to our ecosystems and regional communities.

Australia is well-known as a vast landmass with low population density. Across Australia there exists a wide variety of climatic zones and growing regions that support biomass production, from highly intensive cropping and horticulture to pasture and rangelands, deserts and marginal environments. As a result of this geography, climate and the adaptive management practices of growers, Australia is known as a world-leading exporter of agricultural products (ABARES 2024).

Annual production of most of Australia's major crops can vary significantly from year on year (**Figure 5**) influenced by various factors, and therefore, affecting the reliability and consistency of feedstocks for biofuels.

Australia currently has the capacity to produce over 90 Mega-tonnes (Mt) of biomass as feedstock for LCLFs per year from over 4.6 million square kilometres of land under primary production (55% of the landmass) (Crawford, O'Connor et al. 2016, ABARES 2024). It may be possible to increase the production of biomass for LCLF through changes in farming systems and development of novel feedstocks that can be produced outside food producing areas, without competing with food production. But using this land for bioenergy production is challenging due to transportation over large distances and relatively low yield per hectare, requiring producers to manage larger properties to produce commercially viable volumes of biomass feedstock.

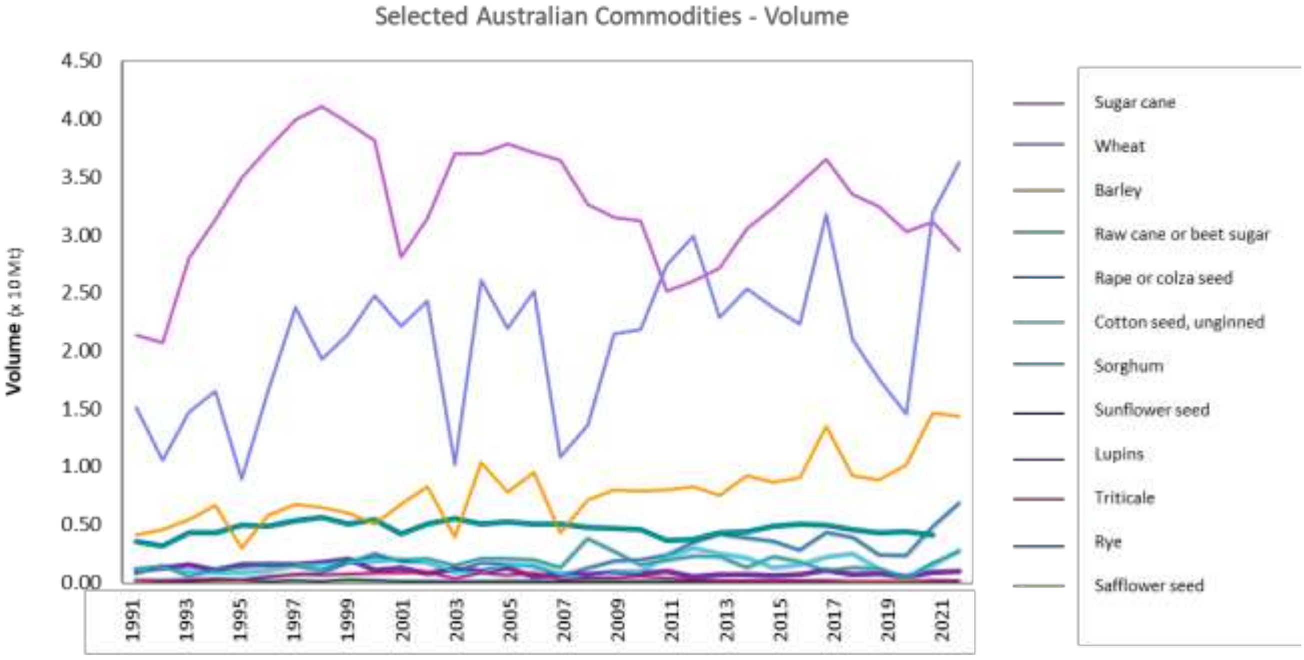


Figure 5: Agricultural output volume of selected Australian commodities

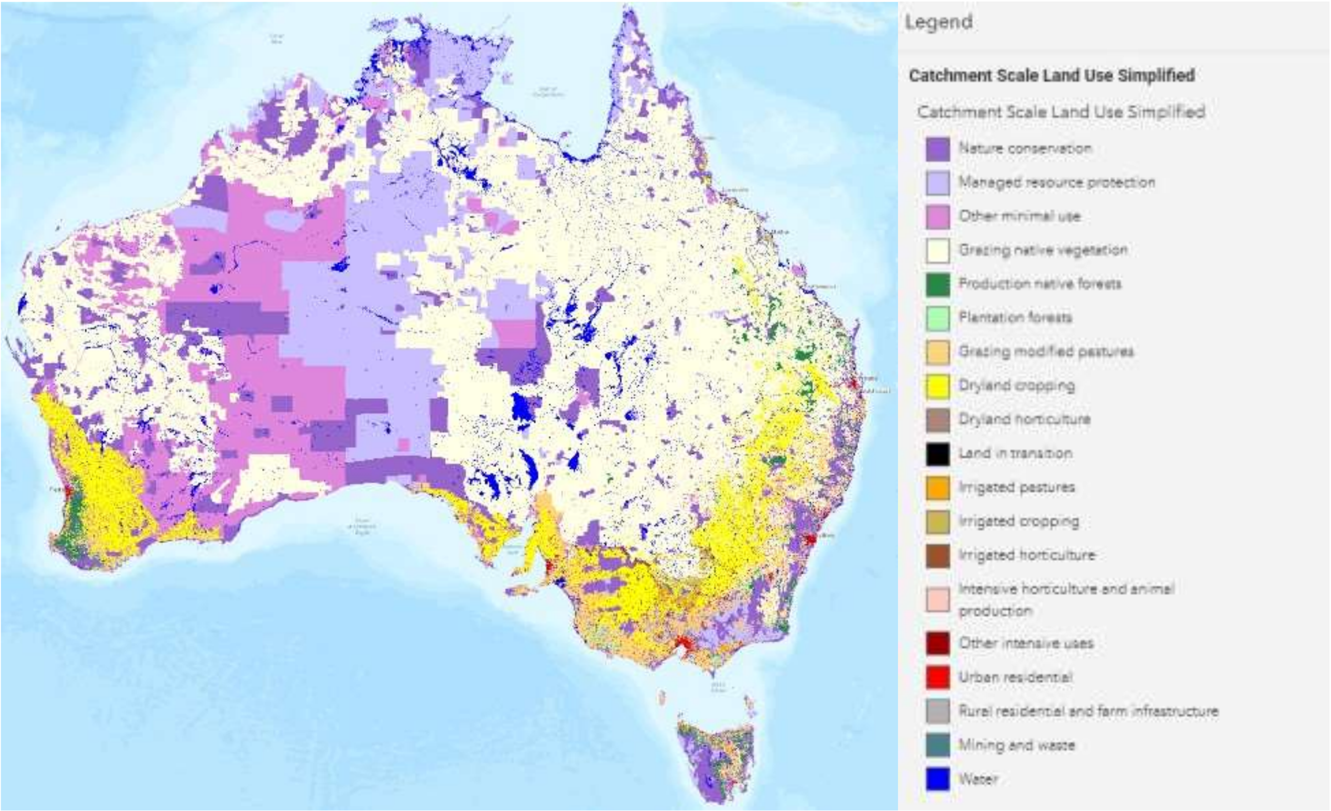


Figure 6: Major land use categories in Australia
Source: https://digital.atlas.gov.au/

A general trend for Australian biomass applies when considering bioenergy applications – the most commercially viable feedstocks tend to be those with existing processing and supply infrastructure, commonly farmed and traded, while the largest volumes of feedstocks, mainly lignocellulosic, are distributed over a much greater area and the requisite infrastructure has not been developed. This means that the most viable feedstocks today are among the most expensive, while the largest volume of feedstocks are lower cost, but harder to access and process.

Conversion to LCLFs

The Boeing-CSIRO SAF Roadmap describes several categories of feedstocks relative to the various processing pathways to produce LCLFs (Figure 7):

- Oilseeds, tallow and used cooking oil (UCO) can be processed through the HEFA pathway.
- Carbohydrates, including sugar, molasses and grain starches, can be fermented to ethanol and converted to sustainable aviation fuel (SAF) or renewable diesel (RD) through the alcohol-to-jet (ATJ) processes.
- Lignocellulosic feedstocks, such as grasses, forestry and sawmill waste, bagasse and short rotation tree crops can be processed either by fermentation or by thermo-chemical pathways like gasification or pyrolysis.
- Finally, mixed wastes, including municipal solid waste (MSW), food waste or manures can be processed by thermo-chemical pathways or anaerobic digestion.

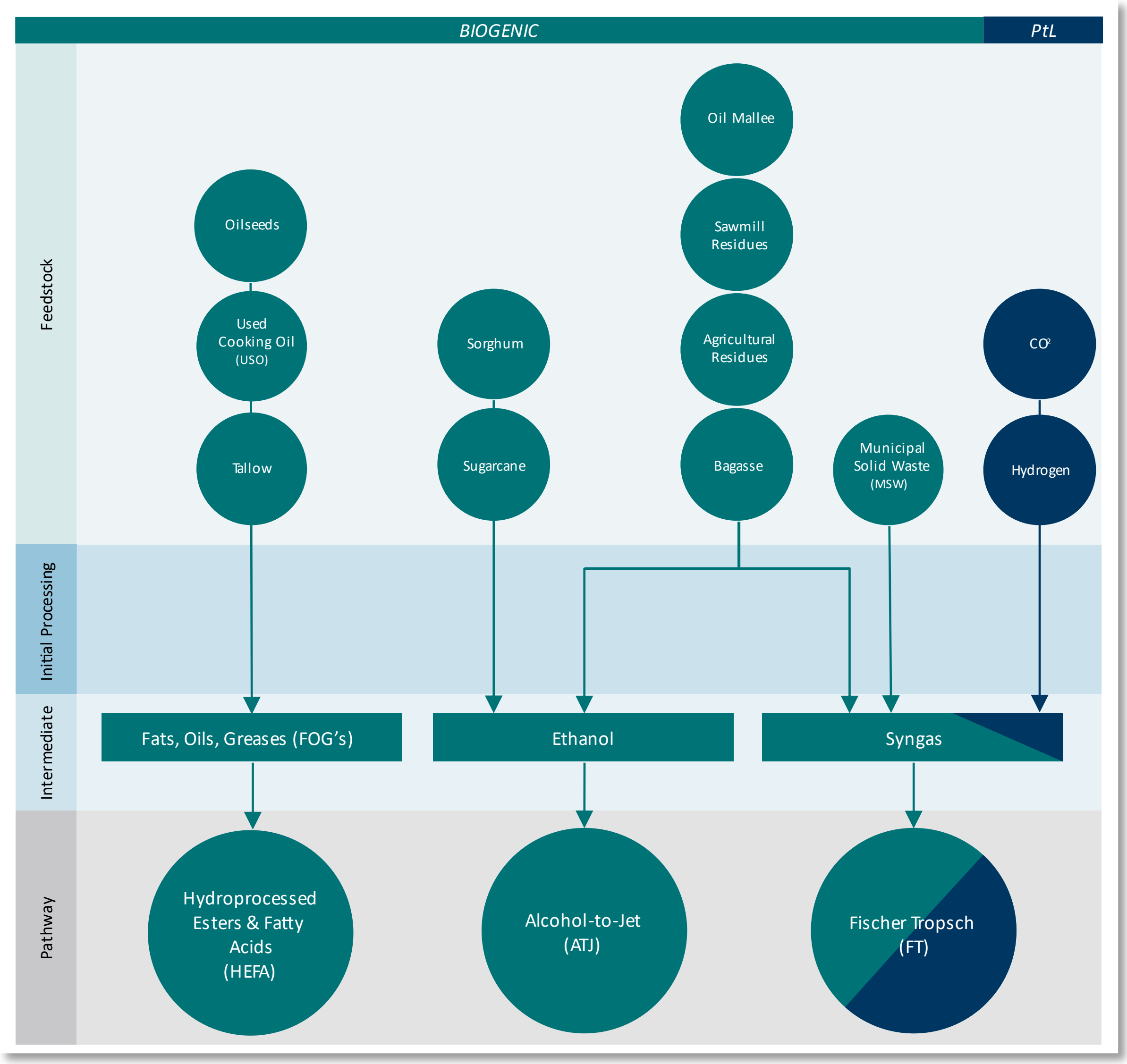


Figure 7: Primary conversion pathways for LCLFs, as in the SAF Roadmap
Source: (CSIRO SAF Roadmap, 2023)

The Roadmap estimates Australia can produce 6 billion litres of liquid fuels from existing feedstocks, which is expected to increase to 8 billion litres by 2050 (CSIRO 2023). This is based on forecast availability of agricultural residues, carbohydrates, waste and oilseeds. A much larger volume of liquid fuels may be produced by using suggested future scalable sources such as micro- and macroalgae, aquatic and salt-tolerant plants, and power-to-liquids technologies based on green hydrogen and captured carbon dioxide (CO_2).

While the total production potential is large, the realisable volumes are likely to be much lower once economic and other constraints are factored in. A viable domestic LCLF industry must either be cost-competitive with subsidised international markets for Australian feedstocks, impose export controls on the most mature feedstocks, such as UCO, tallow and oilseeds, especially canola, or develop new low-cost, high volume feedstock sources not suitable for export – such as lignocellulosic feedstocks from Short Rotation Trees (SRT), agricultural residues or novel crops

3.1 Existing current feedstock sources

The SAF Roadmap provides an assessment of currently available feedstocks for LCLF production (CSIRO 2023). Today, Australian waste sources, including UCO and tallow, are exported for conversion to liquid fuels in California, Singapore and Europe (Australian Renderers Association Inc 2016). Over 65% of Australia’s canola was exported to the European market in 2021-22 (ABARES 2024). Both these feedstocks are converted to liquid fuels through the HEFA pathway. A current snapshot of the feedstocks for LCLFs is given below.

			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	Chemical and industrial processes		●	●
	Carbon dioxide	Vented to atmosphere, food and beverage		●	●

HEFA – Synthesised paraffinic kerosene from hydroprocessed esters and fatty acids

FT – Fisher-Tropsch hydroprocessed synthesised paraffinic kerosene

Figure 8: Summary of Australian feedstocks, current uses and main fuel pathway. Source: (CSIRO SAF Roadmap, CSIRO 2023)

3.1.1 Tallow and UCO

Australian tallow and UCO are highly sought after in export markets. Tallow production is closely linked to the size of the national beef herd, while UCO production is correlated to dietary consumption. The US Department of Agriculture (USDA) notes Australia produced approximately 600,000 t of tallow in 2011 (USDA Foreign Agriculture Service 2021). The national beef herd fell from around 26 million in 2011-2012 to 24.4 million in 2021-2022 (Meat and Livestock Australia 2023). It is estimated that this would have resulted in a fall in tallow production to 510,000 t in 2021-2022, of which the majority (390,000 t) was exported (USDA Foreign Agriculture Service 2021).

It is expected that future growth of the national beef herd will be limited, with a projected increase to ~34 million head by 2030 (Centre for International Economics 2013). This will limit any significant increase in tallow volumes.

Export volumes of UCO are harder to ascertain. The CSIRO SAF Roadmap states that Australia produced approximately 100,000 t UCO annually (CSIRO 2023). USDA notes that Australian UCO's export demand underpins high prices, but they do not cite export volumes. Additionally, production of UCO is strongly correlated to population size and dietary habits, thus future production increases are likely to be modest relative to the demand for LCLFs.

The International Energy Agency (IEA) states that supplies of tallow and UCO are approaching their limits as demand for biofuels increases and emphasises the need to identify and utilise alternative feedstocks (International Energy Agency 2022).

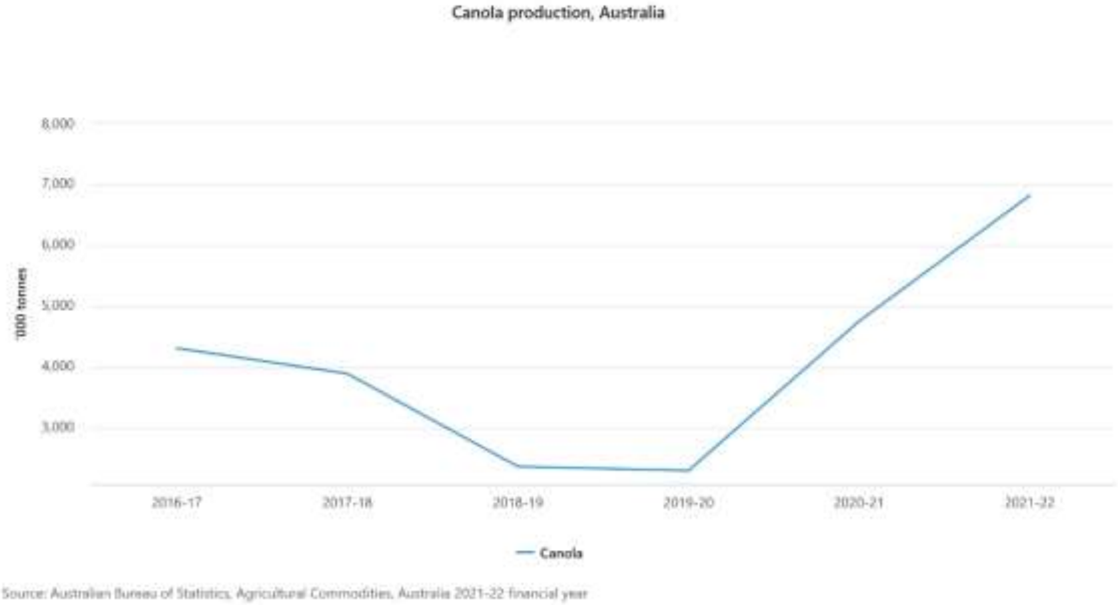
3.1.2 Canola

The majority of Australia's canola crop is locked into existing uses and export demand. The potential to increase production and the impact of emissions regulations in international markets offers an opportunity for the domestic market to divert canola oil production to refining within Australia.

Canola production in Australia has fluctuated significantly in the last ten years in response to prices. The area under cultivation for canola increased from under 0.5 million ha in the early 1990's to over 2 million ha in 2020 (ABS 2022). This was supported by various factors, including improved genetics and disease resistant varieties, recognition of canola as a break-crop in grain-producing areas and increasing global demand for canola (Kirkegaard, Lilley and Morrison 2016). All these, coupled with improved management practices and growing conditions, resulted in a record 6.8 Mt of canola produced in 2021-22 (ABS 2022)(see **Figures 9** and **10**).

Currently, almost all (~65%) of Australia's canola is exported as a liquid fuel feedstock to Europe, Singapore and the US (ABARES 2024). Increasing canola production can cater to domestic demand, but canola's high exposure to international markets makes it a high-cost feedstock for producing SAF and RD. It may be possible to significantly increase the area of canola production by changing rotation practices in grain and cotton producing regions without significantly impacting food production by replacing fallow rotations or introducing low-value animal feed grain rotations with canola or other emerging biofuel brassicas such as carinata, camelina, or mustard (pers. comm.)

Further research is needed to fully assess the potential to increase oilseed production through changed rotation practices including the impact on food production, overall farm productivity (through break crop effects), nutrient demands, GHG emission intensity and farm profit.



Source: Australian Bureau of Statistics, Agricultural Commodities, Australia 2021-22 financial year

Figure 9: Annual canola production volumes in Australia 2016/17 to 2021/22. (Source ABS 2022)

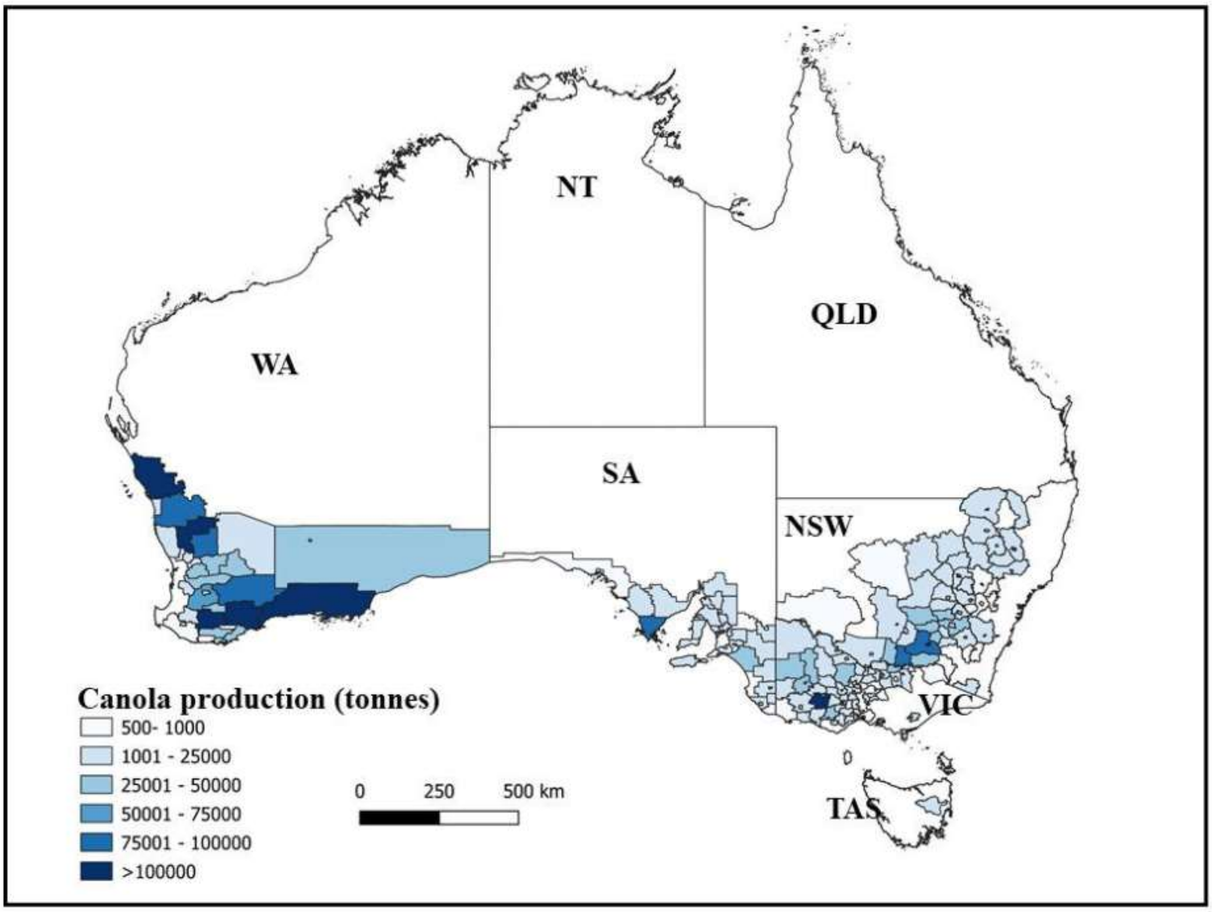


Figure 10: Average canola production quantities from 2015/16 to 2019/20 by statistical area. Source: Australian Bureau of Statistics, 2021b; 2021c

Current production: 6.82 Mt (2021-22)

3.1.3 Sugar cane

Sugar cane is a promising current fuel feedstock particularly through the recently approved Alcohol-to-Jet pathway championed by LanzaJet. This pathway can also produce renewable diesel at a slightly lower cost thanks to the added refining step required for jet fuel production (Geleynse, Brandt et al. 2018).

Australia is a major global producer of sugar cane, with most of it processed to raw sugar for export to Japan and South Korea. Around 30 million tonnes of sugar cane is produced each year (28.7Mt in 2021-2022), around 95% of which is grown in Queensland, and refined to 3-4 million tonnes of raw sugar, 79% of which is destined for export. An additional 1 Mt/year of molasses is produced at Australian sugar mills (Australian Sugar Milling Council 2024).

Raw sugar or molasses can be used as a feedstock for fermentation to ethanol, then further processed to jet fuel in the ATJ process. To support a minimum-scale industrial jet fuel refinery in Australia would require around 540,000 tonnes of sugar per year, or around 15% of total production in 2025 (CSIRO, 2023). At a cost of around $600/t this equates to around AUD 1.08 per litre for feedstock alone in this process. This is a significant component of overall fuel costs once capital and operating costs are added in comparison to fossil jet fuel at around AUD 1- 1.50 per litre.

Feedstock is a key cost driver for most fuel production processes, so reducing this feedstock cost is the primary objective for a fuel production industry. This can be done by identifying future feedstocks that can augment or replace existing sources, and particularly those with scalable supply which do not have competing markets. This is the focus of attention in the following sections – existing new feedstock sources and novel sources.

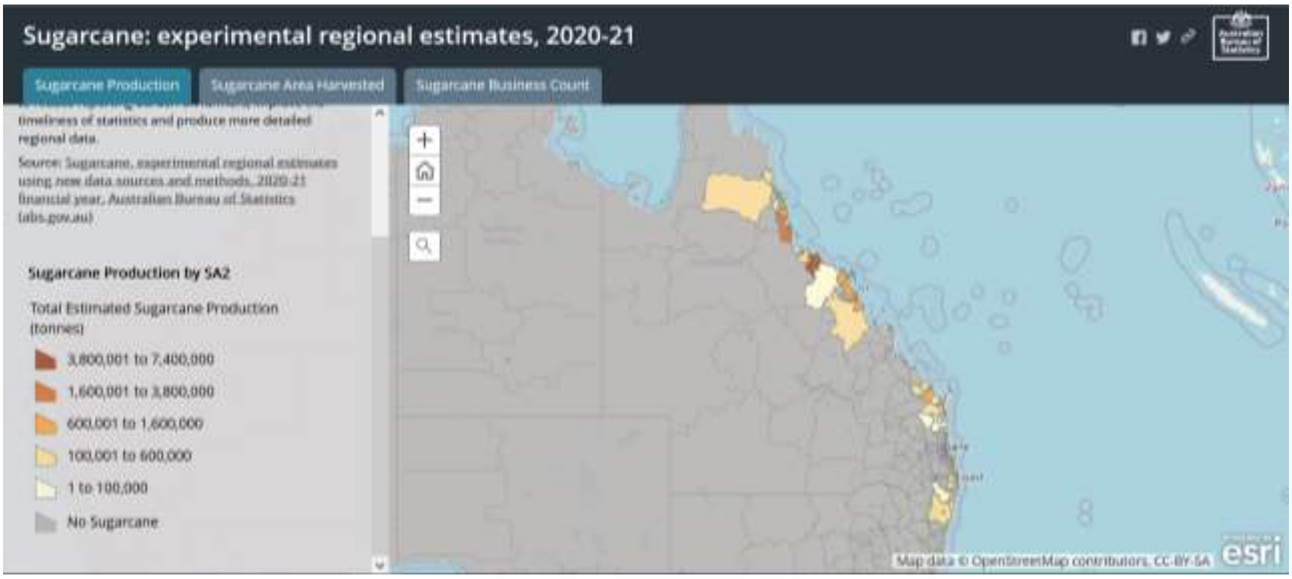


Figure 11: Estimated sugarcane production by region in 2020/21
Source: Australian Bureau of Statistics

Current production: 4.1 Mt (2021)

3.2 Existing new feedstock sources

As identified in the Boeing-CSIRO SAF roadmap, the largest pool of potential LCLF feedstock in Australia today is lignocellulosic agricultural residues and tree crops (CSIRO 2023). These sources are typically much lower cost compared with oilseeds or primary agricultural commodities but there are challenges in the logistics and processing of these materials that need to be addressed.

To assess the overall availability of this category of feedstock, previous work by Crawford et. al (2016) performed a spatial assessment using available data and modelling of annual production of 6 different biomass feedstock types, then applying constraints on volumes available for harvesting and volumes available for diversion from current uses (see Table 3). Further consideration should be given to biomass sources that meet national and international sustainability criteria – such as constraints on the use of forestry biomass and those imposed by Induced Land Use Change (ILUC) regulations (Sandford, Malins et al. 2024).

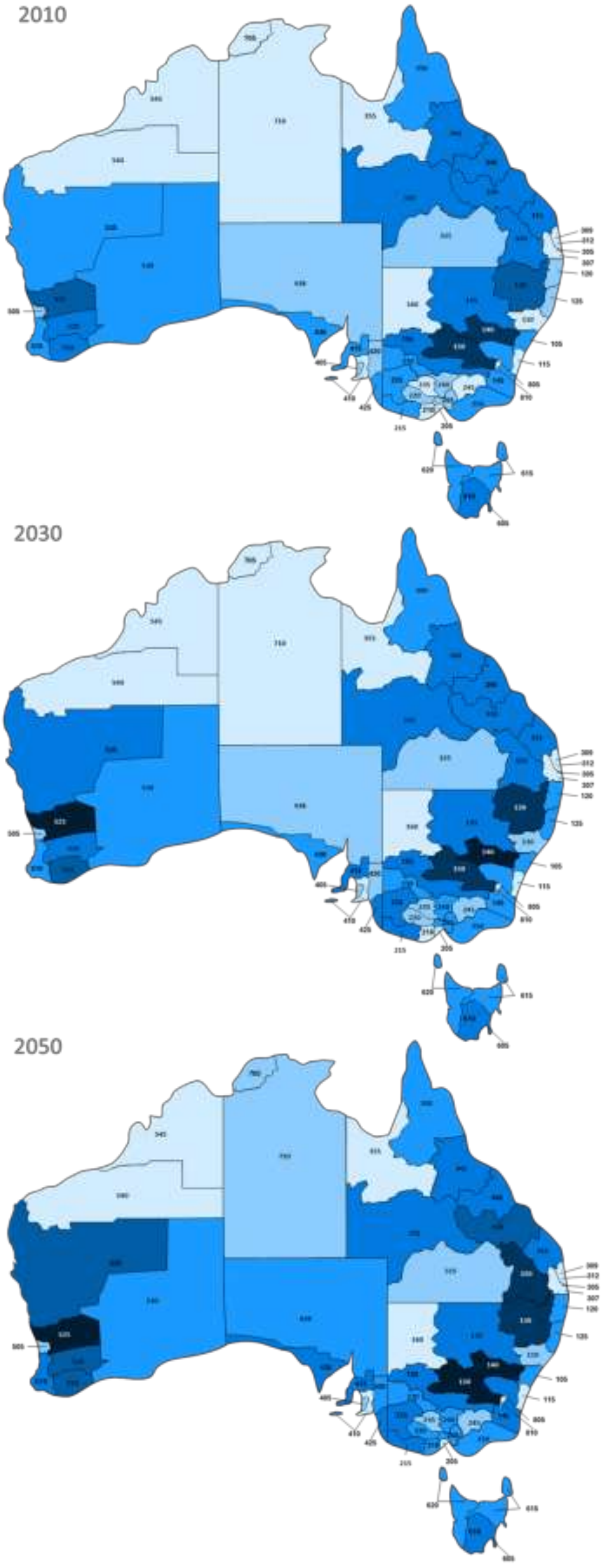
Biomass type	National estimate (low)	National estimate (high)
Crop stubble	7 Mtpa	30 Mtpa
Grasses	13 Mtpa	19.7 Mtpa
Wood (plantation forest)	11 Mtpa	14 Mtpa
Bagasse	5.5 Mtpa	10 Mtpa
Waste	2	11 Mtpa
Short-rotation tree crops	0	29.3 Mtpa
Total (applying constraints)	38.5 Mtpa	114 Mtpa

Table 3: Estimated range of national production for selected biomass sources

Not included in this analysis is future dedicated fuel crops such as Pongamia and algae.

This study reported data at the level of Statistical Divisions (SDs) using 2006 SD layer incorporating 60 divisions covering the whole of Australia (Crawford, O'Connor et al. 2016) (see **Figure 12**).

SD ID	SD Name
105	Sydney
110	Hunter
115	Illawarra
120	Richmond-Tweed
125	Mid-North Coast
130	Northern
135	North-western
140	Central West
145	South-eastern
155	Murrumbidgee
160	Far West
205	Melbourne
210	Barwon
215	Western District
220	Central Highlands
225	Wimmera
230	Mallee
235	Loddon
240	Goulburn
245	Ovens-Murray
250	East Gippsland
255	Gippsland
305	Brisbane
307	Gold Coast
309	Sunshine Coast
312	West Moreton
315	Wide Bay-Burnett
320	Darling Downs
325	South-west
330	Fitzroy
335	Central West
340	Mackay
345	Northern
350	Far North
355	North-west
405	Adelaide
410	Outer Adelaide
415	Yorke & Lower North
420	Murray Lands
425	South-east
430	Eyre
435	Northern
505	Perth
510	South-west
515	Lower Great Southern
520	Upper Great Southern
525	Midlands
530	South-eastern
535	Central
540	Pilbara
545	Kimberley
605	Greater Hobart
610	Southern
615	Northern
620	Mersey-Lyell
705	Darwin
710	Northern Territory-Bal
805	Canberra
810	Australian Capital Territory-Bal



▨	0-500
▨	501-1000
▨	1001-2000
▨	2001-3000
▨	3001-4000
▨	4001-5000
■	5001-6700

Figure 12: Spatial representation of potential annual total biomass (in kt) available in 60 statistical divisions. Adapted from (Crawford, O'Connor et al. 2016).

Transportation, a key cost driver for new feedstocks

Much of the cost of biomass resources derives from harvesting and transportation of low-density, highly distributed materials (Crawford, O'Connor et al. 2016). In the case of cropping production systems such as oilseeds these costs are minimised because the harvested grain is relatively dense, and transport and aggregation systems are established. However, in the case of feedstocks not previously used for bioenergy, particularly stubble, grasses, wood and short rotation trees (SRT) these costs are significant because the biomass is bulky, low density, and spread over a larger growing area. In general, transport distances greater than 100km for raw biomass impose a prohibitive cost on fuel production, and more likely 50km is the upper limit for transportation of raw biomass.

Technoeconomic analysis by CSIRO using a case study in central Queensland found that biomass price for new crops with no competing markets are most sensitive to transport cost fluctuations (Hayward, O'Connell et al. 2015).

Strategies for reducing biomass cost may focus on reducing transport distances, mode-shift (i.e. from road to rail to shipping) or by densifying the raw biomass product to transport a higher-value (lower weight and volume) product.

	Capital	O&M	Biomass	Rail transport	Refining cost	Total
Cost (million $)	1330	2870	1930	440	500	7070
Share of total (%)	19	41	27	6	7	–

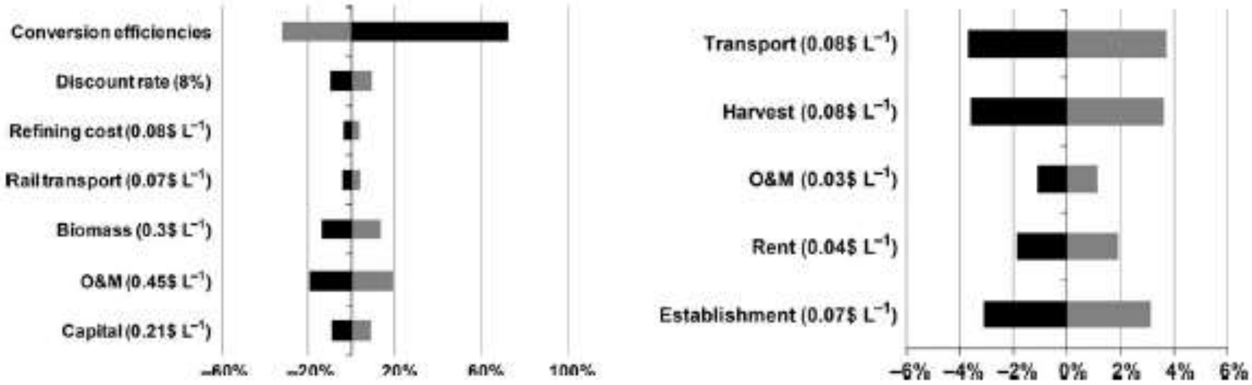


Figure 13: Total discounted costs over 40 years of production by cost component (in million $)

3.3 Growing the Balance Sheet

The feedstock estimates above are largely based on existing crops and current farming practices. With appropriate research and development there is potential to increase the amount of LCLF feedstocks produced while also contributing to the transition of our agricultural systems.

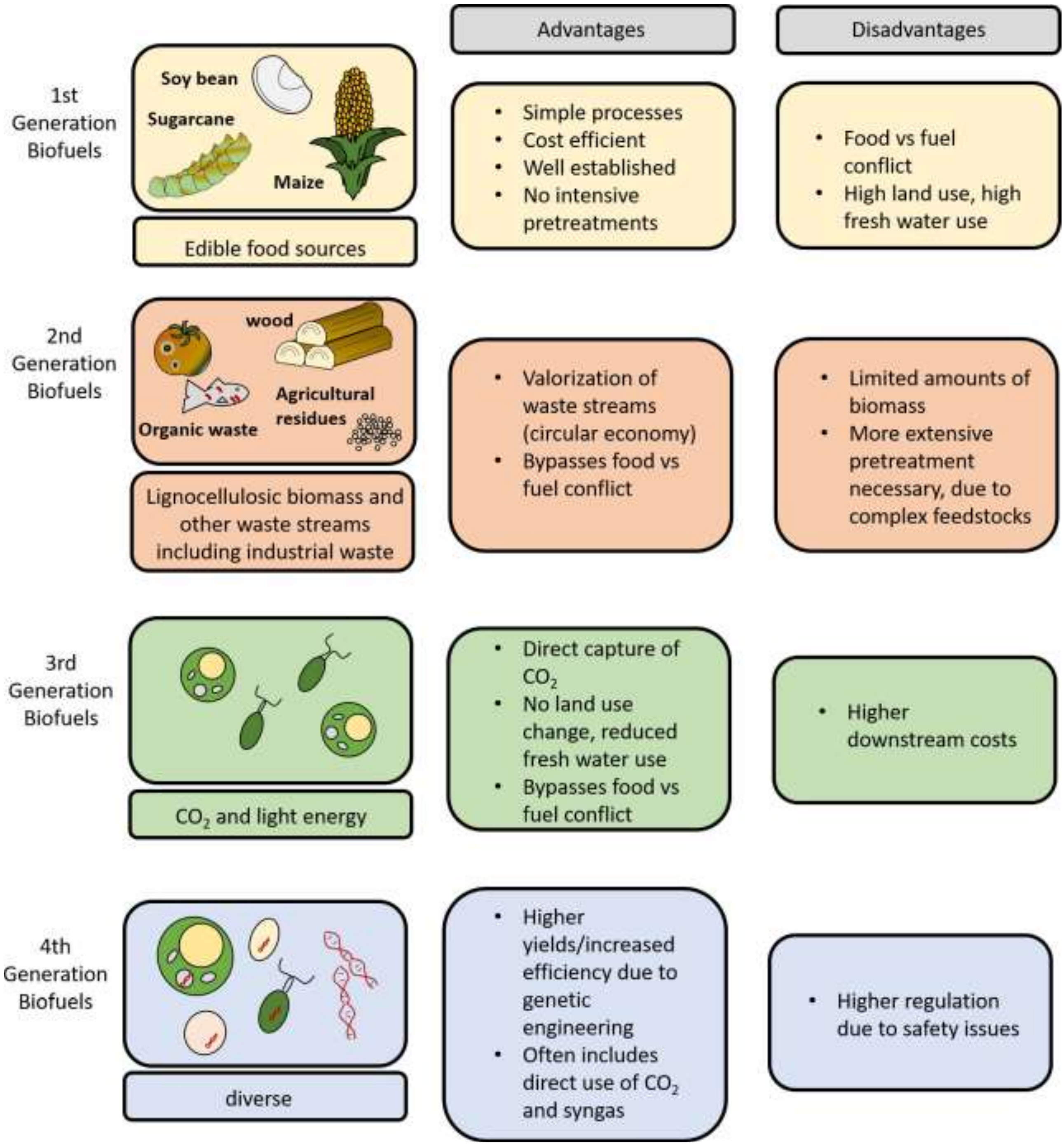
3.3.1 Novel and emerging crops

There are a range of novel feedstocks and emerging crops that are being researched with the goals of increasing options for LCLF feedstock rotations in cropping areas, adapting to more marginal growing conditions, increasing biomass or oil production rates and yields, producing oils or lignocellulosic biomass with properties more amenable to refining processes.

Continued investment in these novel feedstocks may unlock significant innovations to increase feedstock volumes, decrease processing costs, enable realisation of co-benefits and create new value chains.

Feedstocks are broadly categorized into four ‘generations’ (Cavelius, Engelhart-Straub et al. 2023, Dharani, Umapriya et al. 2024) (**Figure 14**). First generation feedstocks are agricultural products traditionally grown as food. Second generation feedstocks are non-edible biomass such as non-food oilseeds, and lignocellulosic materials from bagasse, forestry residue or short rotation trees. Third generation feedstocks include algal biomass, and fourth generation fuels encompass a diverse range of emerging technologies such as gas fermentation, genetically modified plants and microbes and emerging chemical processing technologies.

A recent modelling study highlighted that each generation of feedstock has advantages and limitations (Aron, Khoo et al. 2020). The authors showed that first generation feedstocks can have high production and energy efficiency, but they may not achieve the level of abatement offered by second, third and fourth generation feedstocks. However, third and fourth generation feedstocks are still in development and require innovation to make them more economically attractive. Importantly for the Australian context, second to fourth generation feedstocks are likely to deliver much greater volume of feedstock than first generation feedstocks (Farine, O'Connell et al. 2012, CSIRO 2023).



		Advantages	Disadvantages
1st Generation Biofuels	Edible food sources	• Simple processes • Cost efficient • Well established • No intensive pretreatments	• Food vs fuel conflict • High land use, high fresh water use
2nd Generation Biofuels	Lignocellulosic biomass and other waste streams including industrial waste	• Valorization of waste streams (circular economy) • Bypasses food vs fuel conflict	• Limited amounts of biomass • More extensive pretreatment necessary, due to complex feedstocks
3rd Generation Biofuels	CO_2 and light energy	• Direct capture of CO_2 • No land use change, reduced fresh water use • Bypasses food vs fuel conflict	• Higher downstream costs
4th Generation Biofuels	diverse	• Higher yields/increased efficiency due to genetic engineering • Often includes direct use of CO_2 and syngas	• Higher regulation due to safety issues

Figure 14: Generations of biofuels and corresponding feedstocks.
Source: (Cavelius, Engelhart-Straub et al. 2023)

New feedstocks being investigated include:

- *Non-food, Brassica spp*. Oilseeds, including carinata, camelina, and mustard. Several brassica species that are closely related to canola but have traits that make them attractive as bioenergy crops are currently being developed or commercialised. *Brassica carinata* (carinata), *Brassica juncea* (mustard) and *Camelina sativa* (false flax) have been trialed in Australia. (Campbell, Rossi and Erskine 2013, Seepaul, Kumar et al. 2021)
- *Perennial, oilseed tree species* such as pongamia, palm species, and beauty leaf tree are being explored as potential orchard crops producing annual oilseed harvests in traditionally underutilised lands such as previous rangeland grazing areas. (Murphy, O'Connell et al. 2012, Azad, Rasul et al. 2014, Abadi, Maynard et al. 2016, Ashwath and IOP 2019, Sreekumar, Ashwath and Cozzolino 2023).
- *Algae*, both micro-algae and macro-algae species, continue to be explored for their potential to enable feedstock production outside existing agricultural areas (Su, Song et al. 2017, Araújo, Calderón et al. 2021, Jablonska-Trypuc, Wolejko et al. 2023).
- *Energy cane* varieties are being developed by breeding sugarcane varieties and their wild relatives with traits that are desirable for fuel feedstocks such as high biomass, digestible fibre, and adaptation to a wider range of growing environments (da Silveira, Brasileiro et al. 2016, Barbosa, dos Santos et al. 2020, de Oliveira, Figueiredo et al. 2023, Sica, Mattos et al. 2023)
- *Plants adapted to arid growing zones* such as agave, yucca, and guayule are being investigated for productivity in areas with low rainfall. (Davis, Dohleman and Long 2011, Holtum, Chambers et al. 2011, Chundawat, Chang et al. 2012, Nava-Cruz, Medina-Morales et al. 2015, Pérez-Pimienta, López-Ortega and Sanchez 2017, Sabaini, Boateng et al. 2018, Yan, Corbin et al. 2020, Moreno, Sproul and Quinn 2022)
- *Halophytes (salt tolerant plants)* have been explored for their potential to produce value from salinised land and to grow feedstocks in areas that would otherwise be unproductive for farmers (Al-Rashed, Ibrahim et al. 2016, Sharma, Wungrampha et al. 2016, Debez, Belghith et al. 2017, Fredsgaard, Hulkko et al. 2021).
- *Genetically modified plants that generate leaf oils* have been developed by expressing genes that ordinarily produce oils in seeds, in the leaves and stems of plants. The technology was initially developed in model crops such as Arabidopsis and tobacco but has also been demonstrated in sorghum (Slocombe, Cornah et al. 2009, Yurchenko, Shockey et al. 2017, Gao, Mao et al. 2018, Vanhercke, Belide et al. 2019). This technology could greatly increase the yield of oil per hectare and has the potential to be deployed in a range of high-biomass crops.
- *Precision fermentation*, using oil-accumulating bacteria and protists such as Thraustochytrid spp. is being explored as a way to decouple biomass production from land use and to grow both biofuel feedstocks and single cell protein for food and feed (Martínez, Raghavan et al. 2015, Castro, Rocha et al. 2016, Marchan, Chang et al. 2018, Chintagunta, Zuccaro et al. 2021).

Potential new feedstock evaluation

New feedstocks take time to come to market. Not only do they require CORSIA approval and certification by independent certification schemes such as RSB and ISCC, the resulting fuels may require ASTM approval and face supply chain constraints such as the need for nurseries to supply seeds, changes to farming practices and, in some cases, equipment, and downstream processing such as crushing infrastructure. As such new feedstocks that are significantly different from those produced today face major barriers to adoption in the <10-year timeframe.

However, for longer-term industry development and benefit for Australia, new feedstocks should be considered today and their development prioritized to overcome these barriers. It is recommended that a comprehensive assessment of potential feedstocks should be undertaken as part of a large-scale coordinated program of work to develop feedstocks that offer benefits specifically to Australian conditions and allow broadening of our feedstock base.

These should include native varieties – including learning from indigenous science which draws on sustainable practices in place for thousands of years – and also new technologies such as crop breeding and trait selection. A comprehensive program should also evaluate conversion technologies, and match these with a wide range of crops including oilseeds, lignocellulosics and carbohydrate options.

3.3.2 Novel farming systems, co-benefits and nature positive feedstocks

Possibly the most significant means of increasing LCLF feedstock availability will be through enabling changes to our farming systems that encourage growers to integrate production of crops, animals, feedstocks with practices that sequester carbon and build biodiversity. Unlocking novel feedstocks and developing LCLF value chains has the potential to provide a range of pathways to help Australian agriculture through the transition to a low carbon future.

The value of canola as a biofuel feedstock has already had significant impact on Australian cropping systems. Canola plays an important role in both cereal and cotton systems as a break-crop to decrease plant disease risk and increase productivity. As noted above, the amount of canola in rotations has increased 0.5 million ha in the early 1990’s to over 2 million ha in 2020 (ABS 2022). This has significant positive impacts on the health of the farming system while also improving farm profits and decreasing risk through diversification (Kirkegaard, Lilley and Morrison 2016).

Mixed systems farmers are also beginning to adopt dual-purpose canola which allows for both fodder and oilseed value to be gained from a single crop. The young canola plants are grazed by sheep or cattle early in the season after which the animals are removed and the crop is allowed to grow out to produce seeds at maturity. This management practice has minimal impact on the final yield of the grain (Kirkegaard, Sprague et al. 2008).

The development of markets for oilseeds as biofuel feedstocks, along with the development of new crop variety options, will give farmers more options for rotational crops that can be integrated into the cropping cycles. For example, soybeans in sugar systems, and carinata, camelina and mustard in cereal systems could all foreseeably increase rotation options for Australian cropping farmers.

The integration of short rotation trees into cropping and grazing systems through increased agroforestry has the potential for a range of positive co-benefits including improved animal welfare and productivity through the use of shelter-belts, increased on-farm carbon storage in stumps and roots, increase soil carbon accumulation, and improved biodiversity (McGrath, Goss et al. 2017).

The development of an agroforestry industry is reliant on development of lignocellulosic processing pathways that are logistically viable and cost competitive with other feedstocks. While this requires R&D, it could be argued that it has the most transformative potential for Australian farming systems. Enabling the repurposing of woody biomass, crop stubbles and grassy feedstocks could provide the greatest volumes of feedstocks while also giving farmers a pathway to improve the carbon intensity of their farms through tree planting and biomass generation (Farine, O'Connell et al. 2012, Crawford, O'Connor et al. 2016). It will also be required to unlock the productivity of marginal lands. First generation crops are highly unlikely to yield sufficient volume on marginal lands however, hardy trees, shrubs and grasses that are adapted to arid or saline areas could be sources of feedstock over large areas of inland Australia that is currently only lightly used (Miyake, Smith et al. 2015).

The development of third generation feedstocks has the potential to provide bioremediation and circular economy options for aquaculture producers by growing algae on nutrient rich effluents from fish and prawn farms or by growing halophytes in areas between land-based farms and receiving waters (Mathimani and Pugazhendhi 2019, Fabris, Abbriano et al. 2020, Fredsgaard, Hulkko et al. 2021).

Since LCLF feedstocks need to have the lowest possible carbon intensity, the development of a feedstock market could help to incentivise farmers to adopt low carbon and nature positive farming practices. Practices like decreased fertiliser use, improved soil carbon, use of carbon sequestering inputs like biochar and rock flour, and increased tree planting can all lower the carbon intensity of the crops produced but they come at a cost to farmers that needs to be recouped. An LCLF market that values low carbon and nature positive feedstocks could give farmers a path to adopt these positive practices.

3.4 Blending in a green hydrogen industry

Chart 1 illustrates that Australia has sufficient domestic feedstock available for a significant LCLF industry. Growth in production is projected as a result not only of developing new biomass sources and production, but also by increasing the fuel yield from the same volume of biomass, and by using a bio-based LCLF industry to create demand for green hydrogen and synthetic fuels. Green hydrogen and synthetic fuels can be blended in over time as demand increases and costs are reduced.

A bio-based LCLF industry can be designed to create the market conditions for investment into green hydrogen, which offers a significant scalable source of fuel and other value-added export products.

Figure 15 illustrates the impact of blending green hydrogen into thermochemical processing pathways for biomass to increase yield and production of fuel.

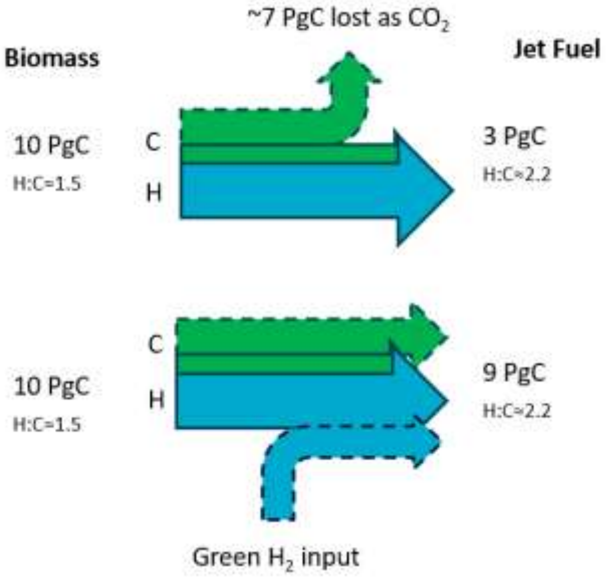


Figure 15. Increasing biofuel production with green hydrogen.
Image produced based on (Hillestad et al 2018).

Woody biomass is a mixture of mostly carbon, hydrogen and oxygen, with an average hydrogen-to-carbon ratio of approximately 1.5. Liquid hydrocarbon fuel, for example jet fuel, is made up almost exclusively of hydrogen and carbon, with a hydrogen-to-carbon ratio of approximately 2.2.

Therefore, to convert biomass alone to jet fuel requires a reduction in carbon content, which is lost as CO_2, resulting in a practical carbon efficiency of around 30-38% (Hillestad et al 2018).

Alternatively, the hydrogen-carbon balance of the process can be increased by blending in green hydrogen - converting a greater proportion of biogenic carbon to fuel (estimated at up to 90%).

This increase in carbon efficiency results in a greater fuel yield from the same amount of biomass.

Hydrogen can be blended incrementally – creating a market for green hydrogen which can scale as costs reduce, increasing conversion efficiency from 10% up to 90%. This creates a pathway to embed variable renewable electricity into value-added liquid fuels for domestic consumption and export using Australian biogenic carbon as a hydrogen carrier.

3.5 Examples of specific regional opportunities

While a national or state-wide assessment of available bioresources is valuable for guiding industrial development investment, the variability between growing regions, seasons, crop types and crop rotation options necessitate a targeted assessment for each growing region or fuel production concept (matching biomass production with processing and fuel production technologies). This specific regional- or project analysis requires a much more detailed analysis of the key parameters in a production system.

The following three examples of regional assessments illustrate the critical cost drivers and variables that must be considered.

Lignocellulosic fuels from the Fitzroy Catchment, QLD

A detailed study on the prospects for biofuel production from the Fitzroy Catchment in Queensland was conducted in 2015 (Hayward, O'Connell et al. 2015). The ultimate production goal of 470ML was achieved through two biomass production scenarios:

a) Production of woody biomass from SRT and natural vegetation regrowth and coppicing

b) Mixed production including the above SRTs plus grasses displacing demand for coppiced natives

Two fuel technology scenarios with a two-step process – refining of bio-oil to jet fuel at a centralised large-scale refinery, and pre-processing of biomass to bio-oil at smaller, distributed plants in the study region using:

a) Fast pyrolysis – considering two different scales of operation (20ML and 60ML)

b) Hydrothermal liquefaction (HTL) at 20ML and 60ML units

These pre-processing units are located at a maximum of 50 kilometres from biomass resources, then stabilised bio-oil was transported 1000 kilometres by rail to a central refinery located adjacent to Brisbane airport.

Changes in conversion efficiency were found to have the greatest influence on the cost of production of jet fuel.

Project advantages

This proposed system benefits from the use of low-cost lignocellulosic feedstocks produced using low-input crops from mixed plantings reducing the risk associated with inter-seasonal variability. Infrastructure exists for transport of biomass and bio-oil, including a well-developed road network, rail to Gladstone and Brisbane, and a deep-water port in Gladstone. Although the distances across the catchment area are large, the multi-modal transport infrastructure allows for cost-effective transport of densified products.

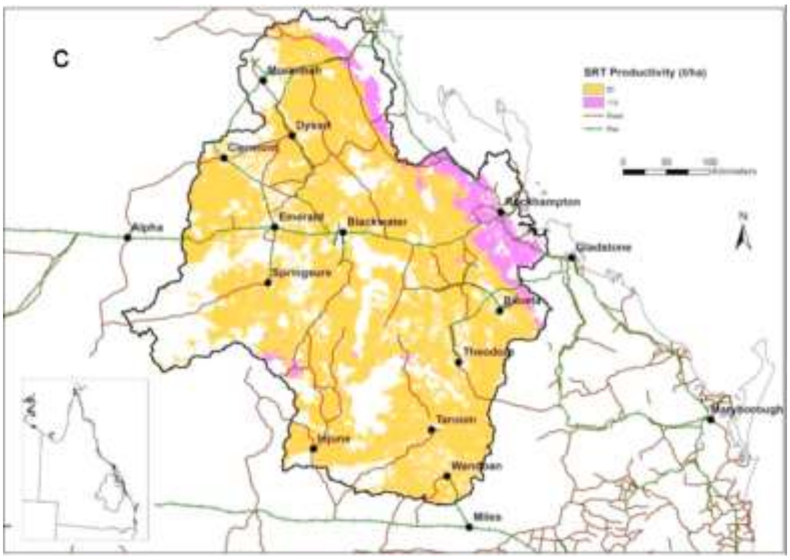


Figure 16: Productivity of short rotation tree (SRT) crops (in t/ha)

Source: (Murphy et al., 2015)

Project risks

The high inter-annual variability in growing conditions creates biomass supply risk and adds cost in the form of downtime for preprocessing plants and refinery. While transport infrastructure is well-established, more infrastructure for harvesting and processing of grasses and woody biomass is required and likely beyond the capability of a single project proponent. Further counter-party risk exists from farmers and other land managers who must be relied on for managing crops – particularly SRT crops which require 5-10 years of management before harvesting. Operations and Maintenance (O&M) costs for pyrolysis plants are high, requiring dedicated skilled staff and continuous supply of services including hydrogen.

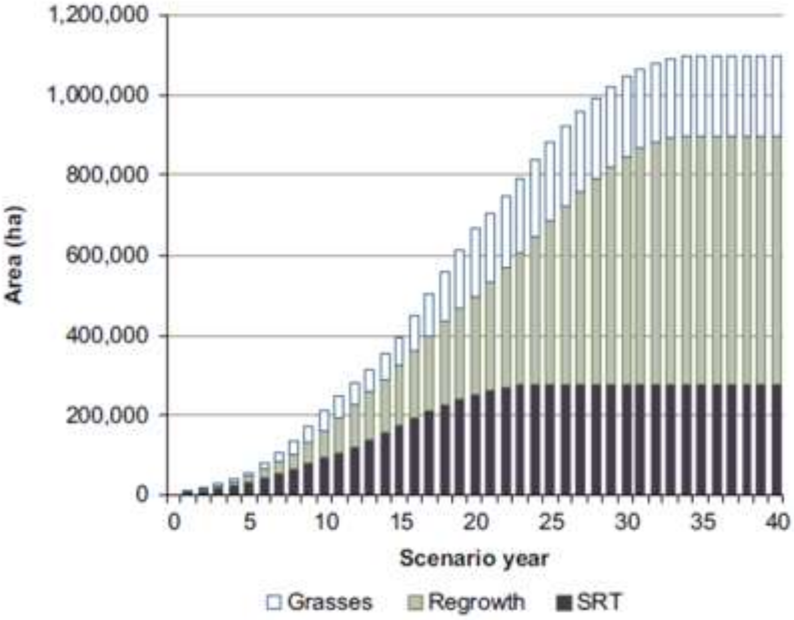


Figure 17: Area under cultivation for lignocellulosic feedstocks from grass, regrowth and short rotation tree (SRT) crops.
Source: (Murphy et al., 2015)

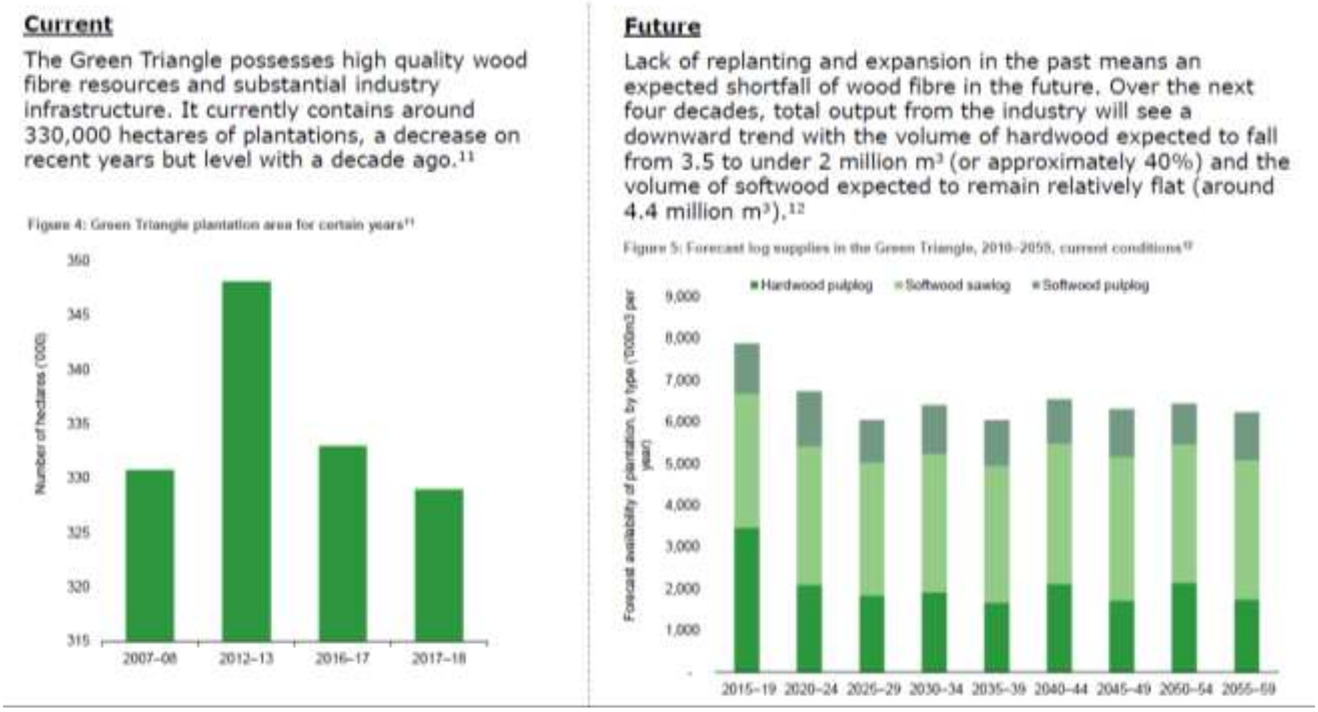
Cellulosic ethanol production from the Green Triangle, VIC and SA

Another regional use case is provided for the region surrounding Mount Gambier in South-Eastern Australia known as the Green Triangle.

The Green Triangle region has been home to managed forestry for over 100 years, covering over 334,000 hectares or 17% of Australia's forestry area, within a larger region of over 6 million hectares (Rodriguez, May et al. 2011, GTFIH 2019). Production includes hardwood and softwood, sawlog and pulp. Future production of hardwood from the Green Triangle is expected to decline from 3.5 to under 2 million cubic metres due to a lack of replanting (**Figure 18**).

Analysis from the Centre for Markets Values and Inclusions, University of South Australia and reported by ERC Economic and Financial Analysis commissioned by the Green Triangle Forest Industries Hub (2019) estimates that at a price equivalent to a $30/t carbon price over 18mtpa of new hardwood production would be generated, and at a price equivalent to $80/t over 90mtpa of hardwood and 120mtpa of new softwood would be produced.

While constraints to managed forestry production are imposed by environmental regulations, a bioenergy industry based on processing coppiced lignocellulosic biomass could support planting of diverse native species fulfilling both biodiversity outcomes as well as bioenergy outcomes.



Current

The Green Triangle possesses high quality wood fibre resources and substantial industry infrastructure. It currently contains around 330,000 hectares of plantations, a decrease on recent years but level with a decade ago.[11]

Figure 4: Green Triangle plantation area for certain years[11]

Future

Lack of replanting and expansion in the past means an expected shortfall of wood fibre in the future. Over the next four decades, total output from the industry will see a downward trend with the volume of hardwood expected to fall from 3.5 to under 2 million m^3 (or approximately 40%) and the volume of softwood expected to remain relatively flat (around 4.4 million m^3).[12]

Figure 5: Forecast log supplies in the Green Triangle, 2010–2059, current conditions[12]

Figure 18: Current trends and outlook for the Green Triangle plantation estate
Source: Green Triangle Forest Industry Strategic Plan, 2019

Project advantages

The Green Triangle region has extensive established infrastructure and skilled labour for managed forestry, along with established plantations which remove a major constraint faced by new plantation areas. The region also offers port infrastructure at Portland and near Mount Gambier, and forestry supports over 7 thousand jobs in a region that's home to over 180,000 people. A variety of lignocellulosic products can be produced from this region, including hardwood and softwood, agricultural and sawmill residues and coppiced native biodiverse plantings.

Low-cost feedstocks for lignocellulosic processes can be liberated at over 250,000 tpa (lowest cost) and over 1.5mtpa (highest cost) from residues and waste, while at appropriate market prices significant additional woody biomass can be sustainably produced while contributing to biodiversity and other natural capital goals.

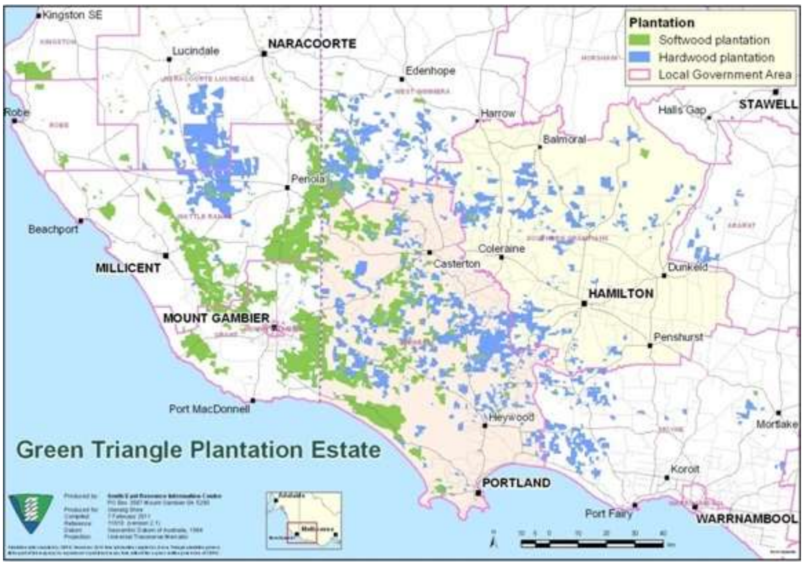


Figure 19: Green Triangle in Victoria and South Australia. Source: https://www.glenelg.vic.gov.au/Discover-Our-Shire/Business-and-Industry/Why-invest-in-Glenelg/Timber-Fishing-Aquaculture-and-Agriculture

Project risks

Forestry has been a controversial topic in Australia in recent years, with bans on native logging in place in South Australia and taking effect in Western Australia in 2021; Victoria and South East Queensland regional area in 2024; and coming under pressure in New South Wales. Further constraints are being imposed on managed forestry as well, with limited new regions for expansion of the industry. Limited supply of land and resources is likely to create upward pressure on timber prices and residues.

Short rotation Mallee crops in WA

Mallee eucalypts can be integrated into farming systems using agroforestry practices to provide additional revenue source as well as ecosystem and farm co-benefits such as shelter and water table management. More than 12,000 hectares of mallee planting has taken place since 1994, and evidence confirms that mallee planting stores carbon in below-ground root biomass. By combining income from below-ground carbon sequestration with commercial harvesting of above-ground biomass the use of mallees in agroforestry scenarios can provide an additional economic benefit to farmers while supplying woody biomass at costs low enough to support a bioenergy industry.

Spencer et al (2020) highlight the economic opportunity for mallee agroforestry at three of 11 sites in south-west Western Australia. The study found that favourable conditions for mallee agroforestry included low agricultural gross margins coinciding with high biomass productivity.

Project advantages

Co-benefits in the form of additional revenue from carbon sequestration and sale of biomass combined with dryland salinity management and animal shelter deliver enhanced returns to farmers. Natural capital outcomes and maintenance of biodiversity deliver additional benefits to the wider region. The combination of these outcomes reduces the required rate of return for mallee biomass, reducing cost to a viable threshold for a bioenergy industry.

Project risks

The long-term supply of biomass in this system is heavily dependent on a large number of farmers adopting and sustaining changed management practices. Not all areas within the region are profitable under such a regime – with high variability depending on agricultural land productivity and farm returns. Given the dependency on long-term management (more than 10 years for short rotation coppicing) it is essential that the industry aligns with regional community values.

3.6 Alternative demands for bioresources and land

It is widely acknowledged that biofuel feedstock production must be carefully managed to avoid conflict with alternative demands for bioresources, land and water. Globally, efforts have been made to regulate land use change and avoid real or perceived impacts on food supplies through a range of different certification schemes including CORSIA, RED II, ISCC, RSB, RFS (Morone, Strzałkowski and Tani 2020).

We have some general knowledge of the kinds of alternative demands for bioresources including food and animal feed, materials, heating and bioelectricity generation. However, to fully understand the true availability of feedstocks and their highest value uses, we need more granular data and material flow analyses to understand and track the true flows of bioresources, and the future biomass production potential to aid decision making about highest value use (either economic, environmental or social value).

CSIRO recently released the “Australian material flow analysis to progress to a circular economy” report (Miatto, Emami et al. 2024) which describes the material inputs, outputs and circular flows throughout the economy (see **Figure 20**). This report includes a relatively high-level section on biological materials showing the total inputs (domestic plus imports = 388 Mt), and outputs to exports, solid and liquid wastes, air emissions, seeds and fertilisers, plus recycled flows. While this analysis is very informative for quantifying the size of biomass flows relative to other, non-biological materials in our economy and showing the circularity rate of those materials, it does not have the level of granularity required to illustrate the alternative uses of those materials within the economy.

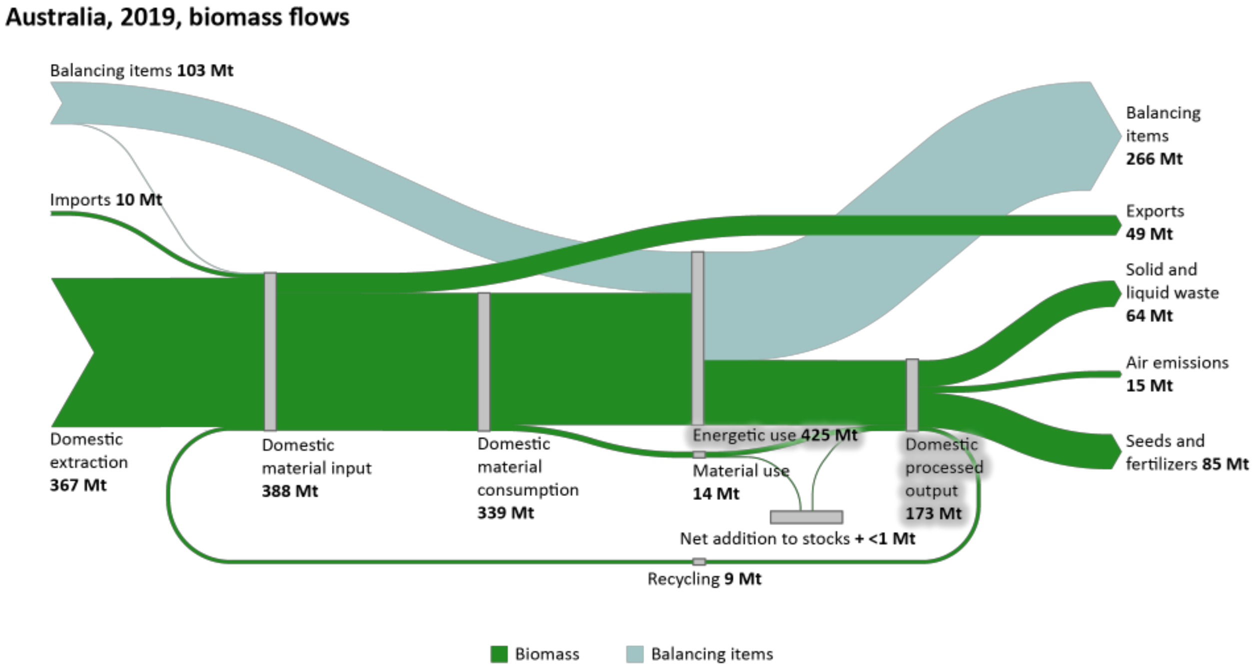
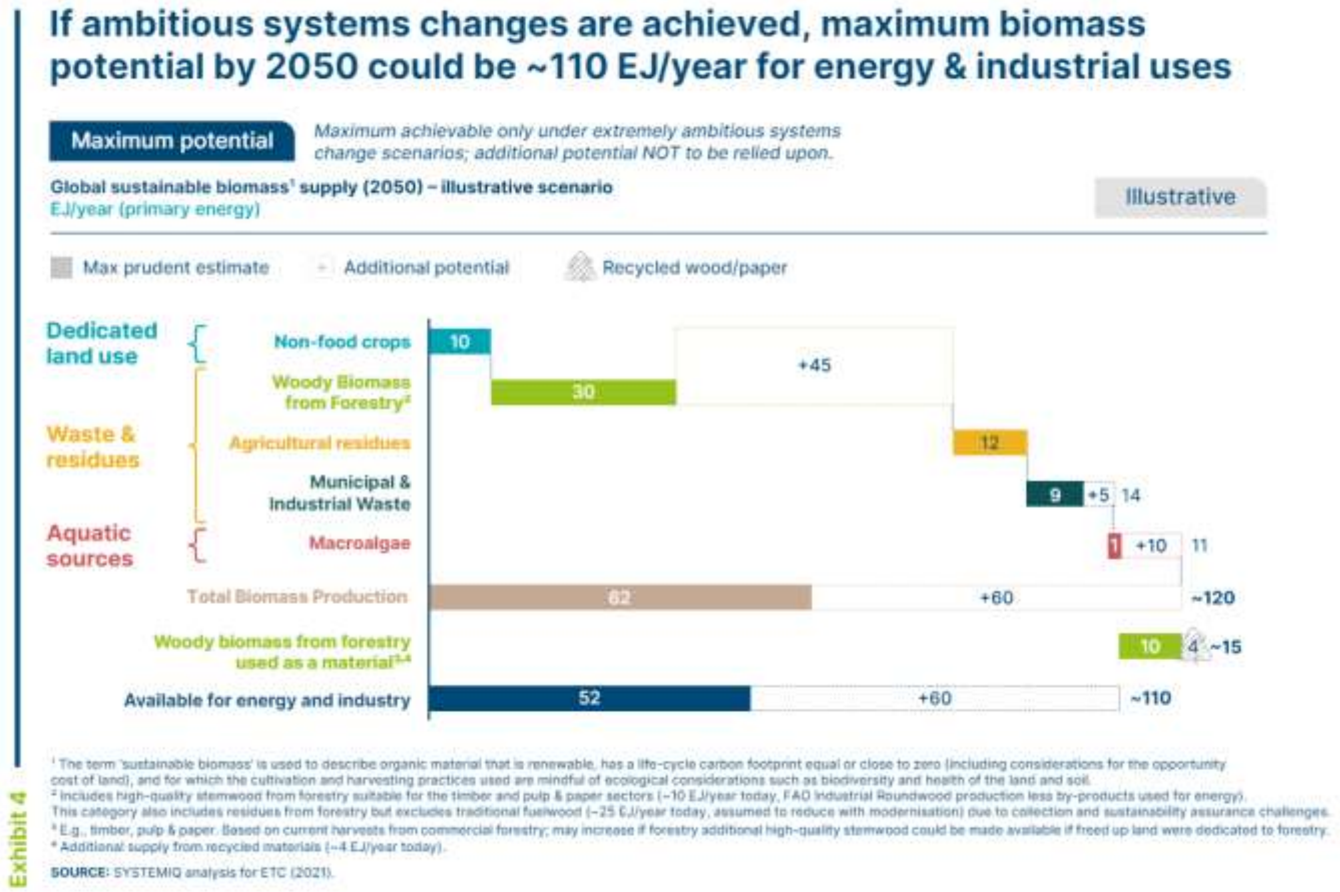


Figure 20: High level biomass material flow analysis for the Australian economy 2019.
Source: (Miatto, Emami et al. 2024)

The EU has recently published a similar analysis but focussed in on the production, uses and flows of biological materials in the European economy (Avitabile, Baldoni et al. 2023). This report zooms in on the bioresources and outlines the volumes produced in different forms and by which industry sectors, what volumes flow to competing demands, how this impacts on the economics of those materials and the environmental implications of the growing bioeconomy. The analysis allows the authors to estimate the bioenergy potential of the available feedstocks, rather than estimating total volumes and making assumptions about their availability. Within their analysis they also projected future potential for increased bioenergy resources that do not impinge on alternative uses or land use change (**Figure 21**).



[1] The term 'sustainable biomass' is used to describe organic material that is renewable, has a life-cycle carbon footprint equal or close to zero (including considerations for the opportunity cost of land), and for which the cultivation and harvesting practices used are mindful of ecological considerations such as biodiversity and health of the land and soil.

[2] Includes high-quality stemwood from forestry suitable for the timber and pulp & paper sectors (~10 EJ/year today, FAO Industrial Roundwood production less by-products used for energy). This category also includes residues from forestry but excludes traditional fuelwood (~25 EJ/year today, assumed to reduce with modernisation) due to collection and sustainability assurance challenges.

[3] E.g., timber, pulp & paper. Based on current harvests from commercial forestry; may increase if forestry additional high-quality stemwood could be made available if freed up land were dedicated to forestry.

[4] Additional supply from recycled materials (~4 EJ/year today).

SOURCE: SYSTEMIQ analysis for ETC (2021).

Figure 21: Projections of future feedstock availability in European Union calculated based on detailed material flow analysis of bioresources across the EU.
Source: (Avitabile, Baldoni et al. 2023) Bioresources within a Net-Zero Emissions Economy

A similarly detailed analysis is required to fully understand the current state of the bioeconomy in Australia and to act as a baseline for decision making about our future bioeconomy. Such detailed analysis can bring to light bioresource demands that are not immediately apparent

For example, Hetherington et al (Hetherington, Juliano et al. 2022) discusses a detailed material flow analysis of food losses and waste using data from Food Innovation Australia (FIAL 2021). Their analysis showed that of the 17802 Mt of food waste generated in Australia in 2021, only 18% was sent to landfill. The remainder was used for a range of alternative products including animal feed, energy production, fertiliser, and non-food products, with small fractions disposed on-farm (**Figure 22**).

This level of granularity takes significant effort and time to source available data and model outcomes, however, it is this level of detail that is required to fully understand the competing demands for our bioresources to inform decision-making.

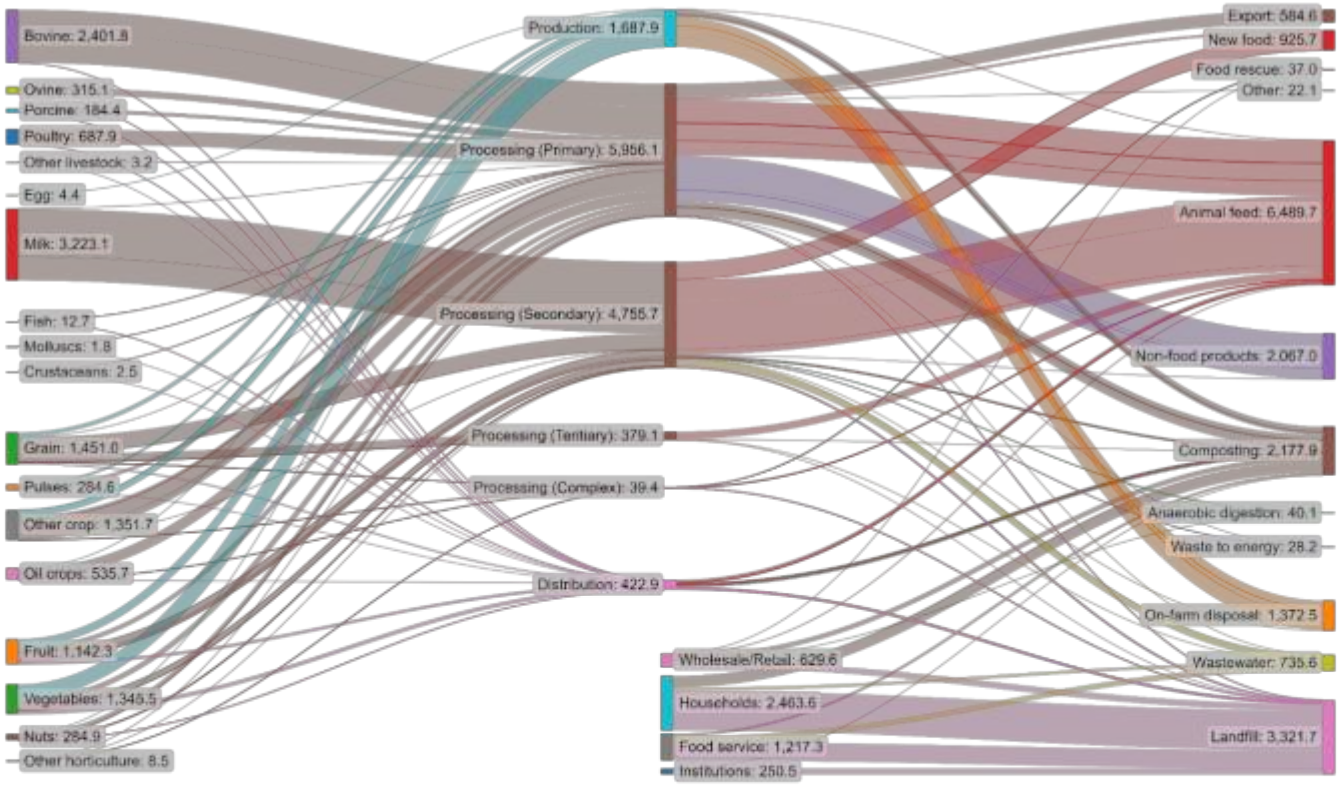


Figure 22: Sources and end destination of recovered, lost and wasted food in Australia for 2012 (kilo tonnes p.a.). Source: Hetherington, Juliano et al. 2022)and (FIAL 2021).

3.6.1 Alternative demand for oilseeds

Oilseeds can be broadly classed into food and non-food categories. Currently, food oilseeds are most commonly grown in Australia. Canola is our third most valuable grain crop after wheat and barley. The primary uses are food (canola oil), bioenergy feedstock and animal feed (canola meal) (Australian Export Grains Innovation Centre 2020).

The vast majority of Australia's canola is exported. We are a major supplier for biodiesel feedstock for the European market (Eady 2017). USDA predicts that canola exports from Australia will reach a record 5.1 Mt in 2024/25, along with 230,000 Mt of oil from local crushers (USDA Foreign Agricultural Service 2024). Japan, Europe and Mexico are among the largest markets for Australian canola.

The majority of locally crushed canola (~1.2Mt) produces oil that is used for food, with approximately 1/3 used to make spreads (e.g., margarine) and cooking oil, and the remaining 2/3 used in the commercial food sector (GRDC 2017).

Canola meal, a co-product of canola oil, is valued as a stock feed because of it's high protein content, amino acid profile, and vitamin and mineral content (Australian Export Grains Innovation Centre 2020). It is primarily used for pork, poultry and dairy feeds but it is also used for fish and beef cattle.

Production of other oilseeds is very small in comparison to canola. The small volume of soybeans produced in Australia (~40000t) are primarily used for food. However, we are a net importer of soybean isolates and meal for both food and animal feed purposes.

Cottonseed is another major oilseed produced in Australia. Approximately 50% of the mass of picked cotton is made up of cottonseed. Cottonseed oil is used as a food oil for frying, margarines and dressings, and for a range of industrial products including soap, emulsifiers, cosmetics, pharmaceuticals, rubber, paint, water proofing agents and candles. The meal and hulls that remain after pressing of cottonseed to remove oil are valued as livestock feed (Cotton Australia 2024).

A range of emerging oilseeds that are being explored as biofuel feedstocks, including carinata, camelina, and pongamia, are not yet produced in meaningful volumes and do not have current markets for alternative uses.

3.6.2 Alternative demand for grains and carbohydrates

Grain starches and sugar can be used to produce biofuel through fermentation to ethanol and subsequent alcohol to jet processing. Cereal grains (wheat, barley, sorghum) and sugar are also two of our largest agricultural commodities with a combined forecast value of $AUD16.7 billion in 2024/25 (ABARES 2024).

In 2023-24 Australia was projected to produce 37.8 Mt of wheat (26.5 Mt), barley (10 Mt) and sorghum (1.3 Mt) (USDA Foreign Agricultural Service 2023). Approximately 67% of this volume is destined for export. Australian cereal grains are primarily used for both human and animal feeds. The Department of Agriculture, Fisheries and Forestry (DAFF) have reported that demand for grains for livestock feed is likely to increase in coming years as a result of increasing demand for red meat in particular (DAFF 2022).

More than 80% of sugar produced in Australia is exported, mainly to South Korea, Indonesia, Japan and Malaysia primarily for use as food (DAFF 2023). Molasses, a co-product of sugar refining is used as an ethanol feedstock and as animal feed.

In 2022, Australia produced 175ML of bioethanol (USDA Foreign Agriculture Service 2021). The majority of this was produced from grain starches by Manildra who own a 300 ML capacity ethanol plant in Nowra, NSW. Wilmar runs a 60 ML capacity plant producing ethanol from molasses in Sarina, QLD (USDA Foreign Agriculture Service 2021) .

Simple sugars are the feedstock for a range of microbial processes so significant numbers of biorefinery and precision fermentation systems are looking to these feedstocks to produce a range of materials (e.g. bioplastics), ingredients (e.g. alternative proteins, food colourants) and therapeutics and nutraceuticals (e.g. insulin), textiles and fuels (Lips 2022).

3.6.3 Alternative demand for tallow and used cooking oil (UCO)

In 2022-23 the value of inedible tallow exports exceeded $1 billion for the first time (DAFF 2024). The Australian Renderers Association (ARA) notes that tallow has a range of uses including high-grade edible tallow used for frying, as a shortening or to make margarine, industrial tallow, used for production of soap, cosmetics and industrial chemicals, feed grade fats used in the manufacture of pet food, livestock and aquaculture feed, yellow grease (UCO) and tallow for biofuel (Australian Renderers Association Inc 2016).

In 2015-16, ARA quoted the volumes in Table 5 for tallow and UCO flowing to export and various domestic uses.

Total Production	**611,180 tonnes**
Exports	448,120 tonnes
Domestic Oleo-chemical and industrial	7,000 tonnes
Domestic edible applications	35,000 tonnes
Domestic intensive animal production	50,000 tonnes
Domestic aquaculture feeds	16,000 tonnes
Domestic pet food	30,000 tonnes
Domestic biodiesel and fuel	25,000 tonnes

Table 5: Uses of recovered animal fats (tallow and poultry oil).
Source: Australian Renderers Association Inc., 2016

The International Energy Agency notes that demand for tallow and UCO has been increasing sharply for several years and it likely reaching supply limitations, with their projections indicating the demand will exceed supply by 2027 (International Energy Agency 2022).

3.6.4 Alternative demand for Bagasse

Bagasse has been widely studied as a feedstock for biorefineries for the production of a range of different products including bioenergy and biofuels, packaging and textiles, industrial chemicals, enzymes and microbial biomass (Karp, Burgos et al. 2022)

Currently, the primary use of bagasse in Australia is as a source of heat, steam and bioelectricity in Australian sugar mills (Australian Sugar Milling Council 2022). A significant proportion of the 10 Mt of bagasse produced in Australian mills each year is combusted on site to produce 485 MW of heat and steam, used to drive milling processes, plus bioelectricity, which is exported to the grid (Australian Sugar Milling Council 2021).

The Australian Sugar Milling Council has been exploring the techno-economic feasibility of liberating more bagasse for bioenergy production. They report that upgrades to existing mills will liberate enough bagasse to produce between 680 and 1736 MW of bioenergy. They also considered the production of both biofuels and biogas but consider co-generation of heat, steam and bioelectricity as a more attractive option until policies shift, and biofuel markets mature.

Presently, 56% of the bioenergy produced from bagasse is used to power mill operations, with the remaining 44% exported to the grid (Australian Sugar Milling Council 2022). If the bioresource potential of bagasse as a feedstock for biofuels, biomaterials and industrial chemicals is to be realised, significant upgrades to mills are required to improve energy efficiency and/or integrate alternative forms of renewable energy.

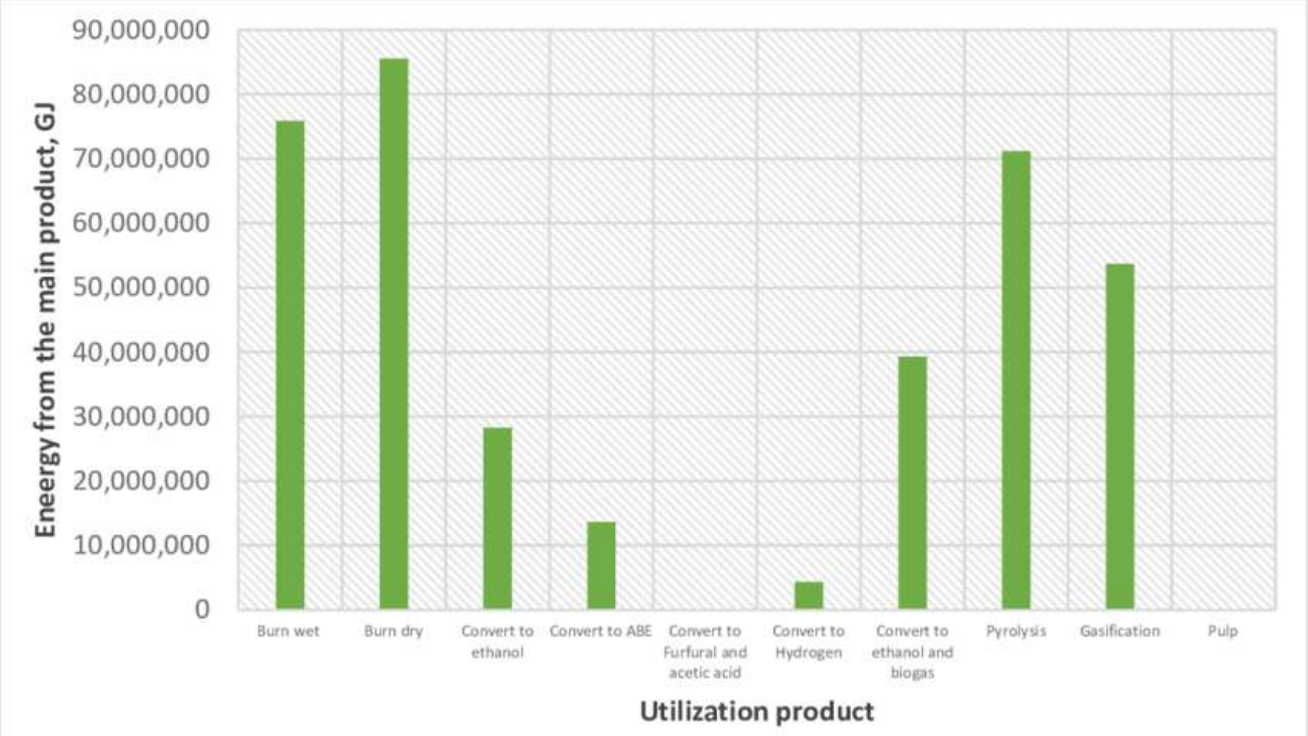


Figure 23: Energy produced from different processing pathways for sugarcane bagasse globally. Source: (Hamawand, da Silva et al. 2021)

3.6.5 Alternative demand for forestry residues

Woody biofuel feedstocks and be broadly classed into purpose grown lignocellulosic crops (e.g. short rotation coppiced trees), forestry residues and sawmill wastes. ABARES published a detailed market analysis of the potential uses of forestry and sawmill wastes (excluding purpose grown bioenergy tree crops) in 2018 with projections out to 2050 (Lock and Whittle 2018). Their report focuses on harvest waste (stumps, bark, crown material and tree heads and butts) and sawmill waste (solid wood offcuts, woodchips, sawdust, shavings and bark). They note that harvest wastes are often left in forest and not reported in estimates of log harvest or production and therefore estimates of potential volumes are somewhat uncertain. Estimates that they cite vary with species and range between 30% and 60% of above ground biomass being left in the forest as harvest residues for native forest and between 19% and 35% for softwood operations. They note that an ARENA study cited potential volumes of >7 Mt in harvest residues across Victoria, Tasmania, Queensland and New South Wales.

Estimates of sawmill waste volume are equally uncertain. Lock and Whittle (2018) note that data on sawmill waste production is not aggregated as agreements are often negotiated directly between wood processors and uses. The authors estimate that approximately 5.2 Mt of sawmill residues could have been produced nationally in 2016–17.

Harvest residues are largely left in the forest to rot (Lock and Whittle 2018). Retention of some fraction of these residues is likely required to maintain soil health, carbon and nitrogen dynamics and forest productivity (Corbeels, McMurtrie and O'Connell 2000, Mathers, Mendham et al. 2003, He, Xu and Hughes 2006, Tutua, Xu et al. 2008, Smolander, Kanerva et al. 2012, Mendham, Ogden et al. 2014). However, Lock and Whittle note that a significant fraction of the harvest residue could potentially be valorised. Some research into the sustainably harvestable residue amounts have begun but further research is required across different forestry systems and environments (Dupuis and Ghaffariyan 2020).

Currently the most common uses of sawmill wastes and harvest residues are wood products, including woodchips for exports, pulp for domestic paper manufacturing and wood-based panels, or fuel for heat and electricity at sawmills (Lock and Whittle 2018). Lock and Whittle (2018) discuss several emerging options for use of woody residues including as solid fuels (briquettes and pellets), feedstocks for platform chemicals, chemical products or biochar (**Figure 24**). Finally, they note that woody residues are used for landscaping and animal bedding. Their market analysis suggests that by 2050 the majority of harvest residues will still be left in the field, but sawmill waste will be used for a combination of wood and energy/fuel products.

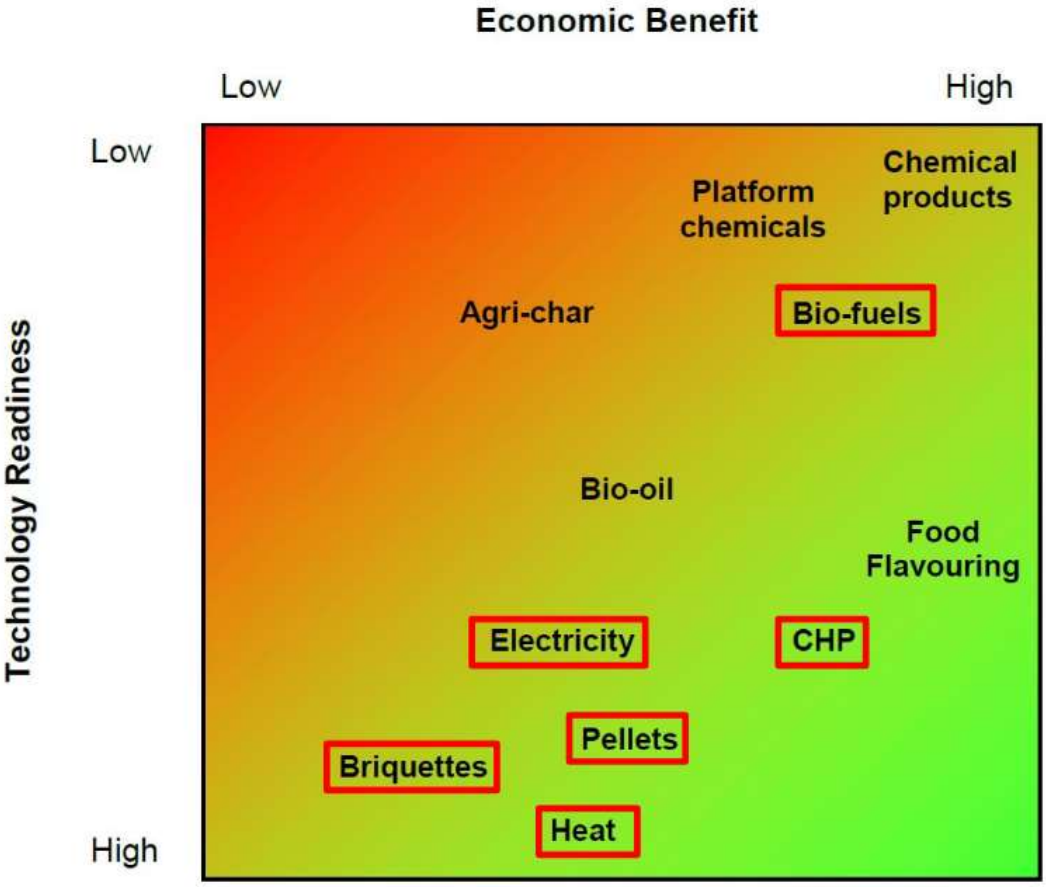


Figure 24: Alternative uses of forestry harvest residues and sawmill residues.
Source: (Lock and Whittle 2018)

3.6.6 Alternative demand for agricultural residues

Most assessments of bioresources for bioenergy projects state the importance of second-generation feedstocks like lignocellulosic material from crop residues (straw, stubble) or purpose grown biomass like grasses or short rotation tree crops.

The potential volume of these materials dwarfs some of the other potential feedstocks (section 3.2). However, these materials do have alternative markets that need to be considered.

Crop stubbles perform several important functions in farming systems:

- Many cereal, pulse and oilseed crops can be used as a source of feed for grazing animal in mixed farming systems (Thomas, Toovey et al. 2021)
- Retention of stubble plays an important role in protecting soil from erosion and aiding water infiltration in conservation farming practices (Herr, Greiner and Stoeckl 2004).
- Crop residues are a source of both carbon and nutrients required to build soil carbon and prevent mining of soil fertility (Zhao, Bryan et al. 2015).

In 2014, ABS reported that 15.6 million ha of cropping land had stubble retained or grazed compared to just 2.3 million ha where stubble was burned (ABS 2014). However, several studies have explored what fraction of stubble could be harvested without impacting on soil health and carbon, with results showing that greater than 50% of crop residues could be harvested while maintaining the ecosystem benefits of stubble retention (**Figure 25**) (Zhao, Bryan et al. 2015).

Crop residues like straw can also be baled and sold as animal bedding, landscaping, mushroom compost or, in some cases, animal feed. Some international work has begun to explore how farmers assess the importance of alternative uses of crop residues and how this affects the prices they are willing to accept for these materials (Zuo, Hou and Huang 2020).

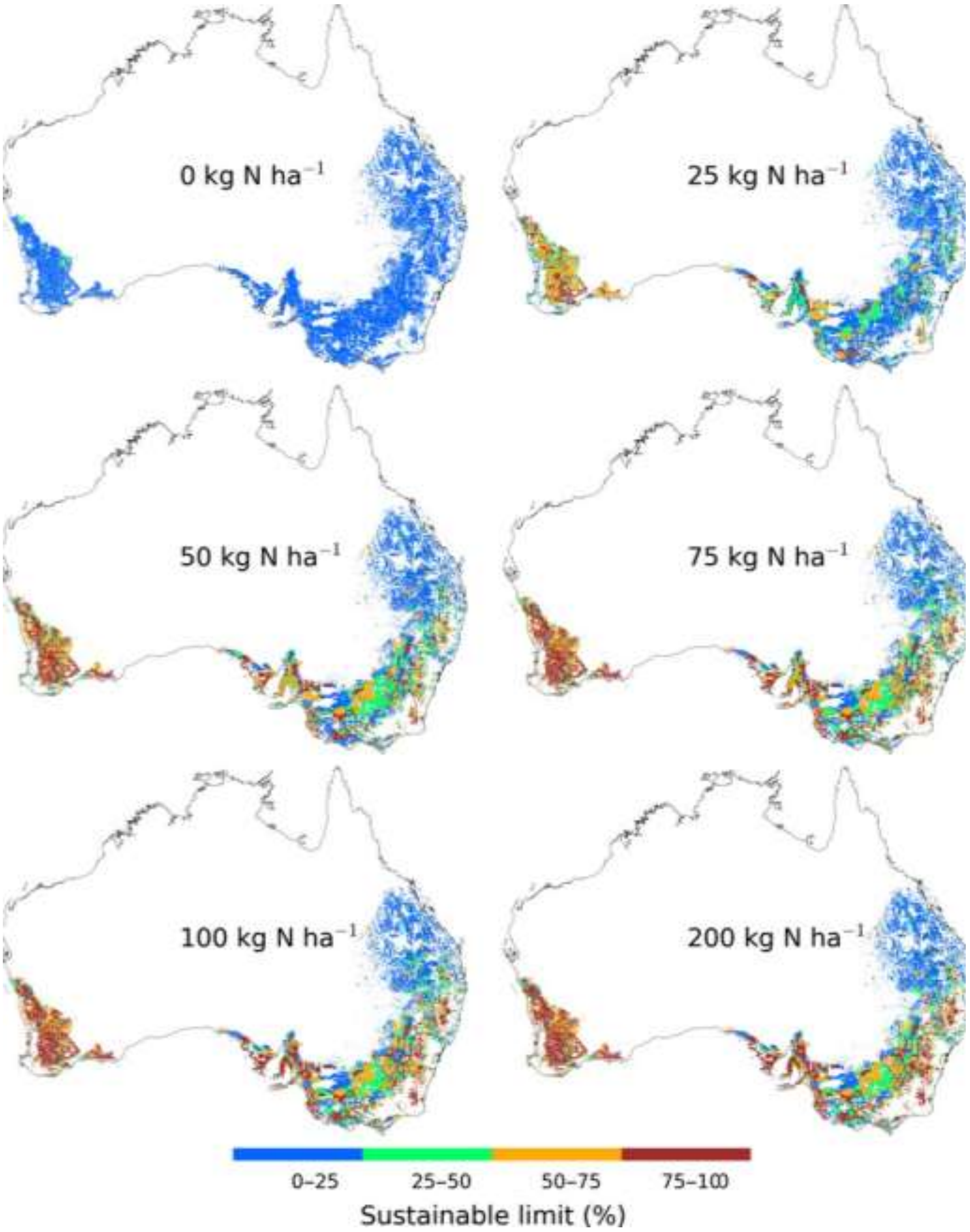


Figure 25: Sustainable crop residue harvest limits under six fertilisation regimes
Source: (Zhao, Bryan et al. 2015).

3.6.7 Alternative demand for MSW and food wastes

The alternative uses of the organic fraction of MSW and food wastes have received much attention, but the granularity of data varies.The range of alternative uses of food wastes are very well documented (see **Figure 22** above) (Hetherington, Juliano et al. 2022). However, this data analysis is confined specifically to food waste so does not consider MSW or other organic wastes such as urban green waste, manures, etc.

It is desirable to retain food grade materials within the food chain where possible. The National Food Waste Strategy aims to halve Australia's food waste by 2030. Importantly, the National Food

Waste Strategy feasibility study, which outlines how the strategy is to be enacted, focuses on waste reduction, recycling as alternative food products or valorising as animal feed (FIAL 2021). Reuse options that are further down the circular economy hierarchy, such as anaerobic digestion or composting, are not desirable under this approach.

Several local government agencies around the country are implementing or considering FOGO (food organics, green organics) management programs to increase diversion of organics from landfills (Blanchard, Harris et al. 2023). Composting is one of the most common current uses for this diverted FOGO waste (Pickin, Wardle et al. 2020).

MSW and organic waste are also being explored as feedstocks for waste to energy projects that will produce heat and electricity rather than LCLFs, such as the Kwinana Waste to Energy project (ARENA 2018).

It should be noted that even organic waste that ends up in landfills in Australia often has an alternative value because of the potential for landfill gas capture (see **Figure 26**). The National Waste report 2022 states that ~2.3 Mt of waste is recorded as used for energy recovery with landfill gas collection accounting for ~1.9 Mt of that total (Pickin, Wardle et al. 2020). Approximately 47% of landfill gas was captured and 80% of the captured gas was used to make energy with the remainder flared.

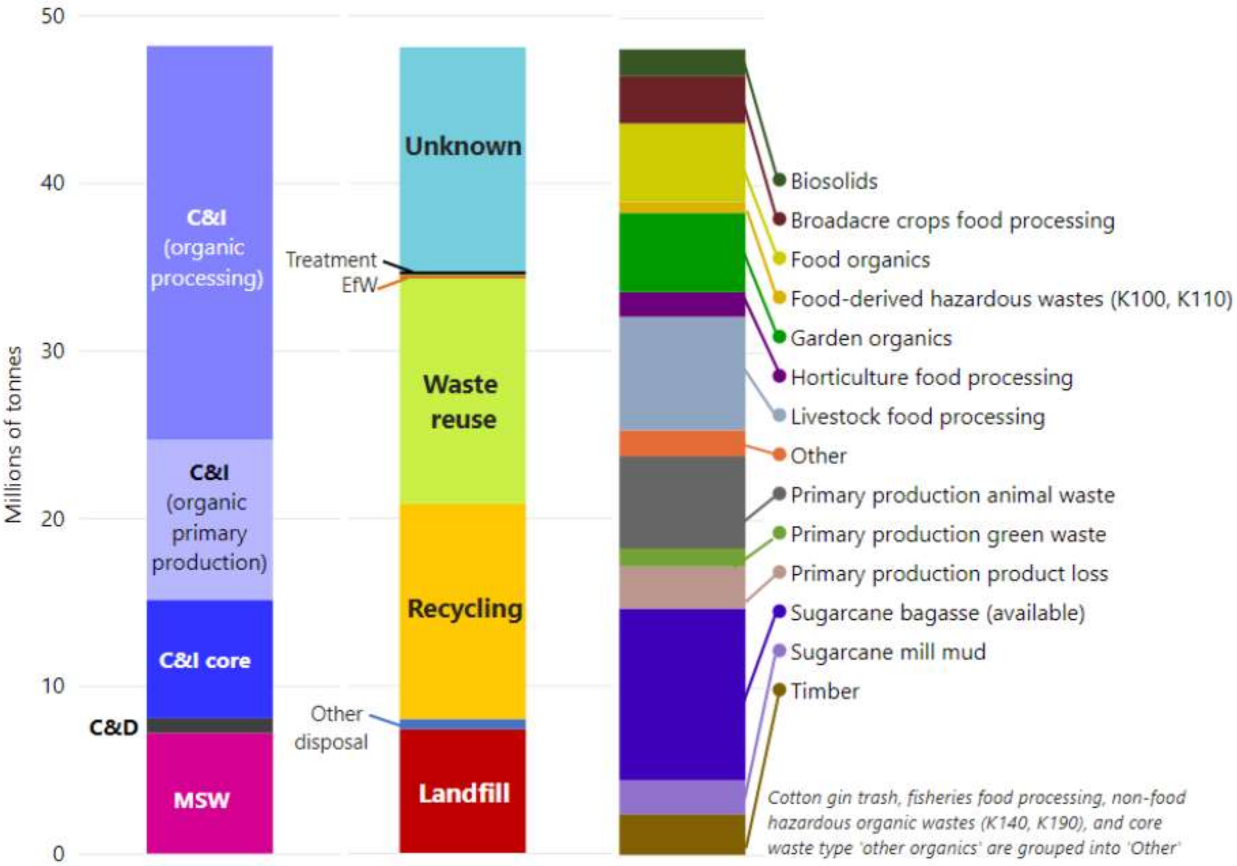


Figure 26: Generation, management method and type of organic wastes considered in the National Waste Report, Australia 2020-21, showing the major destination categories for organic wastes.
Source: (Pickin, Wardle et al. 2020).

3.7 Alternative demand for land and water resources

3.7.1 Food versus fuel

The rapidly emerging demand for biofuel feedstocks has created some concerns about competition with food production for the biomass itself (where food crops are used as feedstocks), for land, and for water and nutrients.

Discussions of alternative demands for land and water resources are dominated by concerns about competition between food and fuel feedstock production. There is a significant body of literature examining the risk and mitigations for this competition. Rosillo-Clarke (2016) provides a thorough discussion of the evolution of the food versus fuel debate in recent years. They note that debate took hold with publications from (Fargione, Hill et al. 2008, Searchinger, Heimlich et al. 2008) which led to several follow-up papers. However, they point out that these early studies were overly simplistic and the concerns that they raise about the impact of biofuel feedstocks on food prices have since been proven to be overstated. They failed to present a realistic estimate of the impact of land use because their methods were too simplistic or incomplete (Rosillo-Calle 2016). More recent studies have shown that the impact of feedstock production on both food supplies and land use change is much less than initially feared (Dumortier, Hayes et al. 2011, Brown and Brown 2012, Rosillo-Calle 2016, Tomei and Helli16, Filip, Janda et al. 2019)

Rosillo-Calle (2016) points out that the debate has now divided in two; a media debate and an academic debate. The emerging consensus in academic literature is that it is possible to grow the balance sheet of biofuel feedstocks without seriously impacting on food security or land use change. However, care is needed when assessing the literature in this space because there are now both anti-biofuel and pro-biofuel lobbies who are arguing their cases. Readers need to ensure that arguments are supported by data produced from reliable studies using good methodologies.

In recent years there have been significant shifts in some agencies such as FAO, who initially opposed biofuel feedstock production, to a more pragmatic approach in line with the emerging evidence. New studies showed that many of the negative impacts attributed to biofuels, such as food shortages and increased prices were in fact caused by a complex combination of factors including crude oil prices and speculation in commodity markets. These findings have led to a softening of the position of some agencies. For example, Rosillo-Calle (Rosillo-Calle 2016) cites that the Director General of FAO (Jose Graciano da Silva) in 2015 recognized the role that biofuels have to play in the future of global agriculture which will be more complex, global and interconnected.

International sustainability frameworks for biofuels have been emerging to enable the development of LCLFs industry while protecting both food security and environmental sustainability. Use of food crops is limited to 7% of transportable fuels under REDIII, and palm oil is currently banned due concerns about land use change, however other jurisdictions may not be as strict (Sandford, Malins et al. 2024). For example, canola, soybean, and palm oil are all permitted under CORSIA but it does consider both direct and indirect land use change associated with growing these crops within the sustainability assessment (ISCC and CORSIA 2022).

There are a variety of modelling approaches that allow for calculation of land use change risk factors that are required to be reported for certification of biofuels (Sandford, Malins et al. 2024). Under REDIII, taking land out of food production to produce biofuel feedstocks could be considered equivalent to diverting the food itself (Sandford, Malins et al. 2024). However, there are ways for biofuel crops to be produced with low land use change risk. CORSIA refers to the 'yield increase approach' which includes a variety of practices that can increase the amount of food and/or feedstock produced on a parcel of land (ISCC and CORSIA 2022). Practices may include:

- rotational or intercropping to grow biofuel feedstocks alongside food/feed crops
- improved management which leads to yield gains through soil improvement, pest control, genetic improvements or chemical inputs
- reduced post-harvest losses and waste
- mechanical improvements (e.g. precision farming or improved harvesters that decrease losses)

3.7.2 Co-benefits

Another consideration in the food versus fuel discussion is the potential use of co-products from biofuel feedstocks as animal feed or food products. In many cases, the meal remaining after extraction of oils from oilseeds has value as a high protein animal feed. Canola meal, cottonseed meal and soybean meal are all co-products from the production of oil which are sought after as a high protein feed for livestock (Bernard 2016, Shurson 2017). Spent brewer's grain, which is produced during ethanol production from grains like sorghum is also valorised as animal feed (Stahn, Storandt et al. 2023). This means that a single parcel of land is functioning to produce both biofuel feedstock and food/feed within a single season.

There is also potential for dual purpose or integrated cropping systems that could provide co-benefits in Australian farming systems. For example, dual purpose canola is already being used to provide both forage for animal feed and grain for oil and canola meal production (Kirkegaard, Hocking et al. 1997). Livestock are grazed on the young plant as a source of forage. After several weeks, the animals are removed and the crops are allowed to grow out to maturity, producing grain with similar yields to an ungrazed crop.

Studies around the world have shown the value of narrow or distributed plantings of short rotation trees as shelter belts in both grazing and cropping areas. These trees can act as windbreaks, animal shelter, native habitat, erosion protection and provide carbon sequestration in their roots and stumps. Every 3-10 years, depending on the species and the growing conditions, the branches and leaves are harvested as feedstock and the trees are then allowed to regrow for the next cycle (McGrath, Goss et al. 2017).

3.7.3 Carbon sequestration

The recent assessment of Australia's carbon sequestration potential (Fitch, Battaglia et al. 2022) considers several land uses that could compete with both food and biofuel feedstock production but have important impact on our carbon budget.

Scalable sequestration activities that could require significant amounts of land include permanent environmental tree plantings and shelter belt plantings, plantation and farm forestry, and avoided land clearing.

For permanent plantations alone, the report found potential area of 6.3 Mha for environmental plantings and 41.9 Mha for mallee plantings (Fitch, Battaglia et al. 2022). Plantation and farm forestry represent ~25 Mha (Fitch, Battaglia et al. 2022). However, the opportunity for permanent plantings and forestry were considered independently of each other in this study so these areas may overlap. Much of the area considered suitable overlaps with cropping and grazing lands (**Figure 27**).

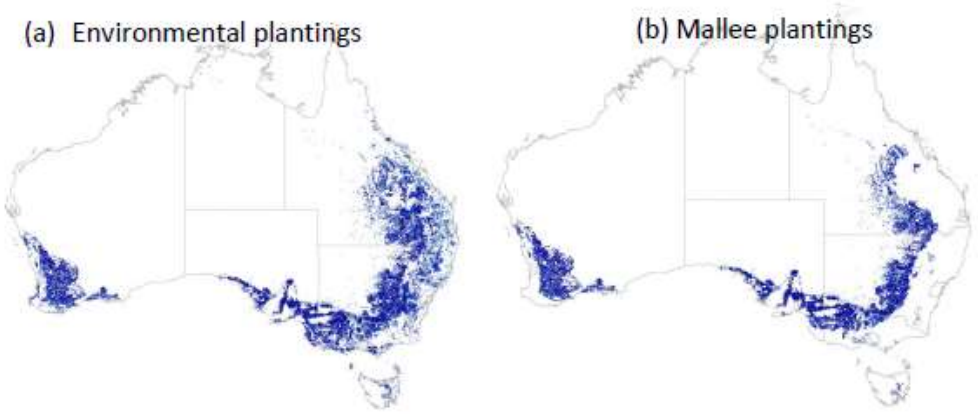


Figure 27: The potential extent of environmental plantings (a) and oil mallee plantings (b) for carbon sequestration. Source: (Fitch, Battaglia et al. 2022).

There are some carbon sequestration methods that have the potential to be integrated into biofuel feedstock production systems. On-farm forestry using short rotation trees are discussed above but there are other methods to enable carbon sequestration within farming landscapes. Enhanced rock weathering is a passive carbon mineralisation technology where rock-based soil amendments are applied to soils used for cropping or pastures to increase soil fertility. As the rocks weather, they release cations that interact with atmospheric CO_2 to form dissolved bicarbonates in soil pore water, which can eventually be precipitated as inorganic carbonate minerals (Beerling, Kantzas et al. 2020). The use of biochar to store carbon and build soil health is also practiced on farms, as is changing farm management practices to build soil carbon (Fitch, Battaglia et al. 2022).

The CSIRO carbon sequestration report states that avoided land clearing, establishment of permanent plantings, human induced forest regeneration, plantation and farm forestry and building soil carbon all have high commercial readiness and lower cost of abatement than the other carbon sequestration methods considered such as pyrolysis-biochar systems, geological storage, and BECCS (Fitch, Battaglia et al. 2022) (see **Figure 28**).

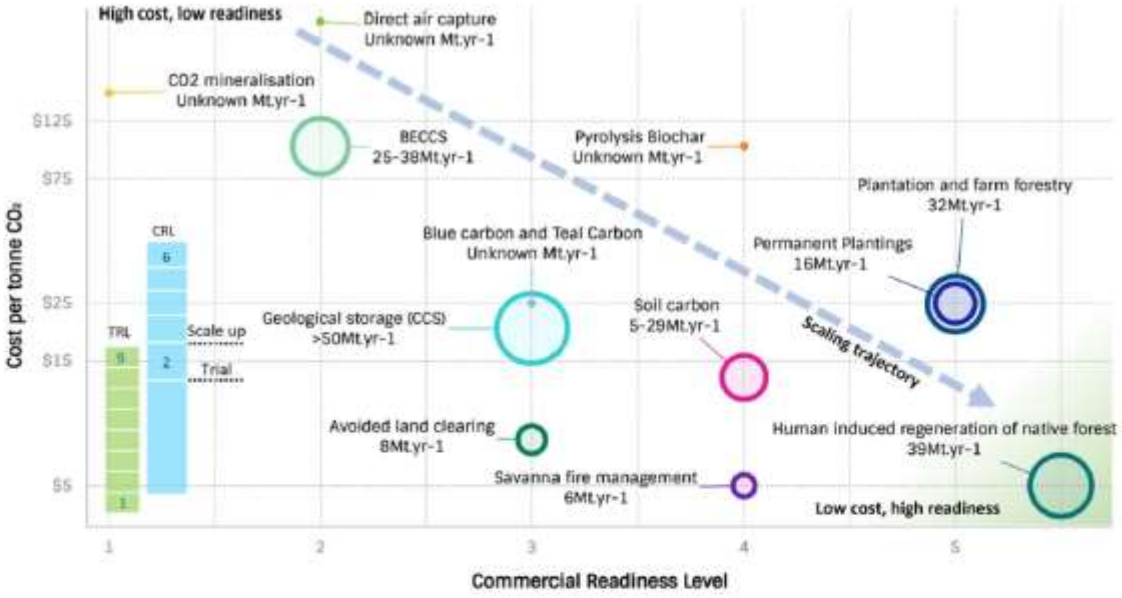


Figure 28: Carbon sequestration methods, their commercial readiness levels and associated cost per tonne carbon dioxide sequestered Source: (Fitch, Battaglia et al. 2022).

3.7.4 Renewable energy – solar and wind

Recent expansion in the area of agricultural land devoted to solar and wind energy projects has raised some concerns in the community (Davis 2019). Some argue that the extent of land use change for renewable energy developments is small relative to the total extent of agricultural land use in Australia (Blakers 2024). However, the need to site utility scale solar and wind developments near transmission lines means that they tend to coincide with prime agricultural land in Australia (Prasad, Taylor and Kay 2017).

A recent study from Canada explores the competition for land between solar installations and bioenergy crops (Calvert and Mabee 2015). They found that solar and bioenergy tend to compete for marginal and degraded lands that are not highly valued for other uses. They also proposed a methodology for establishing mutual land use for both solar and bioenergy production.

Integration of solar installations with biofuel feedstock production through agrivoltaics could be a beneficial dual use of these lands (Trommsdorff, Gruber et al. 2020).

4 Methodology for regional opportunity assessment

Australian regions stand to benefit from an LCLF industry, and targeted interventions can maximise this value. Project-level assessment helps in understanding the specific mix of value and benefits for a given region. However, a general methodology provides a guide for assessing benefits, identifying risks, aligning with local community values and strategic planning to maximise and deliver value to all stakeholders.

While a national biomass assessment is valuable for guiding the development of an LCLF industry and associated technology, a much more detailed assessment must be carried out for an investment case into specific developments. This would help to determine the current availability of regional biomass, and the potential for increased production in the future. Such higher-resolution assessments can also yield insights into the barriers to increasing yield, infrastructure gaps, economic impacts including for the community and more.

CSIRO has previously developed an approach to estimating supply cost curves for a mix of biomass feedstocks and bioenergy technologies at national, regional and project scale. This modelling methodology uses a biophysical constraint on biomass supply and implicit spatial dependencies and trade-offs combined with economic analysis to establish upper and lower cost boundaries.

Using this modelling approach, the economics and commercial viability of bioenergy projects can be more precisely estimated, considering biomass availability, reliability and concentration.

The model has been applied to agricultural residues across Australia and found that all but 10-25% of available biomass is accessible within 25% of minimum cost.

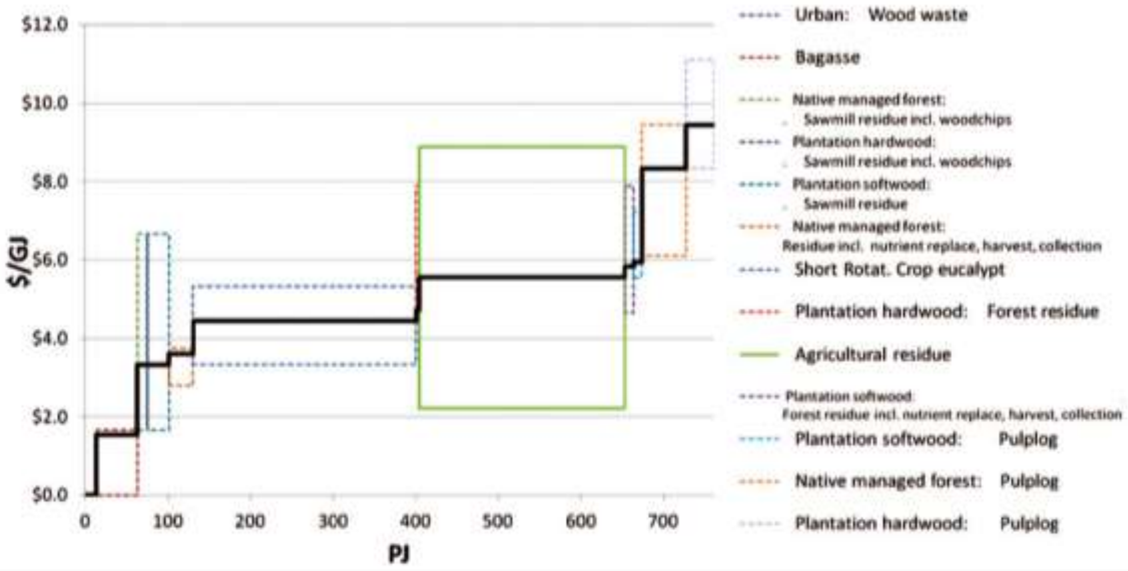
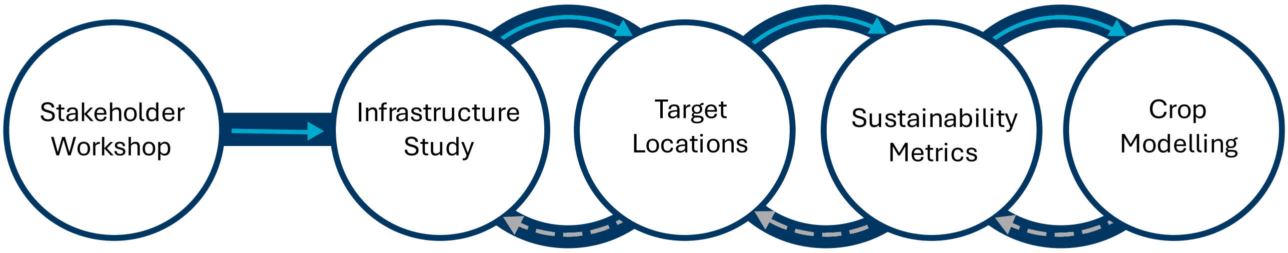


Figure 29: National cost curve for lignocellulosic biomass
Source: Brinsmead et al. 2015

To add to this approach, a generalised framework for regional opportunity assessment that accounts for factors extrinsic to economic considerations, including infrastructure requirements, sustainability issues, regional community values and future production changes, has been developed and is being tested through collaborative projects with industry (see **Figure 30**).

This approach includes community co-development that is critical to identify risks to the viability of a bioenergy project, combined with sustainability assessments and modelling to understand the potential feedstock supply response.



- Identify and convene critical value chain and community stakeholders in appropriate workshops
- Reveal value settings to understand hidden drivers and barriers to action
- Identify risks to necessary actions beyond the direct control of the project and actions to align values and reduce risk to coordinated action

- Map existing infrastructure – particularly for transport (roads, rail, shipping) but also biomass processing including oilseed crushers, pelletisers etc.
- Identify gaps in infrastructure required for processing of the breadth of potential biomass

- Based on transport corridors identify areas of potentially cost-effective biomass production and collection to processing and refining centres
- Model costs for transport of raw and densified biomass and draw boundaries for target regions based on increasing cost, and corresponding value of biomass type.

- Evaluate supply chain sustainability metrics (like water demand, carbon intensity, land use changes etc.)
- Understand carbon emissions calculations for primary producers
- Evaluate Induced Land Use Change impacts
- Compare frameworks like GREET, CORSIA and ReFuelEU

- Analyse changes in supply of existing and new (alternative) crops
- Analyse changes in cultivated area and potential to increase productivity
- Calculate cost of feedstock, including opportunity costs associated with alternative crops, ensuring revenue includes cost of emissions abatement

Figure 30: Methodology developed for regional opportunity assessment
Source: CSIRO, Towards Net Zero 2024

Stakeholder workshop – participatory co-development

A key feature of the transition to Net Zero emissions, and particularly, the development of a LCLF industry, is the shift from a relatively simple, linear model of oil supply-to-refining to a complex, cross-sectoral, multi-stakeholder value chain spanning across biomass producers (i.e. farmers), aggregators and processors, refineries with new bioenergy processing technologies, in addition to sustainability life cycle assessments and substantiation.

In this scenario, biorefineries – either as new capacity in existing oil refineries or as new purpose-built projects – are heavily dependent on a reliable supply of biomass within the specifications of the processing plant and at a cost threshold that ensures financial viability. As with any industrial facility, biorefineries require a minimum operational capacity, or up-time to be financially viable. Considering the cost of transporting biomass, a biorefinery is critically dependent on producers in a relatively limited growing region.

In comparison to traditional refinery business models that have access to global crude oil trade, a biorefinery is much more intimately dependent on farmers. Farmer practices reflect regional community values – while contracts can be established for biomass supply, these are typically not long-term contracts, and the seasonal variability of growing conditions limits the ability of farmers to fulfill contracted supply. This makes reliable and secure contract terms more complex and agricultural business models. Contracting arrangements may be significantly different to those currently used by refineries and involve third parties such as feedstock aggregators, processors and logistic providers. In addition, individual farmers have control of the farming practices employed to grow their crops. It may be necessary for refiners to negotiate or contract the desired management practices to meet required carbon intensities, ILUC factors and biodiversity outcomes of biomass feedstocks.

This dependency on coordinated action among upstream suppliers who are largely beyond the influence of a refinery creates a real, business-critical risk to biorefinery business models. A refinery may be making an investment of hundreds of millions of dollars in new biomass processing capacity, and this value chain counter-party risk may often prohibit access to capital investment or render a project unviable if the regional community support is lost.

Considering this, a bioenergy value chain greatly depends on more than social license – it requires a sustained alignment with regional community values. Therefore, in the proposed regional assessment methodology above, CSIRO has included an important phase of participatory co-development, represented by stakeholder workshops.

Infrastructure study

Infrastructure for economic harvesting, aggregation, transport and pre-processing of biomass into feedstock is essential for an efficient, cost-effective bioenergy industry. Infrastructure requirements vary depending on feedstock type. While roads, rail, shipping and pipelines are essential for transportation, the oilseeds require crushers and oil extractors, woody biomass may require chippers, pelletisers, steam explosion or other methods of pre-processing, and sugarcane requires small gauge rail for transport to shredders and mills. These infrastructure elements must be strategically located for lowest cost and maximum capacity to densify biomass to be cost-effective for longer-distance transport to centralised refining facilities.

In a comprehensive approach to regional assessment, an infrastructure study stage is included to map available infrastructure and identify gaps. This requires, first the identification of a potential economically harvestable region, then an assessment of the range of biomass available through existing and changed farming practices, followed by mapping existing infrastructure and identifying gaps for strategic location of new infrastructure to make use of future feedstock volumes.

In more established value chains, like grains or livestock industries, the role of logistics, aggregation and pre-processing, is often undertaken by a third party independently of the producer or processor. For example, GrainCorp, CBH and Cargill provide logistics, aggregation and pre-processing for the grains industry. The availability or interest of logistics providers in the selected regions should be considered in the infrastructure assessment.

Once transport and processing infrastructure has been mapped and the gaps identified, detailed assessment of locations within the growing region can be carried out.

Target locations

Once a first-pass regional identification, coupled with an overlying infrastructure scan, is completed, more targeted locations can be narrowed down for biomass production. The primary goal of this sequence is to identify not only the current production and available biomass, but future production potential in the target regions and then modelling new crop rotations and yield increases that can be realised through changed farming practices.

Once specific locations are identified, crop rotations can be modelled more precisely, with realistic, commercially relevant and implementable results. This includes more reliable projected costs for harvesting, processing and transport.

Sustainability metrics

Quantifying sustainability-related measures for different feedstock-processing combinations is critical to ensure access to LCLF markets. LCLFs incur a cost penalty and rely on a ‘green premium’ to be competitive. In most markets, this green premium is dependent on substantiating climate impacts, and other sustainability impacts such as water intensity, natural capital, induced land use change and other aspects.

While generalised feedstock-technology combinations can be modelled and established as accepted pathways, a location-specific quantification of sustainability impacts is required to underpin the business case for regional bioenergy projects.

Quantification of sustainability metrics is accomplished by a combination of direct measurements and modelling using location-specific, regional and national measures.

It is critical to ensure that the selected sustainability metrics and indicators used to assess a project/region align with relevant international frameworks for the desired end market for the biofuel product. At present, there is a proliferation of different monitoring, reporting and verification (MRV) tools for different international frameworks. SAF is generally assessed according to CORSIA rules and locally produced SAF will need to meet the international regulations as it is not possible to segregate domestic and international supply chains. All biofuels uploaded at an airport must meet both domestic and international sustainability standards. Renewable diesel is more complex because it may be possible to segregate a domestic supply and/or to export to specific regional markets. This means that feedstocks for renewable diesel or biodiesel may be assessed under a range of different international frameworks. CSIRO completed a report assessing the GHG footprint of canola with a view to meeting the requirements of the EU Renewable Energy Directive II regulations (Eady 2017).

Similar sustainability assessments may be required for different feedstocks and different target markets, with due care taken when selecting the tools for modelling, measurement and verification to ensure that they meet the relevant regulatory requirements.

Crop modelling

While historic and existing biomass supply data for target regions is readily accessible, biomass production is elastic and responds to factors like market demand, inter-seasonal variability, long-term climate change, farming practice changes and capital investment. Highly specific modelling can be carried out to understand the potential volume and type of biomass supply, and the likely future production.

CSIRO has been instrumental in developing the APSIM crop modelling tool which is now used around the world. APSIM takes account of soil conditions, climate conditions, crop types and rotations to produce actionable data to inform farming strategies. The potential yield and impact of switching from one crop type to another can be accurately predicted, including the introduction of new rotational or cover crops.

The impact of changing farming practices is substantial. It is estimated that over 35% increased yield can be achieved in some systems, while increasing food production rather than negative impact. This will be critical as ILUC considerations become more important in end-use markets.

Conclusion

The use of an economic approach to identify lowest cost locations and feedstock technology combinations is critical to the success of early bioenergy projects. Equally critical to the ongoing viability of these projects is an assessment of the extrinsic factors including alignment with regional values, common use infrastructure, sustainability metrics and predicting the potential biomass production response. By combining both approaches, a more actionable, granular comparison between candidate regions can be established, along with the potential distribution of new value to regional communities. A holistic framework is under development that can more effectively assess the viability and value of regional bioenergy projects.

5 Latest trends in Australian conditions

End use demand for LCLFs is growing in line with industry commitments and evidenced in procurement today. Much has changed since the last coordinated effort to develop an Australian industry about 10-15 years ago. New technologies can produce high-quality drop in fuels acceptable to users and manufacturers at up to 100%. Costs have fallen by more than 50%. New pathways enable an industry to build co-benefits including for food production, biodiversity, resilience and regional economic value. Maximising the abatement from an LCLF industry will depend much more on developing a full range of feedstocks and commercial avenues to market than they will on prioritising one end-use sector over another.

Previous investments have been made to establish an LCLF industry in Australia, including ethanol mandates for light road transport and notable investment into R&D between 2010 and 2015. These were made in the absence of an overarching supportive investment climate, lacking nationally coherent policy, and uncertain international and national industry commitments. Today, a lot has changed – at the national and international levels, as articulated policies, goals and commitments, and industry action are emerging at a rapid pace.

Some notable developments for industrial LCLF demand are summarised in **Figure 31**. Large users of liquid fuels have made commitments to reduce their Scope 1 and 2 emissions, and in many cases, specifically towards the purchase of LCLFs.

Mining

Diesel is a major source of energy and emissions for the mining industry, and one of the first targets for decarbonising their operations. Around 42% of BHP's operational emissions are attributable to fuel and distillate – mostly diesel (BHP Sustainability Report 2019). While some functions on mine sites can be electrified, and companies are making significant investments in this space, significant demand for drop-in fuels is likely to remain because of functions that are difficult to electrify and the long lifecycle of mining fleets. Rio Tinto has converted its entire US Borax operation in California to use renewable diesel instead of fossil diesel in May 2023, saving up to 45,000 tonnes of CO_2-e emissions per year, and has begun converting the Kennecott mining operation in Utah which will save approximately 495,000 tonnes per year. As discussed in Section 8, the US and in particular, California has strong incentives for converting to LCLFs. These investments demonstrate the readiness for large mining companies to switch to renewable diesel if barriers to its adoption can be addressed.

Shipping

The shipping industry is another major buyer of liquid fuels – both heavy fuel oil and diesel. As an international sector, the industry is exposed to trends in regions around the world and varying standards across jurisdictions supply chains delivering fuel and infrastructure needs.

The International Maritime Organisation (IMO) is the global governing body for establishing standards in the industry – a specialized agency under the UN established in 1948 with 176

Member States. The IMO agrees on treaties which are implemented into national laws enforceable for ships flying under national flags.

The IMO has been developing a comprehensive approach to net GHG emission reduction together with Member States with the common ambition to reach net zero from international shipping by or around 2050. This includes a new GHG Strategy to reduce carbon intensity by 40% by 2030, supported by an enforceable commitment to purchase 5% (striving to 10%) of emissions reduction measures including LCLFs (BloombergNEF 2019).

The new IMO GHG Strategy was adopted in July 2023 including provisions for the goal-based marine fuel standard regulating the phased reduction of marine fuel GHG intensity plus an economic mechanism to incentivise the transition to net zero emissions. These mechanisms are currently the focus of discussions at international IMO meetings with a decision due in the Northern Autumn of 2024 and expected to take effect in 2025.

Marine fuel demand worldwide is around 5 million barrels per day (BloombergNEF 2019, IEA 2019), and in Australia, in the 12 months to April 2024, 863ML of fuel oil (approx. 5.3 million barrels/year) was sold (DCCEEW 2024). Marine transport is projected to transition to a focus on diesel as well as potentially methanol or ammonia, or other emerging fuels under consideration (US DOE Bioenergy Technologies Office 2024).

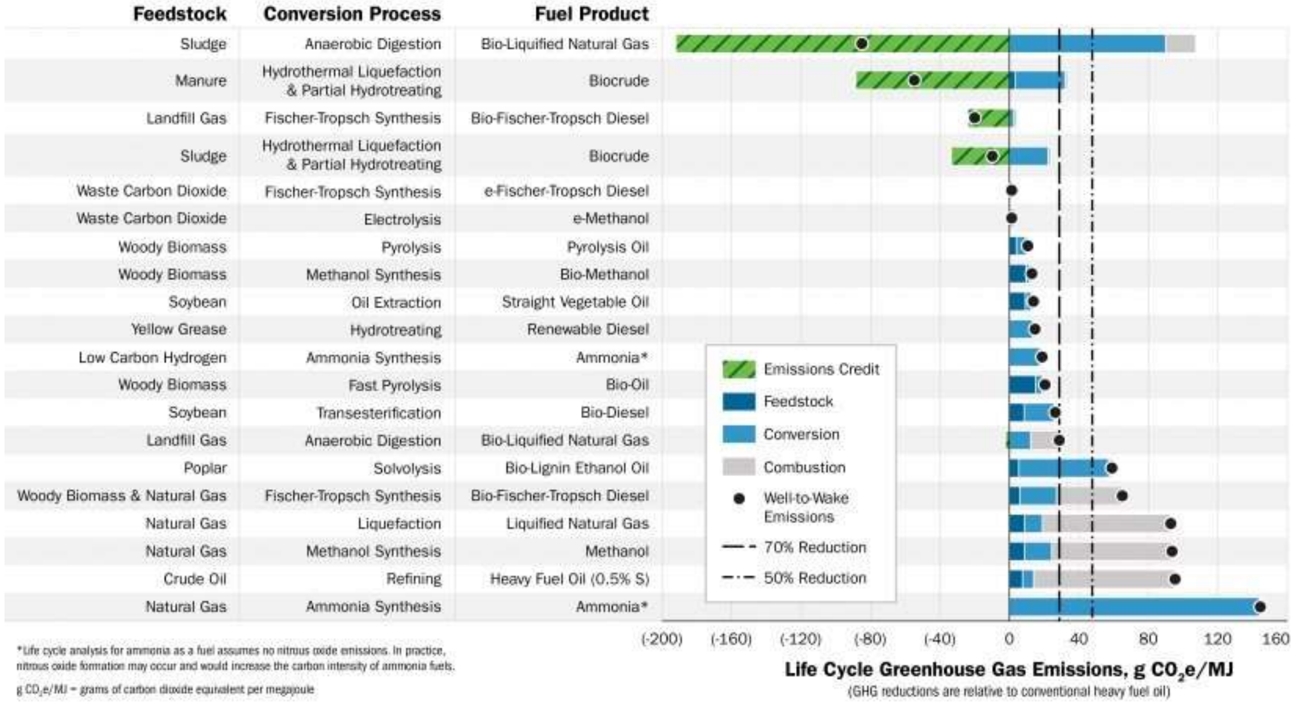
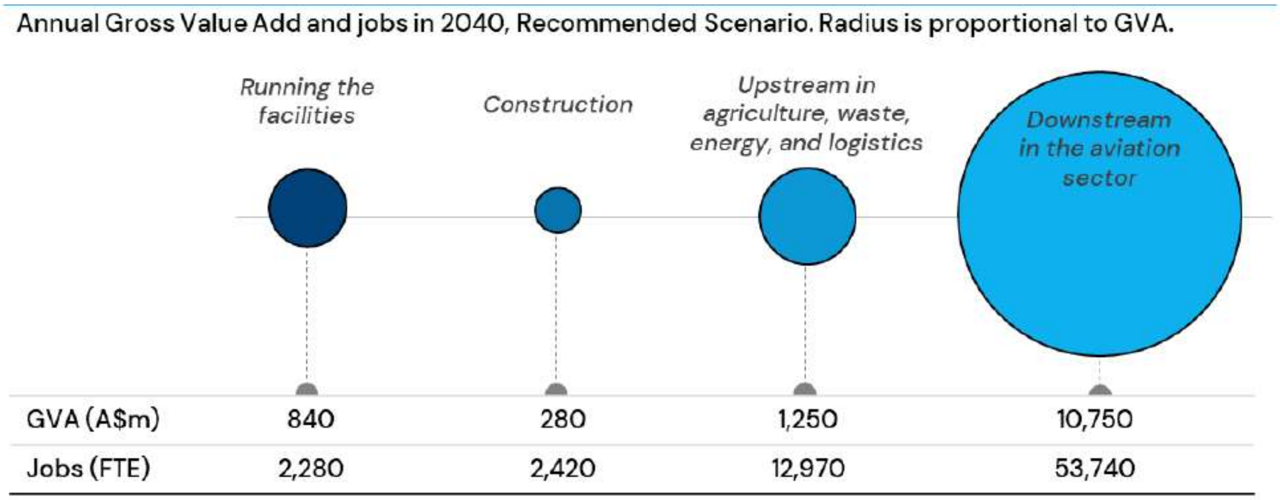


Figure 31: Major feedstocks, conversion processes and end fuel product, and their corresponding lifecycle GHG emissions.
Source: https://www.energy.gov/eere/bioenergy/sustainable-marine-fuels

Aviation

There is intense growing international interest in the development of sustainable aviation fuels (SAF). Globally, airlines are ensuring their ability to transition to new fuels in anticipation of strengthening regulations. There are few alternatives for addressing the climate impact of aviation – particularly for long-haul flights. More discussion on aviation fuel regulations appears in Section 8. Around 9GL of aviation fuel was sold in Australia in the 12 months to April 2024, resulting in approximately 5.8Mt of CO_2 emissions, still lower from a high of 9.5GL in 2018.

The recently published CSIRO-Boeing Sustainable Aviation Fuel Roadmap found that a local SAF industry could be an important driver for development of sovereign capacity for fuel production, which may be increasingly important for fuel security issues, along with contributing towards climate goals and delivering economic opportunities. A subsequent report from ICF sponsored by Qantas and Airbus found that a domestic SAF industry can deliver around $13b per year in new value, including direct employment of over 2 thousand jobs in refineries, construction and upstream logistics in regional Australia, and over 10 thousand downstream jobs in the aviation sector (see **Figure 32**).



	Running the facilities	Construction	Upstream in agriculture, waste, energy, and logistics	Downstream in the aviation sector
GVA (A$m)	840	280	1,250	10,750
Jobs (FTE)	2,280	2,420	12,970	53,740

Figure 32: Gross value addition and creation of new jobs in 2040
Source: ICF-Qantas Developing a SAF industry to decarbonise Australian Aviation, Nov 2023

Demand for SAF is growing and is likely to persist (**Figure 33**). Qantas announced a commitment to purchase SAF equivalent to 10% of its overall fuel mix by 2030, and 60% by 2050. Other international airlines have similar commitments, along with other jurisdictions like Europe, and more recently Singapore has mandated SAF blending on all flights beginning with 1% in 2026 and rising to 3-5% by 2030. In Australia, the establishment of the Jet Zero Council and the recent inclusion of LCLFs in the federal budget signal a higher commitment to SAF as part of the national decarbonisation plan.

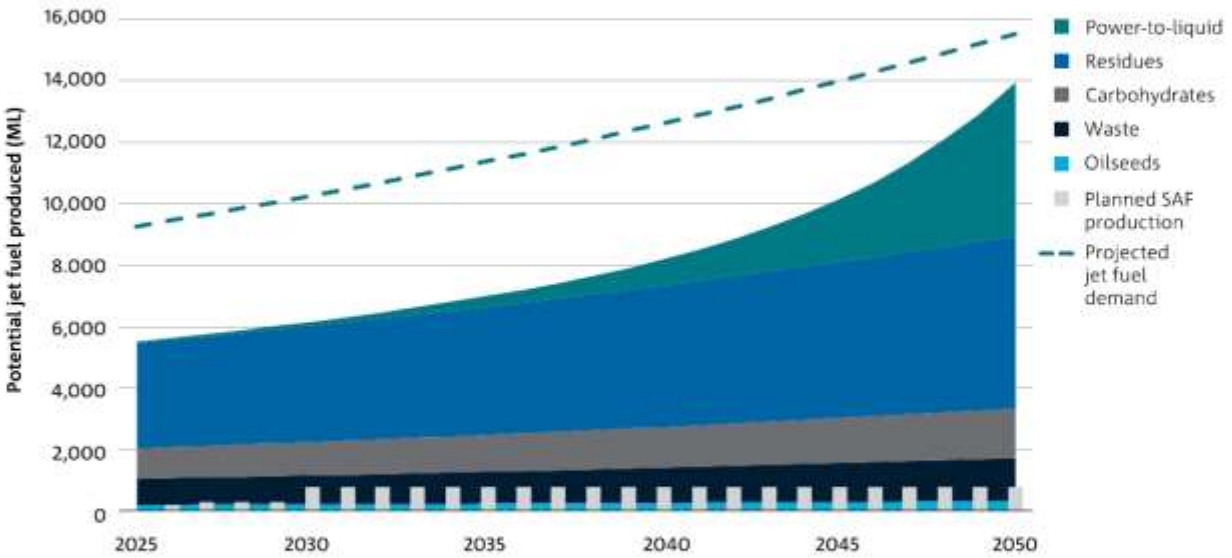
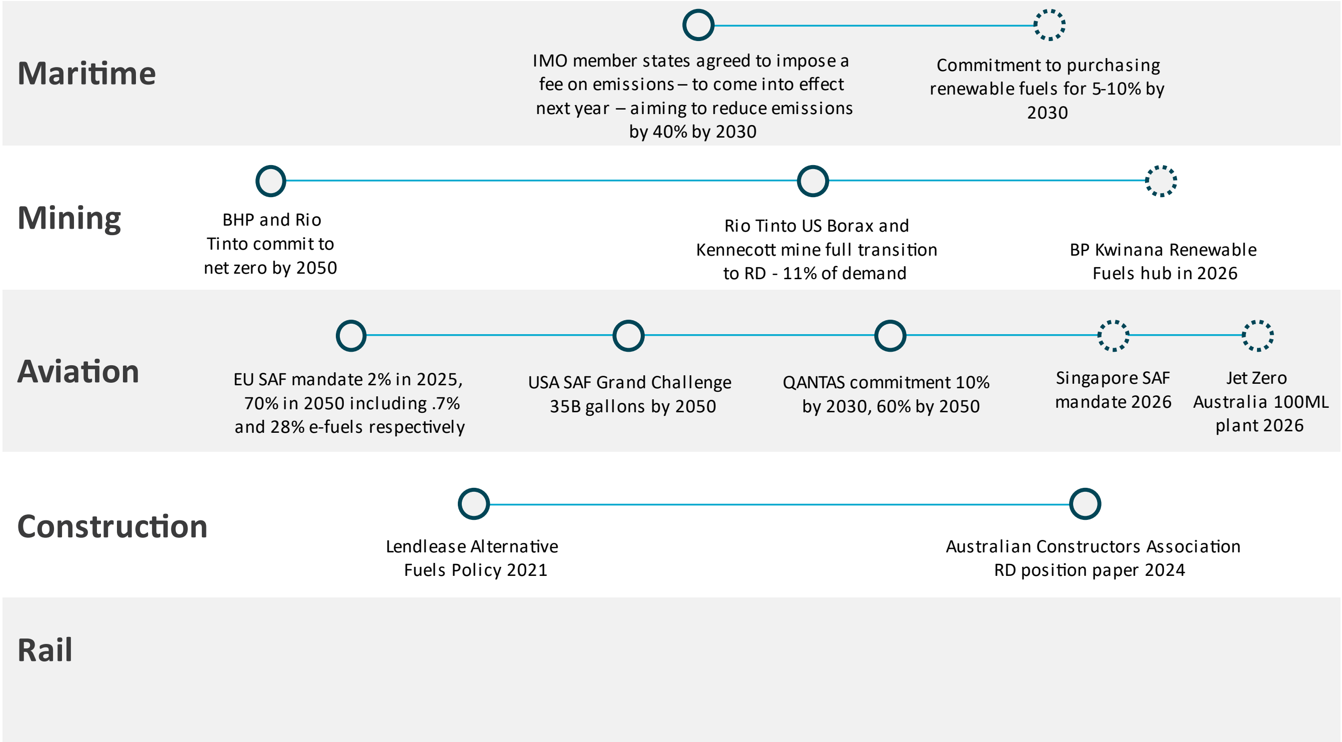


Figure 33: Projected jet fuel demand and production from different feedstocks in Australia, up to 2050
Source: CSIRO-Boeing SAF Roadmap 2023



Maritime

IMO member states agreed to impose a fee on emissions – to come into effect next year – aiming to reduce emissions by 40% by 2030

Commitment to purchasing renewable fuels for 5-10% by 2030

Mining

BHP and Rio Tinto commit to net zero by 2050

Rio Tinto US Borax and Kennecott mine full transition to RD - 11% of demand

BP Kwinana Renewable Fuels hub in 2026

Aviation

EU SAF mandate 2% in 2025, 70% in 2050 including .7% and 28% e-fuels respectively

USA SAF Grand Challenge 35B gallons by 2050

QANTAS commitment 10% by 2030, 60% by 2050

Singapore SAF mandate 2026

Jet Zero Australia 100ML plant 2026

Construction

Lendlease Alternative Fuels Policy 2021

Australian Constructors Association RD position paper 2024

Rail

Figure 34: Timeline of key developments on decarbonisation goals and commitments by transport sub-sectors in Australia
Source: CSIRO, Towards Net Zero 2024

Supply costs

While in previous sections, this report has reviewed biomass availability and emerging sources, the past ten years have also seen new technologies for conversion of biomass to fuels, and consistent cost reductions in technologies appropriate for Australian conditions.

The preceding sections of this report have described the abundance of high biodiversity value, low-input biomass feedstock available in Australia for conversion to LCLF, and the co-benefits that these feedstocks can provide to our ecosystems, farmers and regional communities. Three case studies have been provided which illustrate the range of opportunities, and how projects must be assessed and developed on a case-by-case basis. A generalised methodology for assessing region-specific projects is included, along with options for ensuring alignment with regional community values to ensure project deployment can be accelerated.

Developing specific projects will depend on the availability of cost-effective energy technologies, or conversion processes, to convert biomass into fuel refining feedstock. The conversion processes are a critical step and a key cost driver for all bioenergy projects.

Over the past decade, a wide variety of conversion technologies have progressed in their development to the point where they might be demonstrated for commercial deployment. For example the diagram below from IATA (see **Figure 35**) illustrates the technologies assessed and approved for use as aviation fuel (IATA 2023). In 2012, only two conversion processes were approved, limiting the potential to capitalise on Australian feedstocks.

Figure 35: Timeline of evolution of approved technologies for aviation fuel production
Source: IATA Fact Sheet 2, Sustainable Aviation Fuel: Technical Certification

Today, there are 11 ASTM-approved technology routes for aviation fuel production. There are a number of other technologies for converting feedstocks to other fuel products. Some of these are particularly relevant for Australian conditions and feedstocks. One such example is fast pyrolysis. While the cost of anaerobic digestion is relatively insensitive to scale, and gasification technologies tend to decrease in cost dramatically with scale (see **Figure 36**), developments in pyrolysis technologies have driven costs down for small-scale facilities.

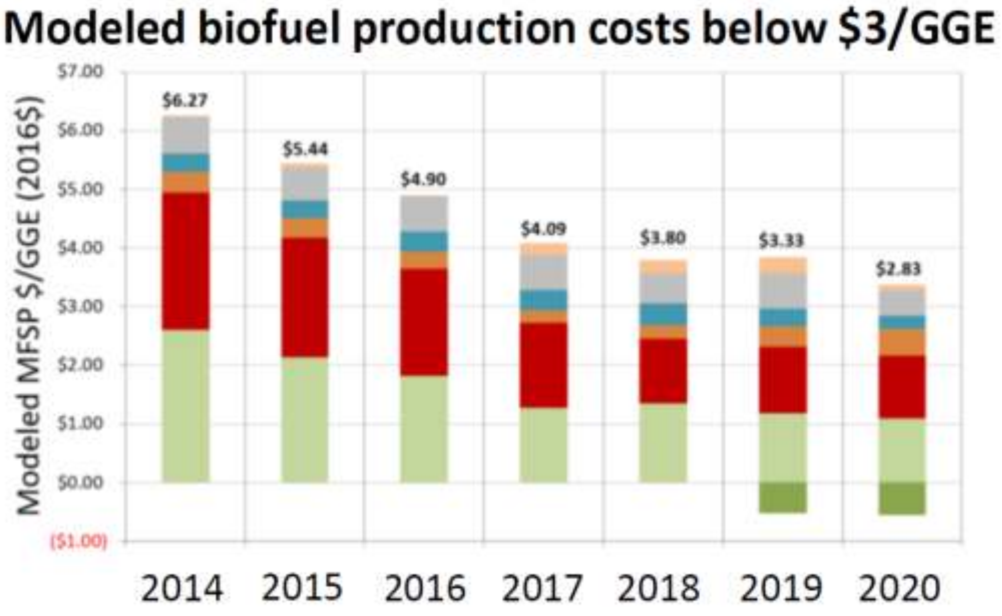


Figure 36: Example of modelled biofuel production costs, decreasing over time with improvements in costs and technical efficiencies
Source: https://www.nrel.gov/docs/fy19osti/71954.pdf

The example above meets the requirements of the Fitzroy catchment case study introduced in Section 3. Techno-economic analysis carried out as part of that project in 2014 projected biomass-based jet fuel from such a project is viable at a price of $1.10/L biocrude and a jet fuel price of $1.50/L.

Cost reductions since 2014 have been experimentally validated as illustrated in **Figure 36**. Further technical barriers have also been addressed. Due to the highly dispersed nature of Australian lignocellulosic biomass, this project concept depends on distributed pre-processing using small-scale pyrolysis and transport of stabilised bio-oils to a central refinery. The US DOE demonstration for this technology has successfully stabilised bio-oil suitable for long-distance transport, and efficiency of conversion necessary for cost-effective small-scale operation.

Further demonstration of technologies necessary to exploit Australia's large, distributed low-input lignocellulosic biomass can unlock large-scale expansion of the bioenergy industry. Furthermore, lignocellulosic feeds offer intrinsic advantages as these are more difficult to export internationally, and hence, are less exposed to competition from highly subsidised markets as compared with canola and waste.

6 The LCLF opportunity for Australia

Market analysis and international experience strongly indicates the need for both demand-side and supply-side measures to capture the full opportunity of LCLFs for Australia. This should include direct support to demonstrate investable processes to utilise Australia's abundant second and third generation resources of low emissions lignocellulosic feedstocks, which are further down the commercialization pathway than first generation oil and carbohydrate feedstocks.

International commitments present a sustained, long-term opportunity for a competitive Australian synthetic fuel industry, but this will require development of an LCLF market here first.

Drop-in replacements for hydrocarbon fuels are an essential component of a transition pathway to net zero. For hard-to-abate sectors such as long distance, heavy road and rail, maritime and aviation transportation, these fuels are indispensable in the short to medium term. Transport currently represents around 20% of Australia's national emissions and its share is growing, as other sectors decarbonise more rapidly. Developing alternatives for fossil liquid fuel emissions will be critical to meeting Australia's climate targets as part of an economy-wide approach.

LCLFs from domestic biomass and waste sources have the potential to reduce emissions by up to 12%, eliminating almost 4Mtpa of CO_2-e emissions from the transport sector while establishing new value chains that deliver returns to and drive investment in rural and regional Australia. Longer term transition utilising the growing green hydrogen industry with biogenic or fully synthetic fuels through Power-and-Biomass-to-Liquids or Power-to-Liquids (PBtL or PtL) can achieve higher emissions reductions, up to 100% over time.

Transitioning the Australian liquid fuels sector through biogenic fuels, and ultimately blending in synthetic fuels, is critical to Australia meeting its Paris Agreement commitments, but will also enhance domestic fuel security in the context of geopolitical issues, and can support Australia's Renewable Energy Superpower vision for long term prosperity based on the country's international competitive advantages in abundant renewable energy, land, water and biomass resources, and strategic location.

To capture this opportunity an investment environment for LCLFs must be carefully considered. Numerous major investors are planning investment in new LCLF assets, but uncertainties related to feedstock production and cost contribute risk which may cause significant delays, or even prove to be prohibitive, if not addressed. Three primary insights have been identified through modelling performed with Deloitte:

1) The gap between industry's willingness to pay and feedstock costs must be overcome to mobilise private finance for a bioenergy industry.
2) Feedstock markets will respond to demand, but economic and environmental outcomes likely depend on bridging the fuel production cost gap through both demand-side and supply-side measures.
3) Fuel producers need to transition to biofuels to decarbonise, but favourable policy settings are required to stimulate early investment decisions.

6.1 Comparison of LCLF end markets

Sustainable Aviation Fuel

National and industry commitments around the world are creating reliable demand for SAF. In the US, SAF consumption grew by 300% between 2021 and 2022, driven largely by the Low Carbon Fuel Standard on top of federal incentives and the SAF Grand Challenge of 50% reduction in GHG emissions and 100% SAF by 2050.

As discussed earlier, all liquid fuel end users in Australia are signalling their demand for lower-emissions fuels, with many making binding commitments to procurement of significant volumes. Aviation in Australia is one of the biggest markets for fuel, consuming over 7.7 billion litres averaged over the last 5 years (Deloitte 2023).

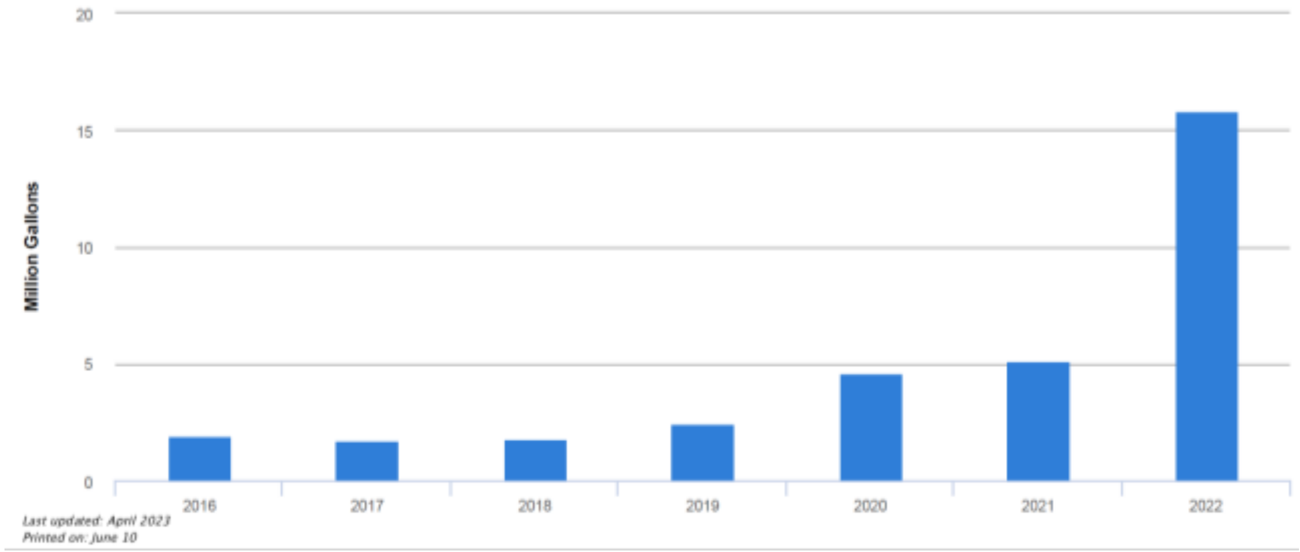


Figure 37: Estimated consumption of Sustainable Aviation Fuel up to 2022
Source: Alternative Fuels Data Centre, US Department of Energy (https://afdc.energy.gov/data)

Qantas Airways, a major Australian air carrier, has committed 10% of its fuel procurement to come from sustainable sources by 2030, and 60% by 2050 (Qantas Group Climate Action Plan 2022). While demand for SAF is growing both in volume and binding commitment, the supply-side risks constrain investment in necessary infrastructure to grow, harvest, collect and process biomass into SAF. Significant capital investment is required to build the refinery infrastructure for a SAF industry, which relies on de-risking the upstream supply chain.

Renewable Diesel

Diesel is the biggest single energy source in Australia – surpassing electricity in the past decade.

Australia's diesel consumption has continued to grow consistently over the past two decades – a contrast with petrol consumption which has trended consistently downwards. Driven by off-road/off grid applications (mining and stationary energy), long-distance road, freight and marine applications, diesel consumption has risen from around 20 billion litres in 2009 to over 32 billion litres in 2023.

Diesel is also a critical energy source for Australia's neighbours – with Pacific Island economies depending on high-cost imported diesel for both transport and stationary energy with fewer options available for load-balancing power.

6.2 The emissions abatement opportunity

Liquid fuels represent around 25% of Australia's emissions. Diesel alone represents 86 Mtpa CO_2-e emissions or 20% of national emissions, compared with 144Mtpa CO_2-e from electricity sector emissions. Biomass feedstocks can produce a wide range of fuels. The opportunities arising from emissions abatement potentials of different feedstocks is much greater, significant and decisive in charting Australia's progress to net zero, than the potential between different sectors. A more significant barrier to realising abatement from different sectors is the speed to market rather than emissions intensity.

Most modern biomass-to-energy conversion technologies produce a range of renewable hydrocarbon products suitable for all end-use sectors. Conversion technologies like FT, ATJ, HEFA and Pyrolysis to bio-oils have the capacity to produce not just aviation fuel but a full range including renewable diesel and naphtha (see **Figure 38**).

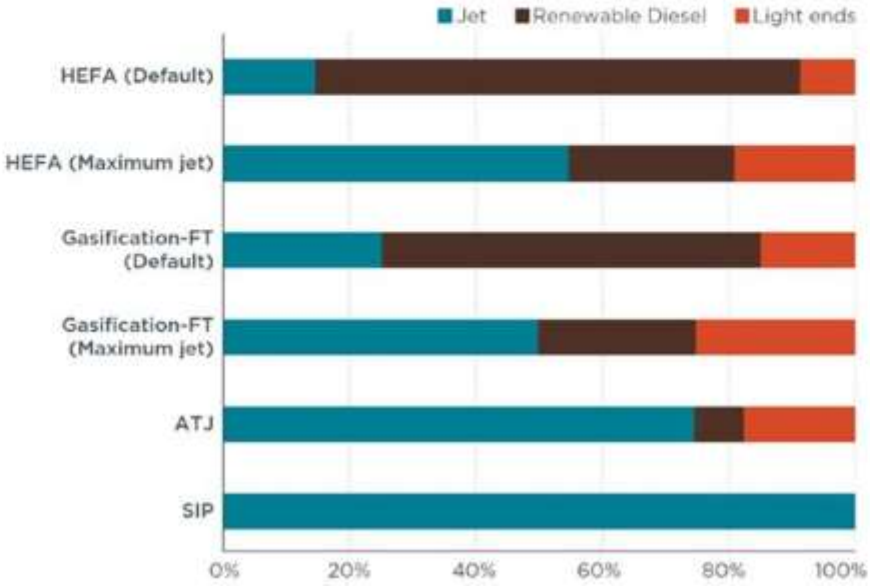


Figure 38: Estimated share of LCLFs produced through different conversion processes
Source: NREL analysis, 2022 (https://www.nrel.gov/docs/fy23osti/83755.pdf)

The emissions savings for converting from fossil jet to SAF as compared to fossil diesel to RD are minimal when compared with the difference in abatement between feedstocks and technologies (see **Figures 39** and **40**). For example, the ICF-Qantas report modelled life cycle emissions from HEFA from soybean (41.51 gCO_2e/MJ), sugarcane ATJ (29.11 gCO_2e/MJ) and wood waste FT (8.06 gCO_2e/MJ) – a variance of +/- 70%. (Mu, Haris et al. 2022)(Mu et al, BCG, 2023).

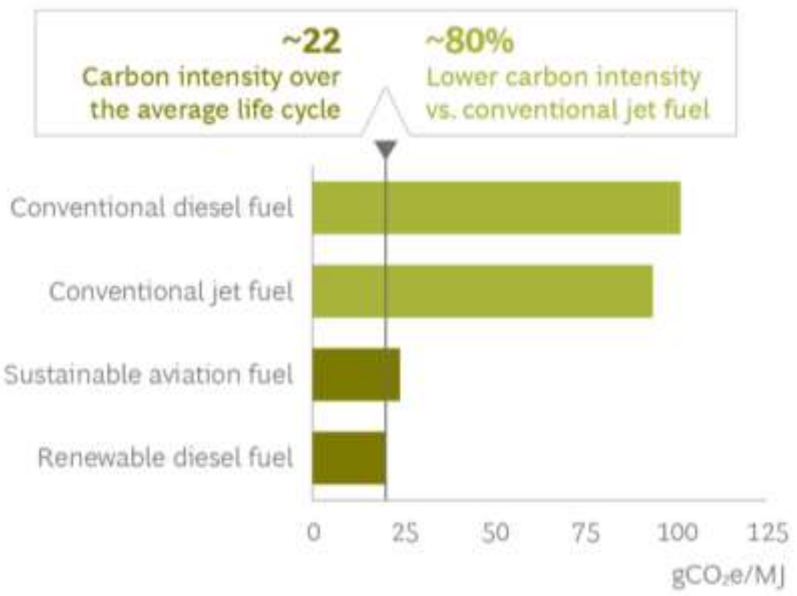


Figure 39: Comparison of average lifecycle carbon emission intensities of conventional liquid fuels and LCLFs Source: (Mu, Haris et al. 2022), BCG analysis (https://www.bcg.com/publications/2022/what-it-will-take-to-reap-the-rewards-of-renewable-fuels)

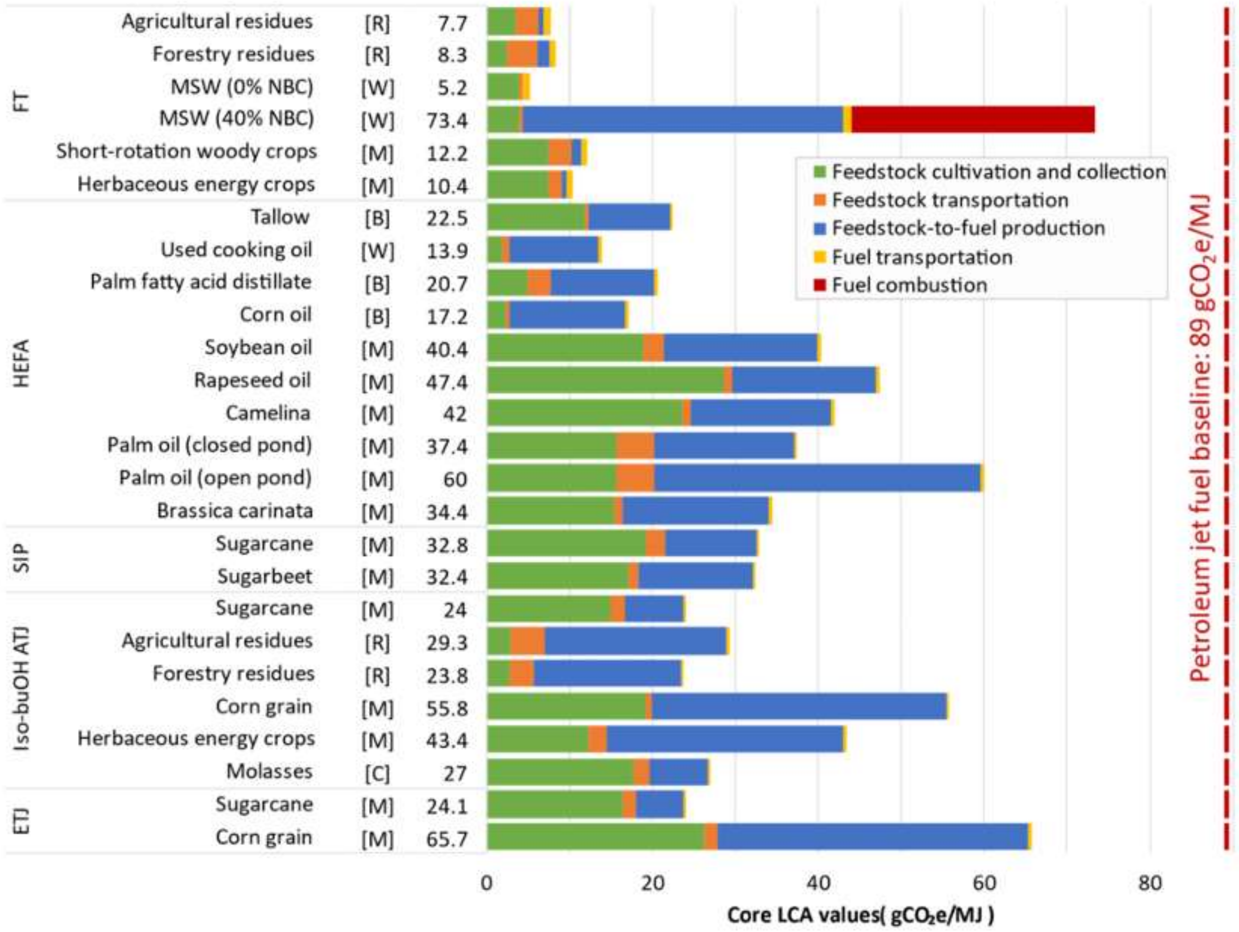


Figure 40: LCA values of biofuels associated with different value chain stages up to fuel combustion, vis-a-vis petroleum jet fuel
Source: (Prussi, Lee et al. 2021) (https://doi.org/10.1016/j.rser.2021.111398)

The CSIRO-Boeing SAF roadmap modelling projects emissions savings of between approximately 20% (Canola-HEFA) up to 90% (forestry and agricultural residues-FT) for SAF. If this is applied across fuel products, up to the 8 billion litres of fuel potential, this would result in an ultimate emissions abatement of between 5-25Mt CO_2-e from a LCLFs industry. Capturing the greatest abatement from this opportunity relies on developing pathways to utilise the highest potential feedstock regardless of end use sector.

Carbon intensity of all pathways can be further reduced through the incorporation of green hydrogen. This presents an additional opportunity to use the emerging biofuel industry as a market for green hydrogen, spurring its development and building capacity for a future power-to-liquids synthetic fuel industry, which can potentially grow to an export opportunity based on Australia’s natural competitive advantages in abundant renewable resources.

6.3 Renewable Energy Superpower vision

Australia has major natural advantages in a future net zero global economy leading to a competitive advantage and opportunity to create new industries supplying our renewable energy in value-added products to markets around the world.

These low carbon products include LCLFs – Australia has all the ingredients for production of large export volumes of synthetic renewable fuels produced from the combination of Direct Air Captured (DAC) carbon and green hydrogen. Power-to-liquid fuels (PtL) or Power-and-biomass to liquid fuels (PBtL) offer the opportunity for Australia to use its abundant solar and wind resources to produce intermittent green power to run DAC facilities and produce green hydrogen from electrolysis of water, then downstream synthesis processes for production of liquid hydrocarbon fuels.

To realise this vision Australia needs to accelerate development of a vast industry – requiring refining infrastructure, skills and market conditions to incentivise low-emissions fuels. While PtL and PBtL fuels are far from being economically competitive, Australia can begin developing these fundamental building blocks through development of a biofuel industry.

Forecasting LCLF industry development

Using CSIRO feedstock production and energy technologies data presented in earlier sections, along with insights from the CSIRO-Boeing SAF roadmap, Deloitte used a simplified, stylised market clearing model to simulate the development of a biofuels market in Australia. Due to the lack of operational data, this model is necessarily simplified and incorporates significant assumptions but illustrates the development of a domestic market and identifies critical risks, constraints and needs for efficient market development. The complete modelling analysis by Deloitte appears in Appendix 1. Key messages and findings from the modelling are described below.

Meeting Australia's Net Zero goals will be impossible without action to address transport sector emissions.

Transport ranks behind only industry and the grid in terms of its contribution to Australia's emissions profile. Diesel is the largest single fuel source in Australia. To meet the 2030 and 2050 goals, Australia will need to address emissions from liquid fuels. This presents the opportunity to establish a domestic fuel industry on a path to a Renewable Energy Superpower future. This may become particularly important as the transition of the grid increasingly confronts more difficult challenges such as new site development, tradeoffs and build-out of new transmission infrastructure.

Electrification of transport will impact transport decarbonization, particularly for light vehicles and short-haul operations, but it is estimated that 43% of transport energy demand will require liquid fuels in 2050.

While light road and some mining applications can be electrified, transport sub-sectors such as aviation, marine, heavy or long-distance road and off-road mining applications will continue to rely on liquid fuels over the forecast period. Biofuels provide a critical bridge to hydrogen-based PBtL or PtL liquid fuels in 2050.

Biofuels are an important transitional option for long-term decarbonisation of surface transport, and a long-term emission reduction option for aviation

Today, a small-scale industry has developed with the support of mandates in Queensland and NSW, but these are yet to be fully enforced, and similar mandates have failed to take hold around Australia. In the US, biofuels are growing rapidly, with a goal of producing 35 billion gallons per year of aviation fuel. Using the IEA projections, Australia should be pursuing strong biofuel usage to 2030, reaching 180PJ, with a mix of end uses requiring renewable diesel and SAF during early industry development but evolving over time to prioritise aviation as other end user move away from transportable fuels and demand from aviation grows to dominate the market.

Other markets have moved sooner and faster than Australia, providing both an opportunity to learn and refine domestic policies, but also a template for growth.

Renewable diesel has seen strong growth in both the US and Europe, at a compound growth rate of around 31% and 9%, respectively. Initial market settings have proved to be sticky – the long-term investments made in response to new policies require sustained commitment to market settings.

Policies in the US favoured diesel and have required a renewed focus on SAF to address the imbalance. Current SAF production credits have led to a lower LCA benefit and reduced competitiveness of fuel. Californian policy has led to a bias towards diesel and away from biomethane. EU RED schemes have created tension with ILUC settings.

Having led the adoption of biofuels, the US and EU have gained an advantage and developed the momentum to shift to a hydrogen-based economy. Non fossil fuel market structures have been developed, creating a blueprint for future hydrogen industry development, with the oil and gas sector seeing a clear transition pathway and the workforce developing the necessary skills and capabilities. Lessons from the US, EU and Brazilian experience can help to guide the development of an LCLF industry in Australia. The suite of measures being implemented under the Future Made in Australia initiative draws on this international experience and addresses areas of regionally specific strengths, opportunities and conditions.

Two major barriers to a domestic bioenergy industry exist – cost and infrastructure. Supportive policy, accurate data and decision-ready insights are required to enable industry development, or the opportunity will be lost.

Australia’s biomass production potential presents a major opportunity to decarbonise transport and build the foundations of a future internationally competitive LCLF industry. But using biomass for bioenergy involves trade-offs with other uses and requires bridging the cost gap to fossil fuels. To catalyse industry development, supportive policy must be established, informed by continually updated information (a National Evidence Base).

Scenario modelling

Using the stylised market clearing model developed by Deloitte, four different scenarios were designed to explore the boundaries of an Australian LCLF industry.

No intervention – in this scenario no policy intervention takes place, resulting in a lack of market price signal or producer incentives for changing practices or investment into common infrastructure. No industry development is observed due to the prohibitively high barriers to investment, poor returns and lack of infrastructure.

Unconstrained demand – when demand is allowed to expand the model also demonstrates a poor response from biomass and fuel producers due to the capital investment required and remaining lack of infrastructure.

Unconstrained supply – despite allowing for limitless production of biomass, the model still demonstrates little market development due to the price premium required for any meaningful market clearing.

Fully unconstrained market – under conditions where both supply and demand are stimulated the market clearing model developed by Deloitte suggests that a biofuel industry does develop, but the full abatement potential is unrealised because cost is prioritised over emissions impact. For a biofuel industry to fulfill both its economic and climate goals, this scenario strongly suggests that capital flows must be carefully directed to the highest impact combination of biomass feed and energy conversion technology.

Supply and demand insights

Through exploring the stylised market clearing model developed by Deloitte, several key observations can be made:

- Biofuels are not cost-competitive with fossil fuels without recognising the cost of GHG emissions. Less than 2% of volumes required to meet net zero commitments will be fulfilled without policy intervention.
- On the supply side, Australia’s high agricultural variability combined with limited foresight analysis and infrastructure create a high-risk investment environment for private industry – preventing investment into biomass supply for a bioenergy industry.
- Competing uses for biomass exceed the capacity to pay for bioenergy, which creates flows away from biofuels and towards uses with less emissions reduction impact.
- Feedstock production is constrained by capital flows and profitability well before productivity becomes limiting.
- Numerous strategies exist for increasing production, notably crop rotations, and different production systems are available to maximise abatement.

The Future Made in Australia suite of measures can be used to target key enablers

Under the Australian government's Renewable Energy Superpower ambition and Future Made in Australia suite of measures to support it, there are opportunities to target support specifically to enablers identified in this report.

Cost

The primary and by far most important enabler for an LCLF industry is creating a favourable investment environment under which low emissions fuels are recognised and rewarded for their advantageous properties.

Traceability and substantiation

New low emissions products such as fuels can only attract higher prices if they are trusted and recognised for advantageous properties. International frameworks such as CORSIA and CBAM, through certification schemes reward low emissions products. Trustworthy systems to validate and trace products through the supply chain are critical to this. Australia's Guarantee of Origin scheme should focus on trustworthiness, capturing key sustainability metrics for each commodity, design to enable future scalability to new metrics which deliver to Australian values, and interoperability with current and future frameworks dictating market access to key export markets.

Feedstock supply, diversification and pathways

To capture the full productive capacity of Australia's bioresources, avoid locking-in dependency on any one limited feedstock and ensure maximum broader benefits from investment (such as regional prosperity, ecosystem resilience and natural capital stocks) it is important to ensure a diversity of LCLF production pathways are developed and investable. The $3.2b support for innovation and demonstration, through ARENA and other agencies, can be targeted to pulling through new processes which offer significant benefit to Australia, to the point of demonstration where industry can invest. Such processes include options for lignocellulosic biomass – such as pyrolysis, gasification and 3rd generation fermentation. Such pathways, if commercially demonstrated, can open up a vastly greater supply of biomass from agricultural residues and short rotation tree crops which can be grown in biodiverse plantings and deliver resilience for farmers through agroforestry. Thermochemical pathways also offer the potential to blend in green hydrogen, increasing the fuel yield from the same volume of biomass, and creating a transition pathway to grow the green hydrogen and power-to-liquid fuel industries.

7 Commercial drivers, barriers and key issues for Australian industry

Multiple industry stakeholders are ready to invest in an LCLF industry, including existing and new refiners, investors, feedstock producers and aggregators. Significant international investment currently focuses on Australia as a source of feedstock, or direct investment in land for feedstock production. Enabling regulatory measures can reduce substantial risks and increase investment flow to build this industry, some of which can be to support co-processing, demonstrate new processes, close the cost gap for end-users and reduce system-level risks.

A consolidated view of the key industry drivers and barriers was developed through industry engagements and consultations, including direct value chain stakeholders and through fora like Bioenergy Australia, Sustainable Aviation Fuel Alliance of Australia and New Zealand (SAFAANZ) and Australia Jet Zero Council.

A critical theme emerging from these consultations strongly suggests that setting up a LCLF industry in Australia will require diversification in the current state of play to include novel material flows, wider capital allocation and expanded infrastructure networks, along with fostering innovations in transport, energy and agriculture. Of critical immediate importance is establishing the sustainability credentials of Australian feedstocks. An interplay of upstream and downstream interventions will be necessary to strengthen cross-sectoral linkages, improve the transfer of co-benefits and equitably distribute value across the supply chain.

The following section details the key commercial drivers, barriers and issues faced by Australian industry, including those pertaining to supply, demand, technology and finance. It also outlines some of the key value chain priorities, and areas for market interventions.

7.1 Supply-side challenges

Feedstock uncertainty, competing demands and impact of changing climate

Biomass, or bio-derived inputs are key feedstocks for several LCLF process pathways approved by ASTM International[2]. High variability in biomass supply is a critical uncertainty posing a significant commercial risk associated with bio-based fuels.

Agricultural feedstocks sourced from sugarcane, corn, sorghum, wheat, cottonseed, canola and other oilseeds are subject to dramatic seasonal changes, farmers' choices and market forces. In the last decade, annual agricultural output has shown variation from 20% to 180% yield,

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[2] Formerly American Society of Testing and Materials.

depending on the crop type (ABARES 2023)[3,4]. Additionally, the supply of feedstocks like MSW, UCO and tallow is determined by dynamic trends in human consumption, shifting dietary preferences and competing international demand, thus reducing their reliability as domestic feedstock in the longer run.

An ideal feedstock for biofuels should have low external dependency, stable supply, low life cycle emissions and be compatible with high efficiency, low-cost energy conversion technologies.

Competing uses: Most feedstocks are currently allocated to various alternative demands and higher value uses, domestically as well as globally. The likelihood of conflict with food systems and nutrition is often cited as a major concern in sourcing agricultural feedstocks for biofuels. As discussed in section 3.5, most agricultural residues have existing on-farm uses, such as mulching into the fields or constituting animal feed, especially for residues from corn, soybean, sorghum and oilseeds. Sawmill residues and sugarcane residues are fed into different industries as raw materials and alternative energy sources. Feedstocks like tallow, UCO and canola have strong export markets in the US, the EU, Singapore, China and South Korea, which limits their domestic availability. In 2022-23, Australian tallow exports generated over AUD 1 billion in revenue, most of it driven by global biofuels demand (DAFF 2024)[5]. With a highly profitable export market, producers have limited incentive to shift to their preferred markets domestically.

There is a strong need to increase the overall feedstock supply, but there are limited insights on the underutilised capacity or ‘slack’ in current growing systems to accurately evaluate the feasible remainder and the potential to increase supply for biofuel production.

Climate change impact: Climate stress can impact productivity and lead to higher variability between seasons in different regions around Australia. Studies indicate that changing climate conditions are likely to have varying impacts for different regions, over time (CSIRO and BOM, 2015; Hughes & Gooday, 2021).

In the short term, climate stress is likely to have more significant effects on agricultural yield and quality in Western and inland regions compared to the major farming areas of Eastern and Southern Australia. However, estimates suggest that climate change is likely to increase the long-term vulnerability of agriculture across all farming regions due to effects like increased instances of droughts, diseases, flooding, forest fires and other natural disasters (CSIRO and BOM, 2022). Farm management systems will need to increase their adaptive capacity to respond to these conditions.

Robust export markets and influence of external trends

Export markets compete for Australian feedstocks. Effective subsidies in several prominent jurisdictions with favourable regulations render an unregulated domestic market uncompetitive. These include California, which benefits from both US federal measures in addition to State-based

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[3] Selected ABARES data on crop yields from 2010-2020.

[4] ABARES. (2024). “Australian Crop Report”. Link: ABARES report template (sirsidynix.net.au)

[5] DAFF. (2024). “Overview – Agriculture, fisheries and forestry exports in 2022-23”. Link: Overview – Agriculture, fisheries, and forestry exports in 2022–23 - DAFF

support; Singapore, through its new SAF mandate; and the European Union, which has a mature renewable fuel policy framework under the Fit for 55 Framework.

Australian canola is a prime target for these jurisdictions – particularly Europe which has the largest considerable market demand for canola as a fossil diesel replacement. New ILUC rules under the Renewable Energy Directive (RED) may impact canola exports, but waste feedstocks such as UCO and tallow are likely to continue being considered the highest quality bioenergy feedstock due to their evaluated emissions profile and lack of competition with other land uses.

There are also rising global investments in Australia as a feedstock source for LCLFs. In 2023, Idemitsu, a Japanese energy company, announced partnerships with J-Oil mills and Burnett Mary Regional Group, to undertake planting and management of Pongamia pinnata trees, which is an underexplored non-food feedstock for SAF, in Queensland with the aim of building a stable SAF supply chain. Another similar investment is by HIF Global, an international e-fuels producer, to build a commercial scale facility synthesising renewable energy from the grid with carbon dioxide from plantation biomass in Tasmania to produce e-fuels.

Integrated, tailored post-farm-gate infrastructure (aggregation, collection and storage)

As a major national economic sector, agriculture has well-defined logistics, transportation and infrastructure. These networks are primarily designed and optimised for farming systems producing commodities for the food industry. A biofuels value chain requires tailored infrastructure for collection, storage and transportation of feedstocks from fields and plantations, through different intermediate stages up to fuel processing and refining. Introduction of additional value chain stages like residue collection from farm gate, feedstock aggregation and pre-processing will be critical for streamlining the input feed into bio-refineries.

In the case of low-density perishable feedstocks, such as lignocellulosic biomass, agricultural straw residues and MSW, stages like densification and pre-treatment ensures greater biomass flowability, easier transportation and processing, and an overall stable and consistent feedstock supply (Gong, Meng et al. 2023)[6]. An ideal logistics setup should aim to minimise carbon emissions and enable essential economies of scale.

The hub-and-spoke model is a good example of logistical setups (Gong, Meng et al. 2023). Different co-location arrangements can be established, based on the surrounding geography, economic costs and feasibility of different transportation modes. In the case of small-scale operations, a centralised biorefinery can receive feed from various farms within a defined radius.

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[6] https://doi.org/10.1016/j.rser.2023.113520

Security of supply through reliable offtake agreements

Production variability, competing uses and markets described above create additional uncertainty over reliable fulfilment of supply contracts. As recognised in the National Interest Framework (NIF) under the Future Made in Australia suite of policies one of the main challenges for commercializing sustainable fuels in Australia is aligning sufficient offtake agreements between feedstock providers and users at appropriate scale. Advice from consultation with industry for this report has identified previous experiences with biorefinery business models in Australia failing, at least in part, as a direct result of supply chain counter-party risk wherein suppliers of feedstock have failed to fulfill supply agreements to biorefinery operations. This may be due to a variety of factors, including seasonal variability in production, dramatic changes in production cost and price changes in competing markets, creating sufficient incentive for suppliers to break contracts.

LCLF demand in Australia is expected to grow significantly, and along with individual users it also includes a small number of major buyers such as airlines and major mining companies. Such demand can provide reliable contracted offtake agreements to suppliers of feedstock. Maintaining a viable biorefinery business model relies on these offtake agreements to be fulfilled, or adequate financial contingencies to cover losses should supply not fulfill demand commitments. In light of the nascent stage of the bioenergy industry in Australia and the multiple variables impacting on supply, innovation is needed to ensure supply agreements between multiple users and multiple feedstock suppliers are reliable at a scale that can support a major biorefinery operation.

7.2 Demand-side barriers

Green premium burden, with limited incentives

Broader consensus from different transport sub-sectors like aviation, heavy road vehicle, maritime, construction and mining, reflects strong buyer-side preference for LCLFs as a near-term pathway for decarbonisation. The carbon emission reduction potential of these drop-in substitutes (estimated 70-80% lower than fossil-derived fuels[7]), without the need for major asset overhaul, makes them an ideal solution for small and large transport and heavy machinery operators, alike.

However, a key barrier to the uptake of these fuels is the higher price point per unit of LCLFs, also referred to as the ‘green premium’ relative to fossil fuels. In the case of aviation, the price per unit of SAF is estimated to be about three to four times higher than conventional jet fuel. There is a need to design incentives through policies and regulatory frameworks that provide usage-related benefits (for e.g. tax credits), bridging the gap between users’ willingness to pay and the fuel production costs.

Additionally, current sustainability reporting standards and frameworks do not adequately recognise and reward the use of LCLFs. This highlights the need to expand reporting considerations and develop greater coherence between national and global frameworks.

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[7] Estimates by National Renewable Energy Lab and the US Department of Energy.

Any future policy decisions should consider guarding against adversely spreading the burden of green premium, particularly towards individual end-users with lower agency and influence.

Limited forecasting to support business decisions

As described in an earlier section, the biofuel value chain is much more highly dependent on actions taken by value chain stakeholders throughout the industry vis-à-vis fossil fuels. While a fossil fuel refinery can purchase seaborne crude oil traded on an international market and be comparatively certain of supply, and within a narrower price range, a biorefinery is dependent on a large number of biomass producers in a localised region. A biorefinery relies on biomass producers committing to changing farming practices, as well as inter-seasonal variability affecting supply and competing markets affecting cost.

Therefore, the assessed risk associated with a biorefinery model is greater than a fossil refinery, and to address this, there is a need for availability of granular, timely information to enable investment decisions and continued operation of a biorefinery.

Limited comparability between emissions abatement options

Different liquid fuel user sectors (transport as well as non-transport) operate with varying cost margins and investment risk appetite. Most long-haulage truckers are small operators with lean profit margins, much like those of farmers using heavy machinery and equipment. Any capital investment in upgrading vehicle fleet and machinery is viewed as a significant cost contributor, partly due to the long asset life (between 15-20 years on an average). This constrains their pace of adopting changes and new technologies.

Larger industries like mining are more likely to minimise their short-term expenses and await significant policy or industry developments before investing in new technologies. Aviation, on the other hand, has limited decarbonisation options – drop-in LCLFs being the primary option in the near term – and relies heavily on the development of a cost-competitive LCLF (or biofuels) supply chain to procure aviation fuel.

These factors necessitate the ability to measure and compare the outcomes of opting for different decarbonisation options, and the associated time horizons. The range of options can be widened to include market-based mechanisms such as flexible carbon pricing (ACCUs with no caps), trading system for carbon credits, and the expansion of the Safeguard Mechanism to include transport. These, along with physical decarbonisation of transport (such as biofuels, synthetic fuels, electrification and hydrogen adoption), offer a comprehensive set of measures that transport operators can choose from to mitigate the adverse, near-term effects of changes while also planning for the longer term. Availability of accurate and reliable datasets can improve the ease of comparability between market mechanisms and physical decarbonisation pathways.

7.3 Processing and refining challenges

Choice between producing SAF and RD

The transportation sector comprises various modes with unique assets, each representing different demand preferences for fuel and energy. Renewable diesel (RD) and ethanol blending have the potential to fulfill demand from road vehicles (light and heavy), offroad mining vehicles and rail in the short term, until improved feasibility of electrification and future hydrogen-powered engines. On the other hand, the aviation industry relies almost entirely on sustainable aviation fuel (SAF) to reduce its carbon emissions, where advanced solutions will require significant capital investments.

Process mapping and insights from refineries indicate that RD and SAF can be produced through largely similar pathways, with additional stages for SAF. In the HEFA-based pathway, altering the output quantity between SAF and RD is accompanied by significant investments and infrastructure expansion at the refinery level, that needs to be supported by corresponding demand-side economic signals.

A nuanced decision-making capability that accounts for dynamic system interactions (such as those between changing prices, demand signals, business environment, policy frameworks etc.) and recognises the complementarity between different LCLFs (like SAF and RD), is needed to determine the optimal allocation of capital and resources between fuels with higher demand and those with higher processing needs.

Need for standardised bio-derived input streams into refineries

A common challenge faced by fuel refineries is the risk to facilities posed by the variable quality and concentration of unwanted constituents in bio-derived feedstocks. Unmanaged introduction of constituents like oxygen, chlorine, phosphorous, potassium, arsenic and water in the refining process chain can lead to adverse effects like catalyst degradation, equipment corrosion and process disruptions, and reduced conversion efficiencies.

Designing refinery infrastructure to manage highly variable feedstocks leads to increased costs, and the impact of contaminants in feed can degrade performance or lead to failures resulting in further costs, downtime and potential safety concerns. Ensuring uniform standards for bio-derived input streams can help to address these risks by ensuring delivered feedstocks fall within a tighter range of composition, potentially requiring pre-processing of diverse feedstocks to ensure conformity with established standards.

Technology trade-off: Near-to-market or cleaner, higher abatement

Currently, the industrial landscape views first-gen biofuels produced through HEFA as the most economically viable fossil-alternative fuels as they have abundant low-priced feedstocks, among the various ASTM-approved pathways. HEFA feedstocks include animal fats, vegetable oils, lipid-rich agriculture residues and UCO (Cavelius, Engelhart-Straub et al. 2023), and are pegged at a maximum blending ratio of 50% with fossil fuel for the aviation market (ICAO

2023). However, studies show that first-gen biofuels do not provide the greatest GHG abatement potential (El Akkari et al. 2018, Jeswani et al. 2020). Additionally, the perceived abundance of their feedstocks faces extensive competition and is likely to reduce in the long term, making them unviable.

Second-gen biofuels (using non-food lignocellulosic feedstocks, industrial waste) and third-gen biofuels (using directly captured carbon dioxide, green hydrogen, and algae) are found to be more sustainable and technically efficient with higher emission reduction potential but face significant commercial and scaling up challenges (Daystar et al. 2015, El Akkari et al. 2018, Mahapatra et al. 2021, Roy & Dutta, 2013, Stephenson et al. 2010). They have steep technology learning curves, additional pre-processing stages, limited feedstock, and overall higher downstream costs. All these factors lead to profit horizons that are further away and deter investors, thus inhibiting the business case for these advanced fuels.

Future policy design and investments towards technical capability, capital infrastructure and skills needed for a biofuels value chain should carefully balance the appeal of near-to-market processes like HEFA, against technically advanced, future processes. There is considerable risk of ‘technology lock-in’ favouring low cost-low abatement options, and therefore, a strong need for developing energy transition strategies that enable processing pathways with higher GHG emission abatement potential.

Co-processing: Need for improving evaluation and feasibility

Co-processing is an emerging interim step being explored by various refineries before setting up dedicated biorefineries utilizing fully biogenic feedstocks. The co-processing pathway can be implemented in two ways – one, by processing biogenic inputs with mineral oils, and the other, by processing feedstocks of different bio-origins (such oilseeds, UCO, tallow etc.)

The former offers a lower cost option of integrating biogenic feedstocks into existing refining infrastructure, requiring a smaller upfront capital outlay compared with the need for major capital investments in new equipment and facilities for a dedicated biorefinery. With necessary pre-processing steps to remove undesirable constituents, low carbon feedstocks like UCO and oils from crops (like canola) can be processed with fossil-derived inputs (up to 10-20%), to produce cleaner liquid fuels. These fuels have a lower carbon intensity and can be stored, transported and distributed using the same infrastructure as fossil fuels. This ensures that existing refineries can offer an improved lower emission drop-in fossil-substitute without incurring higher investment costs or creating a larger dependency on consistent, large volume biomass inputs (Su et al., 2021).

However, the wider adoption of co-processing is inhibited by the lack of mechanisms to value and attribute the emission reduction benefits of the renewable fuel molecules, from the producer all the way to the end user. Current reporting mechanisms like NGERS do not offer a clear, defined method to account for and attribute the true carbon benefit from such fuels. A precursor to solving this challenge is the need to develop accurate traceability methods to track the journey of renewable molecules through the complex refinery processes (which varies based on the feedstock insertion point), up to the end user/product.

ASTM has developed some methods to track and physically measure the renewable content of co-processed fuels using carbon 14 (C-14) analysis, namely, ASTM D6866 method B (using accelerator mass spectrometry, AMS, and is more reliable, ‘gold standard’) and C (using liquid scintillation counting, LSC, and is a cost-effective alternative) (ASTM International). These methods require highly specialised laboratories, new equipment and complex processes. Groups like Chevron and Los Alamos National Laboratory are also developing alternative carbon traceability methods that are likely to be more time- and cost-efficient and reduce the complexity of the ASTM methods (Su et al., 2021).

Besides these, there are other non-direct methods of tracking renewable molecules like the mass balance approach and free mass attribution method, such as that developed by ISCC (ISCC Mass Balance). These carry some advantages as they do not require specialised equipment, and most refiners are familiar with the methods. However, the underlying assumptions reduce the effectiveness and reliability of these methods in standalone applications (Schimmel et al., 2018).

Further improvements are needed to simplify traceability and accounting methods of renewable molecules to enhance the overall feasibility of co-processing in existing refineries. National frameworks and regulations (such as a Guarantee of Origin scheme for LCLFs) can ensure holistic reporting metrics and standardise traceability methods. Additionally, the feasibility and applicability of nuanced chain-of-custody models like book-and-claim need to be better understood to enable wider spread of carbon reduction benefit in industries.

7.4 Investment and finance support

Support to demonstrate outcomes and determine supply variability

Large investors and project financiers prefer funding long term projects, typically over 20-25 years. This necessitates certainty and predictability on key aspects such as input supply, technology maturity, cost recovery and demonstrable results. The biggest risks for most biorefinery projects are feedstock supply variability and limited demonstrable returns from the processing technology in use.

Agricultural yield in the last decade was found to be highly variable, fluctuating between >50% to 200% relative to the historical mean. Variable natural occurrences like rainfall, seasonal patterns, heat and frost, exacerbated by increasing unpredictability due to climate change, makes it harder to ascertain consistent feedstock supply. While this can be mitigated by steps like pre-processing and densification, it is important to evaluate the current biomass availability, forecast future supply and analyse climate risks affecting an LCLF value chain. Developing a National Bioresource Evidence Base integrating key dynamic factors that affect supply can lend confidence to wary investors.

Additionally, most LCLF processing pathways are relatively new by industry standards and their potential to yield consistent returns over time remains to be fully evaluated. Access to low-risk funding for nascent technologies, such as public sector grant funds or accelerator programs as have been a focus under the Future Made in Australia suite of measures can create an innovation environment that de-risks demonstration of process performance and offers an opportunity to showcase tangible results for interested private investors.

Need for tailored assessment metrics and sophisticated financing structures

Biorefinery projects typically require high capital investment, subject to the various risk factors outlined above. It is important to tailor the metrics for evaluating these projects and their returns on investments.

External influences like favourable megatrends (such as increasing international alignment on low carbon fuels, sectoral decarbonisation and business reporting standards), and supportive national policy and regulatory developments (such as the Australian Government Green Bond Framework, NGERs reform, and the recently released Sustainable Finance Roadmap by the Treasury) can provide positive signals to project sponsors and equip them to develop strategies mitigating the risks and unknowns. Quantification of specific outcome-focused metrics like reduced carbon emissions, biodiversity conservation, ecosystem services and regional economic opportunities, can be included in an expanded definition of return on investment for such projects. Measuring associated cross-sectoral benefits for other industries can also be used to broaden the evaluation criteria of LCLF projects (see Section 9).

A combination of government and private-backed funds can provide the right impetus for a domestic LCLF industry. A suite of financial options can be designed for technologies and feedstocks based on their commercial maturity. While newer concepts with limited testing may benefit from grant funding to de-risk the learning curve, those with relatively more mature commercial prospects can utilise more equity-driven funding and investment. Staging the evaluation processes also offers a way to reduce investor risk, while encouraging technology developers to improve their value proposition.

Future regulations should also examine the use and effectiveness of ‘credit-stacking’ across provisions to support industry development. A stable and definitive policy environment can provide the necessary drivers to channel private investments into LCLFs. Access to a diversity of options, such as debt, equity, credits and incentives, supported by government and private investors will provide a robust financing landscape, while ensuring that no single technology pathway or feedstock becomes an unintended determinant of an emerging low carbon transport sector.

7.5 Identified priorities for industry development

Consolidating stakeholder insights and perspectives on critical commercial drivers, barriers and emerging opportunities allows a clear distillation of early-stage priorities to support a domestic LCLF value chain (**Figure 41**).

7.5.1 Macro-level view of industry needs and gaps

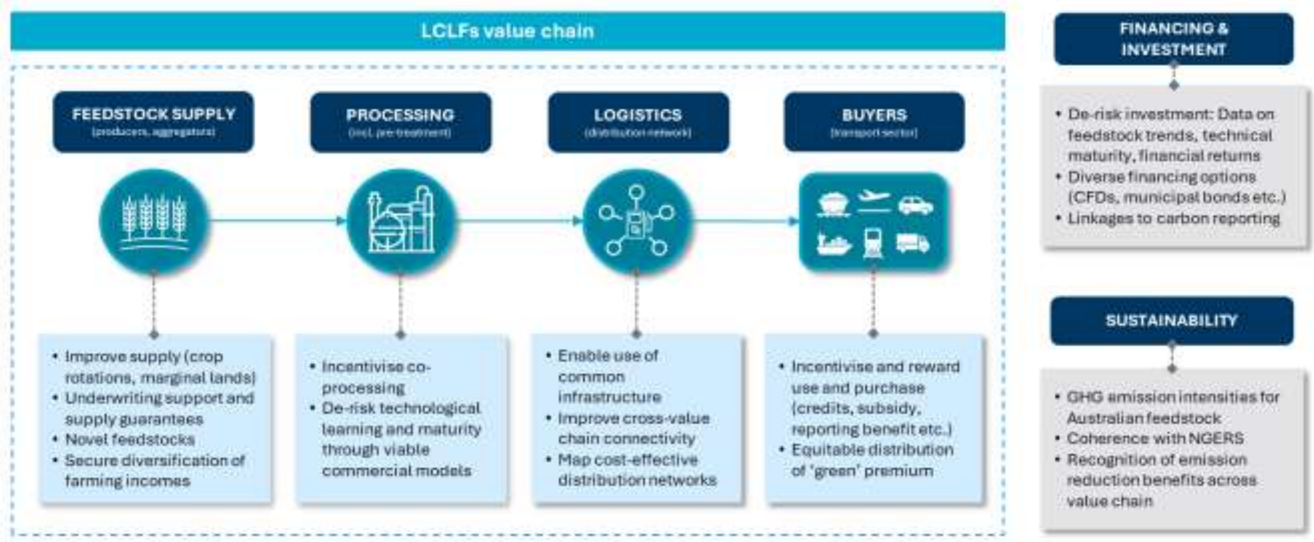


Figure 401: Priorities for different LCLFs value chain stages, along with overarching enabling factors
Source: CSIRO, Towards Net Zero 2024

Stage-by-stage priorities

Diversifying feedstocks to include more novel, low-carbon sources with reduced externalities and limited competing uses should be a key priority for growing the LCLF industry to support future, advanced decarbonisation pathways. This will require de-risking technological learning to improve the feasibility of advanced processing pathways. There is also a need for tailored infrastructural arrangements and cost-effective logistical networks to reduce midstream costs like biomass aggregation, storage and transportation. Prior to this, it will be important to evaluate suitability and scope of adapting existing infrastructure like fuel refineries and distribution logistics for LCLFs (such as co-processing). Additionally, mapping existing skills and capabilities to those needed by an LCLF industry will help in identifying critical skill gaps and re-skilling opportunities. Most importantly, ensuring buyers and end users have the right incentives and drivers will help in shaping a future-relevant LCLF industry.

Enabling factors

Supportive financial structures and sustainability frameworks are some of the key underlying value chain enablers. Financial mechanisms should be designed to mitigate challenges across stages through underwriting support, positive incentives, de-risked technology testing, and accelerated commercialisation and scaling-up. These structures should also articulate clear linkages to relevant sustainability frameworks. This will ensure that the 'real value' created by the LCLF supply chain is measured beyond the direct financial and economic benefits. Sustainability metrics for these value chains should align with key global and region-specific frameworks (like those by TNFD, RSB, ISCC-CORSIA, US GREET and EU's RED III, among others), and at a minimum, should capture GHG emission intensities, land use changes, biodiversity impacts and ecosystem services. Additionally, there should be mechanisms to define and measure the value created for nearby regional areas and communities. A prospective, longer-term goal should ensure equitable distribution of the created value and co-benefits among all stakeholders.

7.5.2 Critical areas for market intervention

Using insights from market modelling, industry feedback and technology review, the priorities for designing appropriate operating conditions for an Australian LCLFs industry can be highlighted. These observations identify key risks and potential actions for policymakers to ensure that both economic and climate objectives of an LCLF industry can be fulfilled.

Seven key pieces of market intervention are identified, and each must take account of impacts, trade-offs and market incentive structures:

1) **Regulated demand** – to lift the willingness to pay (WTP) to meet the cost of production.
2) **Supply-side price support** – to reduce risk and enable capital investment in the required infrastructure and new practices.
3) **Direct support** to expand Australia-specific feedstock supply and the technologies to process them into fuels – specifically, distributed lignocellulosic feedstocks.
4) **Sustainability standards and certification** – to provide confidence and a reliable market
5) **Establish sustainability baselines** – clear default factors recognising Australian-specific conditions at an appropriate scale to ensure multiple benefits are balanced from the feedstock production industry.
6) **Emissions trading infrastructure** – to enable market access to the broadest user base and efficient allocation of capital for the greatest impact.
7) **Communication and demonstration** of benefits and reliability of LCLFs to address pre-conceptions from previous experience with first-gen fuels (ethanol and biodiesel), build confidence in the market among users and Original Equipment Manufacturers (OEMs) and provide long-term certainty for investors.

7.6 Carbon Intensity and certification of fuels for market access

Life Cycle Assessments (LCA) measure the overall emissions abatement potential of a fuel derived from a specific feedstock and conversion process. Recognised LCA data certified by independent schemes such as RSB and ISCC are used to approve fuels for sale into jurisdictional markets such as the EU, sectors such as aviation under CORSIA or voluntary schemes aligned to corporate frameworks. There is a growing focus on the secondary impact of producing biofuel feedstocks – attempting to avoid adverse trade-offs like displacing food production or carbon-absorbing forests. This is captured in Direct Land Use

Change (dLUC) and Indirect Land Use Change (ILUC) factors added to an LCA. Default factors for LCA, dLUC and ILUC are being established using data from foreign farming systems, predominantly in the Northern Hemisphere. These farming systems are significantly different from Australian conditions, and in some cases penalise Australian feedstocks inappropriately.

There are several potential pathways to improving the core LCA, dLUC and ILUC factors for biofuel feedstocks produced in Australia but all require research to generate the data required for submission to the governing bodies.

Both canola and carinata are recognised as CORSIA eligible fuels (ISCC, 2023) but there are concerns that the application of the global default values over-estimates the carbon intensity of oilseeds produced in Australian farming system, particularly for canola. Canola is a variety of rapeseed. Rapeseed is the preferred term in many Northern Hemisphere countries, so this is commonly used in regulations including CORSIA and EU RED but the two can be considered interchangeable as shown by the use of both terms in the published CORSIA default values (ICAO, 2024).

Pongamia, cottonseed, sunflower and safflower are not yet recognised as eligible fuels under CORSIA (ISCC, 2023).

Importance of regionally specific Core LCA

Australian farming systems are significantly different to the global average. Our climate and ancient soils dictate that most broadacre farms are dryland (because of limited water for irrigation) and low input (because yields are capped by rainfall, so farmers aim to match use of expensive fertilisers and pesticides to demands imposed by water availability). Many Australian farmers have adopted conversation tillage or no-till farming practices in a bid to preserve delicate soils and build soil health. All of these factors mean that the carbon intensity of Australian farming systems can be significantly different to the more intensive farming systems in the Northern Hemisphere.

However, most of the LCA modelling that has contributed to the development of default values in CORSIA and EU RED regulations, are based on Northern Hemisphere systems, particularly for our most important oilseed crop, canola.

In 2017 CSIRO carried out an LCA to assess the carbon intensity of canola produced in each state as part of a requirement to meet certification for export into the EU. At the time of the analysis, Australia was exporting approximately 58% of produced canola to the EU. The introduction of Renewable Energy Directive II required demonstration of 60% GHG savings relative to fossil fuel for biofuels. The analysis by Eady., (2017) considered the upstream portion of the value chain only (cradle to farm-gate) and showed that GHG emissions from canola cultivation varied across the states and that in dryland cropping area of NSW, Vic, SA and WA, which account for 97% of Australian production, emissions are significantly lower than global defaults (see **Table 6**).

Crop	Location	Farming system	Average Carbon Intensity	production (tonnes)	production (%)	Reference
Canola	**NSW**	**Dryland**	**19**	**1019231**	**29**	(Eady, 2017)
	NSW	Irrigated	36	46360	1	
	Vic	**Dryland**	**18**	**639399**	**18**	
	Vic	Irrigated	35	20536	1	
	Qld	Dryland	30	1156	0	
	SA	**Dryland**	**17**	**386117**	**11**	
	WA	**Dryland**	**20**	**1345694**	**39**	
	Tas	Dryland	37	1413	0	
	National weighted average		**19.13**	**3459906**	**100**	
CORSIA Core LCA default values (cultivation only)						
Rapeseed	US		28			(CORSIA, 2019)
	US		29.7			
	Canada		24.8			
	EU		30.1			
	EU		31.4			

Table 6: Carbon intensity of canola production (cradle to farm gate - not including post farmgate processing and refining) using regionally specific data from each Australian state versus CORSIA default values.

There are several reasons for differences in carbon intensities between states.

1. Higher intensity systems have higher carbon intensity as irrigated crops demand higher inputs of lime and fertiliser to achieve higher yields.
2. States with higher uptake of no till farming practices (that preserve soil integrity) have lower carbon intensity.
3. States with higher yields (through better climate fit, modern farming practices, etc) tend to have lower carbon intensity as carbon inputs are spread over greater volume of product per hectare.

The national average carbon intensity for Australian canola cultivation (weighted by the production in each state) is 19.13 g CO2e/MJ FAME. This compares to CORSIA default values for the cultivation of canola (not including post-farmgate processing) that range from 28 to 31.4 g CO2e/MJ.

Australian specific ILUC values have not been calculated to date (see comments below). If it is assumed that the carbon intensity of post-farmgate processing and refining of canola oil to SAF in Australia will be similar to the global average, and taking the global default value, it is possible to estimate the impact of regionally specific core LCA on CORSIA carbon intensity values (see **Table 7**).

Table 7: Life cycle emissions factors including estimates using Australian specific data for canola in comparison with CORSIA default values for canola, and carinata and with LCA of Pongamia based on Australian trial data.

Region	Fuel Feedstock	Core LCA (gCO2e/MJ)	ILUC LCA (gCO2e/MJ)	LCEF (gCO2e/MJ)	Reference
EU	Rapeseed/Canola	47.4	24.1	71.5	(CORSIA, 2019; ICAO, 2024)
Global	Rapeseed/Canola	47.4	26	73.4	
Australian national weighted average cultivation CI*	*Canola*	*38.11*	*26*	*64.11*	*(CORSIA, 2019; Eady, 2017)*
Brazil (multicrop - 2nd crop in same season)	Carinata	34.4	-20.4	14	(CORSIA, 2019; ICAO, 2024)
USA (multicrop - 2nd crop in same season)	Carinata	34.4	-21.4	13	
Global (multicrop - 2nd crop in same season)	Carinata	34.4	-12.7	21.7	
Australian trial data	*Pongamia*	*47*	*Not available*	*Not available*	*(Cox et al., 2014)*

*Note: Australian national weighted average CI for canola and Australian trial data CI for Pongamia are not recognised by CORSIA.

The CSIRO team who undertook this LCA analysis of canola have also explored the potential impact of inclusion of soil organic carbon changes in LCA calculations and showed that the accumulation of organic carbon in soils under canola cultivation can help to reduce the overall carbon footprint of the crops in Australian systems (Sevenster et al., 2020). Increasing the available data on changes in soil organic carbon under different crop rotations and farming practices could be another route to more accurately calculating the carbon intensity of Australian crops.

Importance of region-specific data in models for dLUC and ILUC.

Regionally specific data and farming practice scenarios can also have a major impact on land use change calculations. Bontinck et al., (2020) adapted the Blonk tool in Excel which is used to calculate carbon emissions associated with dLUC according to Volume 4 of the IPCC Guidelines for National Greenhouse Gas Inventories and in Annex B of the PAS 2050-1 specifications to assess greenhouse gas emissions from horticultural products. They added regionally specific data for Australia with specific focus on carbon stock in living forest, 20-year variation in annual and permanent crop land use, climate, and soil type.

After running the model, they found that GHG emissions associated with dLUC using the regionalised data were 82% lower than estimates using the default factors. They give the following reasons for this large difference;

- carbon stocks in living forests were considerably overestimated.
- climatic region and soil type in the default were based on the whole area of Australia while Australian agriculture occurs in specific areas of the country with significantly different climate and soil profiles.
- the approach to calculate cropland expansion did not allow for the fact that Australian farming systems include a significant proportion of temporary pastures and temporary fallow land in rotation with crops. This means that the total existing cropland encompasses more than the sum of harvested areas in any one year.
- The same estimation of cropland based on harvested area can lead to double counting of land where double cropping enables production of two crops in the same year.
- The use of a 3-year rolling average to estimate land use does not fit with systems where decadal rainfall patterns determine the way land is used in any 3-year period.

This work demonstrates the importance of regionally specific data and farming systems knowledge in the application of modelling to determine land use change impacts.

The GLOBIOM and GTAP-bio models that are used to calculate ILUC for CORSIA do not have regionalised data for Australia. It is likely that regionally specific data and practices, akin to those described for the modelling of dLUC could result in similar differences in the ILUC associated with introduction of biofuel feedstocks into Australian farming systems. This could be particularly important for canola, given that the default global ILUC in CORSIA is based on higher-input Northern Hemisphere farming systems. CSIRO and collaborators at Australian universities are working to develop the database and model adaptations needed for regionally specific calculations in GLOBIOM and GTAP-bio but these projects are small and underfunded. Investment in R&D in this space could be a key input to enabling submission cases for regional LUC to ICAO Fuels Task Group.

Applicability of Low ILUC Guidelines to Australian farming practices.

ISCC has published a Guidance for Low LUC Risk Certification (ISCC, 2023). Within this report they describe two pathways for achieving low LUC risk feedstocks,

1. the yield increase approach and
2. the unused land approach

The yield increase approach applies to practices that enable the production of a greater amount of feedstock from the same parcel of land in the same year. This may be through the application of improved farming practices, improved fertiliser or disease management, mechanisation, or the use of double cropping (where a winter crop is paired with a summer crop to grow two crops in the same cropping year).

The unused land approach describes production of feedstocks on underutilised lands such as marginal or degraded pasture lands.

Research is needed to establish how these guidelines apply to Australian farming systems. For example, canola is grown as a dedicated break-crop in Australia. It has a place in multi-year rotations in cereal producing system where it serves as a "break" for cereal diseases. When cereals are grown year on year the risk of disease outbreak increases with each crop as many diseases that infect wheat also infect other common cereals such as barley, and oats. Broadleaf crops such as canola or legume like soy, are not infected by the same set of pathogens so they serve to 'break' the disease cycle (Kirkegaard et al., 2016). Canola also acts as a biofumigant by releasing compounds from its roots that act as a natural fungicide/pesticide (Kirkegaard et al., 2016). This means that the cereal crop following canola often have a higher yield than it otherwise would. Several potential biofuel crops serve this function in different farming systems in Australian (Table 7).

It is not clear if this function in the farming system is recognised within the "increased yield" methodology or the rotations, where they replace a fallow or pasture rotation, would qualify under the "unused land" methodology. In theory, application of either methodology would decrease the ILUC score of Australian canola.

NuSeed is carrying out the first large scale trials of carinata with a view to establishing it as a double crop in cotton producing systems (see **Figure 42**). This use is slightly different to the traditional crop rotations described above. In this case the carinata crop would be grown over winter, following the cotton crop and prior to either a summer fallow or sorghum crop. This means that the same parcel of land would produce two crops within the one year.

Figure 41. Source: NuSeed https://nuseed.com/au/carinata/

This scenario is likely to meet the requirements of the low ILUC guidance and attract the global default ILUC value for carinata. Trials of carinata in Australia are still in early stages so its fit in other cropping systems has not yet been reported. When carinata is grown as a double crop in US and Brazilian systems it attracts a negative ILUC score because of the boosted productivity of the parcel of land (see **Table 8**). Several other crops including sunflower can be used in this way as a double crop in areas where sufficient water is available (table 8). Development of the Globiom and GTAP-bio models is required to add these crops to the database and enable Australian specific assessments of these double cropping systems.

Broadacre crops are likely to deliver poor yields on marginal or underutilised pasture lands because of limitations of water, soil quality, nutrient availability or temperatures. It has been noted that in some areas cropping lands are increasingly being converted into extensive grazing land because cropping is no longer profitable as those lands become more marginal (Miyake et al., 2015). It has also been stated that all cleared land in Australia is used for some purpose, and in 'marginal' areas that are usually extensive grazing or forestry (Farine et al., 2012).

Under Australian conditions, the most promising use of underutilised grazing land for feedstock production is through agroforestry. Several authors suggest that Pongamia plantations could be established on grazing lands and paired with either continued grazing, or with inter-row crop production (Degani et al., 2022; Miyake et al., 2015; Wylie et al., 2021). Similar co-benefits can be realised from Short Rotation Tree crops (SRT), particularly nitrogen-fixing varieties which can build soil health. Inter-row cropping is preferred when trees are young as the management of the crops can help to control weeds which can overshadow young plants. Sheep or cattle can be introduced after approximately 3 years when the saplings are large enough to withstand damage from the animals(Murphy et al., 2012). Development of Pongamia plantations on underutilised grazing lands will likely attract a low ILUC penalty. The integration of cropping or grazing could even result in a negative ILUC score.

Table 8: How oilseeds fit into Australian rotational farming systems.

Crop	Season	Sowing	Harvest	Region	Farming systems	Type of rotations	Notes
Canola	Winter/ spring crop	Autumn (mid-April and May, to early June)	Spring/ early summer (October, November)	Northern	Cereals (wheat, barley), pasture, pulses	Increasing interest in substituting canola for other winter break crops (chickpeas, faba beans), depending on rainfall	Canola is not recommended to be included in rotation more frequently than once every four years, to reduce the risk of canola disease build-up Subsequent cereal crops following canola often show a yield increase due to biofumigation Preceding canola with a nitrogen fixing legume may provide more organic nitrogen to canola crop
				Southern	Barley/canola/wheat is common rotation in grain-only systems (no grazing) Dual-purpose canola is common as part of mixed farming systems (livestock and crops)	Recommended rotations for mixed farming systems: Legume pasture (clover or lucerne) – canola – cereal – pulse (lupin or field pea) – cereal – cereal (GRDC) Common: 4 years pasture/ long fallow wheat or canola/ short fallow wheat/ short fallow barley	

Crop	Season	Sowing	Harvest	Region	Farming systems	Type of rotations	Notes
				Western	Grain and sheep: Canola is part of 53% of rotations in southern wheatbelt, and 30% of northern wheatbelt rotations (Harries et al. 2015)	94% farm paddocks use some combination of wheat, canola, lupins, barley or pasture Wheat/wheat/canola: 15% Wheat/ canola/wheat: 16%	
Carinata	Winter crop	May	November	NSW and QLD	Cotton	Irrigated cotton: After cotton and before short summer crop (sorghum) or fallow Dryland cotton: After cotton and before fallow, ahead of another cotton rotation	Currently being trialled in cotton systems (Nuseed) as double crop.
Juncea	Winter crop	May-early June	Spring/ summer	South-western Australia	May be grown in similar regions to canola, but also in hotter and drier regions due to higher heat and drought tolerance		
Safflower	Winter	June-August (NSW to SA)	January	NSW to South Australia	Cereal (wheat)	Adapted to higher rainfall cereal regions, often sown in wheat systems	Used to control herbicide resistant weeds; typically requires more water than other crops in wheatbelt regions
Sunflower	Spring/ Summer	August -October (Spring)/ Feb-Mar (Summer)	Avg 120 days after sowing	NSW to Qld	Northern cereal (wheat, barley, sorghum)	Two sowing windows allow fit as rotation with winter cereals (summer crop window) or prior to summer sorghum	Drought and heat tolerant. Good disease break for cereals. Recommended

Crop	Season	Sowing	Harvest	Region	Farming systems	Type of rotations	Notes
						(spring crop window). Fits as double crop following winter cereal and before summer sorghum crop if sufficient water is available.	not to plant more than once in three years due to broadleaf disease risk. Early planted Spring crops at risk from late frosts. Late planted Summer crops at risk from high temps during establishment and fungal disease.
Soy	Summer	Nov/Dec (NSW and VIC) Dec (Qld)	March-April	NSW, Vic, Qld	Qld and Nth NSW – sugarcane Sth NSW and Vic – winter cereals	Used as a cover crop/green manure in sugar systems in Qld. Grain generally not harvested in Qld because wet conditions limit paddock access in harvest season. Higher prices could change practices.	Some varieties can be used as forage/hay crop. Can be used as a double crop in irrigated systems in South.

8 Global policy landscape

Globally, countries are working to develop domestic low carbon liquid fuels industries for fuel security, decarbonisation and economic growth. The rapidly developing regional LCLF hubs provide valuable lessons for Australia to shape a supportive investment environment.

Maximising environmental and economic benefits will depend on a mix of demand- and supply-side policies, aligned sustainability measures, international advocacy and direct support to develop the most promising feedstocks. While demand-side measure can reduce the cost gap for fuel users, supply-side measures and direct support will be required to de-risk high abatement potential feedstocks through demonstration and infrastructure support.

Enabling new feedstocks and conversion technologies of relevance for Australian conditions determine the climate and economic impact of the industry. Among the novel feedstocks, lignocellulosic biomass represents the largest category of feedstocks with significant potential for climate and economic impact.

A bio-based LCLF industry can build the necessary conditions for a future power-to-liquids industry. This may offer a major export opportunity for Australia based on conversion of green hydrogen into export-oriented synthetic liquid fuels. Enabling policy design will shape the nature of the biofuel industry and its potential to support future PTL pathways.

"The role of government policy is to enable and protect – enable the targeted activity and protect people and the planet from any harm that might come from that activity." (ICAO 2023)

Conducive policies and regulations will play a decisive role in decarbonising the transport sector and enabling an LCLF industry in Australia. As discussed in previous sections, there are several conversion pathways to produce LCLFs, but multiple barriers constrain their large-scale commercialisation and use. These include limited robust, resilient supply of bio-feedstocks, the cost differential between LCLF and fossil-based fuel, and difficulties in attracting investments.

The regulatory frameworks in effect in the United States (US), the European Union (EU) and Singapore serve as exemplars that are accelerating LCLF uptake by de-risking associated technologies and pathways.

8.1 Overarching principles for developing an LCLF policy framework

The LCLF industry has multiple goals – going beyond economic growth, to include fuel security and emissions abatement, as well as regional economic development and investment in ecosystem services. This analysis strongly indicates that an unconstrained market (i.e. a market in the absence of policy and regulations to guide both supply of feedstock and fuels and demand for resulting LCLF) will not be able to optimise the multiple trade-offs and benefits associated with an LCLF industry.

Achieving the multiple objectives and co-benefits requires fostering an investment environment that realises not only a *rate* of growth, but also a *direction*. A carefully designed industrial policy would likely be needed to determine the success in capturing the LCLF opportunity for Australia.

LCLFs face an uphill task of feedstock reliability, limited infrastructure for production, storage and supply, and higher costs compared to conventional carbon intensive alternatives. Countries and jurisdictions that are committed to the decarbonisation of their transport have realised the importance of a supportive policy structure and, in the case of SAF alone, there are now at least 37 specific national and international regulations in effect around the globe today, with several in development (Watson, Machado et al. 2024). The barriers faced by LCLF industry development in each country or jurisdiction are distinct given the specific feedstock availability, infrastructure, technological readiness, economic profiles, climates, natural resource availability and unique political frameworks.

ICAO, realising that each state will have a unique policy framework to support SAFs, has provided a set of guidelines as a knowledge base to guide implementation.

According to the ICAO (2023), policies need to have three fundamental characteristics for successful SAF uptake:

1. Feasibility: the policies should be readily implementable
2. Effectiveness: the policies should have the capability of producing required results, and
3. Practicality: the policy is outcome-focused rather than fixated on theory or ideology

Additionally, other guiding principles identified (Deloitte 2023) and adapted for the Australian context require policies to:

- Favour Australian economic development and local emissions reduction
- Enhance competition and support productivity growth
- Be technology inclusive
- Be implementable
- Provide value for money, and
- Encourage equitable distribution of cost-gap bridging efforts

8.2 Policy analysis for pathways and combinations

Based on ICAO guidance and the policies enforced in various countries, a few policy considerations and mix of options can be described for possible implementation in Australia.

A comprehensive policy approach

Results from market modelling conducted by Deloitte (Appendix 1) suggests that if the entire supply chain from feedstock to end-user is not considered, it will be economically unfeasible for stakeholders to maintain sustainable demand, leading to a subsequent decline in supply and inadequate investment in LCLF enabling infrastructure. This, in turn, leads to a negative feedback loop where lower supply and low economy of scale can negatively impact price points and demand. Therefore, published studies suggest supply and demand side support for LCLF production, as well as other market enabling interventions are required for sustainable LCLF industry development (Santos and Delina 2021).

Policies can include interventions that unlock a wider array of LCLFs and feedstocks through grant funding for research, development, demonstration, and deployment of new pathways; or can activate demand by implementation of mandates and government procurement. Other interventions that may not be directly considered supply or demand enabling are often equally important for LCLF uptake such as streamlining regulatory approvals for new fuels and financial vehicles for multi-party investments into infrastructure.

The results of modelling, insights from consultations and technology evaluation suggest that to maximise the economic potential, including volume and regional co-benefits, as well as the emissions abatement potential of an LCLF industry, a mix of market interventions is required instead of isolated policies. Additionally, if a wider array of policies is set up to enable LCLFs, it provides higher degree of assurance to potential stakeholders (ICF, Qantas Group and Airbus 2023).

Support for multiple pathways

ICAO guidelines for SAF, and applicable to wider LCLFs, identify the need to develop multiple pathways for production by recommending that policies “be technology-neutral to enable diverse production pathways and supply chains to develop” and that they “incorporate mechanisms to encourage significant advances in production capacity expansion, further technology innovation, and drive efficiencies to provide sufficient supply to achieve decarbonisation of the aviation sector” (ICAO 2023).

The LCLF supply chain can often comprise of multiple smaller supply chains categorised as one. This is because the type of LCLF produced depends heavily on the type of feedstock used which determines the conversion technology. Australia has a wide variety of potential feedstocks that can be used for LCLF production (CSIRO 2023). Given these conversion technologies are at different Technology Readiness Levels (TRL), LCLF production may suffer from path dependencies and a focus on only the low-risk technologies, such as HEFA. This may lock out certain feedstocks. Therefore, continuous support for emerging, higher potential technologies is needed to ensure that co-benefits are delivered to all regions producing a variety of LCLF feedstocks.

Additionally, modelling results (Appendix 1) suggest that merely relying on market forces, even near-to-market pathways like HEFA will develop much later and at a substantially smaller scale than necessary to meet 2030 and 2050 targets. A scenario of HEFA-fuel lock-in may also expose the Australian transport sector to price volatility and international competition for oilseed feedstocks.

Furthermore, results from the US experience, forecast by the Bioeconomy Scenario Modelling team at the National Renewable Energy Laboratory (NREL) and validated through experience over the past ten years confirms this observation (Newes, Han and Peterson 2017). As illustrated in **Figure 43**, despite multiple supply and demand side interventions, the mature and high TRL HEFA pathways were only able to unlock a fraction of total potential LCLF production over the temporal scope of the study. Conversely, interventions that have the capacity to unlock and support multiple pathways, such as cellulose-to-hydrocarbon, can futureproof the LCLF industry from feedstock limitations, international competition, technological and infrastructure lock-ins, and ensure robust LCLFs growth to meet medium- and long-term abatement targets. This is specifically relevant for Australia's highly variable growing conditions and large but, highly distributed lignocellulosic biomass (CSIRO 2023).

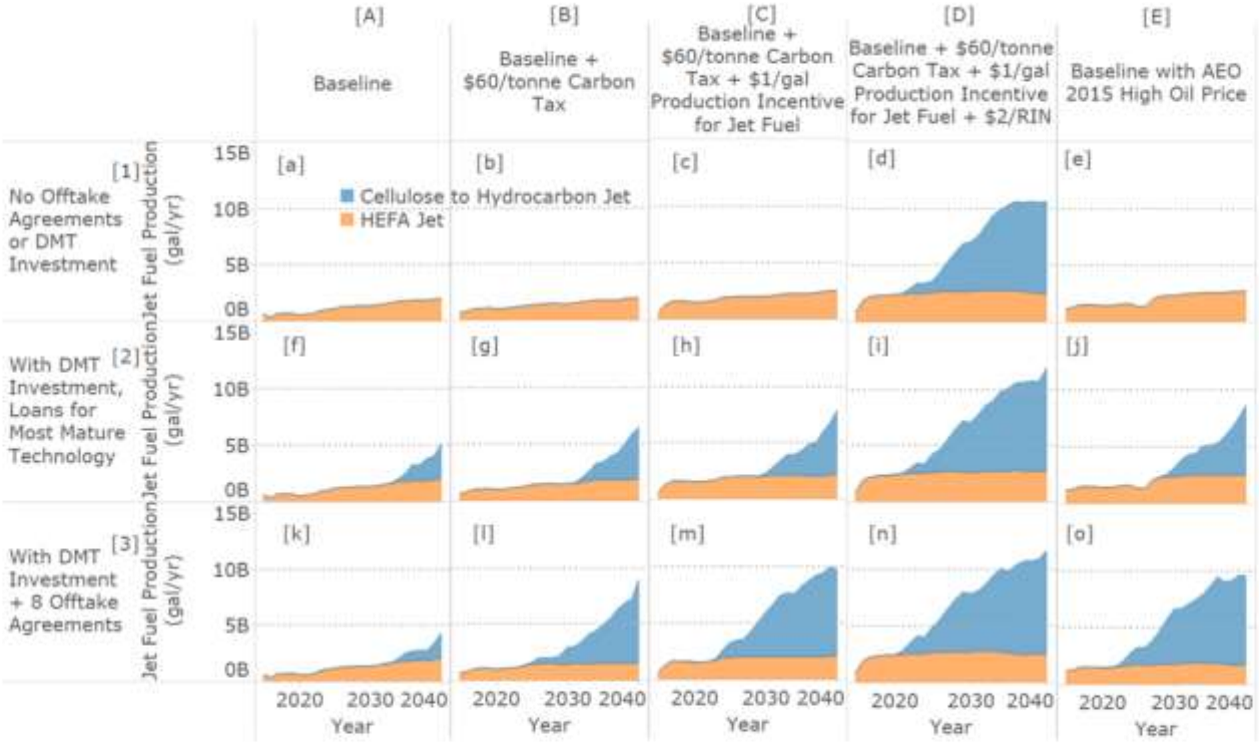


Figure 42. Influence of policy interventions on SAF production volumes in USA. RIN = renewable identification number, DMT = Demonstration and Market Transformation Investment, AEO = Annual Energy Outlook.
Source: (Newes, Han and Peterson 2017)

A policy environment with multiple support measures would need to address supply issues for both scaling up of existing LCLFs and feedstocks and unlocking new ones. For example, previous work (Newes, Han and Peterson 2017, ICF, Qantas Group and Airbus 2023) has shown that direct support mechanisms such as grants, and incentive payments may be effective in unlocking a larger pool of high-abatement feedstocks such as lignocellulosic biomass (USDA Farm Service Agency 2010).

Similarly, refineries being a critical infrastructure element, need accelerated investment. This includes enabling co-processing through either a framework for crediting biogenic carbon in different fuel products, or physical tracking and substantiation of biogenic carbon in fuels.

Policies such as contracts for difference (CfD) and other similar measures that underwrite, partly or completely, the green premium between LCLFs and conventional fossil-based fuels are also identified as highly supportive for LCLF producers. Conversion facilities with measures such as the Blenders Tax Credit are also found to positively impact LCLF uptake (The White House 2023).

Given the variety of pathways that need to be enabled and the diversity in policy interventions that could possibly be deployed, it is also important to look at policy interventions as a vehicle for sequencing the support for different pathways at different stages of LCLF market development to ensure resilient and sustainable market development and growth. Policy sequencing takes the form of the adoption of certain enabling policies that remove barriers to enable a later more ambitious policy landscape for LCLF uptake. It has been observed that policy interventions, when instituted in a step wise fashion can build path dependency by identifying positive and negative feedback loops. Positive feedback loops can then be reinforced to enhance the ambition and scope of sustainability targets, whereas negative feedback can be actively managed through enhancing monitoring and enforceability provisions. Additionally, successful policy interventions and sequencing allow for new technology and processing pathways development, subsequent reduction in production and scale up costs, development of institutional and governance frameworks and increasing support and appetite within the general public for more stringent targets (Anna Leipprand, Christian Flachsland, Michael Pahle Starting low, reaching high? Sequencing in EU climate and energy policies 2020).

Generate sustainable demand

While supply-side interventions can develop target feedstocks for capturing the abatement potential, these alone may be insufficient to adequately elevate the buyers' willingness-to-pay (WTP) to close the price gap. In such scenarios, it becomes necessary to develop methods to establish sustainable demand.

In some countries, government procurement is used to create direct demand from air and maritime fleets, such as in Canada (Government of Canada 2024) and US military (US DOE, 2024). However, it has been reported that government-backed demand may not be enough for sustained growth at scale (JetZero Council 2023).

Alternatively, other demand levers may need to be explored, such as mandates for LCLF blending which are a cornerstone of LCLF policies for the aviation and transport sectors for many states in the EU (Soone and Claros 2022, UK Department for Transport 2024).

Blending and uptake mandates ensure a sustained and increasing demand over a set period of time allowing for development of more effective supply-side incentives and interventions and can also be effective in ensuring the emergence of alternative pathways. An example of this is the UK Jet Zero mandate's requirement of blending 22% LCLF in aviation fuels by 2040, of which only 35% can be HEFA based and at least 3.5% has to be through power-to-liquid fuels (UK Department for Transport 2024). When coupled with cap-and-trade type interventions, mandatory blending requirements can deliver further dividends by driving carbon markets such as in the US and the EU (European Commission 2024, US EPA 2024).

Longevity and certainty of policies

It has already been discussed that policies enabling LCLFs may need to encompass the entire supply chain and may also need to be applied to a multitude of technologies at different TRLs. Policy interventions will need to be stable over the long term to provide investor confidence to unlock private investment and reduce sovereign risk. ICAO guidelines articulate this as LCLF policies need to “be of a sufficient duration to reflect project development timelines” (ICAO 2023).

The effects of policy longevity are numerous (ICF, Qantas Group and Airbus 2023), whereas policy uncertainty deters financiers and stakeholders leading to a smaller or delayed investment, as observed in the UK. Therefore, it is crucial that a policy framework for Australia is developed for a similar temporal scope as the abatement targets such as through to 2030 or 2050, and is also actively and appropriately communicated to encourage private investments.

Sustainability standards

As new feedstocks and conversion technologies are unlocked, investors and stakeholders will require some form of transparent reporting mechanisms to build confidence in the abatement potential of the LCLFs.

Market enabling policies that create sustainability standards and certifications will need to be a part of the overall LCLF support framework (CSIRO 2023). International standards like CORSIA for aviation fuels provide a basis for country and state sustainability standards and need to be modelled based on the abatement targets and potentials of specific jurisdictions in which they are applied (ICAO 2023). Sustainability standards also provide the supplementary benefit of creating a carbon intensity (CI) tie-in, where pathways with lower CI are identified and increasingly incentivised.

Developing Australia-specific sustainability standards will be effective, feasible and practical through stakeholder inputs on the scope, magnitude, timing, compliance and enforcement requirements that are firmly adapted to Australian conditions.

While standards and certifications are critical to ensure the performance and integrity of the qualification and production of new LCLF fuels, the cost, complexity and required investment of time of compliance can become a substantial barrier to the development and deployment of new fuels and fuel pathways. Therefore, with the establishment of stringent standards, corresponding development of institutions and initiatives such that can facilitate the evaluation and qualification of eligible LCLFs also becomes an increasingly critical market enabling policy lever. Similar initiates have been set up in other jurisdictions such as the UK’s SAF Clearinghouse with the objectives of providing advice to Low Carbon aviation fuel producers enabling new fuel pathways from a range of sustainable sources on testing and qualifications requirements to meet required standards, to certify the emissions reduction of new low carbon fuels and to support commercialization of eligible fuels.

Renewable Diesel development

As discussed in Section 5, there are additional constraints to development of export-facing fuels such as SAF due to the compliance requirements of both ASTM and CORSIA. By contrast, renewable diesel (RD) production for a domestic market may be more suited for rapid scale-up. Another factor impacting RD production is willingness-to-pay and the potential to adjust existing support mechanisms.

Diesel in Australia today, for eligible activities, attracts a fuel tax credit of 20.8 cents per litre for use in heavy vehicles and 49.6 cents per litre for other business uses. Deloitte estimates the willingness to pay (WTP) between different sectors as the fuel cost plus cost of existing abatement options (ACCU price). The difference between respective on-road diesel and mining activity WTP is estimated at over AUD 15/GJ (see **Figure 44**). If credits for off-road use of diesel are targeted at renewable diesel, mining activities will represent the highest WTP from all modelled end-user sectors. The mining industry has demonstrated a strong interest in purchasing renewable diesel, as evidenced by Rio Tinto's investments at US Borax and Kennecott (see Section 5). Directing liquid fuel support to renewable diesel over fossil, combined with direct investment to demonstrate pathways for lignocellulosic biomass will further incentivise the growth of high abatement potential pathways in Australia.

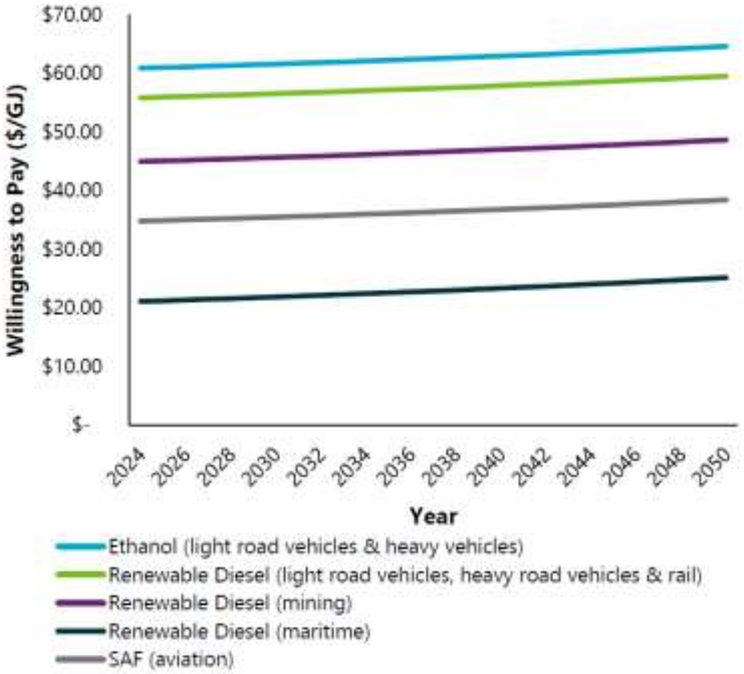


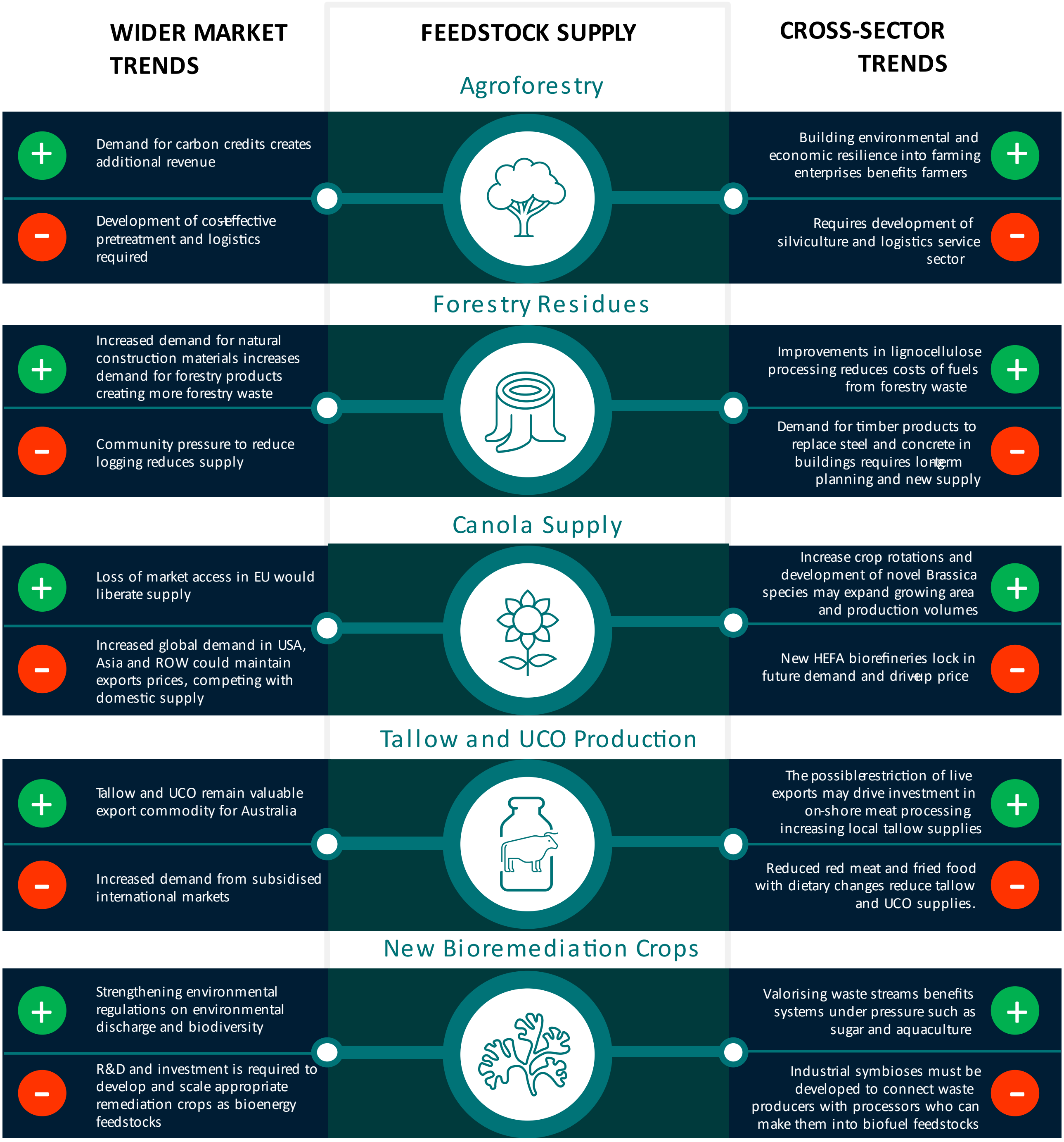
Figure 43. Transport subsector willingness to pay for biofuels (inclusive of a ACCU price)
Source: Deloitte, 2023

Leveraging cross-sectoral opportunities

Strong parallel trends in adjacent sectors can support the development of liquid fuel pathways. For example, the pressure on the red meat industry to reduce emissions is driving behaviour change away from diets rich in red meat. Developing pathways for fuel production from agroforestry can leverage this trend by providing cattle farmers with revenue from lignocellulosic biomass which can provide co-benefits in the form of shelter, animal welfare, soil rehabilitation, biodiversity benefits and carbon storage.

The Australian construction industry is driving action towards replacing emissions-intensive concrete and steel with timber products. Lack of new forestry plantings creates a long-term domestic supply gap, and necessitates offshore sourcing of timber products, thereby slowing the construction of new dwellings. Additional revenue from forestry residues to biofuels can improve the business case for new forest plantings and augment the shift to low carbon building materials.

Other cross-sectoral opportunities can be identified where targeted policies can leverage, augment and accelerate strong parallel trends in adjacent sectors. The figure below (**Figure 45**) shows selected examples of cross-sectoral trends and wider market mega-trends and how they can impact bio-feedstock production. Targeted market intervention can be used to augment parallel trends to capitalise on the potential of new feedstocks for abatement and supply volumes.



Agroforestry

+ Demand for carbon credits creates additional revenue

− Development of cost-effective pretreatment and logistics required

+ Building environmental and economic resilience into farming enterprises benefits farmers

− Requires development of silviculture and logistics service sector

Forestry Residues

+ Increased demand for natural construction materials increases demand for forestry products creating more forestry waste

− Community pressure to reduce logging reduces supply

+ Improvements in lignocellulose processing reduces costs of fuels from forestry waste

− Demand for timber products to replace steel and concrete in buildings requires long-term planning and new supply

Canola Supply

+ Loss of market access in EU would liberate supply

− Increased global demand in USA, Asia and ROW could maintain exports prices, competing with domestic supply

+ Increase crop rotations and development of novel Brassica species may expand growing area and production volumes

− New HEFA biorefineries lock in future demand and drive up price

Tallow and UCO Production

+ Tallow and UCO remain valuable export commodity for Australia

− Increased demand from subsidised international markets

+ The possible restriction of live exports may drive investment in on-shore meat processing increasing local tallow supplies

− Reduced red meat and fried food with dietary changes reduce tallow and UCO supplies.

New Bioremediation Crops

+ Strengthening environmental regulations on environmental discharge and biodiversity

− R&D and investment is required to develop and scale appropriate remediation crops as bioenergy feedstocks

+ Valorising waste streams benefits systems under pressure such as sugar and aquaculture

− Industrial symbioses must be developed to connect waste producers with processors who can make them into biofuel feedstocks

Figure 44. Cross-sectoral and market trends impact on LCLFs
Source: CSIRO, Towards Net Zero 2024

Options for direct investment and intervention

There are a range of policy options for direct intervention to ensure high abatement and long-term economic potential feedstocks are developed and demonstrated. These include grants and other direct investment measures, or loan guarantees, rebates or tax credits to stimulate private investment in pre-commercial opportunities.

8.3 Policy considerations

Australian biomass presents a major opportunity for creating new value and supporting the transition to net zero emissions. To maximise both environmental and economic opportunities from an LCLF sector, and broader value for regional Australia, careful policy intervention should be considered with an awareness of the trade-offs, risks, co-benefits and disbenefits.

Based on multiple analyses, stakeholder consultation and international evidence, both demand-side and supply-side measures are likely to be required to maximise the impact of the industry.

Within supply-side measures it is important to ensure a diversity of feedstocks – this can be done through direct support for lignocellulosic pathways to avoid lock-in to a limited supply of oilseeds.

Support for early investment is important such as co-processing through establishing means for crediting refiners and enabling a growing supply of biomass into refineries.

Existing schemes to support fuel provision in remote Australia could be reformulated to prioritise LCLFs. For example, reform of the Fuel Tax Credit and other mechanisms such as the road user charge can build on increasing industry willingness to pay. Directing the Fuel Tax Credit to support RD could elevate WTP among mining companies to close the cost gap between fossil and renewable diesel.

Prioritising end-use sectors is important for the long-term industry development. Mining and heavy road users will take longer to electrify or find other zero-carbon alternatives, but aviation and maritime will provide the long-term demand for liquid fuel. Policies should be cognisant of the long-term evolution of the industry.

But for maximum abatement potential, the focus of policy should be on developing new and diverse supply of feedstock. It is important to note that the net emissions differences between end-use and fuel products are minimal compared with the abatement outcome of HEFA versus lignocellulosic biomass. The long-term costs of becoming locked into a HEFA pathway will also limit the economic impact and expose Australia to global price competition, while capitalising on our lignocellulosic resource will alleviate price competition and provide a low-cost, large volume foundation for an industry.

8.4 Recommended actions

In addition to creating a supportive policy environment with a balance of demand-side and supply side measures, there are several specific actions that could be considered to enable the LCLF industry to establish and scale.

Ensure new feedstocks and technologies are developed and demonstrated

Without intervention, the market will favour low-cost, mature supply chains such as canola-HEFA, leaving Australia’s large pool of non-food feedstocks, lignocellulosic materials, underutilised Such technology and feedstock lock-ins will likely increase prices in the long term and compromise realisable emissions abatement. It is crucial to de-risk earlier-stage technologies and make them investible for industry. Some options are supply-side measures directly targeting feedstock and investment in demonstrations of new-to-market conversion technologies.

Develop clear enforceable standards for sustainability assessment and support capability

Australian ecosystems are unique, and we are a major exporter of food to the world. A bioenergy industry can have a major positive or negative impact on land use and the environment. Strict sustainability standards and the capacity to measure and report the impact of LCLF value chains likely to be needed. This includes an ongoing capability to track sustainability metrics and verify credentials to provide evidence and advocacy for Australian commodities into international markets.

Establish a National Bioresources Evidence Base

'Australia's fundamental bioresources are under increasing pressure from both climate change and decarbonisation transition, demand from carbon markets, biodiversity commitments, increasing food demand and changing growing conditions. A comprehensive, coordinated, living capability can be established to provide consistent and sustained decision-making for managing Australia's bioresources for long-term sustainability.

Establish a framework to enable co-processing of biofeedstocks in existing refineries

For an early-stage LCLF industry, co-processing of biogenic feedstocks in existing fuel refining pathways has several advantages. These include lower capital investment and lower risk than construction of greenfield biorefineries making them economic at a lower scale without imposing a dramatic increase in bio-feedstock demand. Multiple options exist to enable co-processing and could be considered in more detail to enable investment. Emerging technologies are being developed that enable detailed tracking of carbon from biogenic and non-biogenic sources to ensure abatement goals are being met. These technologies will enable refineries to blend more bio-based feedstocks into their operations over time and make use of existing infrastructure to being building LCLF supplies while new greenfield bio-refineries are under development.

Focus effort on developing LCLFs as a source of demand for green hydrogen

Hydro-processing of biogenic fuels can be optimised to build demand for green hydrogen. Careful design of a regulatory framework can build future green hydrogen capacity and support a power-to-liquids (PtL) industry with potential to grow into an export opportunity.

Communication and demonstration

A successful transition to LCLFs will depend on favourable community response and support from users and OEMs. This can be supported through a coordinated engagement with stakeholders across the value chain from feedstock producers, processors and refiners, fuels uses and their customers on a range of topics including

- Two-way communication efforts to both educate the community about LCLFs and listen to their concerns,

- demonstration of the benefits of modern LCLFs, particularly in contrast to biodiesel and ethanol
- demonstration of new pathways and fuel uses such as production and their performance and engine compatibility in modern trucks and aircraft
- communication of the sustainability frameworks and supporting regulations designed to minimize conflicts between food and feedstock production, land use change and biodiversity protection.

8.5 Future research opportunities

Development and demonstration of high-potential feedstock-technology combinations

To maximise environmental (including abatement and biodiversity) and economic impact, and create opportunities for Australian regions, cost-effective pathways for a range of feedstocks, particularly second generation, lignocellulosic feedstocks and third generation, novel feedstocks should be demonstrated. Conversion technologies of most relevance for Australian conditions exist but are not currently investible due to risk throughout the value chain. Investment in research and demonstration can help to de-risk these technologies and progress to investment stage.

Life Cycle Assessment for each Australian feedstock-technology combination

CSIRO’s work on Australian canola demonstrates unique advantages and potential for lower carbon intensity and induced land use change (ILUC) risk compared with European and other feedstocks. LCAs and ILUC risk assessments for each feedstock and processing pathway should be developed to inform decision-making and capture the maximum value from LCLFs. This requires a deep ongoing capability to continually update and streamline assessments. See section 7.6 for more detail.

An Australian LCLF Clearing House

The UK SAF Clearing House model is an example of effective development, testing, validation and streamlining of new technologies through accreditation for fuel production. A similar Australian facility can test and validate processes, including technologies from international vendors as well as those developed in Australia, in integrated systems to scale-up and pull through investible processes for the market.

Development of Future Farming Systems

A coordinated effort to develop and demonstrate farming system changes can drive feedstock production and ensure maximum co-benefits such as increased resilience and biodiversity. This includes demonstration of low carbon agriculture to enable low CI feedstocks, integrated nature positive agri-energy landscapes that support production of food, fuel feedstock, renewable electricity and biodiversity, and novel feedstocks that unlock marginal land, aquatic systems and intensive fermentation systems.

A National Bioresources Evidence Base and Material Flow Analysis

Growing demands from food, fuel, fibre, mineral processing and carbon offset industries put increasing pressure on bioresources, which also face changing growing conditions. Better data and insights and a living capability to support decision making, like material flow analysis, is needed not only for LCLFs but also to ensure maximum benefit and long-term resilience of Australia’s bioresources.

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102

Appendix - Selected global policies on LCLFs

ICAO classifies policies on LCLFs into three broad categories – supply-side, demand-side or market-enabling (ICAO 2023) (see **Figure 45**).

Supply-side policies seek to ensure that users can access a robust, stable fuel supply and can include policies that address concerns around feedstock availability and support technological investment into conversion of feedstock to fuel. They can be sub-classified as those focusing on feedstock production and those on fuel production. Feedstock-focused policies seek to either increase supply by unlocking new feedstocks or encourage production of existing feedstocks; or they aim to ensure feedstock availability by providing resilience and robustness to current supply. Similarly, fuel-focused policies can enable new production pathways or support the scaling up of existing viable pathways.

Demand-side policies can be sub-divided into mandatory or regulatory, economic or market-based and voluntary. Mandatory policies are enforced though laws and regulations and can often carry economic penalties. On the other hand, economic or market-based demand policies use economic levers to drive uptake of these fuels. However, not all market-based policies are pot sweeteners. Some can influence market levers to favour specific fuels by applying economic penalty measures on fossil-based fuels, either directly through taxes or indirectly as carbon pricing. Voluntary policies offer environmentally conscious individuals and corporations the chance to participate in enabling schemes. These policies usually have a lower impact but serve as a good tool for educating the wider public and thus, driving demand. Some examples include CO_2 emission reduction targets, blending mandates and tax incentives aim to reduce the offtake risk by ensuring a return on investment and providing incentives.

Market-enabling policies are those that fall neither under supply nor demand side. These aim to reduce the burden of doing business and remove barriers to entry, develop platforms for stakeholder engagement and increase confidence in trading fuel and feedstocks. These policies can be further divided into those actively stimulating trade, such as tariff reduction, free trade agreements and similar policies that do not directly focus on fuel trade. These include certification and standardisation of blends and the setting up of dedicated entities monitoring new fuel uptake and commercial deployment through data collection and analysis.

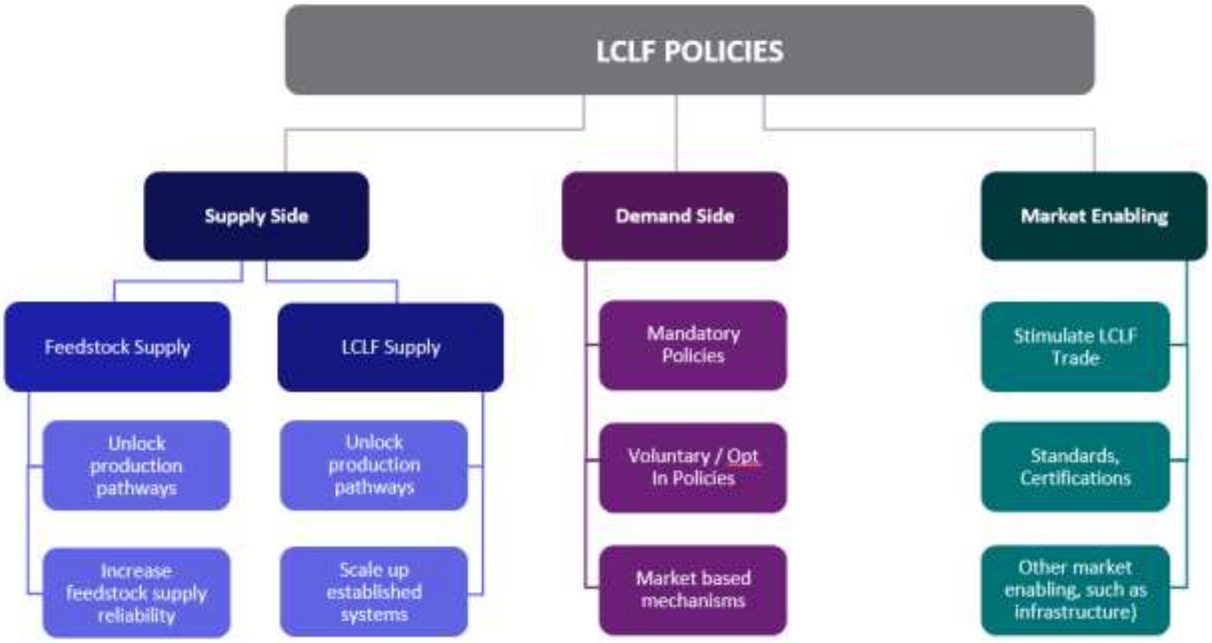

Figure 45: Categorisation of LCLF policies

A summary of the different LCLF policy mechanisms across the globe and their effect on LCLF value chain development and uptake is given below (see Table 9). Detailed descriptions of these policies in provided in below.

In Table 9, major LCLF enabling policies that are in force across the globe are identified and categorized based on whether the policies focus on the supply side, demand side or other market enabling efforts. In the next column in Table 9, the specific type of policy lever is identified, with the fifth column specifying targeted sections within the LCLF value chain. Within the overall value chain, specific policy actions can stimulate the development of new fuels and feedstocks, ensures scale up of low TRL processing pathways and technologies, increases LCLF production through established pathways, or increases LCLF offtake by new and established customer base. Finally, the last column indicates whether the costs associated with a policy are designed to be primarily borne by the private sector the government.

Table 9: Summary of international LCLF policies

Country/ Region	Policy	Policy category	Type	Impact within supply chain	Funding
USA	Inflation Reduction Act 2022	Demand: Market Based	Tax credit and direct grant	New LCLF development, Increased production, Technology Scale up, LCLFofftake	Public
USA	Sustainable Aviation Fuel Grand Challenge	Supply= Comprehensive Market-enabling= Certifications and standardization of process and products + Reducing red tape	Research grants and Loan guarantees	New feedstock developemnt,, Feedstock Scale up ,, Increased LCLF Production, Technology Scale Up,	Public
USA	Renewable Fuel Standard	Demand: Mandatory and Market Based	Tradeable biofuel credits and mandates use	Increased LCLF production, LCLF offtake	Private
USA	Federal Aviation Administration (FAA) Reauthorization Act	Supply:LCLF supply and scale up for the avaiation sector	Research Funding	Increased LCLF Production	Public+ Private

USA	Farm Bill (Agricultural Improvement Act) 2018	Supply: Feedstock production, and LCLF production, and scale up	Loan Guarantees, Grants and Cost Sharing Agreements	Increased Feedstock Production, Increased LCLF Production, Technology Scale up	Public
USA	Executive Order on Tackling the Climate Crisis at Home and Abroad (2021)	Demand: Market-based	Removes subsidies from fossil fuels	Increased LCLF Production, and Technology Scale up	N.A.
EU	ReFuelEU Aviation	Demand: Mandatory	Sets increasingly higher minimum mandates for LCLF blending in the aviation sector	Increased LCLF Production, Technology Scale up	Private
EU	FuelEU Maritime	Demand: Market Based	Sets increasingly ambitious GHG reduction targets for the maritime sector	Increased Feedstock Production, Increased LCLF Production, LCLF Offtake	Private

EU	EU Emissions Trading System (ETS)	Demand: Market-based	Cap and trade framework for emissions that favors LCLFSAF	Increased LCLF Production , LCLF Uptake	Private
EU	Renewable Energy Directive (RED) II	Demand: Mandatory	Sets targets for LCLF uptake	LCLF Offtake	Private
UK	Jet Zero	Demand= Mandatory Supply = LCLF Production Market enabling = certification and approvals	Targets for LCLF blending in the aviation sector Grant funding for Aviation LCLF plants SAF Clearing House for swift LCLF approval for aviation markets	Increased LCLF Production, LCLF Uptake	Public + Private

Descriptions of selected global policies on LCLFs

USA

Inflation Reduction Act (IRA) 2022:

The US IRA 2022 is one of the most significant legal provisions on decarbonisation and transition to a net zero economy. The US IRA 2022 is a demand-side market-focused policy that aims to increase SAF demand by reducing price differentials in the aviation fuels market yet does not impose a penalty on stakeholders who do not invest in or utilise SAF.

This Act establishes new tax credits for SAF and other renewable fuels and extends the life of previous incentives up to 2024 (The White House 2023) . The earlier credits were valued at USD 1.00 per gallon for blending renewable diesel with fossil diesel. Additionally, the Act creates a new SAF-specific tax credit (SAF Credit) through 2024, which starts at USD 1.25 per gallon, with additional amounts of up to USD 0.50 for reductions in GHG emission given that the fuel producers and importers are registered with the US Department of the Treasury. The Act also sets up the Clean Fuel Production Credit (CFPC) with a higher USD 0.35/gallon of renewable aviation fuel credit which is multiplied by 5 to become a bonus credit of USD 1.75/gallon if the production facility meets certain requirements. The credit is also multiplied by an emissions factor to further incentivise fuels with a higher decarbonisation potential.

Furthermore, this Act provides the Department of Transportation 244.5 million for a grant program for projects that produce, transport, blend, or store sustainable aviation fuel as defined by the act f, and another 46.5 million to develop, demonstrate, or apply low-emission aviation technologies.

Sustainable Aviation Fuel Grand Challenge (SAF-GC) 2021:

SAF-GC is an initiative between multiple US government departments including the Department of Energy (DOE), the Department of Transportation (DOT), the Federal Aviation Authority (FAA) and the Department of Agriculture (USDA) (US DOE, US DOT and USDA 2021). The SAF-GC Roadmap includes inputs from stakeholders like producer groups (such as Advanced Biofuels Association), and consumer groups (such as Airlines for America) as well as national labs and academia. These insights allowed for more effective planning of the Research, Development, Demonstration and Deployment (RDD&D) activities under the SAF-GC (US DOE, US DOT et al. 2022).

The SAF-GC clearly articulates the goal of producing 3 billion gallons of SAF annually by 2030, ramping up to 35 billion gallons by 2050, which is projected to be the total US SAF demand by then. Developed as a comprehensive strategy backed by an integrated government roadmap for coordinated RDD&D activities, the SAF-GC covers all areas of the feedstock-to-SAF supply chain, especially in the following areas:

- Feedstock Innovation
- Conversion Technology Innovation
- Building Supply Chains
- Policy and Valuation Analysis
- Enabling End Use, and
- Communicating Progress and Building Support

In addition to funding projects on SAF feedstock and conversion technology, other functions outlined under the 2030 target, include supply-side incentives such as:

- USDA support for American farmers on climate-smart agricultural research and practices such as biomass feedstock genetic development, sustainable crop and forest management at scale, and post-harvest supply chain logistics. USDA will also support fuel producers with carbon modeling components of SAF feedstocks.
- DOE Bioenergy Technologies Office (BETO) will provide USD 35 million for developing feedstock and algae technologies and an additional USD 61 million to advance biofuels and support reduced cost of SAF pathways.
- DOE will offer up to USD 3 billion in loan guarantees to commercial-scale SAF projects that meet certain program requirements.

The SAF-GC will also support market-enabling efforts such as:

- Collaboration between the US Environmental Protection Agency (EPA) and DOE to expedite the regulatory approval process for newly developed fuels and feedstocks.
- US Department of Defense (DOD) funding to certify the use of new and existing approved, commercial SAF pathways for military use.
- FAA awards to the Aviation Sustainability CENTer (ASCENT) university center of excellence to support SAF evaluation and safety testing.
- DOE funding for developing technologies to bridge data gaps in the biofuel supply chain by quantifying feedstock-related GHG emissions and soil carbon dynamics at the field-level.

US DOT published the 2021 Aviation Climate Action Plan and among other net zero transition targets has affirmed the need for SAF uptake goals for 2030 and 2050 (US Federal Aviation Administration 2012). It also recognises the following as Current Actions:

- Continued support for RD&D activities for SAF feedstocks, conversion, testing, analysis and coordination with industry through the Commercial Aviation Alternative Fuels (CAAFI).
- Development of a multi-agency roadmap to implement SAF-GC and to specifically investigate the following:
    - Reducing SAF costs through expanded feedstocks and incentives for conversion.
    - Ensuring SAF sustainability, through development of low ladn use feedstocks, production co-benefits and demonstration of sustainable production systems.
    - Expansion of SAF supply and end use through SAF infrastructure development, commercialisation support for regional feedstock and fuel production.
- Ensure passing of proposed SAF tax credit in the now passed IRA 2022.
- Stimulate purchase of SAF by end users including the US Military.

Renewable Fuel Standard (RFS):

RFS was initially established under the Energy Policy Act of 2005 and expanded under the Energy Independence and Security Act of 2007 and requires transport fuel sold in the US to contain a minimum volume of renewable fuels. These are called the Renewable Volume Obligations (RVOs) that fuel blenders, refiners and importers must meet. Their compliance is tracked through Renewable Identification Numbers (RINs) that can also be traded.

SAF qualifies for RINs and as RINs production is based on energy density, SAF produces 1.6 RINs per gallon of SAF produced compared to 1 RIN per gallon of corn ethanol. While it may appear to incentivize SAF production, renewable diesel is allocated a higher RIN (1.7 RIN per gallon), which makes it necessary to have other stackable incentives to allow SAF to compete with renewable diesel.

Federal Aviation Administration (FAA) Reauthorization Act of 2018:

The FAA Re-authorization Act of 2018 empowers the FAA to allocate research funding towards Continuous Lower Energy, Emissions and Noise (CLEEN) technologies, including SAF. One of its greatest advantages is to encourage research collaboration among entities, specifically with NASA to develop alternative fuels and provide funds to initiate cost-sharing cooperative programs for the development, maturation, and testing of certifiable CLEEN technologies, including fuels.

Farm Bill (Agricultural Improvement Act) of 2018:

The 2018 Farm Bill builds on the Farm Security and Rural Investment Act of 2002, to identify and affirm SAFs as eligible biofuels in the 2002 Act that includes provisions for their development.

The Farm Bill makes SAF eligible for funding and support through the US Government's bioenergy programs and thereby, extends funding for feedstock development to include dedicated energy crops as well as other feedstocks to ensure reliable supply for biofuel production.

The 2018 Bill also provides funding for the development, construction, and commercial demonstration of biorefineries and assistance in increasing production and efficiency through loan guarantees, cost-sharing agreements and grants. It also provides grants to inform the public and public institutions about the benefits of biofuels including SAFs to enhance uptake H.R.2 - 115th Congress (2017-2018): An act to provide for the reform and continuation of agricultural and other programs of the Department of Agriculture through fiscal year 2023, and for other purposes. (2018, December 20). https://www.congress.gov/bill/115th-congress/house-bill/2/text).

Executive Order on Tackling the Climate Crisis at Home and Abroad (2021):

While not a direct policy for biofuels, the Executive Order lends broader US Government support to climate change initiatives across a range of sectors including aviation. This includes efforts to ensure the removal of subsidies for fossil fuel production to improve economic viability of biofuel production (including SAF). The order directs US Federal agencies to take actions to address climate change, including reducing emissions from the aviation sector, and specifically directs the Secretary of Agriculture to support the development of bioproducts and biofuels.

European Union (EU)

ReFuelEU Aviation Initiative (2023):

The ReFuelEU Initiative is a part of the EU Fit for 55 package that outlines the Union's overall goals to transition to net zero emissions. The Initiative is specific to the aviation sector and sets the standard for SAF uptake at all airports operating in the EU.

The Initiative encourages increase in SAF uptake by setting minimum SAF blending mandates for conventional jet fuel, starting with 2% in 2025, and then to 5%, 20%, 32%, 38% at every five-year intervals , and ultimately reaches 63% by 2050.

Additionally, within the share of SAF supplied at the airports, the initiative also set the targets for synthetic fuels starting from 0.7% in 2030 and then rising to 5%, 8%, 11% every 5 years, and ultimately to 28% in 2050. The share of synthetic fuels can be used to meet the SAF mandates, but by separating the subset for synthetic fuels, there is an increased impetus to ensure a variety of feedstocks and pathways for SAF are unlocked. (EU Parliament and Council of the EU 2023).

The initiative also obligates EU airports to ensure that reliable infrastructure is set up and maintained to receive, store and refuel aircraft with SAF and SAF blends, while also developing a Union labelling system for aircraft operators' environmental performance. This allows customers to make informed choices on flights and to put additional positive momentum on greener flights.

At a larger scale, this has several favorable derivative effects including (European Union Aviation Safety Agency and European Environment Agency 2022):

- Research focus of different EU member states into different pathways to unlock different SAFs based on local economies.
- Setting up of stricter national SAF mandates by member states to ensure competitiveness of local carriers.
- Corporate targets by European airlines to ensure attractiveness to customers.
- Significant surety in the feedstock and conversion markets given the reliable SAF demand and uptake due to increasing mandates.

EU Emissions Trading System (EU ETS):

Since 2005, the EU ETS has been a cornerstone cap and trade policy focusing on decarbonising European economies and included the aviation sector since 2012.

The trading system allocates emission allowances to airlines operating in the EU by requiring the airlines to account for their emissions. These allowances are tradeable and airline companies that are unable to meet their emissions allowance can opt to buy them from other operators with a surplus or face heavy penalties.

The system incentivises the use of SAF by attributing zero emissions to SAFs that comply with the Renewable Energy Directive (RED) regulations and requirements (see following sub-section). This means that increasing SAF usage can dramatically decrease aircraft operators' reportable emissions, allowing them to sell surplus allowances on the market, while also meeting the standards and targets set in the ReFuel Initiative (European Environment Agency, European Aviation Safety Agency and Eurocontrol 2019).

Renewable Energy Directive (RED) II (2018/2001/EU):

The RED II can be considered as a precursor to the recent mandates set up by the EU. The Directive initially set the targets for the overall use of renewable energy across the EU, including explicit provisions for biofuels with a “voluntary opt-in” for the aviation sector. RED requires that 14% of an EU member state’s transport energy to be sourced from renewable resources by 2030. The method for calculating contributions towards the renewable energy targets are skewed to favour SAF by applying a multiplier of 1.2 for each unit of SAF supplied.

The Directive also encourages the production of advanced and synthetic fuels that are derived from sources other than food or feed-competing crops, and codifies the type of biofuels, their energy content and decarbonisation potential in the EU legal frameworks for use by later policies.

United Kingdom

Jet Zero Strategy (2022):

The UK Government indicated its shift towards SAF though the Jet Zero Strategy, which aims to be a comprehensive net zero strategy for the aviation sector. This policy sets the net zero targets up to 2050 based on three fundamental pillars:

1. Increasing SAF demand in the UK
2. Initiate a UK SAF industry, and
3. Creating long term investment streams for sustainable SAF supply

To generate sustainable SAF demand, the UK Jet Zero Strategy calls for a 2% SAF usage instead of petroleum-based jet fuel by 2025. This mandate then increases to 10% in 2030 and 22% in 2040. Recognising the need for diverse feedstocks and technological pathways to develop a long term SAF supply, the Jet Zero Strategy manages contributions from HEFA to a maximum of 100% in 2025 and 2026, which progressively decreases to 71% in 2030 and 35% in 2040. An additional power-to-liquid fuel obligation is included that rises from 0.2% in 2028 to 3.5% in 2040.This will ensure that a wider array of SAF pathways is unlocked before 2040 and the risk of feedstock-based path dependency in future SAF supply is reduced.

Since 2014, the UK Government is also providing funds worth GBP 171 million as grants to support the development of advanced fuels and included an additional GBP 135 million to reach its target of ensuring that at least five SAF plants are under construction by 2025. The grant funding can be allocated to demonstration and commercialisation projects. The UK Government will also fund a SAF Clearing House to accelerate SAF development by aiding testing and approval of new conversion pathways.