Public Report

Feasibility Study of

Australian feedstock and production capacity to produce sustainable aviation fuel

June 2013

QANTAS
Spirit of Australia

SINCLAIR KNIGHT MERZ SKM

SkyNRG
Sky Energy | The Fuel Future

AltAir Fuels

SOLENA FUELS

Plant Cell Walls
ARC Centre of Excellence

Public report

Document title:	A feasibility study of Australian feedstock and production capacity to produce sustainable aviation fuel
Version:	Public report
Date:	June 2013

LIMITATION

1. The Executive summary and Sections 1, 10 and Appendix A were researched and written by Qantas Airways Ltd. All research credits, errors and omissions should be attributed to Qantas Airways Ltd.
2. Section 2.2 relating to domestic feedstock were researched and written by bio-fuel aviation consultants AltAir, with assistance from the ARC Centre of Excellence in Plant Cell Walls at the University of Adelaide. All research credits, errors and omissions should be attributed to AltAir.
3. Sections 2.3 and 3.3 relating to imported feedstock and marginal land were researched and written by bio-fuel aviation consultants SkyNRG. All research credits, errors and omissions should be attributed to SkyNRG.
4. Sections 3.2 and 3.4 relating to emerging feedstock and pathways were researched and written by Qantas Airways, SKM and the ARC Centre of Excellence in Plant Cell Walls. All research credits, errors and omissions should be attributed to Qantas Airways Ltd.
5. Sections 5.3 to 5.7, 6 and 7 relating to pre-treatment, manufacturing, supply and distribution were researched and written by The Shell Company of Australia Limited. All research credits, errors and omissions should be attributed to The Shell Company of Australia Limited.
6. Sections 5.2 and 8 were researched and written by SKM. All research credits, errors and omissions should be attributed to SKM.
7. Section 9 relating to the Fischer Tropsch pathway was researched and written by Qantas Airways, with assistance from Solena Fuels. All research credits, errors and omissions should be attributed to Qantas Airways Ltd.

Acknowledgements

The study partners would like to thank the following individuals and organisations for their assistance with the report.

From Qantas Airways Ltd (www.qantas.com.au), the project team of Ben Heraghty, Jean Elverton, John Valastro, Flyn Van Ewijk, Louise Burgher and Jenny Branighan, as well as Daniel Dott, Matt Simmons, Justin Merrell, Gareth Evans, Jane Harley, Tino La Spina, Euan Robertson, Megan Morris and Tom Woodward.

This project is supported by the Australian Government through the Australian Renewable Energy Agency (ARENA).

From The Shell Company of Australia Ltd (www.shell.com.au), the project team of Dr Lucas Rye, Catherine Ellis, Joe Kurczycki, Stephen Duniam, Warren Shirley, Peter Drohan, Linda Burke, Andrew Pearce, Matthew Fewster, David Norman, as well as Nikki Gerling, Margaret Kennedy, Edwina Pribyl, and Craig James. From Shell International Petroleum Co Ltd, Dr Alexandra Ebbinghaus, Dr Nigel Tait and Dr Mike Farmery. From Shell Global Solutions International Co Ltd, Dr Ries Janssen. From Shell Global Solutions (UK) Co Ltd, Dr Joanna Bauldreay.

From Sinclair Knight Merz (www.globalskm.com), the project team of Paula Giles, Ariel Hersh, Walter Gerardi, as well as Michael Goldman, Steve Manders, Dr Roslyn Prinsley and Dr Darron Cook.

From AltAir (www.altairfuels.com), Tom Todaro and Evan Smith for sharing their deep knowledge of feedstock.

From the ARC Centre of Excellence for Plant Cell Walls (www.plantcellwalls.org.au), Professor Geoff Fincher, with contributions from Dr Meera Verma (Headland Vision) and Associate Professor Wendy Umberger, Kerry Bormann and Anna Finizio (University of Adelaide).

From SkyNRG (www.skynrg.com), Maarten Van Dijk, Misha Valk and Dirk Kronemeijer for their advice and industry knowledge on all things SAF.

From CSIRO (www.csiro.au), Dr Victoria Haritos for expert advice and assistance.

From Solena Fuels (www.solenafuels.com), Brian Miloski and Angel Prado for sharing details of their business model and the GreenSky London project.

The study team would also like to thank all those industry participants who contributed to this study with comments, facts, figures and general assistance, as detailed in the References section.

Contents

Executive summary

Background

The aviation industry is pursuing the development of sustainable aviation fuel for environmental and economic reasons. Amongst the various means for reducing carbon emissions from commercial aviation, Qantas (like many other airlines), has identified Sustainable Aviation Fuel (SAF) as having the potential to make a significant contribution. However, while there is significant demand for SAF in Australia and across the world, there is no established supply chain capable of producing certified SAF at commercial scale. As this report demonstrates, there are currently many challenges to overcome before this potential can be realised using certified SAF pathways.

In Australia, government, industry and research parties have conducted studies[1] to examine the potential for bio-derived sources of aviation fuel. This study has extended these previous investigations and reports by bringing together key players from each segment of the supply chain to fully explore the conditions needed in the Australian market. It draws on the detailed industry knowledge of the industry partners along the relevant SAF value chain to investigate the practical and commercial conditions needed for a SAF industry in Australia.

To investigate the conditions under which an Australian-based SAF industry could be commercially feasible, Qantas formed a joint study team with The Shell Company of Australia Limited (Shell) and study partners, Sinclair Knight Merz (SKM), AltAir, the Australian Research Council (ARC) Centre of Excellence in Plant Cell Walls at the University of Adelaide and SkyNRG. The project scope was specifically designed to review the commercial and long-term viability of SAF, using certified refining technology and infrastructure in Australia. Therefore, the project partners focused exclusively on the production of SAF from hydroprocessed natural oils and animal fats (the HEFA pathway[2]). To augment understanding of the production of SAF from the certified Fischer Tropsch (FT) pathway, Qantas – independent of the main study partners – commissioned Solena to provide industry insights.

Key findings

Consistent with the previous Australian research this study found that the establishment of a SAF industry in Australia is **technically** feasible. However, to effectively unlock the opportunity that SAF represents there are significant challenges to achieve **commercial** feasibility with regard to the HEFA and FT pathways. This report explores the key elements of this commercial challenge.

Natural oils to fuel (HEFA pathway)

The study partners assessed the commercial viability of SAF using a 3,000 tonnes-per-day reference facility, which would produce approximately 20,000 barrels of renewable hydrocarbons (diesel, SAF, naphtha and refinery gas) per day. Capital expenditure is approximately A$1 billion (2012), which is consistent with industry cost values when considering that the construction of additional, as opposed to the conversion of existing, hydroprocessing equipment is required in Australia. Depending on the process configuration and bio-refinery size, the SAF fraction was between 5% and 35% of Qantas' current domestic fuel demand when certified in a 50:50 blend.

From a technical perspective, the conversion of natural oils and animal fats into renewable fuels using hydroprocessing technology is technically feasible and is already occurring at commercial scale in several bio-refineries around the world. However, these bio-refineries target renewable diesel production for subsidised markets, only producing SAF on an opportunistic basis, if at all. The key findings which impact the commercial viability of a SAF manufacturing industry and supply chain in Australia include:

1. **Feedstock economics:** The main commercial barrier to developing a hydroprocessed natural oil and animal fat-based industry in Australia is that the price of feedstock is generally higher than the price of unsubsidised end products, such as diesel and jet. Under these conditions, the economics of a SAF value chain are not viable.

---

[1] CSIRO Sustainable Aviation Fuel Road Map "Towards establishing a sustainable fuels industry in Australia and New Zealand" May 2011; Advanced bio-fuels study: strategic directions for Australia – Appendix, L.E.K Consulting, Dec 2011

[2] Hydroprocessed Esters and Fatty Acids

2. **Feedstock volume:** Although in theory there is enough natural oil volume in the total Australian market to supply the reference bio-refinery, in practice, there is very limited rateable domestic feedstock currently available, at the right price. The available volume of natural oils from existing feedstock and land availability is therefore insufficient to support a significant SAF industry today. The study also found that imported commodity vegetable oils would be difficult to rely upon for SAF over the medium to long term.
3. **Feedstock sustainability:** The preference of the study partners was to maximise the use of non-food competing feedstock, and to avoid feedstock sourced via unsustainable land use or that breach human rights, consistent with the sustainability practices of the key study partners. In general, sustainable feedstock is in very short supply and attracts a premium to the market price.
4. **Pricing competitiveness:** The study identified a clear correlation between natural oil prices and crude oil price. Traditionally, when the price of crude oil goes up, the perception has been that bio-fuels become more competitive. The study observed that natural oils prices are correlated to crude oil prices, so both products tend to move in the same direction. Therefore, at least for the case of bio-fuels derived from natural oils, the increasing price of crude oil tends to lead to increases in the price of SAF.
5. **Manufacturing:** While the final bio-fuel products can be integrated into existing supply and distribution infrastructure, significant modifications are required to current refineries to process natural oils and animal fats to aviation fuel. A brownfield (existing) refining site is the lowest cost option but still represents a significant capital outlay. In addition, most Australian refineries have insufficient hydrogen to process natural bio-oil or tallow feedstock. Therefore additional hydrogen must be manufactured onsite, which adds significant capital and operating cost.
6. **Diesel versus SAF:** Australian natural oils and tallow feedstock naturally produce a diesel product. Converting diesel to SAF reduces the economic return of the bio-refinery due to increased production of lower value products (i.e., naphtha and gas).
7. **Policy:** Grants provided for bio-diesel and renewable diesel production under the *Energy Grants (Cleaner Fuels) Scheme Act 2004*[3] reinforce the techno-economic tendency towards diesel, and thus further incentivises production towards diesel rather than SAF.

Consequently, to establish a commercially viable SAF manufacturing industry and supply chain in Australia, the following conditions would need to exist:

1. Access to substantial and rateable **volumes** of existing natural oil and/or tallow feedstock at significantly less than current market **prices**;
2. The ability to ramp up emerging and non-food domestic feedstock production programs to provide rateable feedstock volumes at attractive prices, which reflect a weaker price correlation between feedstock and crude-oil; and
3. A balanced **policy** environment that incentivises the production of all renewable transport fuels equally.

The study partners recognise that implementing these conditions would require careful consideration of the implications for other sectors of the economy (e.g., food production, land use) to ensure a balanced and sustainable outcome could be achieved for SAF without unintended distortions.

Waste to fuel (FT pathway)

Conversion of gas- and coal-based feedstock into hydrocarbon products (e.g., fuels, waxes and chemicals) has been commercialised using the Fischer Tropsch (FT) process. Production of renewable hydrocarbons from biomass (including municipal waste) feedstock via FT is theoretically possible; however, this has not been demonstrated at scale.

Although a waste-to-fuel FT plant in Australia has potential, key assumptions remain unproven. This study examined a specific project for Australian conditions based on the **British Airways-Solena GreenSky London FT** venture, which uses municipal solid waste (MSW) as feedstock. Capital expenditure for this project is approximately US$500 million (2012 figures), assuming a brownfield site. The renewable plant would produce

[3] The Energy Grants (Cleaner Fuels) Scheme Act 2004 provides excise relief for producers and importers of renewable diesel and biodiesel whereby excise is first paid and then reimbursed in the form of a grant.

approximately 40% SAF, 40% diesel and 20% naphtha. This is equivalent to 1,000 barrels of SAF per day, or 5-7.5% of Qantas' current domestic fuel demand when certified in a 50:50 blend.

Application of the equivalent FT process components to the Australian context has determined that a similar project may have potential in Australia, but as with the HEFA pathway, there are a number of conditions that would need to be satisfied for the pathway to achieve commercial feasibility:

1. **Technology scale up:** Successful scale up of the waste-to-liquid-based FT pathway from laboratory to commercial scale
2. **Waste supply:** Ability to negotiate with Australian waste companies to receive payment for long-term (greater than 10 years) waste supply agreements
3. **Appropriate site:** Ability to utilise a brownfield site with appropriate utilities in relative proximity to high waste volume sources in Sydney or Melbourne

Policy environment

While the intent of this study was not to conduct an in-depth analysis of government policy, a number of the challenges identified do raise important policy considerations for government, particularly in relation to feedstock supply and production incentives. Primarily, the study identified the importance of a supportive policy environment in facilitating the development of the SAF industry in Australia. Facilitating such an environment should be carefully considered by the Australian Government and be complementary to other policy imperatives at Federal and State government levels.

Opportunities

The short-term opportunities for SAF in Australia are to focus on **improvements in the feedstock economics** of the HEFA pathway and the **technology readiness** of the waste-to-fuel FT pathway. In addition, in the medium term, there is a significant opportunity to explore the feasibility of next-generation pathways that are likely to be certified by the global standards organisation ASTM[4] in the near future. As identified by this report and previous reports, emerging pathways have the potential to involve feedstock that are cheaper, more plentiful and more sustainable than natural oil feedstock, have lower capital expenditure than FT, and in which Australia has a significant advantage compared to the rest of the world.

In a similar manner to this study, future studies (e.g., supported by the Australian Initiative for Sustainable Aviation Fuels or AISAF)[5] might involve key players across the supply chain to assess the practical and commercial conditions under which emerging pathways can lead to the establishment of viable SAF value chains.

[4] www.astm.org

[5] www.aisaf.org.au

1. Setting the scene

1.1 Context

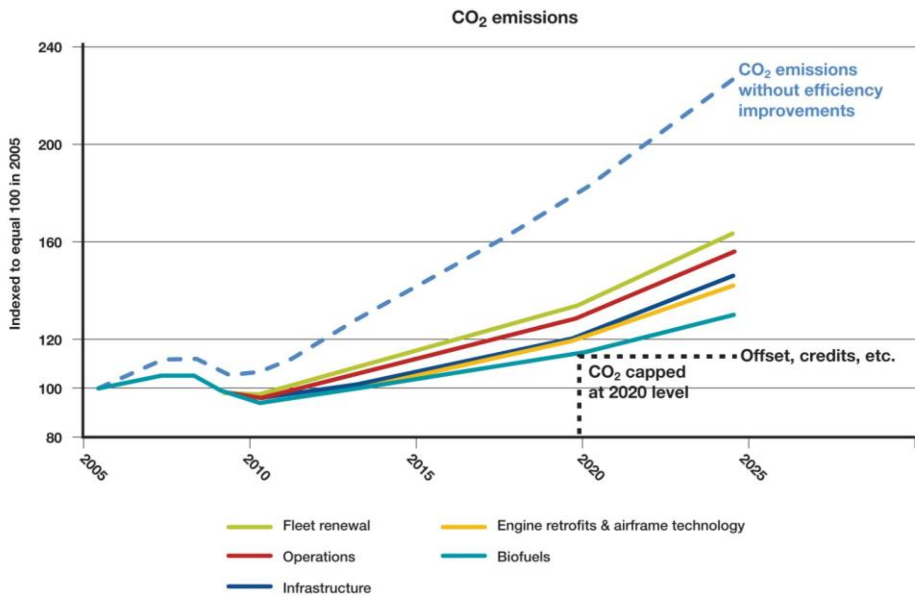
Jet fuel, commonly known as Jet A or Jet A-1, is the standardised product used to power today's commercial aviation industry. The main specifications controlling civil-grade jet fuel quality are the United Kingdom (UK) specification, DEF STAN 91-91, and the ASTM specification, D1655. The underlying commodity used to manufacture jet fuel has traditionally been conventional crude oil feedstock. Over the past decade, increased economic, supply and environmental pressures have led the aviation industry to focus on the development and certification of aviation fuels manufactured from alternative feedstock. To date, commercial quantities of alternative aviation fuel have been manufactured from both coal and natural gas using the certified coal-to-liquid (CTL) and gas-to-liquid (GTL) processes, respectively. However, no biomass-derived alternative aviation fuel has been produced at commercial scale.

From an economic perspective, the aviation industry's reliance on a single, non-renewable product has raised concerns over future supply security and operational costs. Fuel purchases account for approximately 20-50% of an airline's total expenses, with fuel price volatility and increases representing a considerable commercial challenge.

From an environmental perspective, the commercial aviation sector currently contributes 2-3% of total anthropogenic (human-made) carbon emissions. Although relatively small, when considering projected industry growth of approximately 5% per annum[6] and diversification by other industries to lower carbon fuels (e.g., liquid natural gas (LNG) for heavy road transportation), aviation's contribution to global carbon emissions is expected to come under increased pressure.

The International Air Transport Association (IATA) has set a global aviation target of carbon neutral growth by 2020 using a variety of initiatives as shown in Figure 1. IATA has also set a target for reduction of aircraft carbon emissions of 50% by 2050 (based on 2005 carbon emission levels). In addition, Australian domestic aviation is subject to a carbon price from July 2012 of A$23 per tonne, with Qantas Group 2012/13 domestic carbon liability estimated at approximately A$110 million, and total cost to aviation in Australia estimated at A$165 million (2012/13 FY).[7]

Figure 1: IATA: Carbon neutral growth by 2020



Source: IATA (2009)

---

[6] IATA Airline Industry Forecast 2012-2016 http://www.iata.org/pressroom/pr/pages/2012-12-06-01.aspx; Airbus Global Market Forecast http://www.airbus.com/company/market/forecast; Boeing: Current Market Outlook http://www.boeing.com/boeing/commercial/cmo/

[7] Asia Pacific Equity Research 2011, Australian Carbon Pricing – Quantifying the Impacts on Company Earnings Under Various Carbon Pricing Scenarios, JP Morgan.

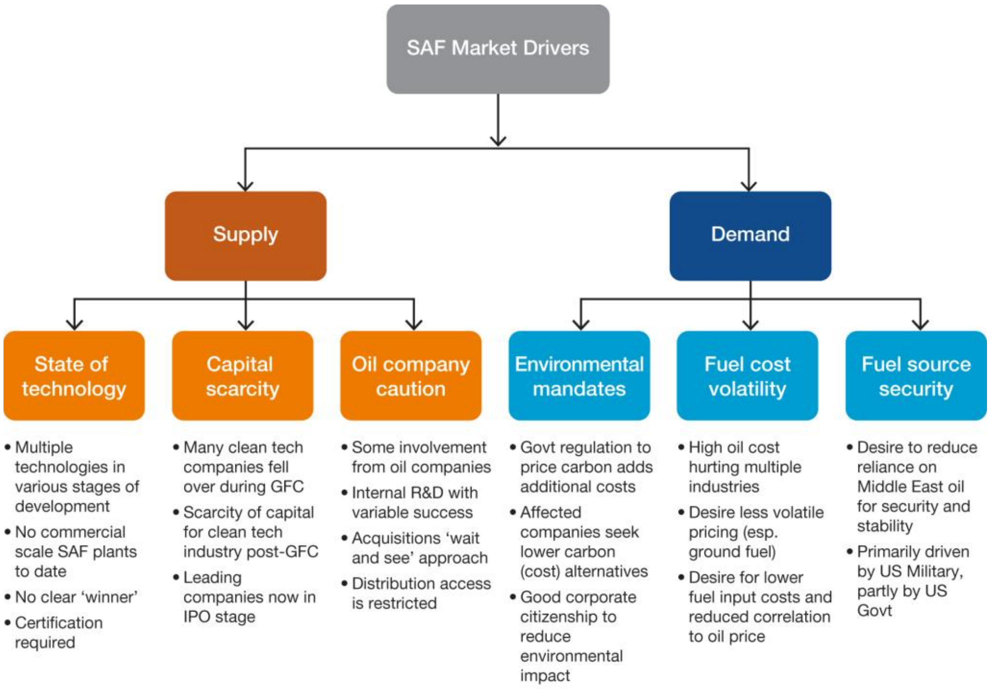
As Figure 1 shows, aviation industry emissions will rise significantly if emission reduction levers available to the industry are not utilised. While fleet renewal and infrastructure are important levers to reduce carbon emissions, fleet choices are generally driven by cost, network, capacity and growth factors, rather than carbon reduction. Fleet and infrastructure decisions also take many years and billions of dollars in investment to deliver results. Operational levers such as weight reduction, aerodynamic efficiency (e.g., winglets), fuel efficiency, ground practices and air traffic management deliver more immediate results. However, these initiatives tend to be smaller and incremental, often with significant dependencies on third parties such as regulators or manufacturers.

SAF has been identified by IATA and Qantas as the lever most likely to achieve significant and sustainable aviation carbon emissions reduction. In recognition of this, in June 2009, IATA set a target of 10% of all aviation fuel to be SAF fuel by 2017.

1.2 Industry drivers

While there is significant demand for SAF in Australia and across the world, there is no established supply chain capable of producing certified SAF at commercial scale. As Figure 2 outlines, there are multiple supply and demand drivers involved in the market, with different weightings in each region or country.

Figure 2: SAF industry drivers



Source: Qantas (2013)

One of the key global drivers has been the US military and its desire for supply security in relation to energy. The US military has been the major financier of early stage alternative fuels for flight testing along a number of different pathways. The US Department of Defense has set a goal of 25% of energy needs from renewables by 2025. In particular, the US Navy has been a key driver and tester of certification for the HEFA pathway and is continuing its innovation drive in multiple pathways in partnership with the US Department of Energy with significant grant programs.[8]

In the EU and Australia, the primary driver has been to mitigate the cost of carbon schemes. In response to an increasing number of carbon schemes around the world[9] SAF is recognised in aviation as a 'game changer' in carbon liability reduction, as aviation's contribution to global carbon emissions is expected to increase with

[8] "Aviation and military bio-fuels: new thinking on finance and fuels", Bio-fuels Digest, 8th Feb 2012, "Inside the Military's Clean Energy Revolution", Atlantic Monthly, 27th Feb 2013

[9] At the time of writing there were approximately a dozen carbon schemes either in planning or operation, including in Europe, New Zealand, Australia, California, Alberta, Shenzhen, South Korea and Japan.

global aviation growth, and therefore come under increasing pressure. In recognition of this, the International Civil Aviation Authority (ICAO) has been working with IATA to build a global market based measure as a platform to achieve its aim of carbon neutral growth for aviation by 2020.[10]

1.3 Aviation fuels

The global nature of the aviation industry means sustainable aviation fuel must be “drop-in” compatible with existing engine, aircraft and fuel distribution systems. Development of a fuel that is incompatible with these systems would result in considerable cost (e.g., aircraft, engine and fuel distribution system modification and duplication) and risk. SAF must also be certified by a representative industry body before the sector can begin operating commercial flights. The certification process involves extensive fuel property, component performance and compatibility testing. The instrument for certification of SAF is ASTM D7566[11].

There are only two ASTM-approved technology pathways to produce certified jet fuel for use in commercial aviation from alternative feedstock. D7566 Annex 1 outlines certification requirements for the Fischer Tropsch (FT) hydroprocessed Synthesised Paraffinic Kerosene (SPK) pathway which produces the product FT-SPK. Annex 2 outlines requirements for the Hydroprocessed Esters and Fatty Acids (HEFA) pathway which produces the product Hydroprocessed Renewable Jet (HRJ) fuel, also known as Bio-Synthetic Paraffinic Kerosene (Bio-SPK).

The ASTM D7566 specification limits the fraction of SAF able to be used in a jet engine to 50 per cent (by volume)[12], the balance being conventional jet fuel derived from crude oil. Unlike ethanol or bio-diesel, Bio-FT and Bio-SPK are chemically identical to hydrocarbon molecules found in conventionally refined products. Therefore, once blended and certified, these products act as a ‘drop-in’ fuel, preventing additional cost and risk.

Figure 3 outlines progress for each of the SAF pathways towards ASTM approval. While the study examined prospects for other certification pathways to SAF at a high level, in the absence of certainty around these technology pathways, the focus of the study was on existing certified pathways.

Figure 3: Technology certification pathways and the ASTM process

Status	Class	Process	Feedstock
Completed			
Annex A1	FT SPK*	FT derived SPK	Coal, natural gas, biomass
Annex A2	HEFA SPK	Hydroprocessed Fats and Oils derived SPK	Triglyceride oils
In the approval process			
	FT SPK**	FT derived SKA	Coal, natural gas, biomass
	ATJ SPK	Fermentation alcohol, oligomerized and hydrated (ATJ) derived SPK	Sugar, alcohol
In development			
	ATJ SKA	ATJ derived SKA	Sugar, alcohol
	CH SKA	Hydrothermal cracking and cyclization derived SKA	Triglyceride oils
	CRJ SPK	Catalysis, oligomerized and hydrotreated derived SPK	Sugar, alcohol
	DSHC SPK	Direct fermentation to SPK	Sugar
	HEFA SKA	HEFA derived SKA	Triglyceride oils
	HDCJ SKA	Hydroprocessed depolymerized cellulose derived SKA	Lignocellulose
	SAK***	Catalysis to SAK	Sugar, alcohol

Source: IATA, Report on Alternative Fuels, 2012[13]

Notes: * FT SPK Synthetic paraffinic kerosene, ** FT SPK Synthetic kerosene with aromatics, *** SAK Synthetic Aromatics, kerosene boiling range

[10] Reuters, “Airline industry leans toward global carbon offset scheme”, 13 May 2013

[11] Fuels approved through ASTM D7566 meet the United Kingdom jet fuel specification (Def Stan 91-91).

[12] In practice the volume of SAF may be limited to less than 50% due to the composition of blend components (Starck et. al. ‘New Route for Increasing the Aviation Alternative Fuels Production and Optimizing the Biomass Usage: Focus on HRJ’, IASH, 2011)

[13] SKA refers to Synthetic Kerosene with Aromatics whereas SPK is Synthetic Paraffinic Kerosene without Aromatics. ATJ stands for Alcohol-to-Jet

Box 1: Renewable diesel vs. bio-diesel vs. ethanol

It is important to differentiate between the products bio-diesel, renewable diesel and ethanol blended petroleum that are used for road transport. These concepts are important because they heavily influence the market dynamics, production landscape, technology choice and policy treatment of SAF in Australia.

Bio-diesel refers to the product resulting from the simple process of transesterification. In this process alcohol is used as a reactant with natural oils (triglyceride) in the presence of a catalyst. A methyl ester (biodiesel) and glycerol are produced. In the transesterification process the oxygen atoms are not removed from the finished bio-diesel. Bio-diesel is therefore not the chemical equivalent of a hydrocarbon and importantly it cannot be used as 'drop-in' fuel with existing infrastructure. The transesterification process is significantly cheaper than hydroprocessing in terms of capital expenditure and operating cost. In Australia, bio-diesel is classified as bio-fuel and attracts 38c per litre per the Energy Grants (Cleaner Fuels) scheme.

Renewable diesel is a product that results from hydroprocessing of natural oil feedstocks. In this process hydrogen is used as a reactant with natural oils (triglyceride) in the presence of a metallic catalyst. Hydroprocessing is the basis of conventional refining. Unlike bio-diesel, all oxygen is removed. As a result, renewable diesel is chemically identical to a conventional product that is made from crude oil. It can therefore act as a 'drop-in' to existing infrastructure. In Australia, renewable diesel is classified as a bio-fuel for the purposes of the excise scheme, even though it is chemically identical to conventional diesel. Under the Energy Grants (Cleaner Fuels) Scheme, renewable diesel attracts a 38c per litre grant. It is important to note that both renewable diesel and SAF can be produced from the same hydroprocessing unit, depending on the configuration of a bio-refinery.

Ethanol is an alcohol-based fuel that is made from sugars using fermentation and distillation processes. Like bio-diesel it has very distinctive chemical properties and cannot be used as a 'drop in' fuel. In Australia and the US ethanol can be blended with petroleum and is encouraged by blend mandates in those countries. However, its different chemical properties limit the volume of permitted blending, effectively creating a 'blend wall'. In Australia, ethanol is classified as a bio-fuel and under the Ethanol Production Grant, attracts a 38c per litre grant for eligible ethanol fuel produced for road transport. Unlike bio-diesel and renewable diesel products, only locally produced ethanol is eligible for the grant.

[14]

1.4 Australian studies

In May 2011, CSIRO published "Flight Path to Sustainable Aviation"[15], a report with industry that outlined key challenges facing the aviation sector and explored the potential for establishing a SAF industry in Australia. This report concluded that only next generation biomass feedstock (non-food parts of crops, plants, trees, algae, waste and other organic matter) can meet all the environmental, economic and technical challenges. One of the key outcomes of the CSIRO study was that "… there will be sufficient biomass feedstock to support almost half (46 per cent) of the aviation fuel needs of both Australia and New Zealand by 2020 and over 100 per cent of fuel needs by 2050"[16]. Since all of the natural oil feedstock volumes analysed within the scope of the CSIRO report would need to be developed over time due to the lack of existing emerging feedstock production, near-term feedstock availability in Australia was based exclusively on lignocelluse (LC) biomass (i.e., non-food parts of crops, plants, trees, waste and other organic matter).

While the CSIRO report was a comprehensive analysis of the potential for SAF feedstock in the Australian context, the ability to commercially develop these LC feedstock into SAF ultimately depends upon the technical and economic conversion and refining pathways to SAF fuel, as well as the approval of these pathways for use in a jet engine by ASTM.

In examining the pathways that can use LC biomass, because LC biomass contains carbon sugars it is not relevant to the natural oils-based HEFA pathway. The only pathway certified by ASTM for use in a jet engine and that can use LC biomass as a feedstock is FT. Despite concluding that the scale of potential biomass production in the region is well matched to the aviation fuel industry's needs, and that local production of SAF

[14] The Energy Grants (Cleaner Fuels) Scheme Act 2004 provides excise relief for producers and importers of renewable diesel and biodiesel whereby excise is first paid and then reimbursed in the form of a grant.

[15] CSIRO Sustainable Aviation Fuel Road Map 'Towards establishing a sustainable fuels industry in Australia and New Zealand' May 2011

[16] Sustainable Aviation Fuels Road Map: Flight path to sustainable aviation, CSIRO, 2011, p6

would bring significant economic, social and environmental benefits to Australia and New Zealand, conversion of LC feedstock to fuel requires significantly more research, development and commercial analysis. The technology processing pathways that are compatible with LC biomass are either moderately attractive at best (e.g., Fischer Tropsch), or are pathways in the early pre-commercial stage of development with no ASTM certification.

In December 2011, the report, "Advanced Bio-fuels Study – Strategic Directions for Australia", prepared by L.E.K and commissioned by the Commonwealth Australian Renewable Energy Authority (ARENA) was released. It concluded that Australia had a comparative advantage in the bio-fuels market and there was significant potential to create a new and sustainable industry for Australia. It also concluded that significant investment and transformative land use change was required to realise this potential.

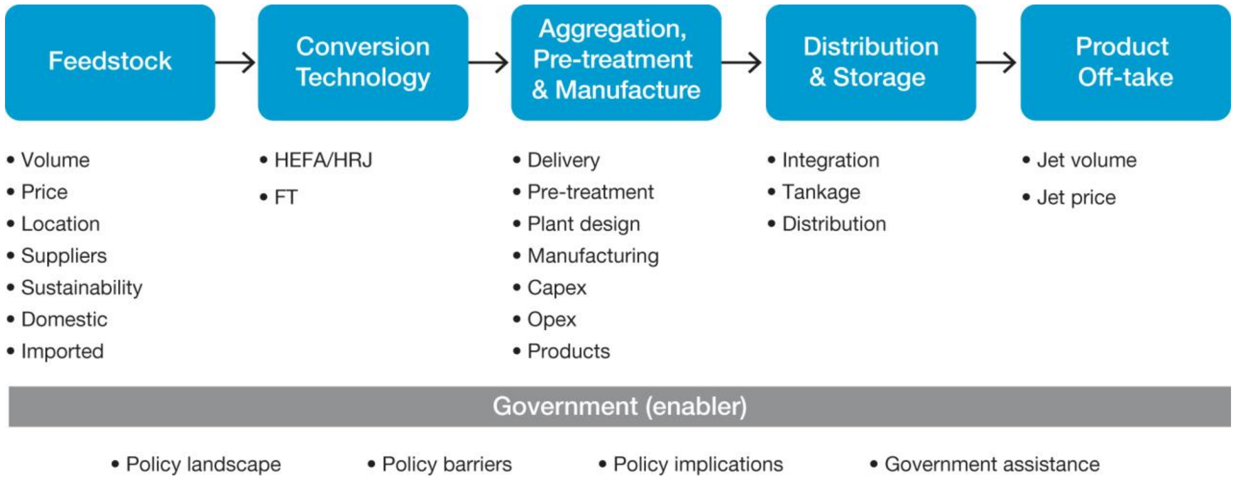
Accordingly, the purpose of this study has been to take the findings and conclusions from previous studies a step further, and understand the conditions under which a bio-fuel value chain can be commercially established in Australia for aviation.

1.5 Scope and objectives

To investigate the conditions under which a SAF industry could be commercially viable, Qantas formed a joint study team with The Shell Company of Australia Limited (Shell) and produced this feasibility study with contributions from Sinclair Knight Merz (SKM), AltAir, Australian Research Council (ARC) Centre of Excellence for Plant Cell Walls at the University of Adelaide and SkyNRG. The feasibility study was financed with a grant from ARENA of A$575,000, as well as an in-kind contribution of approximately A$187,500 each from Qantas Group and Shell.

This study has extended the previous investigations and reports by bringing together key players from each segment of the supply chain so the specific conditions needed in the Australian market could be more fully explored. The study draws on the detailed industry knowledge of the industry partners along the relevant SAF value chain to investigate the practical and commercial conditions needed for a SAF industry in Australia. The study looked at the total integrated SAF value chain in Australia, as outlined in Figure 4.

Figure 4: SAF value chain[17]



Source: Qantas (2013)

The key question for the study was: what are the conditions required to establish an Australian SAF industry value chain, including the technical, financial, economic/market, infrastructure and regulatory requirements, using existing refining technology and infrastructure, and as far as reasonably practical, keeping the value adding steps in Australia?

To date, the project team is not aware of any publically available study in Australia that has evaluated the complete supply chain to the same practical and commercial detail.

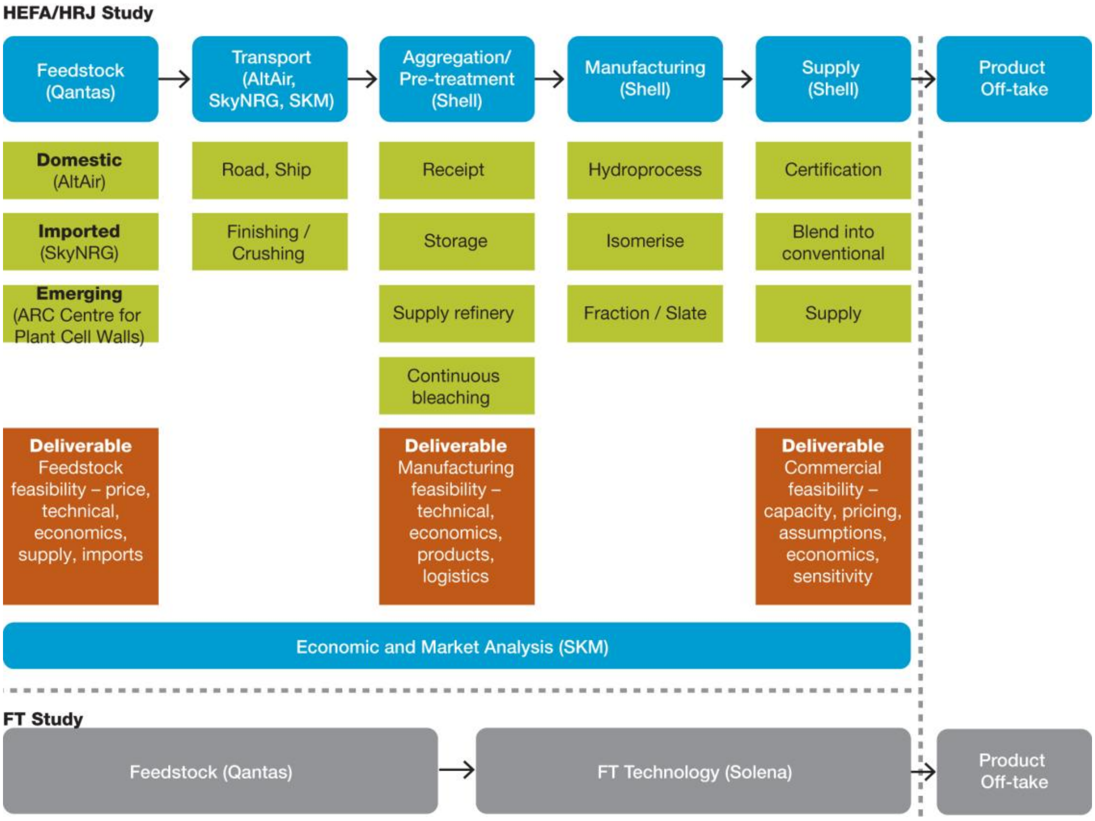
[17] Qantas commissioned Solena to provide industry insights into the FT pathway. The larger project consortium was not involved in this review.

The certification and operation of SAF-powered aircraft has demonstrated that the production of SAF itself is no longer a technical challenge. In fact, data from Qantas Group commercial demonstration flights in April 2012 (Qantas Airbus A330 and Jetstar A320) show that combustion of HRJ provided a fuel saving of approximately 1.5% compared to traditional jet fuel. However, despite the high technological readiness and apparent performance advantages of this certified pathway, the use of drop-in SAF has remained a demonstration activity.

This feasibility study has therefore focused on evaluating the capacity and opportunity to produce SAF using certified hydroprocessing technology (HEFA pathway), and the likely costs involved in producing such fuel. This manufacturing pathway remains the only renewable hydrocarbon technology to be demonstrated at commercial scale[18].

In the absence of any global commercial scale biomass-to-liquid (BTL) plant using Fischer Tropsch technology, Qantas commissioned Solena to provide industry insights into this pathway and its potential in the Australian context. Shell and all other project partners focused exclusively on the HEFA pathway and were not involved in the FT study. Results from the FT study are reported in Section 9. To augment understanding on SAF pathways, Qantas provided a high level review on the current status of emerging conversion technologies. An overview of the study partners' contributions to the study scope is contained in Figure 5 below.

Figure 5: Study scope



Source: Qantas (2012)

1.6 Assumptions

The following boundary assumptions were made in the study.

- **Technology pathways:** Only technology pathways contained within the ASTM standard specification for aviation turbine fuels containing synthesised hydrocarbons (at the end of 2012) were examined in depth – i.e., ASTM D7566 Appendix 1 (Fischer Tropsch Hydroprocessed Synthesised Paraffinic Kerosene or Bio-FT) and D7566 Appendix 2 (Synthesised Paraffinic Kerosene from Hydroprocessed Esters and Fatty Acids (HEFA) or HRJ). A high-level review of uncertified pathways was provided by Qantas.

[18] European refiner Nesté Oil manufactures renewable hydrocarbons using hydroprocessing technology plants at commercial scale in Finland (Porvoo), the Netherlands (Rotterdam) and Singapore.

- **Feedstock**: The focus of the study was on feedstock that are commercially available for HEFA and FT pathways, i.e., natural bio-oils and tallow feedstock for HEFA and waste feedstock for FT. Existing domestic HEFA volumes were profiled in depth, and imported HEFA volumes were analysed at a high level to cover any gaps in domestic supply. Pre-commercial emerging feedstock for HEFA were also analysed at a high level for future volume opportunities, as were emerging feedstock for emerging pathways, such as industrial waste gases and LC biomass. The preference of the study partners was to maximise the use of non-food competing feedstock, and to avoid feedstock sourced via unsustainable land use or that breach human rights, consistent with the sustainability practices of the key study partners. In general, sustainable feedstock are in very short supply and attract a premium to the market price.
- **Location**: Manufacturing and distribution stages were treated as location agnostic at this feasibility level. However, for realistic cost data to be produced the reference points of Greater Melbourne and Greater Brisbane were used for analysing both truck and ship transport costs.
- **Construction scope**: A brownfield site was assumed at either of these general locations to utilise existing infrastructure such as tanks, pipes and transport, and to create the earliest possible integration into existing jet distribution infrastructure. However, construction – as opposed to the conversion of a dedicated bio-oil processing equipment – is required due to specification and technical constraints and the desire not to impact the operation of the existing brownfield site. Additional hydrogen manufacturing equipment was also required due to the general shortage of hydrogen in Australian refineries, and the high requirement for bio-oil processing.
- **Manufacturing capacity**: The study examined two bio-refinery sizes – the base case of 20,000 barrels per day product output (i.e., 3,000 tonnes of feedstock per day or 1 million tonnes per annum), and a Reduced Scale of 7,000 barrels per day product output (i.e., 1,000 tonnes of feedstock per day or 0.3 million tonnes per annum). These sizes were assumed as capable of supplying a material proportion of Australia's demand for SAF beyond 'demonstration scale'. It should be noted that the SAF volume from a single facility is still only 8% of Australia's 2020 jet fuel demand (when blended 50:50). As a cross-reference, the facility sizes are comparable with Nesté Oil's operational 2,100 tonnes per day renewable fuel facility in Singapore.
- **Renewable products**: It was assumed that renewable products do not replace production at the brownfield site. Production at the brownfield site was maintained, thereby offsetting the need to import finished products into Australia.
- **Pricing of bio-fuels**: Bio-fuels – principally renewable diesel, SAF (kerosene), naphtha and gas – were assumed to be at the same price as their equivalent crude oil-based products. Pricing in Australia is based on import price parity.

The following Sections 2 to 8 examine the feedstock, transport, aggregation, manufacturing, product distribution and economics of the HEFA pathway. Qantas, with its study partner Solena, examined the prospects for a waste-to-fuel plant in Australia in Section 9, based on the BA-Solena GreenSky London project. Section 10 oultines the policy environment.

2. Existing feedstock

2.1 Introduction

A fundamental requirement for a successful SAF value chain in Australia is cheap, plentiful, sustainable and rateable supplies of feedstock. In conventional refineries, this takes the form of conventional crude oil. Supply chains for crude have been well established for almost 100 years and are a multi-billion dollar industry. In the current early stage development of SAF and in bio-fuel markets more generally, feedstock supply lines have generally been based on ad hoc and opportunistic initiatives to utilise a specific feedstock in a particular country or region. The use of US and Australian tallow for bio-diesel and renewable diesel is an example of this approach.

Accordingly, there is increasing pressure on scarce feedstock resources in the natural oils space for the HEFA pathway, with little indication of an increase in global supply, especially in the sustainable non-food forms of these feedstock. With bio-diesel and renewable diesel enjoying a "first mover"[19] advantage over SAF and significant government support, creating a reliable feedstock HEFA supply chain for SAF will be challenging.

The study covered the domestic production of the following natural oils feedstock:

- Existing food crops
  - Canola (rapeseed)
  - Cottonseed
- Existing non-food feedstock
  - Tallow
  - Brown grease
  - Used cooking oil (UCO)

The preference of the study partners was to maximise the use of non-food competing feedstock, and avoid feedstock sourced via unsustainable land use or that breach human rights, consistent with the sustainability practices of the key study partners.

The feedstock analysis has been conducted using a target fuel production requirement of 20,000 barrels per day – the equivalent of 3,000 metric tonnes of feedstock input per day or 1 million tonnes per annum. Feedstock requirements have been analysed within this context.[20] Depending on the process configuration, this results in a jet fuel supply of between 5% and 35% of Qantas' current domestic fuel demand when certified in a 50:50 blend.

The timeframe for consideration of feedstock spans the period to 2020. The feedstock focus is on the short-to-medium term volumes available to support the medium-to-long term feasibility of establishing a bio-refinery in Australia for the HEFA pathway.

The study also examined the potential for imports of existing commercial scale feedstock for the HEFA pathway where there is a shortfall in domestic supply.

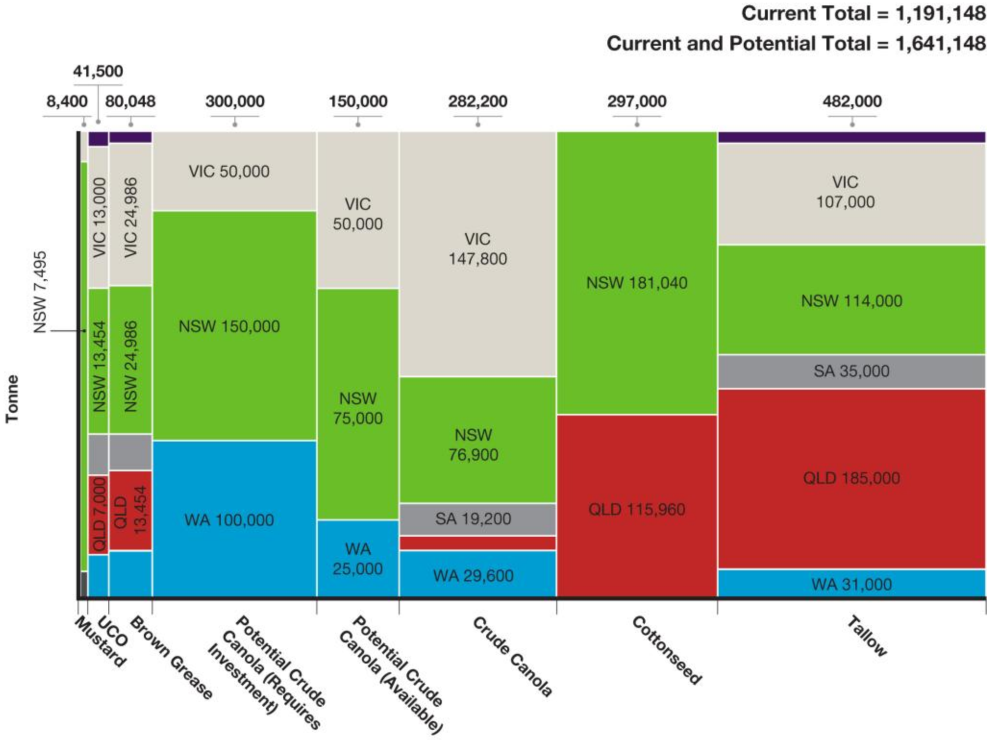
[19] The term 'first mover' is used in the context of bio-diesel and renewable diesel production being a well-established industry.

[20] For comparative purposes, the Nesté Oil bio-refinery in Singapore is approximately 2,100 tonnes per day; Lim, "Neste's bio-fuels back in black for Q1" Business Times, 27th Apr 2013

2.2 Domestic feedstock for the HEFA pathway

The majority of volume for relevant domestic feedstock is composed of Canola[21], cottonseed and tallow, with total potential[22] market volume of approximately 1.6 million tonnes in 2012 as shown in Figure 6. Two-thirds of this volume is edible natural oils.

Figure 6: Existing and potential production natural oils in Australia, by feedstock and by state, 2012 (tonnes)



Source: Feedstock Study Model; ABS[23]

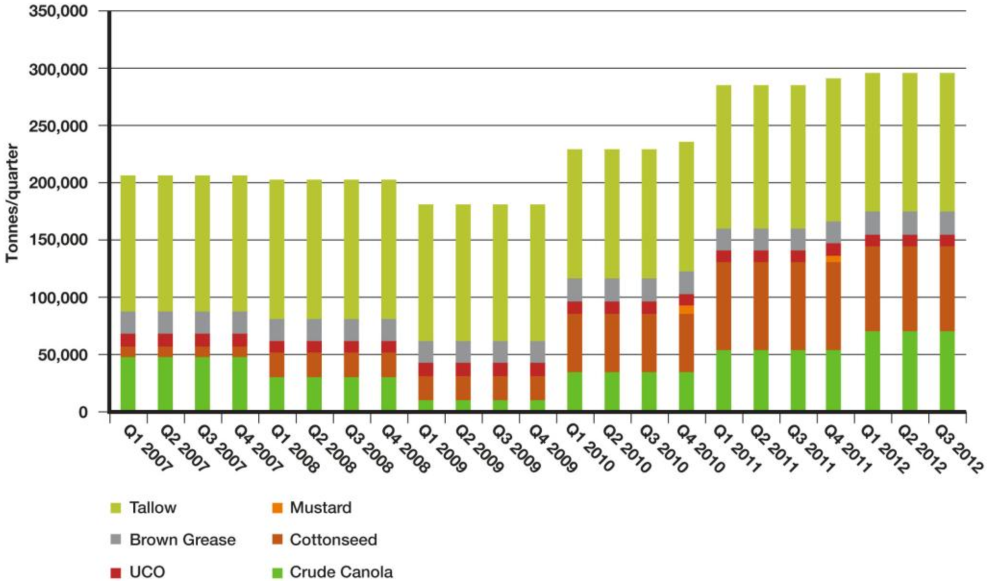
Figure 7 shows total production of natural oils since 2007. While the production of inedible oils (tallow, brown grease and UCO) is relatively unchanged, the production of edible oils has grown approximately 57% during this time, driven primarily by an increase in cottonseed and crude Canola production. The chart is in quarterly volumes to reflect differences in seasonality among certain feedstock. For annualised volumes, quarterly volumes should be added together.

[21] Although Canola is correctly spelled with an initial capital C, (as are Jatropha, Pongamia and Camelina) it is often spelled canola, and used in a generic sense to refer to cultivars that can produce oil suitable for human consumption. Small, Top 100 Food Plants, 2009, National Research Council of Canada. In this study Canola is used as the preferred label.

[22] The potential market for Canola is made up of three components. First, crude Canola refers to the current volume of crude Canola oil available in the market that has been crushed domestically from domestic seed. Second, potential crude Canola (Available) refers to the potential for additional production of crude Canola where there is enough domestic seed for additional oil, and there is enough domestic crushing capacity, but there is not sufficient domestic demand for the seed to be crushed domestically. Third, Potential crude Canola (Requires Investment) refers to potential production volume available where there is enough domestic seed, but investment in additional domestic crushing capacity is required to realise the additional crude Canola oil volume.

[23] Australian Natural Oils Feedstock Model referred to as "Feedstock Study Model", created by AltAir for this study

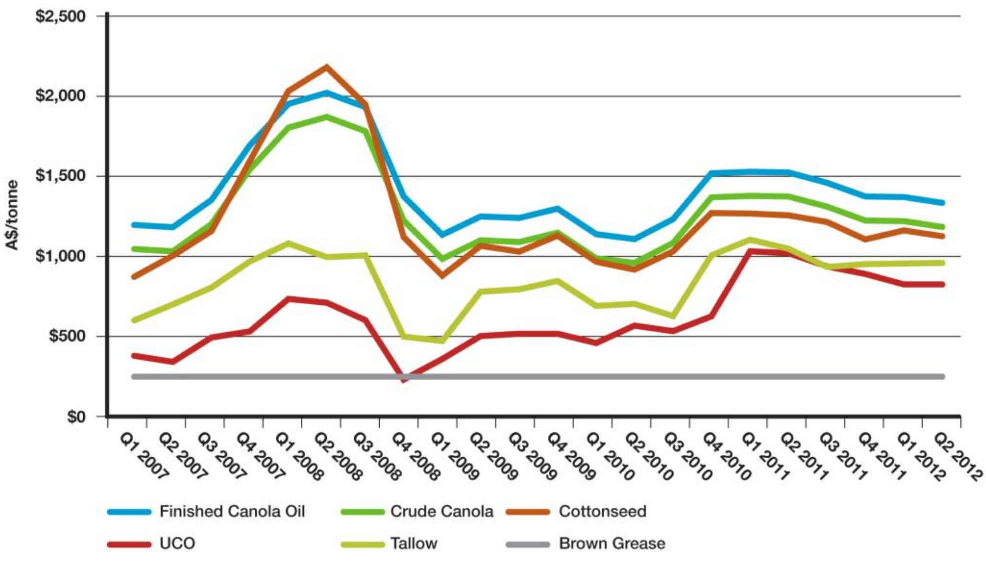
Figure 7: Historical production of Australian natural oils feedstock from 2007 to 2012, by quarter (excludes potential Canola)



Source: Feedstock Study Model, ABS[24]

In addition, market pricing has fluctuated considerably. In part due to the global financial crisis (GFC) and the associated collapse in demand, pricing fell from record highs in 2007-2008, only to return to, and in some cases exceed, those prices by 2011. Figure 8 shows market pricing of Australian oil feedstock since 2007.

Figure 8: Historical pricing of Australian natural oils feedstock from 2007 to 2012, by quarter[25]



Source: Feedstock Study Model, ABS [26]

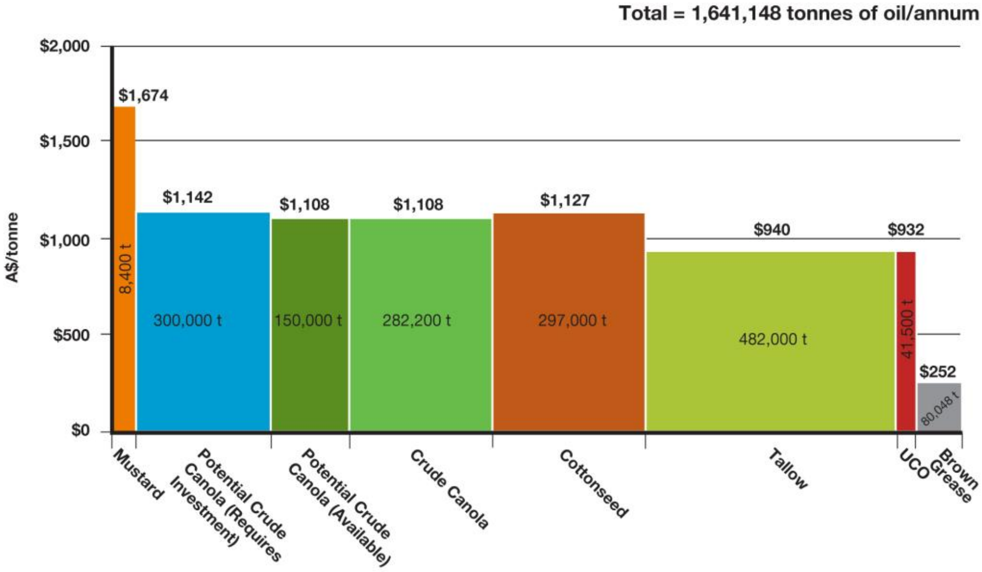
Figure 9 shows a snapshot of volume and pricing for each feedstock, as at September 2012. While not representative of historical or future pricing or volumes, this provides an indicative picture of where feedstock sit relative to each other.

[24] Australian Natural Oils Feedstock Model "Feedstock Study Model", Note that brown grease pricing is an estimate only due to lack market transparency.

[25] Crude Canola oil contains contaminates and is not suitable for human consumption. The majority of the crude Canola oil volume is refined into food grade (finished) Canola oil

[26] Ibid

Figure 9: Market price and availability of current and potential natural oils feedstock in Australia (Sept 2012)



Source: Feedstock Study Model ABS (2012)[27]

2.2.1 Edible oils

Edible oils make up approximately 58% of the Australian natural oils complex. Total production of oilseeds in Australia for the season 2010/11 was 3.8 million tonnes.[28] This was primarily Canola and cottonseed production, with the small balance made up of soy, sunflower, and other oilseeds. Of this, 1.7 million tonnes (45%) were exported, with 2.1 million tonnes (55%) consumed domestically.[29] Of the domestic processed volume, approximately 20% is then exported as processed oil. Overall, approximately 56% of total Australian volume is therefore exported in processed or unprocessed form. While total production, and domestic processing, has grown since 2010/11, the ratios for exports and domestic processing have generally been consistent over time.[30]

The Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) predicts the consumption of oilseeds is set to rise worldwide in 2012-2013, largely due to consumption growth in developing countries and international demand for bio-diesel.[31] Although domestic demand for oilseeds is strong, Australia is forced to compete in the global oilseed markets. This has the following effects on the domestic market for oilseeds:

- In the local market, domestic seed is consumed as whole seed or crushed in various feed applications
- In the export market, Australia primarily exports seed, as opposed to the oil that results from crushing those seeds
- Significant quantities of imported soybean meal and soy oil frequently offset demand for domestically produced oils.

Approximately 1.1 million tonnes of currently utilised seed crushing capacity exists in Australia. Canola and cottonseed comprise the majority (approximately 90%) of this crushing capacity. An additional 160,000 tonnes

[27] Australian Natural Oils Feedstock Model “Feedstock Study Model”

[28] ABARES (2011), Agricultural Commodity Statistics 2011, Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra

[29] ABARES (2011), Agricultural Commodity Statistics 2011, Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra

[30] ABARES (2011), Agricultural Commodity Statistics 2011, Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra

[31] ABARES (2012), Agricultural Commodities: June quarter 2012, vol.2 no. 2, Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra

of crushing capacity is scheduled to come online in 2012-2013.[32] The location and capacity of existing crushing facilities are shown in Figure 10.

Figure 10: Location and approximate capacity of active Australian oilseed crushing facilities

Source: Australian Oilseeds Federation (2012)[33]

Australia has produced significantly more oilseed than domestic crushing capacity over the last three years as increased rainfall and global pricing dynamics have favoured oils relative to cereal crops. If domestic consumption of the oil from oilseeds were to increase due to, for example, a bio-refinery that accepted edible feedstock, significant domestic crushing would need to come online in Australia. Market discussions suggest there is an opportunity to install additional crushing capacity in Australia to increase domestic oil consumption from oilseeds.

2.2.1.1 Canola

Canola is an edible cultivar of rapeseed (*Brassica napus L.)* and the two are often used interchangeably. It is an annual oilseed crop primarily grown for cooking oil and animal feed protein meal. Both Canola and rapeseed oils have found large markets in bio-diesel, especially in the European Union (EU), where they fetch a price premium due to the superior cold weather performance resulting from the largely unsaturated oils. This study uses Canola as the preferred label for this family of crops in Australia.

Canola is Australia’s largest oilseed crop. It is typically grown in rotation with, or at the expense of, wheat. Over the last three years in Australia, Canola production has increased dramatically from historical norms. This is primarily a function of increased rainfall, enabling favourable Canola production economics, and historically high Canola prices relative to wheat and other cereal prices.

Approximately half the Canola crop each year is grown in Western Australia. However, as Western Australia only has two small seed crushers, most of the grain is transported to ports for export. As indicated above,

[32] Australian Oilseeds Federation, Aug 2012

[33] Australian Oilseeds Federation, Aug 2012

Australia has approximately 1.1 million tonnes of seed-crushing capacity, and another 160,000 tonnes of capacity coming online in 2012-2013.[34] The domestic crushing capacity is predominately in New South Wales and Victoria. Domestic demand for crude Canola oil was 190,000 tonnes in 2012. However, crude Canola oil contains metal levels and other impurities that make it unsuitable for edible consumption.[35] Therefore, the bulk of the Crude Canola volume is refined into food grade or finished Canola.[36] The majority of Canola seed in the last five years has been exported as whole seed, where it is crushed in Europe or Asia, principally for use as a feedstock for bio-diesel production in Europe.[37] Australian Canola oil producers struggle to compete with the more efficient edible oil upgrading facilities abroad. As a result, approximately only 90,000 tonnes of additional crude Canola oil is exported.[38]

The total Canola seed crop of Australia has exceeded total crushing capacity for several years, resulting in excess seed crop. In some cases, the economics of exporting whole grain are favourable to those of crushing domestically due to higher overseas demand and limited domestic demand. Therefore, even though there is greater Canola seed production than domestic crushing capacity, idle capacity could produce between 100,000 to 200,000 tonnes of crude Canola oil annually. While Canola oil production has varied over the past five years as other oilseed crops have taken up domestic crushing capacity, a significant increase in domestic demand for crude Canola oil (e.g., from a bio-refinery) is likely to utilise this excess capacity. Any additional crude Canola oil required, in addition to the 100,000-200,000 tonnes, would require a premium to incentivise additional meal production and crushing.

Despite the large volume produced in Australia, Canola has challenges as a primary feedstock due to its high price and the sensitivity to competition in the food market. International vegetable oil pricing determines local oil pricing and, indirectly, the pricing for seed paid to farmers. In addition, Canola meal is an important co-product since the ability to sell the meal for animal feed provides an important source of additional revenue. In Australia there is low domestic demand for Canola meal due to competition from cheap soy meal, which negatively affects the economic viability of additional Canola in Australia.

2.2.1.2 Cottonseed

Cottonseed oil is a co-product of cotton fibre production, primarily from the species *Gossypium hirsutum* and *Gosssipium herbaceum.* Cottonseed oil is a premium, edible oil due to its chemical stability, utility in deep frying (high levels of tocopherols) and low levels of Omega 3 oils. Unlike other oilseeds, such as Canola, cottonseed can be used as a whole seed in animal feed as a source of protein and fibre.

Cottonseed is the second largest oilseed crop in Australia, comprising approximately 33% of total oilseed production. Along with Canola, it is the only oilseed crop of sufficient size to comprise a large fraction of the target refining requirement. Normally around 500,000 tonnes of cottonseed is produced each year, but in recent years, the crop has increased due to abundant rainfall and high pricing for cotton and cottonseed oil.[39] Australian Oilseeds Federation statistics show that cottonseed production for the season 2010/11 was 1.27 million tonnes. Of this, approximately 270,000 tonnes were exported as cottonseed and 14,000 tonnes as cottonseed oil.

As a premium edible oil, cottonseed oil does not represent an attractive primary feedstock for bio-fuel conversion. Its relatively higher price and the preference for its primary use as a human food source are the principal considerations.

2.2.2 Inedible oils

Existing inedible oils considered in this study are tallow, used cooking oil and brown grease.

[34] Australian Oilseeds Federation, Aug 2012

[35] Australian Oilseeds Federation, Aug 2012

[36] Australian Oilseeds Federation, Aug 2012

[37] Cargill Australia, July 2012

[38] Australian Oilseeds Federation, Aug 2012

[39] Australian Oilseeds Federation, Aug 2012

2.2.2.1 Tallow

Tallow is rendered fat from the meat and livestock processing industry. Australia's large beef and dairy industries support robust beef tallow production of approximately 0.5 million tonnes per annum, with the majority exported. Mutton and chicken tallow make up a small percentage of total output and are typically sold locally as animal feed, pet food, or in custom oleo chemical processes. Mutton tallow is often blended into beef tallow in small percentages. This study focused specifically on the largest volume segment of beef tallow. Tallow production is very stable and a function of animal size and slaughter. The majority of Australian tallow is rendered in Queensland.

Australian tallow is primarily exported for use in animal feeds, soap manufacturing, and oleo chemical manufacturing. The majority of tallow is usually exported (2010: 73%; 2011: 75%)[40], in particular to China. Tallow is used to produce oleo chemicals, including soaps, rubber, textiles, cosmetics, plastics, racquet strings and lubricants. Many vegetable oils can be used instead of tallow for soap and cosmetics. Tallow has also been popular in recent years as feedstock for transesterification bio-diesel facilities. Eight bio-diesel facilities were built in Australia from 2006 onwards, but only four of these facilities are now operating. The remaining plants operate below capacity because they find it hard to develop a bio-diesel market in Australia, even with access to the Energy Grants (Cleaner Fuels) Scheme, which provides producers and importers of bio-diesel a A$0.38 per litre grant.

Tallow represents the best near-term feedstock for large-volume, sustainable supply. However, recent international pricing has not been conducive to profitable, domestic refining of tallow to fuel even with access to the Cleaner Fuels Scheme.

2.2.2.2 Used cooking oil (UCO)

Used cooking oil (UCO) or waste vegetable oil is vegetable oil from a deep-fryer that is recovered and stored for removal, rather than being poured down a drain. UCO collection is a separate business from brown grease collection. In the current market, collectors typically pay restaurants for their UCO, aggregate the oil in urban areas, clean – or "finish" – the oil to an agreed specification, and sell it at prices similar to those of tallow.[41]

The UCO collection business in Australia is increasingly challenged. Restaurants have increased the pricing for their crude UCO, charging collectors A$500-800 per tonne through 2012.[42] Growing demand from China is also pressuring domestic operations, and most Australian UCO is now exported through the Asia Pacific region for oleo chemical manufacturing. International market pricing for oleo chemical feedstock (primarily tallow) will continue to drive Australian UCO pricing.

2.2.2.3 Brown grease

Brown grease, or trap grease, refers to waste fats, oils, and greases collected from grease traps and gravity interceptors in wastewater treatment equipment. It is generally highly contaminated and, to the extent that it is recovered from sewage water, is typically landfilled or composted where such facilities exist.

Brown grease requires extreme pre-treatment in order to be processed in a bio-refinery. Supply of brown grease is a function of regulatory requirements and, until recently, was primarily directed to landfill. To the extent that brown grease has been dewatered and filtered, it has been made available at a very cheap average price of A$250/tonne. This pricing is inexact and aggregation has proved difficult in Australia in recent years. Given the small scale and distributed nature of local collection, as well as the special handling requirements and associated costs, brown grease is not a strong candidate for aggregation and refining.

2.2.3 Analysis

For the base case refinery size, approximately 1 million tonnes of feedstock are required per annum. Although there is enough total domestic market volume to feed a bio-refinery of this size, in practice, there is limited

[40] Food & Agricultural Organisation (FAO) of the United Nations, Data Book, 2012; Bill Spooncer, "Export Markets Vital to Australian Renderers", RENDER Magazine August 2012

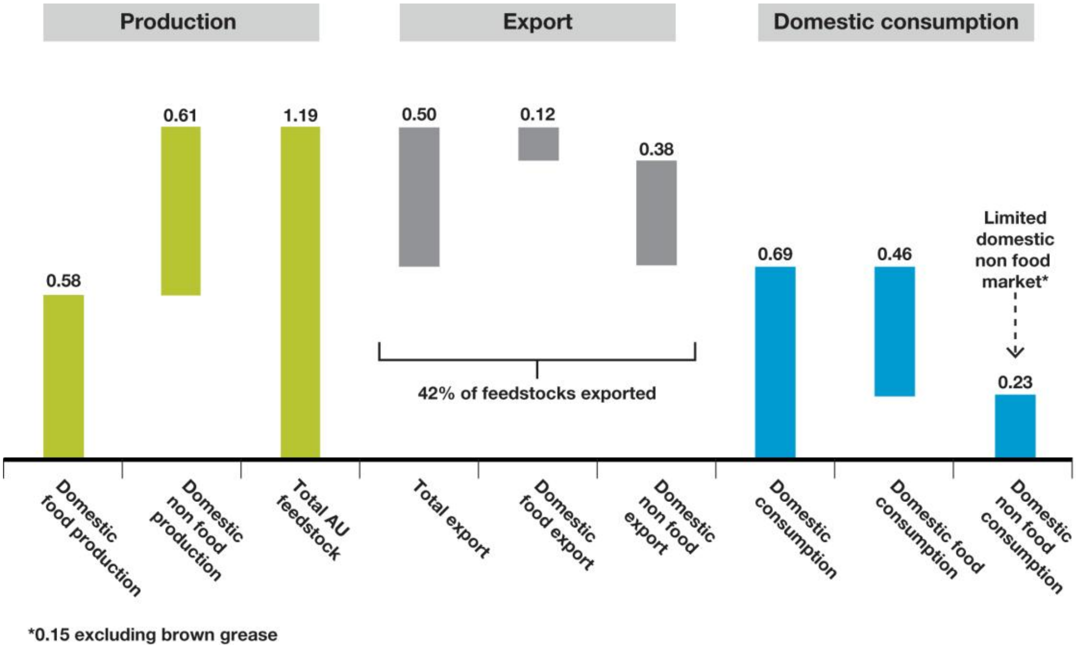
[41] Colyer Fehr, July 2012

[42] Biomax Fuels, July 2012

domestic natural oil feedstock currently available. Approximately 42% of domestic natural oils feedstock is exported at a higher export price, and non-food volume available for domestic use is small at 15%. While food-related natural oils could go some way in filling the domestic demand requirements, the preference of the study partners is to maximise the use of non-food competing feedstock, and to avoid feedstock sourced via unsustainable land use or that breach human rights, consistent with the sustainability practices of the key study partners.

It is important to realise that producing the target bio-fuel quantity of 20,000 barrels per day (equivalent to approximately 16% of the Shell Geelong Refinery's daily production capacity) requires almost all of Australia's natural oils and animal fat volume. Figure 11 shows this gap.

Figure 11: Domestic HEFA feedstock production, consumption and export (million tonnes per annum)



Source: Qantas (2013)

The significant gap in non-food feedstock exists even in the case of a smaller capacity bio-refinery (the 'reduced scale' scenario is outlined in Section 4.3). In a reduced scale scenario a bio-refinery requiring 1,000 tonnes of feedstock per day is equivalent to approximately 300,000 tonnes per annum. Assuming an intervention into the market of two-thirds of the domestic non-food oils market (i.e., 100,000 tonnes), there would still be a 200,000-tonne shortfall.

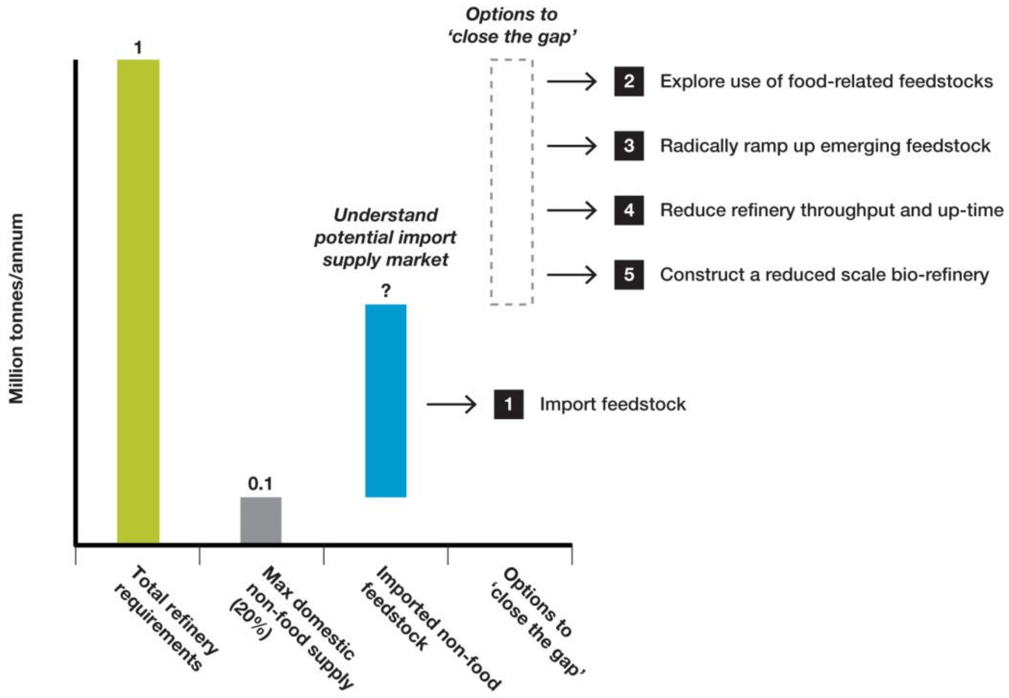
2.3 Imported feedstock for the HEFA pathway

As outlined in the domestic feedstock analysis, there is insufficient rateable, non-food domestic feedstock to satisfy an Australian HEFA bio-refinery with capacity for feedstock of 3,000 tonnes per day (1 million tonnes per annum). Assuming a 1 million tonne demand per annum for a base case bio-refinery, and assuming use of two-thirds of the domestic non-food feedstock market identified in Figure 11, (i.e. 100,000 tonnes per annum, equivalent to 20% of the total Australian non-food feedstock volume)[43] there is an approximate 90% shortfall in supply from domestic feedstock (Figure 12). The feasibility study therefore examined the potential for importing existing feedstock to fill this 900,000 tonne gap for a domestic bio-refinery, with the assistance of SkyNRG and funding from ARENA.[44]

[43] Excluding brown grease

[44] With thanks to study partner SkyNRG who are responsible for researching this section of the report; www.skynrg.com and funding from ARENA

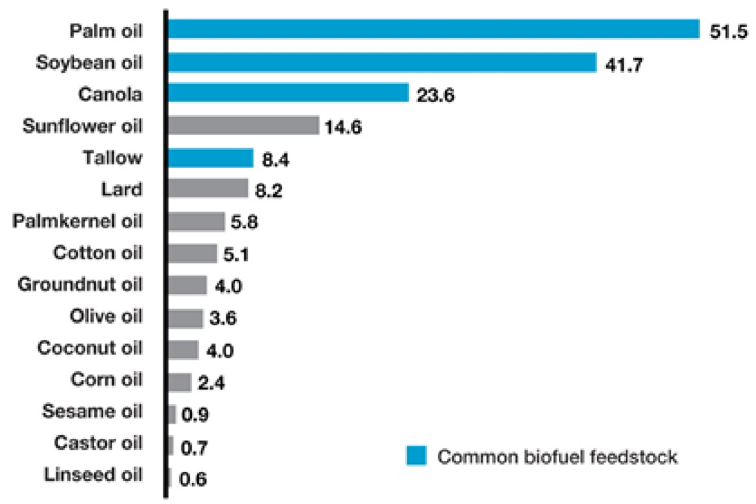
Figure 12: Options to close the feedstock gap



Source: Qantas (2012)

Global vegetable oil volumes (including animal fats) reached an estimated 175 million tonnes in 2012. More than 75% of production came from four major crops: palm, soybean, Canola and sunflower. The eight largest producer countries account for over 85% of total production. Globally, 80-85% of this volume is used for food purposes, with bio-fuel accounting for approximately 10% and the remainder for non-food/industrial purposes. The main bio-fuel feedstock are palm oil, soybean oil, Canola oil and tallow, with sunflower oil generally too expensive for bio-fuels. Globally, around 60% of production is used in local markets, with 40% (roughly 70 million tonnes) of volume traded between countries. Figure 13 shows global oil and fat production volumes by the top 15 products.

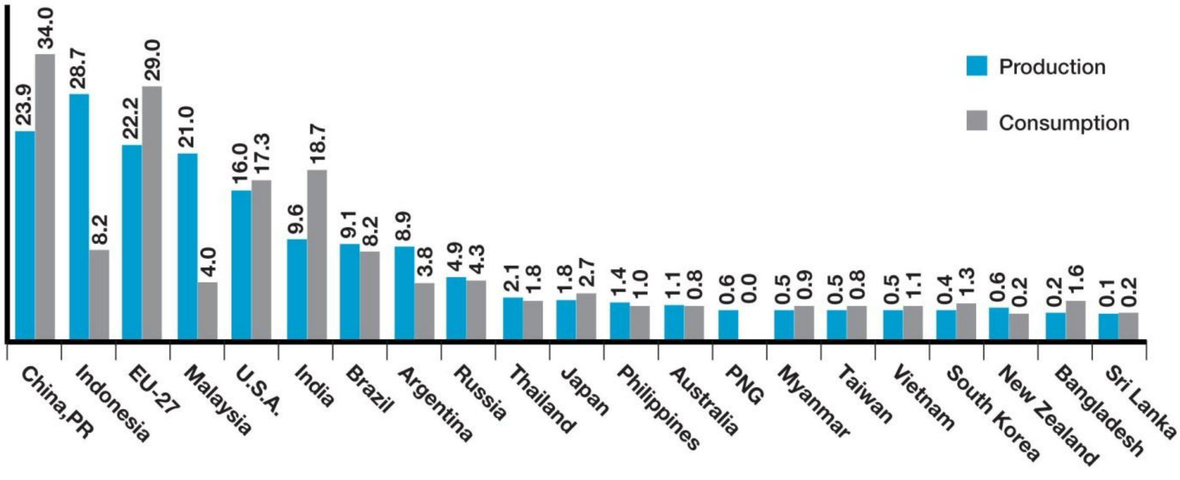
Figure 13: Global oil and fat products (million tonnes, 2012)



Source: Oil World, FAO, Worldbank (2012)

As Figure 14 demonstrates, Indonesia, Malaysia, and to a lesser extent, Argentina, stand out as the only countries with a significant vegetable oil surplus. China, the EU-27 and India, despite their large production, are net importers. Growth in oil and fat demand results mainly from developing country, food-related demand, and to a lesser extent from demand for bio-fuels from developed countries.

Figure 14: Production and consumption of oils and fats (million tonnes, 2012)



Source: Oil World, SkyNRG analysis (2012)

In summary, despite the fact that the required volumes will be available from the global natural oils market, the combination of high price forecasts, high price volatility, a strong pull on edible oil from the food markets, an uneven playing field with respect to road transport globally and increasing strictness on sustainability criteria all make imported commodity vegetable oils difficult to rely upon for SAF over the medium-to-long term. In addition, while there is a large global natural oils market, only a small portion (less than 5%) is non-food. Tallow imports are a possibility, but there is not a strong import-export market globally for tallow, and Australia has enough domestic volumes that would be preferred as a sourcing strategy in the first instance.

3. Emerging feedstock

3.1 Introduction

In this section a variety of emerging and innovative non-food feedstock are reviewed to assess the opportunities to fill the domestic feedstock gap, including:

- Emerging domestic feedstock for the HEFA pathway
- Marginal land feedstock for the HEFA pathway
- Emerging feedstock for emerging pathways

Internationally sourced emerging feedstock for the HEFA pathway are not examined since these feedstock are largely at a pre-commercial and demonstration level. Furthermore, the emerging feedstock volumes are insignificant, and any ramp up of volume is likely to be utilised in the country of origin. A more in-depth survey of emerging pathways utilising emerging feedstock was conducted by Qantas and is contained in Appendix A.

3.2 Emerging domestic feedstock for HEFA pathway

Emerging feedstock crops with potential for the Australian landscape and relevant to the HEFA pathway were analysed to determine whether they have short-to-medium term volume potential. The domestic emerging feedstock assessed were Jatropha, Pongamia, mustard, Camelina, autotrophic algae and heterotrophic algae.

3.2.1 Jatropha

Jatropha curcas (Jatropha) is a perennial tree that produces inedible oil-bearing seeds and can grow on marginal land. Jatropha was one of the first widely adopted and cultivated advanced bio-fuel feedstock. There have been a number of widely publicised crop and business failures in Jatropha internationally since the mid 2000s, primarily due to the planting of undomesticated, unimproved seed and a poor understanding of business practices related to agriculture and commercialisation.[45] A select few companies have invested significantly in Jatropha since, primarily in India and Brazil, and are poised to commercialise the crop within the decade.

The primary commercial barriers to Jatropha production are limited access to capital and underdeveloped knowledge of the plant's local environmental and social impacts.[46] Jatropha yields increase from 30 to 100 per cent of their steady-state potential over a four-year period.[47] This long maturity period has discouraged many potential investors. Concerns over the environmental and social impacts of Jatropha have, in some cases, resulted in public and political pressure to limit its production. There is a significant regulatory barrier for Jatropha in Australia as it is currently listed as a banned, noxious weed in Queensland, Western Australia, and the Northern Territory – the states with a suitable agro-climate for Jatropha cultivation.[48] However, some projections suggest that if Jatropha could be commercialised, it would be a leading candidate for economic SAF production by 2020.[49]

However, considering Jatropha is listed as a noxious weed in Queensland, Western Australia and the Northern Territory, local production is unlikely, at least in the short term.

3.2.2 Pongamia

Pongamia pinnata (Pongamia) is a leguminous, inedible oilseed-producing tree that can provide naturally high oil yields in marginal conditions. Pongamia has received increased attention as an advanced bio-fuel feedstock, and several R&D projects are underway in Australia. However, Pongamia is a very early stage feedstock that

[45] "Jatropha Loves to Fly and It Shows", Bio-fuels Digest, 29th Jan 2013, "Jatropha: A Green Fuel Awash in Red Ink", Bloomberg Businessweek, 15th March 2012

[46] Insights into Jatropha Projects Worldwide, Leuphana University at Luneberg, Dec 2012, p11

[47] Insights into Jatropha Projects Worldwide, Leuphana University at Luneberg, Dec 2012, p17

[48] Weeds Australia (2012), Noxious weeds list, Weeds Australia website, accessed September 2012: http://www.weeds.org.au/noxious.htm

[49] "Some aviation bio-fuels could be competitive by 2020", Bloomberg New Energy Finance, 13th Feb 2012, http://www.bnef.com/PressReleases/view/188

has yet to be domesticated. Few commercial firms or research organisations are involved in the production of Pongamia, and projects have not grown beyond small-scale demonstration sites. Also, Pongamia trees do not produce any oil until four to five years from the date of establishment. The primary commercial barriers to Pongamia production are the lack of investment and the long delay until the trees reach maturity, which extends the potential payback period for Pongamia investments.

Pongamia is likely to receive greater interest in the coming years from commercial interests, R&D institutions, and the public sector as more is learned of its promise as a sustainable bio-fuel feedstock. Assuming further investment occurs, the commercialisation range is wide – Pongamia could be domesticated in five to seven years, and commercial volumes of Pongamia oil could be expected in 10 to 15 years.[50] Pongamia production costs are unlikely to fall below A$2,000 per tonne without significant investments in plant science and agronomic improvements. Those improvements will take several years to make an impact in commercial operations. The high establishment costs and delayed cash flows are the principal barriers to immediate development.

Commercial expansion will be slow due to both a lack of awareness of the crop, and Pongamia's slow maturation rate. Certainly, awareness is increasing as Pongamia is being promoted as a soil retention and reforestation option for Queensland and the Northern Territory due to its deep and broad root structure, and their association with soil nitrogen fixers.

3.2.3 Mustard

Mustard (*Brassica juncea*) has been domesticated and commercialised for centuries. Programs targeting oilseed yield and oil specification have only emerged over the last several decades. Mustard oil is naturally high in erucic acid and its meal contains glucosinolates, which are potential anti-nutrients that reduce its value in animal feed and human consumption applications. Commercial mustard varieties have been grown globally for food-related purposes, and at small scale in Australia. It has been the focus of commercial establishment efforts for non-food applications in Australia for more than two decades. Mustard should be considered a pre-commercial, non-food crop in Australia in the context of large volumes, with potential near-term viability possible.

The principal barriers to the commercialisation of mustard in Australia are yield, and its production sensitivities. Higher yields could help to compensate for sensitivities to herbicides and water, but ultimately these are challenges that must also be addressed to enable widespread commercial adoption.[51] In low rainfall areas in Australia, mustard could be grown on up to 600,000 hectares (250,000 tonnes of bio-oil) annually, based on existing crop rotations.[52]

Mustard is generally considered an attractive option for bio-fuels companies as it is better adapted to lower rainfall and lower yielding environments, so does not compete with Canola-growing regions. The three main intended uses for mustard are as a food crop equivalent to Canola, a condiment crop and a feedstock for bio-diesel. Much of the latest research into mustard varieties is aimed at producing Canola-quality oils, which will largely compete with Canola.

3.2.4 Camelina

The annual oilseed crop *Camelina sativa* (Camelina) is being promoted as a rotational crop with wheat, especially in areas with low rainfall, so has a natural fit to the Australian agricultural landscape. Private companies, research institutions and government agencies have developed dedicated Camelina improvement programs to enhance overall performance characteristics of the crop and its products. Camelina oil is high in

[50] "A Common View of the Opportunities, Challenges, and Research Actions for Pongamia in Australia". Murphy, Helen; O'Connell, Deborah; Seaton, Gary; Raison, R.; Rodriguez, Luis; Braid, Andrew; Kriticos, Darren; Jovanovic, Tom; Abadi, Amir; Betar, Michael; Brodie, Heather; Lamont, Malcolm; McKay, Marshall; Muirhead, George; Plummer, Julie; Arpiwi, Ni; Ruddle, Brian; Saxena, Sagun; Scott, Paul; Stucley, Colin, BioEnergy Research, Sep2012, Vol. 5 Issue 3, p778

[51] Potter (2011), "Development of Brassica juncea as a bio-diesel feedstock in low rainfall areas of Australia", report prepared by the South Australian Research and Development Institute for the International Rapeseed Conference 2011, Prague, Czech Republic

[52] Norton R, Burton W & Salisbury P (2005) Agronomy for Canola quality Brassica juncea in modern cropping systems. In: Potter T. (Ed), Australian Research Assembly on Brassicas 14, 111-115, Port Lincoln, 2005. Proceedings, SARDI, Primary Industries and Resources South Australia

Omega 3 fatty acids, and many of the initial research and commercialisation efforts were focused on producing nutritional supplements for human or animal consumption.

Camelina is being commercially produced on more than 40,000 hectares across the US, with other plantings occurring in Europe, particularly in Spain and Romania.[53] However, only very small-scale agricultural trials of Camelina have taken place in Australia.

Camelina oil has been used as a feedstock for aviation bio-fuel in multiple test flights since 2009, including those of KLM and JAL, and military test flights by the US Navy and US Air Force. Most recently, Nesté Oil announced it will produce 4,000 metric tonnes per annum of SAF using sustainable Spanish Camelina oil and UCO under the EU-funded ITAKA project. The three-year project received A$13.2 million and will feed into the 2 million tonne European Aviation Bio-fuels Flightpath initiative.[54]

The primary commercial barrier to Camelina is co-product development. Although Camelina is an edible oilseed, it has a bitter taste due to high glucosinolate content which has limited its use as edible oil for human consumption. Another significant hindrance to commercialisation is the reluctance of farmers to adopt new crops and to break existing crop rotations.

The Camelina industry is struggling to raise capital and organise sophisticated breeding and modification efforts required to commercialise the crop. The low value meal co-product applications are another principal challenge facing developers. While the nutrient and water use efficiency and demonstrated yields signal promise as a rotational crop with wheat, there are many years of work required to improve the crop, and adapt optimal varieties for Australia.

3.2.5 Autotrophic algae

Autotrophic algae refer to algae that absorb (fix) carbon from the atmosphere via photosynthesis. This is usually, but not always, synonymous with ‘open pond’ algae since the algae are generally grown in large open water ponds to take advantage of sunlight. Other options include the use of a photo-bioreactor[55] to cultivate algae in a controlled space while still utilising sunlight. Autotrophic algae falls into the HEFA pathway since appropriate strains of algae, once fully grown and separated from the water, can yield natural oils.

Over the last five years algae bio-fuel companies have had great difficulty scaling up to commercial viability.[56] Significant financial support from the US and other governments provide some promise that the microalgae industry can scale operations beyond the laboratory and pilot phases to demonstrate commercial production. There are numerous commercial algae-to-bio-fuel projects around the world, but all at very early stages of development i.e., pre-demonstration stage.[57] Despite the enormous promise of this technology platform in relation to yields, land use and sustainability, no algal bio-fuel company has yet demonstrated an economically viable production pathway for commercial volumes of fuel. Algae remain the most promising, and the most challenging, advanced bio-fuel feedstock.

The most promising steps have come from Sapphire Energy who established a demonstration plant producing algae-derived, natural bio-oil in New Mexico, United States. The demonstration plant was funded in part by a US$50 million US Energy Department grant and a US$54.4 million loan guarantee from the Department of Agriculture. It is estimated to produce up to 100 barrels a day by the end of 2014.[58] However, to date, this is the only algae bio-oil production plant of any significant volume.

The structural economic barriers to the commercialisation of algal bio-fuels are rooted in the emerging industry’s unique risk profile of scale up and its challenges in accessing conventional growth financing. There are many challenging technical risks and barriers throughout the algal bio-fuel value chain, which increase the risk of

[53] “Tarom, Airbus partner for Camelina aviation bio-fuels”, Bio-fuels Digest, 24th Mar 2011, “Neste Oil to produce SAF from Spanish Camelina”, Bio-fuels Digest, 24th Dec 2012

[54] “Neste Oil to produce SAF from Spanish Camelina”, Bio-fuels Digest, 24th Dec 2012

[55] Photo-bioreactors: an enclosed tubular or panel system that provides more control over the algae cultivation conditions

[56] “Whatever happened to algae and bio-fuels?” Bio-fuels Digest, 23rd April 2012

[57] “Who’s in the lead? Algae around the world”, Bio-fuels Digest, 12th Jan 2012

[58] “Tesoro Is First Customer for Sapphire’s Algae-Derived Crude Oil”, Bloomberg News, 21st Mar 2013

investment. Both a lack of successful scale ups in the algae space, and a string of algae company failures, have further heightened investment scepticism.[59]

Despite many promising R&D and developmental projects, autotrophic algal oil production is unlikely to be economically viable in Australia in the short term. Commercial scale demonstration (i.e., beyond a large-scale demonstration plant such as Sapphire in New Mexico) is at least 3-5 years away and likely to be 5-7 years in the Australian context. The capital intensity of this pathway implies that commercial scale up, once proven viable, will be a slow process. It is therefore reasonable to assume that competitively priced autotrophic algal oil will only become available domestically over the long term, without significant government intervention.

3.2.6 Heterotrophic algae

Heterotrophic algae are grown in dark, closed fermentation vessels based on a sugar (e.g., carbon) input, rather than through photosynthesis. As with autotrophic algae, the biomass is typically separated from the water, and oil is then extracted and purified from the biomass. The key economic drivers in this pathway are the cost of the sugar input and the capital intensity of fermentation infrastructure.

Heterotrophic algal oil production has occurred on a commercial scale for nutraceutical production and at a demonstration scale for bio-fuel production. Inexpensive, sustainable sugar sources are essential for heterotrophic algal bio-fuel production. However, this is often difficult to achieve with sugar as a traded commodity. Projects are therefore underway globally to develop technologies capable of deriving these sugars from waste biomass sources. Sugar waste (e.g., bagasse) has the potential to be a cheap and therefore commercially feasible feedstock for this path in the medium-to-long term.

Though several companies have used heterotrophic algae to produce algal oils, these have been focused on high-value essential oil and nutraceutical production. Only Solazyme, a US company, is working to develop bio-fuel feedstock, although as a secondary priority to lower volume and higher margin chemicals and nutraceuticals. Qantas has engaged closely with Solazyme over the past two years to assess the potential development of SAF in Australia using this feedstock for the HEFA pathway.

Heterotrophic algal oil production could become commercially viable for bio-fuel applications globally in the next 5 to 7 years, assuming that an adequate supply of low cost, sustainable sugars is available.[60] Given the volatility in price of sugar as a commodity, and the increasing correlation between sugar and energy driven by the Brazilian market, the availability of sugar as a cost competitive alternative will be challenging.[61] In addition, despite the fact that sugar is technically not a food but rather a sweetener additive, there is a risk that the reliance on sugarcane could attract the political repercussions of the fuel versus food debate, especially as it relates to sustainable land use that could be used for food crops.

3.2.7 Summary

Overall, the study found that despite significant developments, the lead time to commercial scale ramp up would most likely be at least five to seven years in Australia. The short-term development and ramp up to commercial scale of key emerging feedstock such as algae will play a critical role in driving affordable feedstock supply for a bio-refinery in the Australian context.

However, despite end-user demand, emerging feedstock is currently caught in a ‘chicken-and-egg’ cycle. Lack of development and scale up means increased investor risk and reduced investor interest, compounded by a lack of bio-refining infrastructure to refine the natural bio-oils into bio-fuels. A comprehensive program with government assistance is likely to be required to break this cycle and ramp up emerging feedstock.

3.3 Marginal land feedstock for the HEFA pathway

The study also analysed the potential to plant existing and emerging feedstock on marginal land across Australia and the Asia Pacific region.[62] The rationale for exploring such a proposition is not only from a

[59] “Whatever happened to algae and bio-fuels?” Bio-fuels Digest, 23rd April 2012

[60] “Crazy 8s: Algae’s 8 crazy-fast cores of innovation”, Bio-fuels Digest, 6th May 2013

[61] Ewing, “Analysis: Big crop, policy revive Brazil's sugar-ethanol mills”, Reuters, 11th Feb 2013, Monteiro et al, “The impact of ethanol production on food prices: The role of interplay between the US and Brazil”, Energy Policy, v41 (2012) 193–199

[62] SkyNRG was responsible for the research and content of this section of the report.

sustainability perspective, but because it allows potential producers to integrate the supply chain and, therefore, potentially reduce the cost of natural oil feedstock.

Marginal lands are defined as bare and herbaceous areas, lands with moderate and steep slopes (8-30%), and land with soil problems: shallow soils, poorly drained soils, soils with low-to-moderate natural rainfall, coarse textured or sandy soils, soils with a gypsic horizon, acid soils (pH <5.5), soils with high calcium levels (calcisols), and peat soils. Excluded are forests, agricultural areas, urban areas, and herbaceous areas under intensive pastoralism.[63]

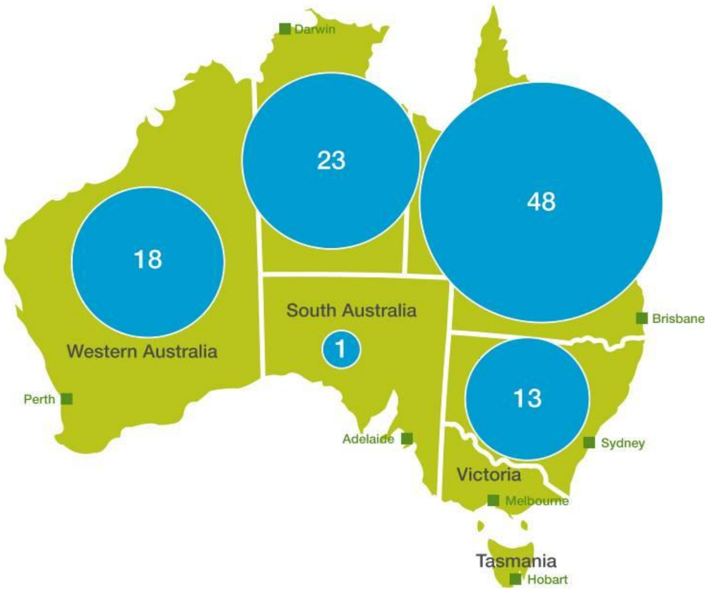
As a general principle, it is preferable to use arable land efficiently for high-demand food products rather than for less optimal energy use, to satisfy the increasing demand for food from developing and developed countries. Marginal lands, where cultivation of food crops is not economically viable, are an interesting option to minimise the potential impacts of the additional demand for natural oils, and, therefore, price increases. The key to determining whether land is marginal is the alternative land use. If land can be used for food, then planting an energy crop is unsustainable as it displaces a potential food source. However, if all other uses for the land have been exhausted, the land is a sustainable platform for energy crops. Marginal land use for feedstock is therefore an inherently sustainable approach, since it is the nature and extent of displacement of land away from food that is unsustainable, not the crop itself.

Using the alternative land use approach, a six-step process (described in Appendix B) was used to exclude arable and utilised land. The methodology used maps of marginal lands, and combined these with maps that predict crop yields based on agro-climatic information, to calculate the potential to produce oil crops. Crops assessed were palm oil, Camelina, Jatropha, tobacco, Canola and coconut oil.

3.3.1 Australia

The study examined the potential for planting sustainable HEFA feedstock on marginal land in Australia using the six-step process described in Appendix B. Natural ecosystems or areas of high conservation value are not considered 'marginal'. Australia has vast areas of marginal land, a well-developed agricultural sector and good infrastructure, which suggests potential capacity to produce oil crops, as Figure 15 shows.

Figure 15: Marginal lands in Australia (million hectares)



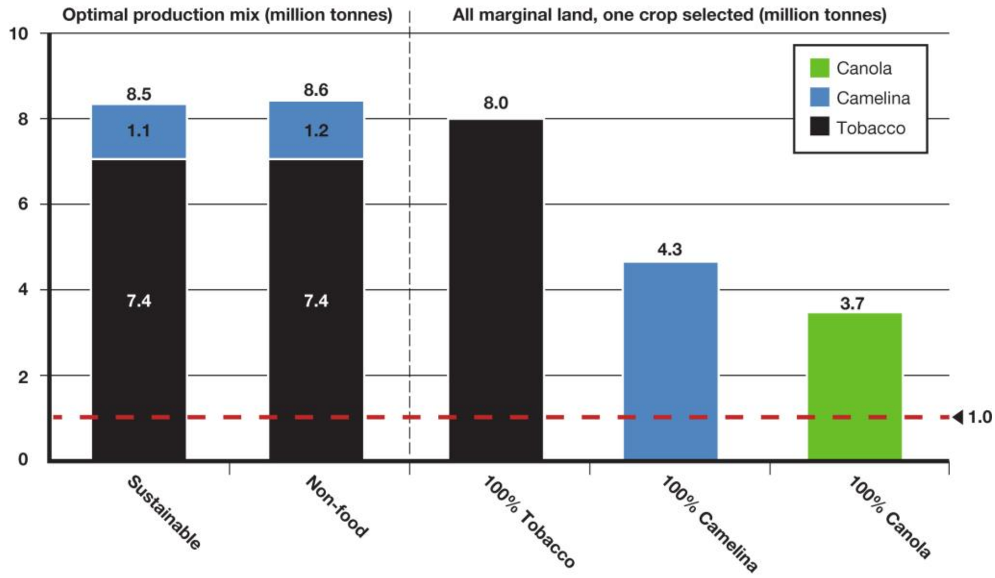
Source: SkyNRG (2012)

As Figure 16 demonstrates, there may be opportunity to ramp up existing and emerging feedstock for use in a HEFA value chain, particularly tobacco. On the left-hand side of the Figure is the optimal production mix which outlines what maximum potential production volumes could be on marginal land utilising both sustainable food

[63] SkyNRG analysis (2013)

and non-food crops. On the right-hand side is the maximum potential production volume utilising just one crop (e.g., providing a more consistent feed to a bio-refinery).

Figure 16: Potential feedstock volumes from marginal lands in Australia relative to target volume (million tonnes)



Source: SkyNRG (2013)

In Australia, large volumes of oil-based, non-food crops such as Camelina, tobacco and Jatropha could be grown, but require a comprehensive program of coordinated planting and investment, in a similar manner to emerging feedstock. As discussed in Section 3.2, Camelina has been extensively tested in the US but requires further study in Australia. Jatropha is well suited to grow in the Australian conditions but is regarded as a weed in most states. Tobacco has been considered a potential energy crop but requires more attention in the Australian context.[64] Overall, the use of marginal lands requires further study to optimise location and type of marginal land plantings across Australia for SAF feedstock. However, it is unlikely this opportunity will be realised without government involvement to coordinate a feedstock program with necessary sustainability criteria and partnerships with the agriculture industry.

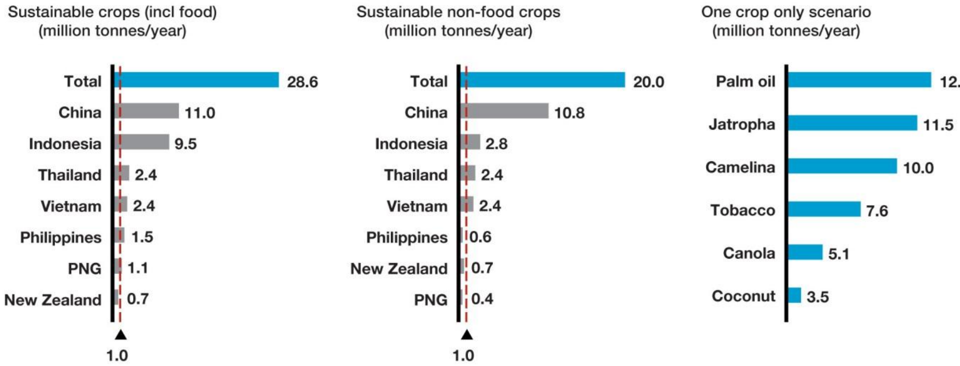
3.3.2 Asia Pacific

Using the same land use approach (Appendix B) the study also identified there is significant potential for oil crop production on marginal lands in the Asia Pacific region. The potential to produce natural oil on marginal land is greater than the demand from a bio-refinery (1 million tonnes per annum), even excluding food crops.

Figure 17 outlines three potential scenarios for marginal land use. Chart 1 (left to right) in Figure 15 refers to the potential volume of crops by country, including food crops, but produced on marginal land and, therefore, classified as sustainable using an alternative land use criteria. Chart 2 shows the same potential volume of crops by country, but excludes food crops. Chart 3 shows the potential volume if only one crop is planted on marginal land, but across multiple countries, to create consistency of input for a bio-refinery. China, Indonesia, Thailand and Vietnam are all attractive options for production of the required volumes, with abundant potential and a well-developed agricultural system. Overall, sustainable palm oil and Jatropha are the best options in the tropical regions whereas Camelina and energy tobacco perform better outside these regions.

[64] Sahagun "UC researchers are engineering the tobacco plant to produce bio-fuels". Los Angeles Times, 29/04/13

Figure 17: Potential volume for sustainable food and non-food crops on Asia Pacific marginal land (million tonnes / year)



Source: SkyNRG analysis (2013)

3.4 Emerging feedstock for emerging pathways

The study also looked at the emerging feedstock such as ligno-cellulosic (LC) feedstock that could be utilised for emerging pathways for SAF.[65] LC feedstock is the biomass that can be derived from plant matter such as grasses, shrubs and trees (e.g., coppice eucalyptus), crop stubble, sugar cane bagasse offcuts and forest residues. LC biomass has the potential to supply a high proportion of low cost jet fuels if cost-effective conversion processes are available.[66]The limitation is that it is difficult to construct a market for these feedstock when there is no SAF demand due to the current lack of ASTM certification and comercially demonstrated pathways. The study examined the following emerging pathways (a survey of the key emerging pathways and companies can be found in Appendix A):

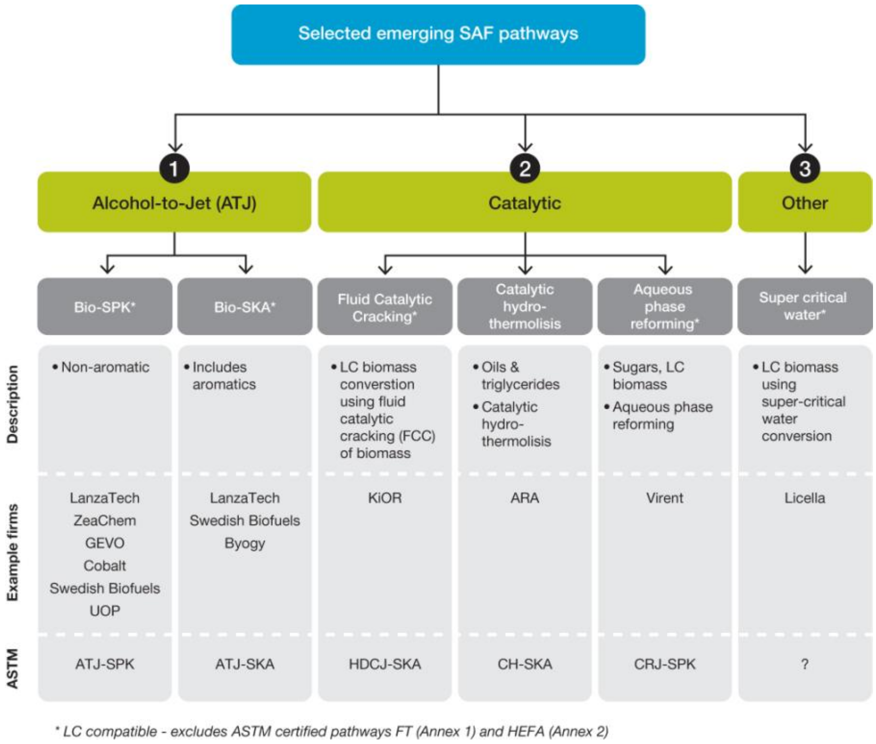
- Alcohol-to-Jet (ATJ)
  - Bio-Synthetic Paraffinic Kerosene (Bio-SPK)
  - Bio-Synthetic Kerosene with Aromatics (Bio-SKA)
- Catalytic
  - Catalytic thermochemical
  - Hydro-thermolysis
  - Aqueous phase reforming
- Thermochemical
  - Super critical water

Figure 18 overleaf outlines the variety of emerging SAF pathways and those utilising LC biomass.

[65] Qantas was responsible for the research and content in this section.

[66] Haritos & Warden (2008) “Future Bio-fuels for Australia–Issues and opportunities for conversion of second generation lignocellulosics”. RIRDC Publication No. 08/117

Figure 18: Emerging SAF pathways



Source: Qantas and interviews (2013)

These technologies are currently either undergoing certification by ASTM, or are planning to undergo certification for use in jet engines. Anecdotal evidence suggests that ATJ and thermochemical conversion may be certified by the end of 2014, but still require significant investment in testing and scientific analysis before approval (Figure 3).[67] As noted by CSIRO in the technical document underlying the Sustainable Aviation Fuels Road Map, there is significant difficulty in assessing these non-approved pathways given their infancy, and data for alternative pathways was deemed by CSIRO to be insufficiently developed for inclusion.[68]

The LC biomass opportunity suffers from the same ‘chicken-and-egg’ problem that afflicts advanced bio-fuels, especially in Australia. While LC biomass is cheap and plentiful, it is geographically diverse. Modern efficient agricultural techniques have not been applied widely to this feedstock, making it difficult and expensive to gather.[69] Since it is not easy to gather and there is no established supply chain, there is no certainty around its supply, and therefore no certainty for those investing in emerging conversion pathways. Similarly, there is no demand for development and aggregation of this feedstock from technology or refining companies, since the technologies are in demonstration phase and not yet at commercial scale. Moreover, in the aviation space, the relevant emerging LC pathways are not yet approved for use in a jet engine. The combination of all these factors means it is challenging for investors to justify development of LC biomass-based projects into commercial projects.

Despite the early stage development of these technologies for LC biomass in aviation, there are several pioneering companies pursuing these emerging pathways. These companies are primarily based in the US and are either at a R&D or small-scale demonstration stage aiming to develop these technologies into commercial reality (see Appendix A for more detail on pathways and companies). Australia, through the Australian Initiaitve on Sustainable Aviation Fuels (AISAF)[70] must keep a close watch on these pathways and develop strong relationships with these renewable technology companies, so it can leverage its comparative advantage in land and LC biomass as the opportunities arise to partner with these companies in the near future.

[67] Brown, “Sustainable Alternative Jet Fuels – Update on ASTM Approval”, US FAA, 18th May 2012, http://www1.eere.energy.gov/biomass/pdfs/10_brown_roundtable.pdf

[68] Sustainable Aviation Fuels Road Map: Data assumptions and modelling, CSIRO, 2011, p9

[69] Exceptions include the development of wood feedstock for the pulp and paper industry, which has been explored by several suppliers, and sugar bagasse that is used for electricity generation – see Appendix A

[70] www.aisaf.org.au

4. Feedstock analysis

4.1 Introduction

Feedstock selection influences transportation, infrastructure and bio-refinery design choices. To investigate the conditions under which a SAF supply chain could be commercially viable in Australia, five feedstock scenarios were developed.

This section details projected domestic feedstock volumes (existing and emerging) and feedstock pricing dynamics, including the effect of external markets and commodity price correlations, before developing the feedstock scenarios. The scenarios are used to inform a broader project assessment framework that includes other external factors.

4.2 Feedstock pricing and dynamics

The Australian government has historically influenced the production of bio-fuels through a range of policy instruments, including production targets (mandates), fuel taxes (excise), fuel quality standards, grants and labelling. The excise tax on road transport fuels is approximately 38 cents per litre. Local bio-diesel (and renewable diesel) producers and importers receive a grant equal to the fuel tax excise through the *Energy Grants (Cleaner Fuels) Scheme Act 2004*. Domestic ethanol producers (not importers) receive an equal rebate for eligible fuel ethanol produced for transport use under the Ethanol Production Grants Program. Both these programs are administered by the Department of Resources, Energy and Tourism. Anecdotal evidence suggests the Cleaner Fuels Scheme will be reviewed in 2021; however, this is not legislated. The Ethanol Production Grant will be reviewed after 30 June 2021.

4.2.1 Domestic and international linkages

The domestic and international fuel markets are clearly linked and influence one another. From a domestic perspective, Australia witnessed a surge in interest in the bio-fuels sectors between 2006-2009, in a similar manner to the US, resulting in an increased capacity for production and a spike in demand for natural oils such as tallow. This boom was soon followed by the closure of many bio-diesel facilities as feedstock costs soared and bio-diesel became uncompetitive compared to other fuel sources, despite assistance through the *Energy Grants (Cleaner Fuels) Scheme Act 2004*.

From an international perspective, the Nesté Oil bio-refinery in Singapore exemplifies the impact of international policy and global commercial demand on domestic bio-fuel strategies. Since the establishment of their renewable diesel plant in 2010, the Nesté Oil bio-refinery has increased its sourcing of Australian tallow volumes for production of renewable diesel for the EU market as domestic demand has lagged. This has increased the price of tallow once again, and moved the tallow price closer towards renewable and bio-diesel prices. Nesté Oil can source natural oil feedstock and still move towards profitability[71] because the mandates in the EU market for bio-diesel and renewable diesel help to keep prices for bio-diesel artificially higher in the EU market. This has a spill-over effect into the domestic market as the price of, for example, domestic tallow, is bid up, reducing the ability to produce competitive bio-diesel and renewable diesel for the local market, as well as the ability to produce SAF. The bio-diesel and renewable diesel mandates in the EU therefore have a strong influence on, and are a key barrier to, a domestic SAF value chain.

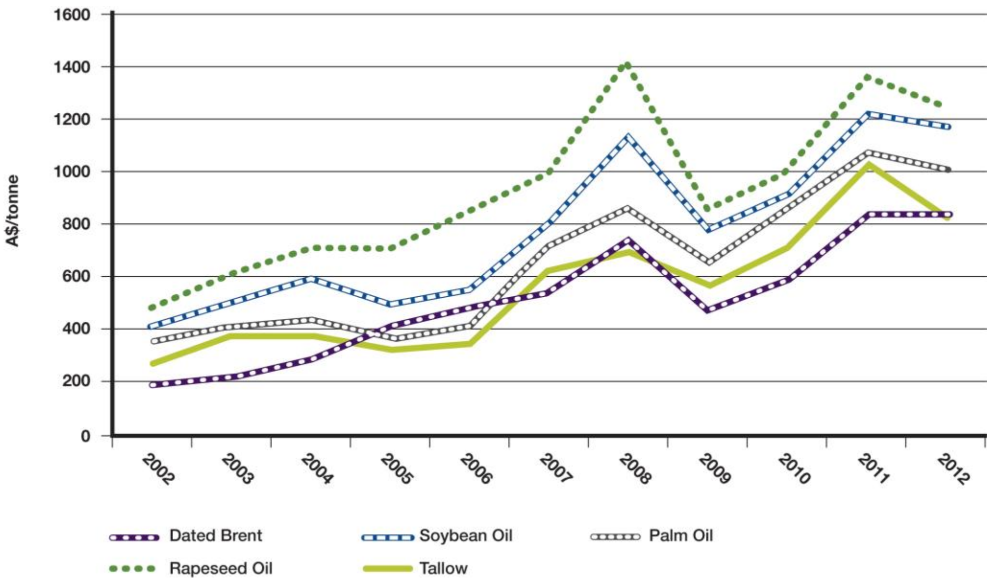
4.2.2 Correlation between crude oil and bio-oil feedstock

A further influence on HEFA feedstock is the relationship with crude oil. Conventional wisdom says that when the price of crude oil goes up, bio-fuels become more competitive. The assumption is that the inputs to bio-fuels are not connected to crude oil and therefore bio-fuels can compete with crude oil-based products. As part of the economic analysis in Section 8, this assumption was tested in terms of the correlation between natural oils and crude oil. The basic relationship can be observed in Figure 19. The economic analysis demonstrated that natural oils prices are correlated to crude oil prices, so that both products tend to move in the same direction. The ability to subsitute bio-fuels into the supply chain, coupled with mandates in the EU and US,has effectively created a price floor for natural oil feedstock. This price floor is the lowest purchase price of feedstock before the mandate creates a stronger pull for suppliers to re-engage in the production of bio-diesel or renewable diesel.

[71] Lim "Neste's bio-fuels back in black for Q1", Business Times, 27th Apr 2013

This implies that increases in jet fuel prices are unlikely to afford profitable SAF production unless natural oils are accessed below their market price. This can be achieved in several ways, but the most likely method is by investing directly, or in partnership with an upstream partner, in the development and production of non-food feedstock. However, this represents an opportunity loss for the producer (i.e. there is a greater return on investment by selling directly to the market). A longer term strategy would require the weakening of the crude-natural oil correlation through either the saturation of current natural oil markets (e.g., food, chemicals and fuels) or the development of emerging feedstock that have limited alternate use.

Figure 19: Relationship between crude oil and oil feedstock prices



Source: SKM analysis (2013)

4.3 Feedstock scenarios

Feedstock selection influences infrastructure and process design choices. Techno-economic analysis of the SAF supply chain therefore requires defined feedstock strategies. To test the boundaries of the refining operations and the economic model, five theoretical feedstock scenarios were created. These scenarios represented the spectrum of feedstock options and were used to test different feedstock compositions and their effects on key variables and outputs. Sensitivities were also applied to these feedstock scenarios as detailed in the Economics section.

The study has assumed feedstock volumes to be non-seasonal. New South Wales (NSW), Victoria (Vic) and Queensland (Qld) were chosen as the local markets, providing for the integration of the manufacturing and distribution stages at a brownfield refinery location in the eastern states. However, apart from tallow, the majority of Australia's natural oil feedstock is available (or crushed) in NSW and Vic. Locating the manufacturing facility in this region would reduce associated feedstock transportation costs. South Australia and Western Australia were excluded due to limited feedstock volumes. Importantly, the manufacturing and distribution stage are refinery agnostic at this feasibility study level.

4.3.1 Base case scenario

The base case scenario assumes that available feedstock was sourced from the domestic market up to the point that the domestic market would not be significantly impacted (estimated to be 30% of the facility processing capacity). Imported feedstock would be used to meet the remaining feedstock requirements.

This scenario assumes the complete diversion of current crude Canola exports and the ability to induce additional Canola seed crushing without capital investment (i.e. Canola demand remains within local crushing capacity). Adopting this Canola strategy provides approximately 20% of the bio-refinery's 3,000 tonnes per day demand. Supply of tallow and used cooking oil (UCO) from the NSW and Vic markets can satisfy 4.5% of the feedstock demand. However, this volume accounts for 20% of each of the respective tallow/UCO markets. The lack of regionally available feedstock is supplemented by assuming the diversion of Qld tallow (the majority of which is believed to be exported) to the local market. Diverting 30% of the Qld tallow market satisfies approximately 5% of the refinery demand. The 70% supply shortfall is assumed to be satisfied via imports. A summary of feedstock composition is shown in Table 1.

Table 1: Base case feedstock composition

Feedstock	Tonnes Oil per day	Feedstock split %	Domestic market %	Location
Tallow (NSW/Vic)	121	4.0	20	NSW/Vic
Tallow (Qld)	152	5.1	30	Qld
Export and available crude Canola	619	20.6	-	NSW/Vic
Additional crushed Canola	-	-	-	-
UCO	14	0.5	20	NSW/Vic
Imports (sustainable palm oil)	2,094	69.8	-	SEA[72]

Source: SKM analysis (2013)

4.3.2 Low cost

A 3,000 tonnes per day low cost scenario was developed to demonstrate the least feedstock price gap to SAF viability. Certified sustainable palm oil was chosen as this feedstock is both available in sufficient commercial quantities and usually sets the natural oil price floor. This strategy also provides a risk mitigation strategy in the case of a collapse in domestic agricultural output (e.g. a drought).

4.3.3 Aggressive domestic

To demonstrate the effect of creating change in the local agricultural market, a 3,000 tonnes per day "aggressive" domestic scenario was developed. This scenario assumes that the proportion of domestically sourced feedstock is increased to a point that is likely to lift prices in the local market towards import parity levels. This scenario targets the same domestic feedstock markets as the base case strategy; however, it assumes that the industry invests in additional oil seed crushing capacity, thereby doubling the volume of available crude Canola oil (40%). UCO and tallow volumes are assumed to remain the same as the base case scenario. The strategy still requires the import of just over half of all feedstock to enable optimal operation of the bio-refinery.

4.3.4 Reduced scale

Limited domestic availability, coupled with the need to import significant fractions of feedstock, even when aggressively diverting current exports back to the local market, encouraged the development of this scenario. This strategy sacrifices economics of scale by considering a 1,000 tonnes per day manufacturing facility. The strategy targets only domestic feedstock, maximising both crude Canola export diversion and localised crushing capacity utilisation (total Canola: 65%). The feedstock balance is made-up using tallow (34%) and UCO (1%).

4.3.5 Reduced scale tallow/UCO

To maximise the use of non-food feedstock an alternative 1,000 tonnes per day scenario was developed. The strategy utilised domestic (34%) and imported (65%) tallow, augmented with a limited volume of domestic used cooking oil (1%). Both tallow and UCO feedstock are perceived to be a relatively low cost. However, the price of imported tallow is inflated to reflect the limited global trade of tallow.

4.4 Feedstock summary

First, the study finds that, in the context of a bio-refinery with 3,000 tonnes per day of feedstock demand, and even at a reduced scale of 1,000 tonnes per day, there is a significant gap in domestic feedstock volume, especially for sustainable non-food feedstock. The Australian non-food natural oils market by itself is unlikely to

[72] SEA: South East Asia

sustainably support a rateable feedstock supply envisaged in the base case of this study. This volume of demand represents almost the entire annual output of natural oils and tallow in Australia. The only feasible way in the short term to increase existing domestic natural oil supply is to crush additional oilseeds that Australia currently produces and exports to international markets. Another alternative is to redirect domestic volume such as tallow into domestic production. However, this demand pull would represent an unsustainable disruption to the Australian natural oils market and would dramatically increase the price of feedstock.

Second, natural oil prices have generally exceeded those of conventional diesel and jet fuel over the last five years, and this dynamic is projected to remain. An Australian bio-refinery would compete with higher priced oleo chemical and food products for these feedstock. An Australian bio-refinery would also compete with US and EU bio-fuel subsidies. These subsidised markets create a strong demand pull in the natural oils markets and create a soft but observable price floor. Access to feedstock below the market price is therefore imperative. However, this represents an opportunity loss for the producer.

Third, current non-food oils will likely continue to represent the lowest priced feedstock available for HEFA in the short-to-medium term. However, the emerging non-food crops have declining cost curves, and in some scenarios, are competitively priced over the next decade. Moreover, their production will increase, while production of current non-food feedstock is likely to remain unchanged. This suggests that emerging feedstock are an important opportunity over the next decade. A coordinated and comprehensive program to encourage and secure emerging feedstock in the future is essential to establishing a HEFA-based SAF value chain. This is unlikely to happen for at least the next five to seven years in Australia without significant government support.

However, the study also observed a clear correlation between natural oils and crude oil. Conventional wisdom says that when the price of crude oil goes up, bio-fuels become more competitive. Natural oils prices are correlated to crude oil prices in the short-to-medium term, so the price of both products tends to move in the same direction. Therefore, the increasing price of crude oil tends to lead to an increase in the price of HEFA-based SAF, at least in the short-to-medium term until the relative markets are saturated with natural oils. This is an economic challenge for the HEFA pathway and is explored in more detail in Section 8 (Economics).

Finally, if emerging feedstock can be ramped up to commercial scale, their pricing will also be driven by various alternative markets (e.g., food, chemicals and more recently fuels). Overall feedstock prices will only decrease as the total market becomes saturated with the supply of natural oils. Some emerging feedstock will act to break the link between natural oils and crude oil in a more effective way since they are not suitable substitutes for all markets, so existing price correlations will weaken more rapidly for these feedstock (e.g., algae, Jatropha or mustard oils). However, the lack of current supply, coupled with the high correlation to crude, will make long-term price competitiveness of natural oils challenging. The ramp-up of domestic emerging feedstock will therefore need to be significant if it is to reduce the long-term market price of this category of feedstock.

5. Transport, aggregation and pre-treatment

5.1 Introduction

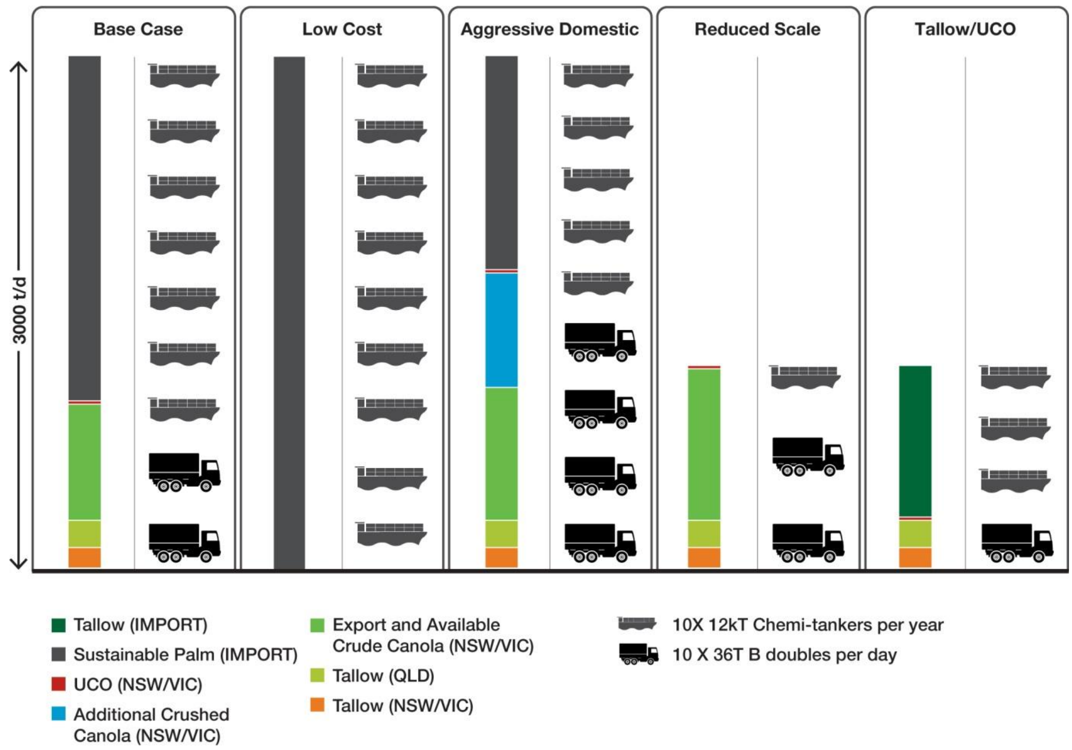
This section details the transportation of feedstock to a suitable aggregation point for pre-treatment. Estimated transport movements and associated costs for each feedstock scenario are provided based upon feedstock location and volumes.

Delivery of feedstock to a dedicated aggregation point is necessary as natural oil and tallow properties differ significantly from conventional crude oil. Aggregation near an existing petrochemical refinery also provides economies of scale and reduces the risk associated with relying on a decentralised supply chain. To ensure natural oils and tallow meet manufacturing stage specifications, aggregated feedstock is pre-treated prior to being delivered to a dedicated bio-refinery. Therefore, this section also outlines the design and costing of a facility suitable for aggregating and pre-treating bio-feedstock for subsequent upgrade in a compatible bio-refinery.

5.2 Feedstock locations and transport movements

The feedstock market locations and the expected demand profiles identified in the feedstock strategies (Section 4.3) were used to calculate transport movements and associated costs. Road and ship were identified as the most probable transport modes as the volumes will be insufficient to warrant the high cost of rail infrastructure (above rail costs and rolling stock). Feedstock in the NSW and Vic region is therefore assumed to be trucked in using 36 tonne b-double trucks, with all other material shipped via 12 kilo tonne chemi-tankers. A breakdown of the transport movements required to supply a Greater Melbourne refinery are provided in Figure 20. Yearly shipping data is based on 346.75 manufacturing days per annum (95% manufacturing operating schedule). In the case of Canola, the Australian Oil Seed Federation advised that the Canola transport mode depends on the volumes purchased and for the purpose of this study, it has been assumed to arrive via road. Subsequent design considerations for the combined aggregation and pre-treatment facility have allowed for both sea and road delivery of Canola feedstock.

Figure 20: Transport movements by feedstock scenario (Greater Melbourne)



Source: SKM and Shell Australia analysis (2013)

Feedstock logistics costs are determined according to a weighted average pricing methodology due to the variability of transportation price rates and relative supply volumes from each region throughout Australia. Weighted average feedstock delivery prices were calculated for delivery to Greater Melbourne and Greater Brisbane refinery locations.

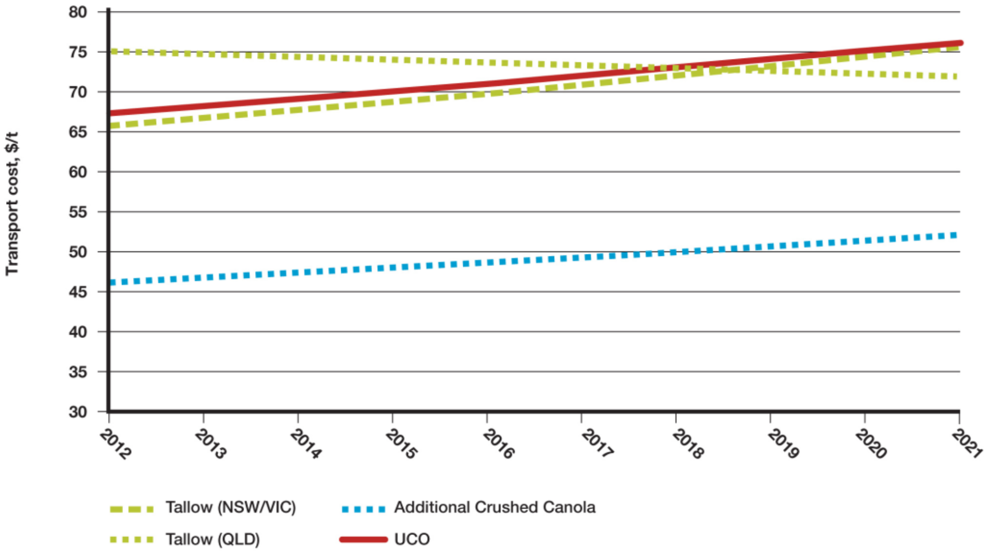
The transport method assumed for each of the feedstock to the Greater Melbourne area is presented in Table 2. The domestic transport costs, provided by AltAir to the Greater Melbourne area, are presented in Figure 21.

Table 2: Feedstock source location and transport method (Greater Melbourne area)

Feedstock	Source location	Transport method
Tallow	NSW / Vic	Truck
Tallow	Qld	Ship
Export and available crushed Canola	NSW / Vic	Truck
Additional crushed Canola	NSW / Vic	Truck
UCO	NSW / Vic	Truck
Palm	SEA	Ship

Source: SKM analysis (2013)

Figure 21: Domestic transport costs (Greater Melbourne area) A$



Source: AltAir analysis (2012)

Notes: Economic analysis has adopted the forecast prices for each individual feedstock route.

5.3 Aggregation and pre-treatment

To maximise return and ensure continuity of supply, the petrochemical industry sources crude oil from multiple locations around the globe. Depending on the crude oil properties, petroleum feedstock often needs to be pre-treated once delivered to a petrochemical complex. Pre-treatment involves the removal of contaminants that may adversely affect refinery operation, maintenance cost and product quality. The ability to pre-treat a feedstock to meet downstream compatibility requirements defines the crude oil types (or diet) that a particular refinery may process.

Production of bio-fuels also requires the aggregation and pre-treatment of bio-feedstock. Like the petrochemical business, the diverse nature of feedstock properties and locations introduces selection, aggregation and treatment challenges. Locating a bio-fuel refinery closer to a feedstock source significantly increases the risk associated with relying on localised feedstock (e.g., crop failures due to drought and/or pests, local market economics). Furthermore, decentralisation removes significant infrastructure and operational synergy achieved by co-locating the manufacture of renewable hydrocarbons on an existing refinery site (Section 6.2.2). Accordingly, the study investigated the infrastructure required and associated processes needed to aggregate and pre-treat different feedstock types near an existing refinery. The study is not specific to an individual brownfield refinery site and is valid for any location with port and road access.

5.4 Technical considerations

5.4.1 Bio-feedstock compatibility

Natural bio-oils and tallow feedstock properties are significantly different from conventional crude oil. Bio-feedstock are acidic, contain a high fraction of oxygen (10%wt[73]), metals and other contaminants that are incompatible with conventional refinery operations. Therefore, unless the conventional refinery has been specifically modified, bio-feedstock must not be cross-contaminated[74]. To eliminate the chance of contamination, a feedstock aggregation facility should be in a separate and segregated compound next to the refinery precinct. In addition, segregation limits the on-site impact of increased transport movements associated with the delivery of bio-fuel feedstock.

5.4.2 Feedstock segregation

Segregation of different feedstock is necessary for both economic and technical reasons. Some feedstock are solid at room temperature and must be heated for material transfer purposes[75]. The heating and insulation of all onsite tanks and pipelines is not practical from a capital prospective. In addition, segregation enables controlled blending of different feedstock. If a single tank configuration is used to receive two different feedstock types, the oil profile could swing significantly depending on the feedstock properties and delivery schedule. For example, Canola oil is highly unsaturated (~94%) while tallow is approximately 50% saturated. If a single tank configuration is used to receive both tallow and Canola oil, the feedstock unsaturates-to-saturates ratio could swing depending on the shipment delivery schedule. In addition, a single heated tank configuration would consume additional energy to unnecessarily heat the Canola oil volume. Feedstock is therefore segregated based on heating requirements and select properties. This ensures a relatively consistent oil profile is delivered to the manufacturing stage.

5.4.3 Feedstock finishing and pre-treatment

Natural oil and tallow feedstock are highly variable in their oil quality and composition. Metals, free fatty acids, water, insolubles and other contaminants exist in all natural oils and animal fats. These bio-feedstock are unusually “finished” or post-processed at the production or collection point to comply with relevant specifications required by the market (e.g., food, oleo-chemical[76], etc). However, in most cases finished oil contains contaminants that are incompatible with hydroprocessing equipment[77]. Consequently, bio-feedstock must be upgraded via a “pre-treatment” stage prior to conversion into renewable hydrocarbons. In Australia, only food grade Canola oil may be processed without pre-treatment. Pre-treatment therefore widens the bio-feedstock diet by increasing the compatibility of multiple feedstock types with downstream processing equipment.

It is not considered practical to require small-volume finishing facilities to refine feedstock to an oil specification that is more stringent than most other markets. Moreover, the degree to which feedstock is pre-treated has many downstream processing implications[78]. This, coupled with the challenge of managing the pre-treatment requirements up the supply chain, led to the incorporation of the pre-treatment stage within the aggregation facility.

[73] %wt: % weight

[74] The BP Bulwer Island has been modified to process tallow feedstock. However both untreated and treated feedstock is kept isolated until the specific processing unit.

[75] Sustainable palm oil and tallow are solid at room temperature; melting point: 35 and 40˚C respectively

[76] Oleo-chemical: chemicals derived from plant oils and animal fats.

[77] Compatibility issues largely relate to catalyst de-activation and/or poisoning by bio-feedstock contaminants (e.g., metal deposits, acidity, phosphorous, impurities, etc). Managing pre-treatment requirements is critical if the economic lifetime of the catalyst is to be achieved. Catalyst selection and engineering design solutions also provide an important role in managing catalyst life.

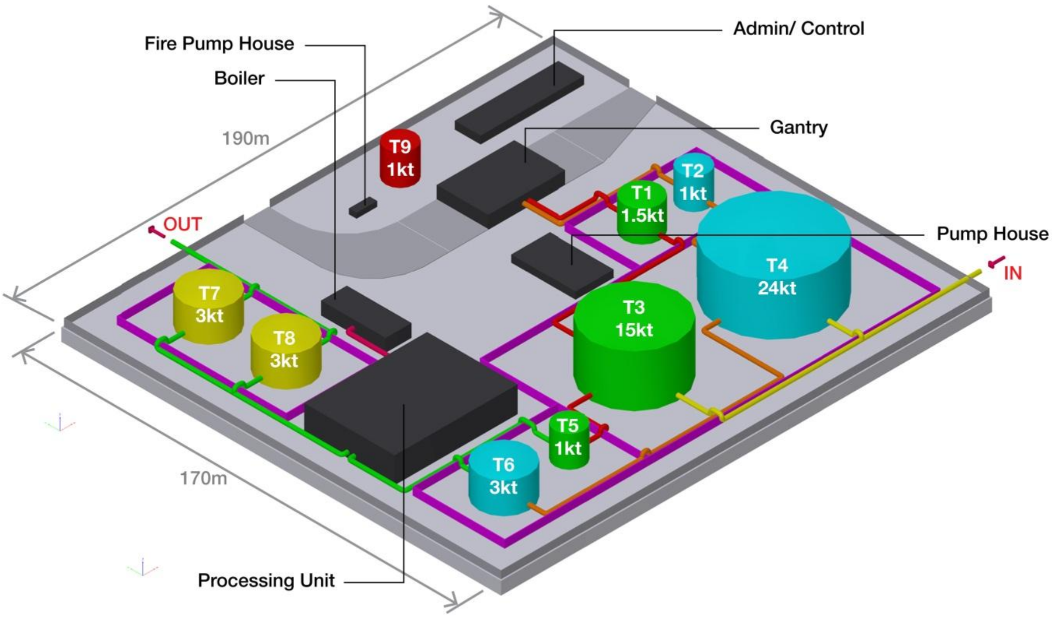
[78] Example: balance between pre-treatment cost and catalyst lifetime

A continuous bleaching process was selected to refine the aggregated natural feedstock to the requirements defined in a proprietary oil specification. The specification contains maximum contaminate limits and is based on industry experience. Directional pre-treatment capital costs were sourced from an external supplier. Estimated operating costs were based on the price of bleaching earth which is understood to dominate yearly costs.

5.5 Aggregation and pre-treatment facility

The location and varying quality of natural bio-oils and tallow feedstock requires the construction of a combined aggregation and pre-treatment facility. Aggregation provides the receipt and storage of various feedstock types, while pre-treatment removes materials that are incompatible with downstream processing equipment. The combined aggregation and pre-treatment facility is illustrated in Figure 22. The schematic is based on the feedstock profile defined in the domestic first (base case) feedstock scenario.

Figure 22: Aggregation / pre-treatment facility



Source: The Shell Company of Australia (2013)

Finished natural oil and tallow feedstock is received via truck and ship (chemi-tanker). A dedicated road gantry provides unloading capacity of tri-axle and b-double vehicles. A direct shipping berth pipeline provides receipt of domestic and international chemi-tanker feedstock parcels. The gantry lines and shipping berth pipeline are heated to ensure tallow (or sustainable palm oil) parcels do not solidify during transfer. Feedstock will be stored in a number of tanks, designed to provide both sufficient ullage and to segregate feedstock. Six tanks of approximate total capacity 45.5 kilo tonne (50 million litres)[79] will be required to store untreated feedstock. Tanks T1 and T2 provide road gantry storage, while tanks T3 and T4 support ship delivery. Tank T1 is designed for Canola oil and used cooking oil storage. The tank is unheated and sized to provide future feedstock diversification. The second road gantry tank (T2) is dedicated to tallow storage and therefore requires heating and insulation[80]. Tank T3 is intended for domestic crude Canola parcels; however, it is compatible with feedstock that do not require heating[81]. Tank T4 is sized to handle both imported palm and domestic tallow chemi-tanker parcels, both of which require heating. Tank T4 is larger than T3 due to the reliance on imported sustainable palm feedstock in the base case feedstock scenario.

---

[79] Density: 0.910 kg/L

[80] Unlike the bio-oil feedstock, tallow is a co-product and therefore tallow production is expected to remain stable (Section 2). Tank T2 has therefore been sized appropriately.

[81] The combined aggregation and pre-treatment facility has been design to handle road and sea delivery of Canola oil. The study partners were advised by the Australian Oil Seed Federation that the Canola transport mode will depend on the volumes purchased. Additional tank capacity provides for flexibility in the feedstock profile.

Untreated feedstock will then be pumped from the larger storage tanks to the day storage tanks (T5 and T6), providing a buffer before blending. Tank T6 (heated) is sized larger than T5 due to the heavy reliance on sustainable palm oil. Inline blending is used to control the feedstock profile. The blended feedstock is then pre-treated in a continuous bleaching facility ('processing unit'; Figure 22). The pre-treatment unit removes contaminants to ensure post-treated oil is suitable for upgrade via hydroprocessing. After treatment, feedstock is stored in one of two insulated tanks (T7 and T8). The renewable feedstock is supplied directly to the bio-refinery from either tank T7 or T8. The two-tank configuration enables one take to be filled while the second feeds the bio-refinery.

In addition to this functionality, ancillary equipment and systems are included in the feasibility design and costing. Major items include slops and waste management, storm water management, interceptors, fire fighting (Tank T9), utilities, power, steam generation and provision, heating fuel, storage bunds, fencing, lighting, telemetry, buildings, administration and security facilities.

The design has been modified to accommodate the additional feedstock supply strategies. Specifically, the import-only strategy (single feedstock arriving via chemi-tanker) excludes the road gantry, associated tanks (T1, T2, T3 and T5), pipelines and the inline blending function. The aggressive case requires the construction of an additional road gantry. The gantry is required to support increased truck movements associated with the delivery of additional crude Canola oil volumes. The capacity of the facility (e.g., tank sizes and pre-treatment) was scaled to accommodate the reduced volumes of the 1,000 tonnes per day feedstock scenarios. The base case facility functionality, however, remains.

5.6 Directional cost estimate

Directional aggregation and pre-treatment capital and operating costs for each of the feedstock strategies defined in Section 4.3 are shown in Table 3. The estimate has an accuracy range of ±50%, which is consistent with project scoping and initial assessment activity conducted by the oil and gas industry. The estimates are based on local experience and are in 2012 Australian dollars. Future costs must be inflated using Australian rates. Directional costs are valid for any Australian location provided suitable port and road access exist.

Table 3: Aggregation / pre-treatment facility CAPEX estimates (A$ million, 2012)

Feedstock scenario	CAPEX ($million)	OPEX ($million/y)
Domestic first (base case)	115	9
Import only	89	9
Aggressive	116	9
Reduced scale	84	3

Source: The Shell Company of Australia (2013)

Operating costs for receipt and storage are based on comparable scale (capacity and throughput) facilities in Australia. Pre-treatment operating costs were based on the market price of bleaching earth as advised from the bleaching technology provider.

The base case design and capital estimate was customised according to the requirements of each feedstock scenario in Section 4. Reducing the facility capacity was not found to materially impact capital cost. Diseconomies of scale result as the reduced scale facility still requires all infrastructure associated with the handling, storage and pre-treatment of both road and sea feedstock deliveries.

5.7 Summary

Production of bio-fuel requires the aggregation and pre-treatment of feedstock. Aggregation is necessary to achieve production economies of scale, co-location synergies and to reduce the risk associated with relying on localised feedstock sources. Removal of finished feedstock contaminants through pre-treatment is essential to maintain feedstock compatibility with bio-refinery hydroprocessing equipment. However, finished and post-treated natural oils and animal fats differ significantly from conventional crude oil, intermediate refinery streams and final products. Therefore, renewable feedstock must remain segregated until upgraded into certifiable fuel molecules[82].

The domestic first feedstock scenario was used to scope preliminary design and costing of a combined aggregation and pre-treatment facility. To ensure segregation of renewable feedstock, the facility is located outside the refinery gate. The design includes both a road gantry and ship discharge pipeline, untreated product storage segregation and inline blending of feedstock before pre-treatment. Segregation and inline blending enable a consistent feedstock profile to be delivered to the bio-refinery. Post-treatment storage tanks and a dedicated pipeline to the manufacturing facility are included in the costing. Directional capital and operating costs for the base aggregation and pre-treatment facility are A$ 115 million and A$ 9 million respectively (2012; accuracy: ±50%).

[82] Unless the refinery has been design and/or modified to handle renewable feedstock.

6. Manufacturing

6.1 Introduction

Most types of natural petroleum (crude oil) will burn straight from the ground. However, if used directly in an engine, the oil will burn poorly, quickly clogging components with residuals and by-products. Conventional refining or 'manufacturing' is used to purify and/or convert the crude oil feedstock into different petroleum products (e.g., gasoline, jet fuel, diesel, bitumen, etc.). The basic process begins by separating the crude oil into different fractions. Various treating processes are then applied to remove undesirable components. Cracking and converting units are used to shift the fractions to better match market demand. However, the properties of crude oil largely dictate product yields. Therefore, just as a butcher cannot produce only scotch fillets from livestock, a petroleum refiner cannot only produce 100% jet fuel from a barrel of crude oil[83].

Renewable bio-oils must also be refined to ensure compatibility with current engine and fuel systems. However, bio-fuel manufacturing differs from crude oil refining, often requiring specific processes not found in a petrochemical complex[84]. To date, the aviation industry has certified the production of sustainable aviation fuel (SAF) via two pathways: hydroprocessing and Fischer Tropsch. Unlike ethanol or bio-diesel fuels, these manufacturing pathways produce synthetic fuel components that are chemically identical to select molecules found in conventional petroleum products[85]. Synthetic fuel components are therefore fully fungible with existing aircraft, engine and fuel distribution systems.

Of the two certified pathways, only hydroprocessing technology is found in a modern petrochemical complex. However, the technology is specifically designed to process intermediate petroleum products, not bio-oil or tallow feedstock. This section details the technical considerations and cost to convert bio-oil and tallow into HRJ using hydroprocessing technology. Uncertified manufacturing technologies (i.e., alcohol to jet fuel and pyrolysis oil to jet fuel) have been excluded. To augment understanding, Qantas commissioned Solena to provide industry insight into the FT pathway. Shell and the other project partners were not involved in the FT study (Section 9).

6.2 Technical considerations

6.2.1 HRJ production at a conventional refinery

Hydroprocessing is a generic term used to describe a range of refinery processes that use hydrogen, along with an appropriate catalyst, to remove undesired components from refinery streams. The technology is core to a modern petrochemical complex, and has been designed to upgrade intermediate petroleum product streams. Broadly, hydrotreatment describes the removal of undesirable materials, including nitrogen, sulphur and residual metals, while hydrocracking describes a hydroprocess used to break down carbon chain lengths, thereby producing lighter, more valuable molecules. In Australia, hydrotreatment (hydrogen desulphurisation) units are used to remove sulphur from diesel feedstock to satisfy the EURO5[86] diesel standards (e.g., product: Ultra Low Sulphur (ULS) diesel[87]). Only BP's Brisbane Bulwer Island Refinery has an operational hydrocracker.

Bio-oil properties differ significantly from intermediate petroleum streams. The unique feedstock properties necessitate the construction of new, or the modification of existing, hydroprocessing (i.e., hydrotreatment and hydrocracking) equipment[88]. It is not possible to process bio-oil and tallow feedstock in an unmodified refinery. Furthermore, the SAF specification requires the neat hydroprocessing of bio-oil feedstock. Any kerosene produced by co-processing bio-feedstock with conventional petroleum streams cannot be certified as HRJ[89].

[83] The refinery business is like a butcher rather than a baker. The baker takes different and flexible ingredients and makes a variety of products to order. In contrast the butcher makes as many different products (both premium and non-premium) from the carcass. Similarly, the refiner can only make use of what is in the crude oil feedstock.

[84] Example: transesterification of bio-oil and animal fats into bio-diesel

[85] n-/iso-alkanes. Note that carbon dating will identify the younger age of the renewable molecule.

[86] Refers to European emission standards that define the acceptable limits for exhaust emissions of new vehicles sold in EU member states. The EURO5 diesel standard has been adopted in Australia. The standard limits sulphur in diesel fuel to 10ppm."

[87] Ultra low sulphur diesel contains a maximum of 10ppm sulphur.

[88] Processing bio-feedstock results in different reaction and temperature profiles than conventional intermediate petroleum products.

[89] The ASTM D7566 specification requires testing and certification of 100% synthetic kerosene.

Production of renewable diesel is, however, permitted, and has been demonstrated at BP's Bulwer Island Refinery, Brisbane.

The shutdown and conversion of the Shell (Clyde) and Caltex (Kurnell) refineries in Sydney may enable the development of a bio-fuel facility. Analysis of the hydrogen desulphurisation units at Clyde found that the plant was incompatible with the conditions required to process bio-oil. This was due to a number of technical constraints relating to the design of the original unit. Even if compatible, the large capacity of existing petrochemical units is expected to exacerbate the feedstock supply issues identified in Sections 2 to 4. However, a suitable (decommissioned) reactor was identified at Shell's Geelong refinery[90]. The inclusion of the unit was found to be indirectly captured in the feasible level costing. This is because the reactor itself represents only a small proportion of the total system cost. Importantly, potential cost savings may be offset by unexpected commissioning challenges; for example, the discovery of poor reactor vessel integrity, and the need to replace the majority of the supporting reactor equipment (e.g., compressors, heat exchangers, pipe work, etc.).

Conversion of an operational hydroprocessing unit to process neat bio-oil was not analysed. Such a conversion would remove the production of conventionally hydrotreated products from the refinery product slate (e.g., ULS Diesel). Furthermore, the requirement to hydrocrack means only the Bulwer Island refinery configuration could target HRJ. Accordingly, the study only considered the construction of a dedicated HEFA-based bio-refinery.

6.2.2 Location and integration

Directional cost estimates are largely influenced by site location. A brownfield site enables refinery assets to be used; for example, utilities and services, flare facilities, laboratory facilities, control room, product tanks, etc. Furthermore, co-location provides direct product integration within the refinery gate. Brownfield site synergies are expected to reduce capital spend by approximately 1.5 times compared to a greenfield (new) site. To ensure this study captures the most likely complete economic cost of producing SAF in Australia, only a brownfield bio-fuel manufacturing facility was considered.

The integration of the bio-refinery into a conventional refinery is illustrated in Figure 23. Importantly, bio-feedstock and intermediate renewable hydrocarbons are incompatible with existing refinery infrastructure. Therefore, following aggregation and pre-treatment, the bio-fuel feedstock is fed directly to a dedicated manufacturing stage. Only finished products are integrated into the existing refinery product pool.

Figure 23: Site diagram (illustrative purposes only)

90 Hydrex Reactor: originally used to breakdown heavy molecules into lighter components.

Source: The Shell Company of Australia (2013)

Capital expenditure (CAPEX) and operational expenditure (OPEX) figures are not based on a specific domestic refinery. Therefore, the results are valid for any Australian brownfield (existing) refinery.

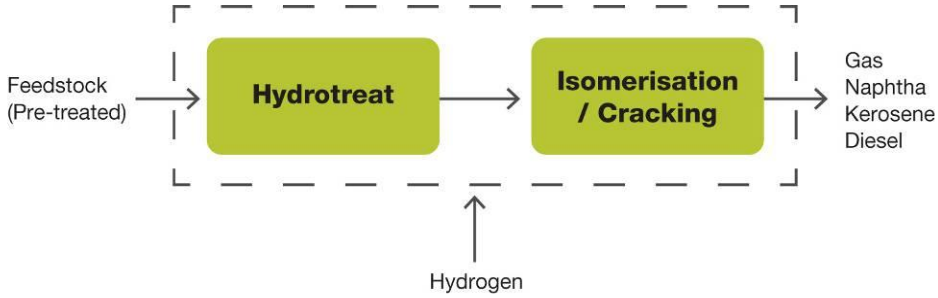
6.2.3 Scale

Feedstock strategies were developed to support the processing of 3,000 tonnes per day of renewable feedstock, producing approximately 20,000 barrels of renewable molecules per day. The facility scale was selected to ensure the project could deliver a significant amount of SAF fuel to the Australian market (beyond a demonstration plant). The processing capacity is large compared to existing bio-refineries (Nesté Oil's Singapore facility is currently the largest at 2,100 tonnes per day). However, the unit throughput is small when compared to a conventional Australian refinery, which are small by world scale.[91] The importance of scale in reducing cost per barrel is demonstrated by adapting the base design throughput (3,000 tonnes per day) to accommodate the reduced scale feedstock strategies (1,000 tonnes per day). The reduced scale costs are calculated by applying industry scaling factors.

6.3 Manufacturing technology

Hydroprocessing technology, when configured to process renewable feedstock (natural oils and tallow) produces renewable hydrocarbons. Depending on the process configuration, these hydrocarbons may be fractioned into renewable diesel, kerosene[92], naphtha (gasoline feedstock) and refinery gas. The specification for aviation fuel containing synthetic hydrocarbons (ASTM D7566) enables renewable kerosene to be blended and certified for use in aircraft gas turbine engines. The dedicated manufacturing unit is illustrated in Figure 24.

Figure 24: Manufacturing Configuration



Source: The Shell Company of Australia (2013)

Hydrotreatment is the first stage in the production of renewable hydrocarbons. This process removes undesirable atoms (e.g., oxygen) from the pre-treated natural oil/tallow feedstock, creating an intermediate hydrocarbon product. This intermediate product must then be isomerised to improve the cold flow properties of the final product. The majority of the isomerised product stream is chemically identical to select molecules found in conventional diesel fuel. This is because most Australian bio-oil feedstock naturally produce diesel-like hydrocarbons when hydroprocessed[93]. Therefore, fractioning[94] the product stream after the isomerisation stage will produce the highest quantity of renewable diesel, with only low volumes of renewable kerosene, naphtha and gas as co-products.

To produce an increased fraction of renewable kerosene, and thereby HRJ, the isomerisation stage product stream (mostly diesel) must be broken down or "cracked". Unfortunately, cracking also produces an increased volume of naphtha and refinery gas, both of which are lower value products. Maximum kerosene production is achieved when the entire fraction of diesel-like molecules are cracked into the jet fuel range. However, this also

[91] The scale of local refineries is small when compared to the Asian 'mega' refineries (e.g., Shell Bukom, Singapore: 500,000 bbl/day; Reliance Refinery, India: 1.24 M bbl/day; Shell Clyde, Australia: 85,000 bbl/d).

[92] Renewable kerosene is a synthetic paraffinic product

[93] Palm kernel and coconut oil will produce a higher fraction of renewable kerosene (certifiable as HRJ); however, these feedstock are not indigenous to Australia.

[94] Fractioning is a standard refinery process used to split hydrocarbons into different fuel groups

produces significant volumes of renewable naphtha and gas. The degree of cracking therefore determines the split between the different renewable products.

Conventional hydroprocessing of intermediate petrochemical products consumes approximately 1% hydrogen by mass of material processed. Manufacture of renewable products consumes approximate three times more hydrogen, largely due to the high oxygen content of the bio-feedstock. However, refinery supply constraints, resulting from the need to de-sulphurise diesel to meet the EURO5 automotive vehicle emission standards, mean most refineries have a shortage of hydrogen. Therefore, additional hydrogen must be manufactured onsite, which incurs considerable extra cost. Hydrogen production, via steam methane reforming technology – the most common method of Hydrogen manufacturing – was included in this study.

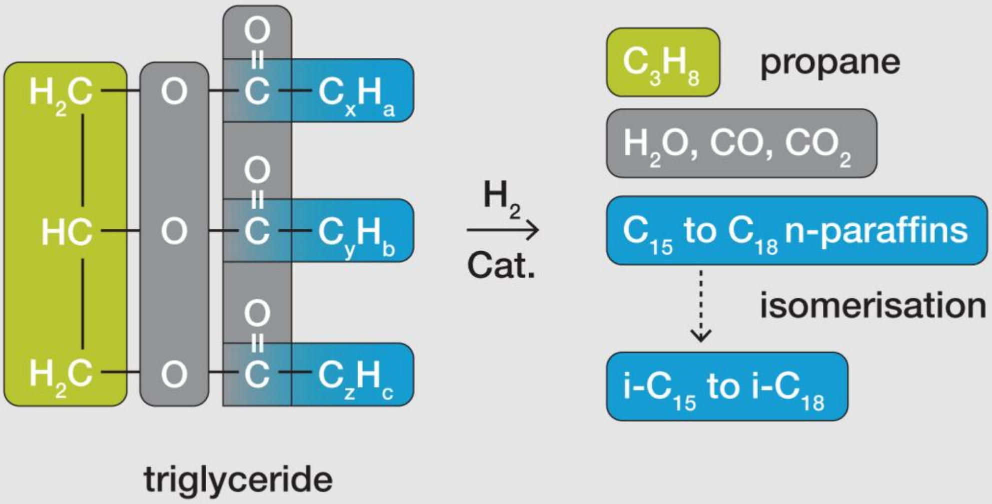
Box 2: Zoom in – technical description of the manufacturing stage

To convert renewable feedstock (i.e. triglycerides) into hydrocarbon molecules, the glycerol backbone (C_3-backbone), oxygen atoms and select carbon atoms need to be removed from the fatty acid chain. In addition, the chain needs to be saturated with hydrogen (hydrogenation). Hydrotreating provides for the hydrogenation and deoxygenation of the renewable feedstock, producing normal paraffin (n-alkane), C_3H_8, H_2O, CO and CO_2. The reaction is shown in Box Figure 1.

The chain length of the n-alkane product is dependent on the triglyceride chain length (C_n) and the hydrotreatment reaction pathways. A hydro-deoxygenation reaction produces n-alkanes with a chain length of C_n (e.g. same a feedstock) and H_2O, while a decarboxylation reaction favours C_{n-1} n-alkane and CO_2 production. The selectivity of the reaction pathway is controlled by the process configuration.

Mild isomerisation is required to satisfy the Australian Diesel fuel cloud point requirements (target minimum -2 °C). Heavy isomerisation followed by additional cracking is required to produce a higher fraction of SPK.

Box Figure 1: Triglyceride hydroprocessing reactions



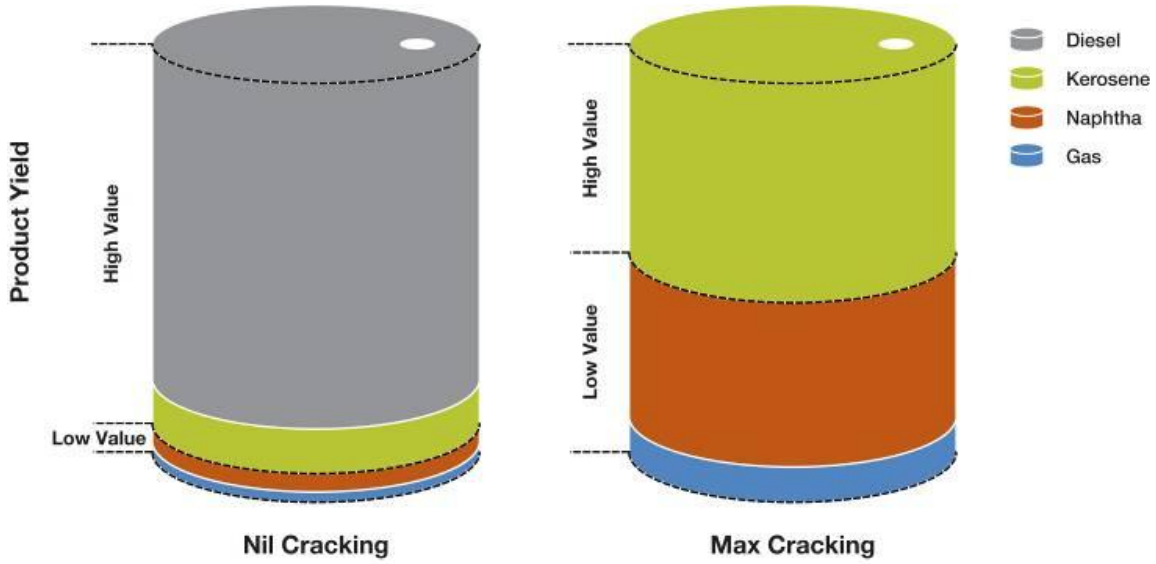
Source: The Shell Company of Australia (2013)

6.4 Product slate

Feedstock composition significantly impacts a refiner's ability to manufacture certain products. Like a conventional refinery, it is not possible to produce 100% HRJ from bio-oil feedstock. The refiner is largely limited to the molecules available in the feedstock; however, the configuration of the cracking stage permits the refiner to target an increased fraction of either renewable diesel or kerosene.

The product stream composition, and thereby product slate after fractionation, has been estimated using the feedstock strategies outlined earlier (Section 4.3). Specifically, theoretical yield results have been calculated for a number of different operating configurations using the feedstock composition data provided by AltAir. Yields are based on the assumption that there is an equal probability of cracking for all the carbon-carbon bonds in the hydrocarbon chain, except for the bonds that would lead to the formation of C_1, C_2 or C_3. Theoretical yield data for the base case feedstock strategy is provided in Figure 25 (non-dimensional).

Figure 25: Theoretical product slate (non-dimensional)



Source: The Shell Company of Australia (2013)

The yield data demonstrates that targeting kerosene production (e.g., maximum cracking case) results in a significant middle distillate (kerosene and diesel) loss. Therefore, hydrocracking renewable hydrocarbons results in loss of revenue as the market price of naphtha and refinery gas is lower than the middle distillates[95]. That is, the economic value of the hydrocracked product slate is lower than the isomerised product slate. To reduce the revenue loss by targeting renewable kerosene production, the manufacturing stage can be designed to selectively crack a proportion of the isomerised stream into kerosene. The degree of selective cracking has the greatest impact on product yield. Selection of available feedstock has minimal impact on the refinery product slate, when compared to the degree of cracking.

The study modelled scenarios of product output by changing the level of cracking for each feedstock strategy. These scenarios were:

1. Maximum renewable diesel output
2. A split of renewable diesel and SAF based on conventional jet fuel yields from crude oil (base case)
3. Maximum SAF (kerosene) output.

6.5 Directional cost estimate

Directional capital and operating costs for the construction and operation of both a bio-feedstock hydroprocessing facility[96] and hydrogen manufacturing unit are summarised in Table 4. Cost data is accurate to ±50%, which is typical of initial project identification and assessment undertaken by the oil and gas industry. Significant additional time and cost (including validation experiments) would be required to obtain tighter cost estimates.

Manufacturing costs are provided in 2012 US dollars and must be inflated using US rates. The high cost of construction in Australia was considered and has been included in the capital and operating (fixed cost) figures; however, the value is conservative based on recent cost overruns seen in Australia. Operating costs are based on a 95% scheduled operating year. The directional costing is valid for any Australian brownfield (existing) refinery.

[95] n conventional refining, hydrocracking is used to break heavy molecules (not diesel) into more valuable products

[96] Hydrotreatment, isomerisation and hydrocracking functions

Table 4: Manufacturing capital costs; base case (US$ million, 2012)

Scale (tonnes/d)	3,000	1,000
CAPEX ($million)	877	406
OPEX ($million/yr)	112	45

Source: The Shell Company of Australia (2013)

Directional costs are based on Shell's experience in this space, and are consistent with industry values when considering the construction – as opposed to the conversion – of hydroprocessing equipment is required in Australia. Nesté Oil, for example, has constructed a 2,100 tonnes per day greenfield manufacturing facility in Singapore for a reported cost of €550 million[97] (US$ 765 million, 2012). Importantly, where existing compatible refinery assets are available, the capital cost may be significantly reduced. Eni, an Italian multinational oil and gas company, for example, is reportedly converting two conventional processing units to bio-oil with a headline investment of approximately €100 million (US$ 130 million, 2012). The target production capacity of the Eni refinery is less than half of the 3,000 tonnes per day base case facility assessed in this report. The importance of scale in the refinery business is demonstrated by the economies of scale achieved between the base case and 1,000 tonnes per day CAPEX as shown in Table 4. AltAir is also retrofitting an existing petroleum refinery (near Los Angeles, California)[98]. The project will target the production of cost competitive renewable diesel and SAF by 2014. AltAir highlighted the capital synergies coupled with cheaper feedstock and bio-fuel development mandates in the United States and the key economic drivers from the projects competiveness.

6.6 Summary

Hydroprocessing technology is core to a modern petrochemical complex. However, bio-feedstock chemistry is significantly different from conventional petroleum streams. Therefore, it is not possible to convert bio-feedstock to aviation fuel using unmodified hydroprocessing units. Furthermore, the SAF specification excludes co-processed bio-feedstock from being certified as jet fuel. HRJ must therefore be manufactured using a dedicated hydroprocessing facility. Our review of potentially idle refinery assets, made available by converting select refineries into import terminals (e.g., Shell, Clyde), identified that technical constraints limit the production of HRJ. Moreover, the size of existing petrochemical hydroprocessing units is expected to exacerbate feedstock supply issues. Accordingly, the construction of a dedicated bio-refinery on a brownfield location is anticipated to provide the most cost competitive configuration for producing HRJ in Australia. Synergies achieved through co-location are expected to reduce cost by approximately 1.5 times compared to a greenfield (new site) facility. Directional costing is based on a 3,000 tonnes per day manufacturing facility.

Manufacture of renewable hydrocarbon fuels via compatible hydroprocessing technology requires the hydrotreatment and isomerisation of bio-feedstock. Hydrogen, a key process input, must be manufactured onsite as the production of ULS diesel means most refineries have a shortage of hydrogen. Hydroprocessing bio-feedstock naturally produce renewable diesel, with only limited volumes of kerosene, naphtha and gas. To increase the fraction of kerosene, and thereby HRJ, the diesel molecules must be cracked into kerosene. However, targeting kerosene increases the production of lower value naphtha and refinery gas, thereby producing a lower rate of return.

Directional cost estimates were found to be consistent with industry values, especially when considering the high cost of doing business in Australia. Construction and operation of a 3,000 tonnes per day bio-fuel manufacturing facility is anticipated to cost US$877 million and US$112 million per annum respectively (2012; accuracy: ±50%). Reducing the processing capacity to 1,000 tonnes per day decreases the capital cost by just under half, thereby demonstrating the importance of scale in the refining business.

[97] Singapore renewable diesel refinery: http://www.nesteoil.com/default.asp?path=1,41,537,2397,14090

[98] United Airlines and AltAir Fuels to Bring Commercial-Scale, Cost-Competitive Biofuels to Aviation Industry, June 4, 2013.

7. Supply

7.1 Introduction

Hydroprocessing bio-feedstock on a brownfield manufacturing site enables direct blending and certification of renewable and conventional products. Unlike alternative fuels, which require segregated distribution infrastructure (e.g., ethanol, bio-diesel), certified renewable hydrocarbons are fully fungible with traditional petroleum products. Therefore, significant synergies may be achieved by distributing the certified products to consumers using the same infrastructure (e.g., pipelines, trucks, hydrant systems, etc.) as conventionally refined petroleum products.

Manufacturing renewable hydrocarbons is considered to be in addition to the existing brownfield production. It is not considered practical to 'turn down' the conventional refinery production rate so the combined brownfield site output better matches local market demand. Apart from economic considerations[99], and that molecules are already transported to other markets, the bio-refinery does not make the same products as a conventional refinery. Therefore, reducing crude oil throughput will limit the availability of products not manufactured (or not manufactured in sufficient volume) by the renewable fuel facility. It is not possible to simply shift production at the conventional refinery to target this shortfall, as crude oil largely determines the end product slate in the refining business. Manufacturing renewable hydrocarbons therefore increases the brownfield site production rate of select products.

The introduction of renewable hydrocarbons is not expected to alter total market demand for hydrocarbon molecules. Accordingly, renewable products will be substituted into existing supply infrastructure to satisfy market demand. Excess hydrocarbon volume will be sold to other markets, reducing the need to import finished petroleum products into Australia. Detailed analysis of existing supply chains is therefore outside the scope of this project. A summary of the Melbourne Airport supply chain is provided in Appendix C as an example of an existing jet fuel delivery system.

7.2 Product integration

Co-locating the bio-feedstock hydroprocessing facility on an existing refinery site enables renewable products to be directly integrated into existing product pools and subsequently, distribution infrastructure. Integration with traditional products provides significant cost benefits compared to alternative fuel supply chains. Renewable diesel and naphtha may be blended directly into their respective conventional product pools. Certified diesel is distributed using existing supply infrastructure, while blended naphtha is used to produce gasoline[100]. Renewable gas may be consumed within the refinery boundary, offsetting the need to purchase natural gas for refinery operation. Additional diesel storage may be required, depending on production rates and the availability of diesel storage capacity. Product quality procedure and certification requirements ensure that the blended products remain within the relevant fuel quality specifications. Certification testing would be conducted onsite at the refinery laboratory.

Integration complexity and cost is largely driven by the alternative jet fuel certification requirements. The specification (ASTM D7566) details the technical requirements an aviation turbine fuel containing synthesised hydrocarbons must satisfy before the molecules may be certified and sold as jet fuel. The criteria are built on extensive testing and are agreed upon by a cross-section of stakeholders. The relevant section of the specification requires the batch certification of 100% renewable kerosene. Certified kerosene molecules are then blended with conventional jet fuel (kerosene volume limited to 50%), creating Jet A-1 with a HRJ component. Once certified, the molecules are 100% compatible with existing jet fuel supply infrastructure, aircraft systems and engines. In fact, the blended product is controlled via the conventional jet fuel specification (ASTM D1655; Def. Stan 91-91). The construction of two renewable kerosene tanks – one for rundown[101], the other for certification – is considered in the capital costing.

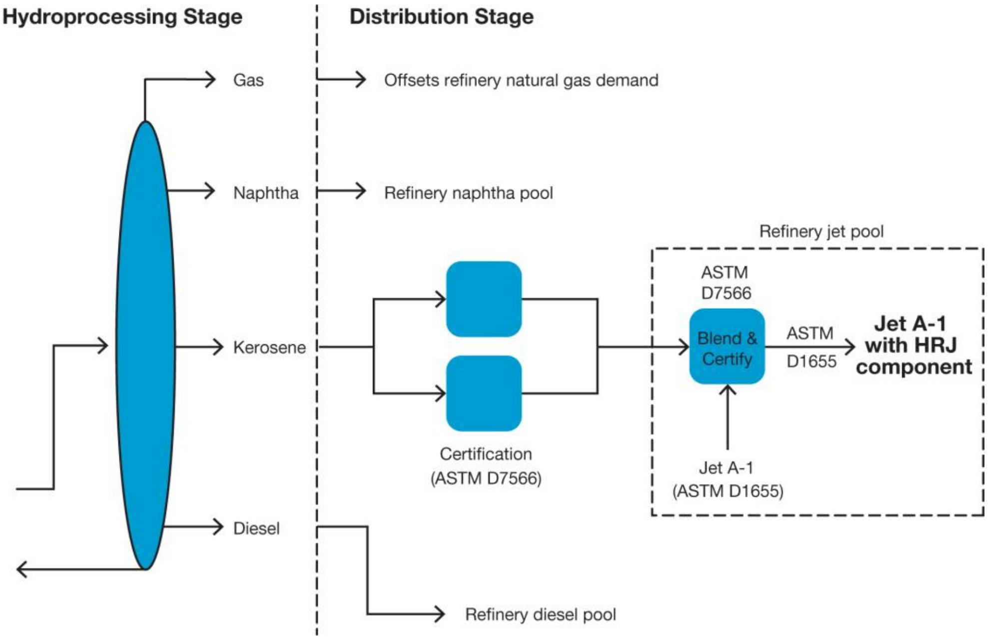
The product integration strategy and jet fuel certification route is summarised in Figure 26.

[99] Example: lower throughput per fixed unit cost

[100] Naphtha is an intermediate component used to produce gasoline in a conventional petrochemical complex.

[101] A rundown tank is filled with product from the operational bio-refinery, while the filled tank is used for batch certification.

Figure 26: Renewable product distribution and SAF certification



Source: The Shell Company of Australia (2013)

Integration of renewable and conventional products may enable economically attractive product blending strategies to be developed. However, no upgradable stream was identified in this study. Relying on a low value refinery stream to create value via blending is risky as the refinery configuration could change due to, for example, regulatory requirements (e.g., EURO5 standard required the reconfiguration of Australia's refineries to produce 10 parts per million (ppm) sulphur diesel).

7.3 Molecule tracking for carbon purposes

The dual nature of the certification and blending processes across both HRJ (Bio-SPK) and Jet A-1 makes it challenging to track the SAF molecules for a carbon scheme. Assuming SAF is zero-rated for the Australian carbon scheme, in theory, using SAF in a jet engine will attract relief from the carbon price for that flight. However, renewable kerosene must be certified separately and then blended with conventional Jet A-1 (maximum 50% kerosene) before it is put into an airport fuel supply chain (Figure 26). Once the kerosene molecules are blended with Jet A-1 and put into the airport supply chain infrastructure, in practice, it is impossible to track the SAF molecules to a particular plane.

This presents problems if the excise is levied on liquid fuel at the point of consumption. In the current excise processes for aviation, fuel is invoiced and excise (including the additional carbon portion of the excise) is collected when the fuel is put "into wing". However, because it is impossible to trace the SAF to the point when it is put into wing, another system is required to efficiently and effectively claim the additional carbon excise relief.

Using the existing excise system, one alternative is to utilise a 'book and claim' system. As in the current process, a fuel company would invoice an airline and the additional carbon price is paid via the excise system at point of fuel consumption into wing. The airline could then 'book' that purchase. The fuel company would then provide a record of the volume of SAF supplied to the airline, and the airline would 'claim' a fuel tax credit from the Australian Taxation Office (ATO) for the amount of the carbon price paid on SAF volume.

This scenario assumes that the airline pays the carbon price through additional excise. If the airline has exercised their right to 'opt-in' to the carbon scheme, to acquit their liability through purchase of credits rather than the excise system, a similar process is envisaged. However, instead of the 'claim' being for fuel tax credits in the excise system, the airline would have to be able to offset their carbon liability against the amount of SAF purchased.

7.4 Directional cost estimate

The capital required for the integration of the renewable product slate into the existing refinery product pool is expected to cost A$ 20 million (2012). This figure is accurate to +/- 50% and is representative of preliminary project identification and assessment conducted by the oil and gas industry. The inclusion of extra diesel tank storage is captured within the figure accuracy. Directional operating costs within the refinery gate are approximately A$ 3 million (2012).

The distribution infrastructure and costing is based on a number of high-level site agnostic assumptions. Distribution costs are, however, closely linked to existing site infrastructure. Therefore, site-specific work is required to increase the accuracy of this directional cost estimate.

7.5 Summary

Manufacturing renewable hydrocarbons on a brownfield site enables renewable products to be directly integrated into existing supply infrastructure. Therefore, the compatibility of hydroprocessed bio-feedstock provides significant distribution cost benefits compared to alternative fuel solutions. Renewable hydrocarbon production is not anticipated to impact total market demand for liquid transport fuels, as renewable products are substituted with conventional products based on consumer demand.

Therefore, increased production at the brownfield site does not pose a constraint on existing supply and distribution infrastructure or affect current distribution costs. Excess volume (either renewable or conventional) will be sold to other markets, offsetting the need to import finished product. It is not considered practical to ‘turn down’ or ‘dial down’ the existing refinery operation to better match local market demand. Directional capital and operating costs for integrating the bio-fuel products within the refinery gate are A$ 20 million and A$ 3 million (2012; accuracy: ±50%), respectively. Distribution analysis outside the refinery gate is location specific and not with the scope of this study.

8. Economic analysis

8.1 Introduction

This section brings together the underlying data and economics of the previous study sections in an over-arching and sophisticated economic model to understand whether the economics of a HEFA bio-refinery are feasible. The economic model looks at the inputs of volume, price and capital expenditure across feedstock, transport, aggregation, pre-treatment, manufacturing and distribution. It uses a variety of different feedstock composition scenarios to test the boundaries of practical economic feasibility.

The analysis looks at technical variables that have an impact on cost and product revenue, such as the proportion of product produced, and key economic variables, including pricing and volume of input feedstock, end products, foreign exchange, discount rates and cost of capital. Importantly, the economic model also looks at the impact of a variety of different policy constraints and opportunities to determine economic feasibility, including grants available through the Energy Grants (Cleaner Fuels) Scheme, implicit carbon pricing and direct government financial assistance. The model is scenario-based and flexible enough to allow each of these levers to be set at different levels.

This section is structured as follows:

- Overall methodology applied to the economic assessment
- Key inputs and outputs
- Treatment of key variables across feedstock, economics, technology and policy areas
- Economic evaluation of the base case scenario
- Economic evaluation of alternative feedstock scenarios and refining capacity scenarios
- Economic evaluation of changes in key sensitivities and variables
- Overall economic results
- Analysis of the impact of government support

8.2 Economic model methodology

At a more technical level, the economic analysis was conducted using a bespoke cash flow model of the fuel supply chain, from source of finished feedstock, transport to an aggregation point, pre-treatment and manufacture of a SAF blend. The model determined a number of economic metrics, including total and annual supply costs, the net present value (NPV) of the cost of producing SAF and the levelised cost of production on a A$ per litre basis, which can then be compared to the benchmark of the imported price of conventional jet fuel.

The model also determined the factors that will enable the project to be economically sustainable. This was done by examining a number of scenarios regarding practical feedstock supply and composition, and conducting sensitivity tests around key assumptions. Five feedstock and capacity scenarios were modelled based on availabilities of feedstock (refer Section 4.3). In general, the base case analysis is used to show and compare results in this study. However, other scenarios around the base case are also highlighted to demonstrate the impact of key variables on the economic results of the study.

While the analysis includes elements of financial modelling and a high-level business case for a bio-refinery, the study is not meant to represent a complete business case for a bio-refinery. Instead, it is designed to show total economic market and industry dynamics resulting from the establishment and operation of the first bio-refinery. Results of the economic modelling should be used to inform the overall feasibility of a theoretical bio-refinery in a newly established industry, rather than as a detailed business and financial model of a specific bio-refinery project.

8.2.1 Economic assessment

The economics of SAF production has been assessed through an economic cash flow model covering the supply chain leading up to and through to departure from the refinery gate. The purpose of the model is to determine the at-gate delivery cost of SAF relative to conventional jet fuel. The model is designed to test the economic conditions under which SAF is likely to be economic against conventional jet fuel and to determine the level of support or action required to make SAF economic.

The modelling involved three steps:

1. Developing an economic model that maps the key cost structure and drivers influencing costs for each stage of the supply chain, enabling bio-fuels to be benchmarked against the imported cost of conventional fuels
2. Conducting sensitivity analyses to provide insights into the key drivers that affect economic viability
3. Using scenario analyses to determine the economic resilience of the preferred bio-fuel supply options under a range of plausible future conditions for key exogenous variables (i.e., feedstock cost, world energy prices, capital costs and international and domestic policy developments)

The model has consolidated the information from the feedstock and refining studies to provide the cost of SAF as delivered to the refinery gate. This can be compared to the imported cost of conventional jet fuel, which sets the benchmark price in Australia.

8.2.2 Inputs

The model is designed to capture the costs and cost drivers associated with each stage of the supply chain. This includes feedstock, capital and operating costs and their relationships (or dependencies) to a number of key variables. The structure and assumptions are based around four key areas and associated factors that drive the final cost (see Table 5). These were used as the basis for setting scenario and sensitivity parameters, which are further described in Section 8.8. The model derives an ex-refinery gate cost of the SAF component in certified jet fuel. It also derives co-products produced, the revenue for which is treated as a negative cost for producing SAF.

Table 5: Key areas and components of the economic model

Key areas	Component
1. Feedstock	• Feedstock pricing • Feedstock volume • Feedstock scenario composition
2. Economics	• Forecast price for crude oil • Forecast price for related petroleum products • Forecast forex • Forex approach • Discount rate (real) • Capital expenditure • Price of end bio-products • Willingness to pay a renewable premium
3. Technical	• Bio-refinery location • Bio-refinery volume capacity • Bio-refinery product yields • Bio-refinery operating time (% available time)
4. Policy	• Cleaner Fuels Scheme (value) • Cleaner Fuels Scheme (timing) • Carbon price (inclusion) • Carbon price (value) • Government capital contribution

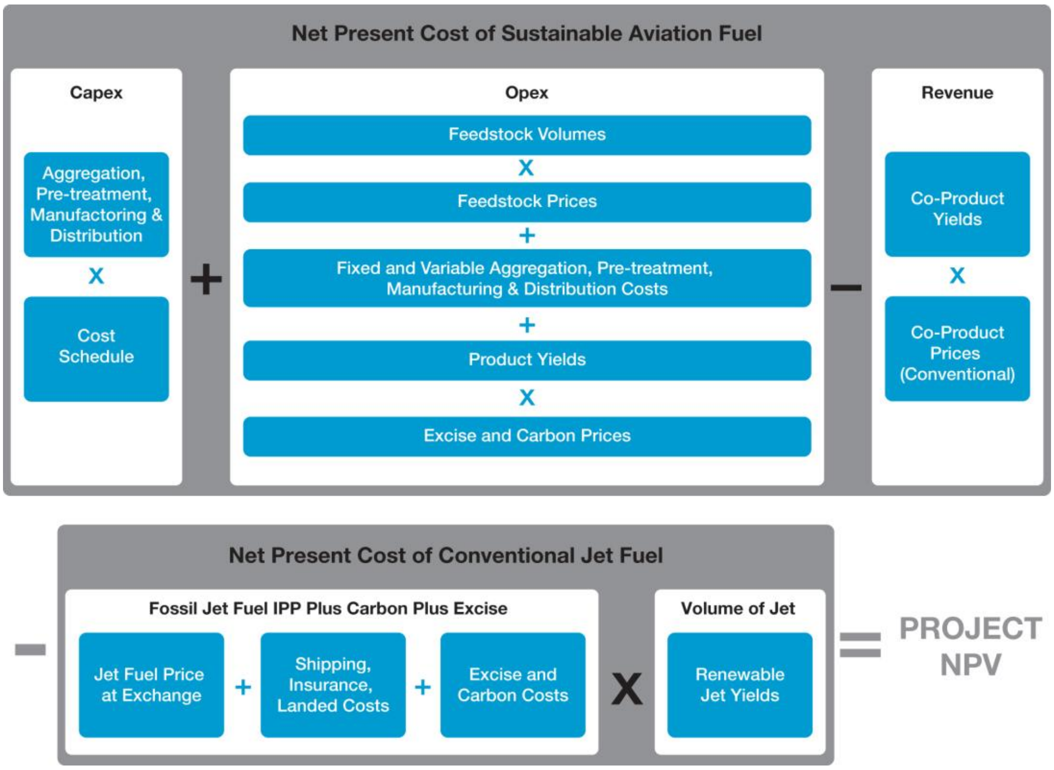
8.2.3 Outputs

Two metrics were used to appraise the economics of the project: net present value (NPV) of project costs in 2012 Australian dollars; and the long-run marginal cost (LRMC) of SAF production in A$ per litre.

8.2.3.1 NPV

The NPV framework determines the viability of the project by calculating the net present cost of producing SAF and comparing this to the net present cost of conventional jet fuel. The comparison of prices of SAF and conventional jet fuel is carried out at the transfer point from the refinery. However, differentials that may impact final price, such as carbon price, are also considered at this point. The definition and calculation of NPV in the economic model is outlined in further detail in Figure 27.

Figure 27: Definition of net present value



Source: SKM analysis (2013)

Key commercial assumptions adopted in the NPV framework include:

- The period of assessment is 23 years, including three years of construction of the refinery and a 20 year economic life of the refinery[102]
- The base case analysis assumes a discount rate of 15% (in real pre-tax terms)[103]
- The analysis is conducted in real 2012 dollars with future cash flows discounted back to 2013.

Historical and forecast data across multiple variables, as well as economic assumptions, have been sourced from a wide variety of sources, including SKM's proprietary material, the study partners, published reports, publically available data from reputable sources (e.g., ABARES) and discussions with industry representatives.

[102] Directional construction estimates were provided by Shell. The estimated economic life of the bio-refinery was selected for the analysis as after this period significant capital investment may be required.

[103] The discount rate is used to capture both the cost of capital and a project hurdle rate. The rate was selected for feasibility analysis only and does not necessarily reflect the assessment rates of the study partners. Importantly, the manufacture of renewable hydrocarbons requires a higher level of return for relevant participants due to the greater financial risk associated with relying on agricultural feedstock (compared to conventional fuels) and a more novel production pathway.

8.2.3.2 LRMC

An economic comparison of the LRMC of SAF and the price of conventional jet fuel was conducted. The LRMC cost of the SAF can be represented mathematically as:

$$LRMC = \frac{PV(Capital\ Costs) + PV(Operating\ Costs) - PV(Co\text{–}Product\ Revenue)}{PV(Output\ of\ Sustainable\ Aviation\ Fuel)}$$

The LRMC represents the unit revenue required on SAF production to cover all costs of production (including feedstock, operating and capital). If the LRMC is greater than the predicted price of the conventional jet fuel (at the refinery gate) the project is unlikely to be economic relative to conventional jet fuel.

The LRMC is also calculated over the SAF production, not total renewable fuel production. Revenue from renewable co-products is deducted from total costs to calculate the net costs. It is assumed that this net cost is attributed to SAF production. The results for LRMC should be compared to a projected average conventional jet fuel price range of A$0.65 to A$0.95 per litre in 2012 dollars over the next two decades.[104]

8.3 Key inputs and variables

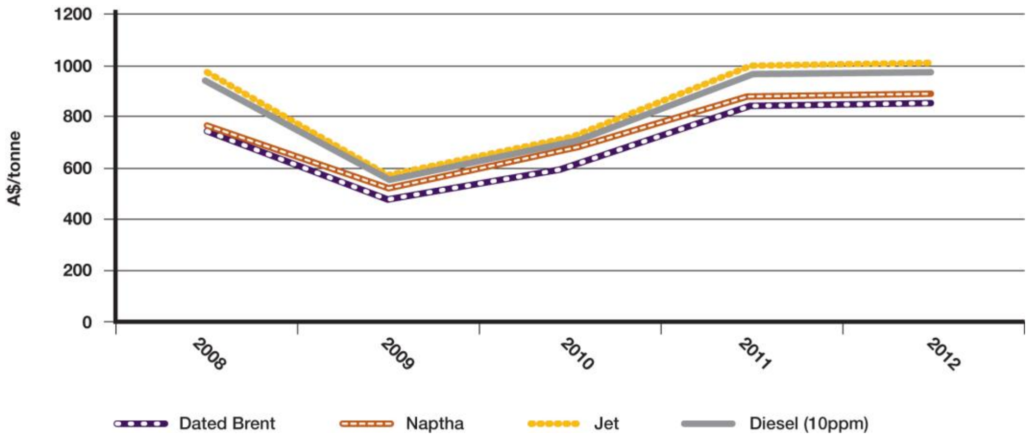
The methodology for assessing and constructing each of the key variables and inputs in the economic model is outlined in this section and applied in Sections 8.4 to 8.7. The variables and inputs are categorised under feedstock, economic, technical or policy areas.

8.3.1 Feedstock

8.3.1.1 Feedstock and commodity pricing

The pricing of commodities, including both the project's feedstock and products, is critical to the feasibility assessment of a SAF project in Australia. The feedstock cost comprises over 85% of the cost of the project. Within the context of the NPV analysis, a consistent approach to commodity pricing is required. For this reason, the economic analysis is carried out using a derived relationship between crude oil and derived petroleum products, as well as crude oil and renewable fuel feedstock. Before 2007, vegetable oil prices were relatively stable, and reflected the cost of production. However, since then, vegetable oil prices and price volatility have increased dramatically, showing a strong correlation to crude oil price developments Figure 28 shows the observed correlation between crude oil and derived petroleum products, while Figure 29 shows the observed correlation between crude oil and natural oils. These demonstrate the likelihood of a strong correlation in the short-to-medium term between natural oils and crude oil. This is due to the substitution effect of bio-fuels and conventional products in the market place.

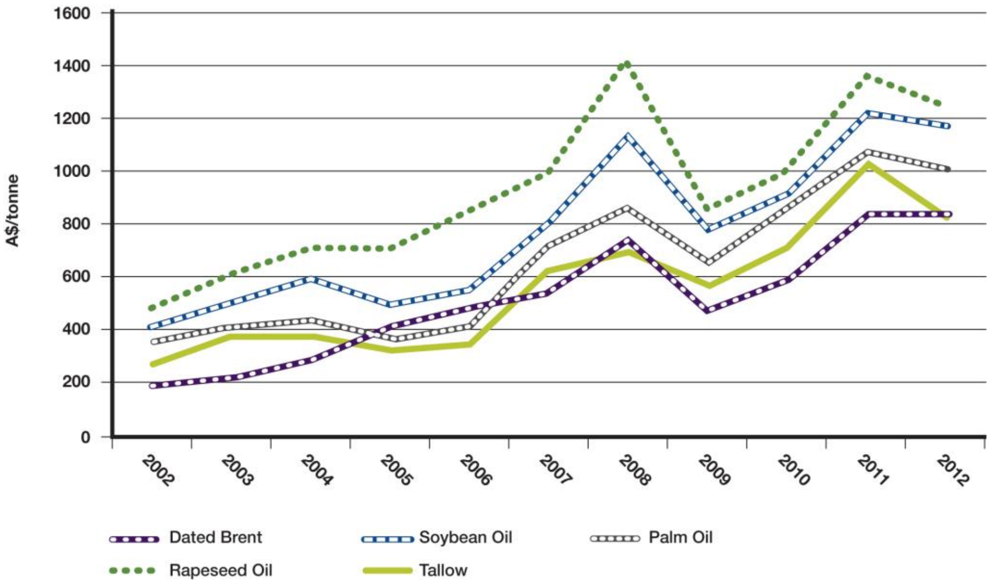
Figure 28: Relationship between crude oil and petroleum products, A$/tonne



[104] This method of cost allocation is not necessarily how the project partners would cost the production of SAF (e.g., product energy content may be a more appropriate measure)

Source: SKM analysis (2013)

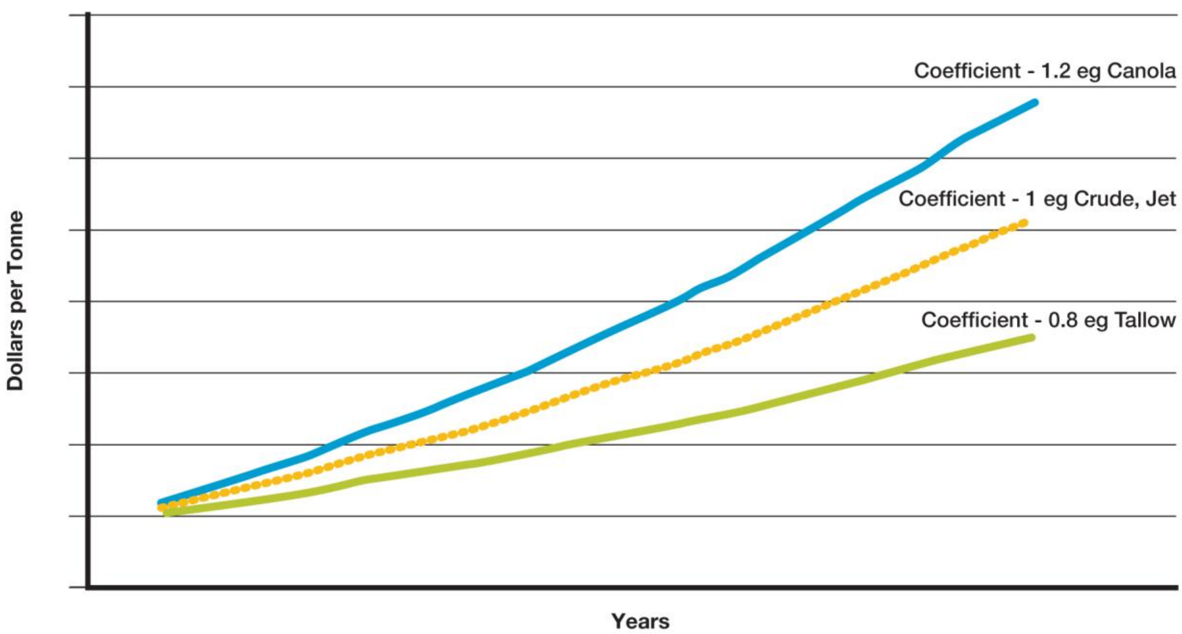
Figure 29: Relationship between crude oil and natural oil feedstock, A$/tonne



Source: SKM analysis (2013)

A regression analysis was then conducted to derive coefficients between renewable feedstock prices and crude oil. As illustrated in Figure 30, the study analysed each correlation coefficient for natural oil feedstock and crude oil. For example, when compared to the petroleum product prices, Canola becomes more expensive each year as a feedstock source, while tallow becomes less expensive. However, both are linked to a greater or lesser extent to crude oil prices and move in the same direction. Because of this relationship between the commodity prices and crude oil prices, the feedstock component of operating costs and the product revenue are strongly correlated to the price of crude oil. Using this derived relationship with crude oil, each of the feedstock and products are then priced somewhere between export price parity and import price parity. The latter is used as a proxy for price effects when accessing the existing oil seed and tallow markets (e.g., market elasticity). Relevant feedstock coefficients are detailed in Appendix D.

Figure 30: Coefficient between commodities and crude oil



Source: SKM analysis (2013)

Note: . A coefficient above one will cause a commodity to become more expensive each year in comparison to crude oil, and a coefficient less than one will do the opposite.

8.3.1.2 Imported price parity

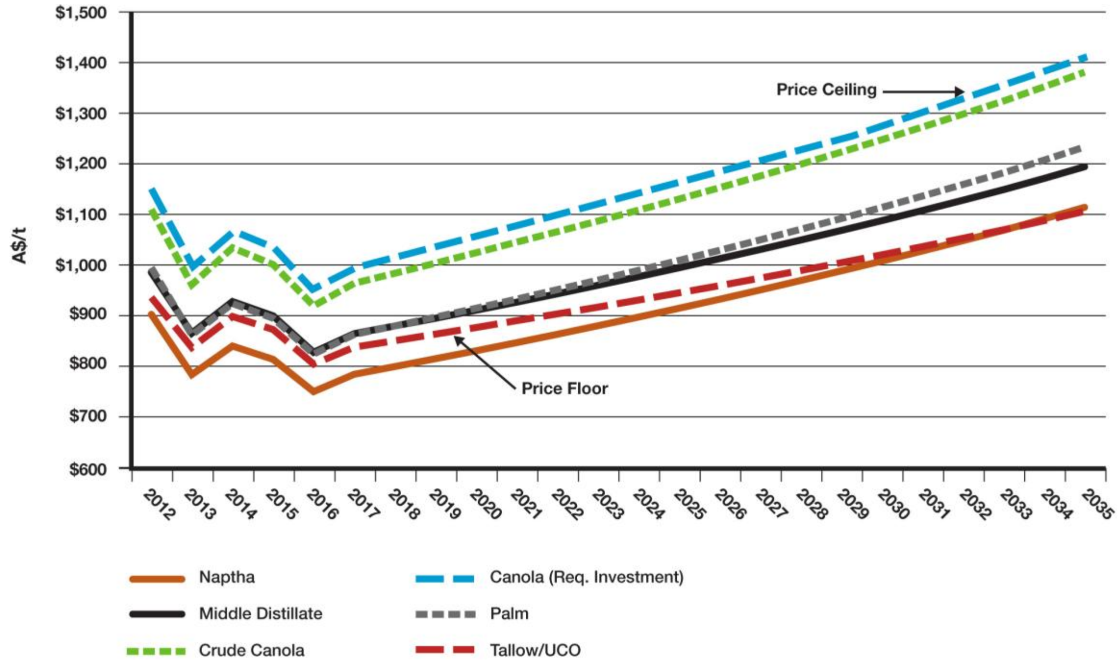
Import price parity (IPP) represents the price of importing an international commodity. The price is equal to the international reference price plus the freight and insurance costs of importing the commodity. This price represents the most a purchaser of the commodity would be willing to pay in the domestic market, as the purchaser could import the product at this price. The import price and freight price for the relevant products and feedstock have been calculated using world-scale data, published data on insurance costs and prices provided by the imported feedstock study.[105]

8.3.1.3 Export price parity

Export price parity (EPP) represents the price that a producer could receive by exporting a commodity to the international market. The price at an Australian port is equal to the international reference price minus the freight and insurance costs of exporting the commodity. For the Greater Melbourne area, the price is equal to the international reference price minus the freight and insurance costs of exporting the commodity plus the domestic transport cost from the producer to the feedstock aggregation point.

The EPP price, including the domestic transport cost, cannot theoretically exceed the IPP price. The EPP price represents the lowest price that a seller of the commodity would be willing to receive in the domestic market, as the seller could export the product at this price. The handling and freight costs for the relevant products and feedstock have been based on high-level estimates from AltAir and prices provided by the imported feedstock study.[106] The feedstock prices determined, as delivered to the Greater Melbourne area, are presented in Figure 31.

Figure 31: Feedstock pricing forecasts (Greater Melbourne)



Source: SKM analysis (2013)

8.3.1.4 Elasticity

In Section 4.3, a series of five feedstock scenarios were outlined to cover the spectrum of possible feedstock options available and allow for economic comparison. The price of each feedstock is calculated for each of these scenarios separately, as it is assumed the quantity of feedstock supply taken out of the market in each scenario will affect the feedstock prices, since the HEFA refinery volumes are generally large interventions into feedstock supply markets. Therefore, a feedstock that is currently priced at EPP in the domestic market may increase towards IPP as the bio-refinery takes product out of the market. This price premium, or elasticity, is

---

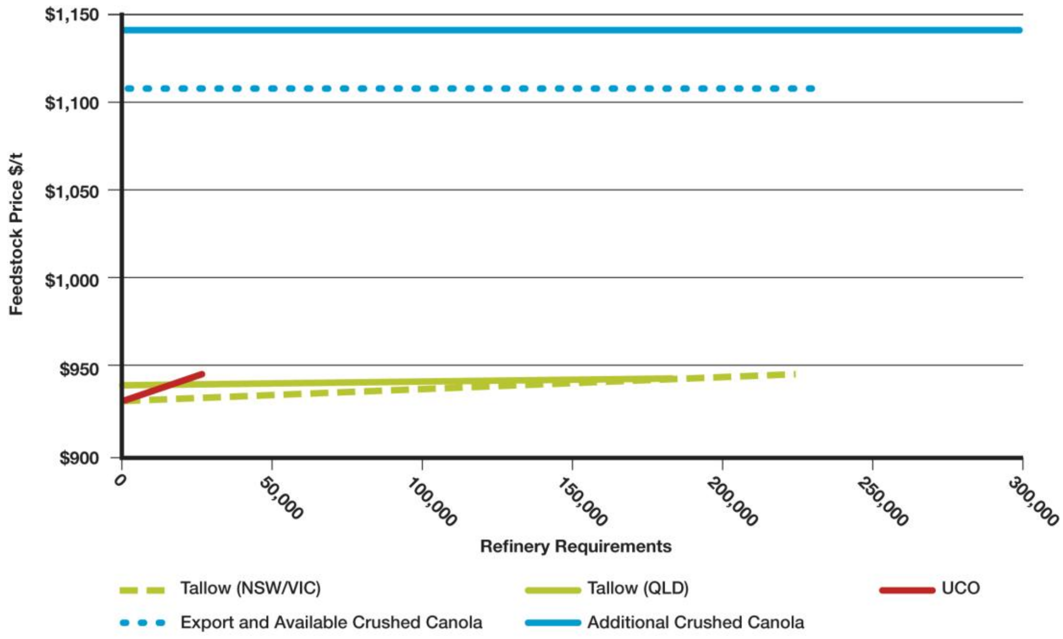
[105] SkyNRG (2013)

[106] Ibid

calculated by proxy as an increase from EPP to IPP, equal to the proportion of (previously exported) product used by the bio-refinery. This price cannot exceed IPP, as the manufacturer could import feedstock at this price.

Elasticity is applied for all bio-feedstock that do not induce additional supply, for example tallow. However for those feedstock that would induce supply (e.g., through the use of surplus crushing capacity) the price would remain at EPP, for example available crushed canola. The price of each feedstock is calculated as a function of the amount of supply taken out of the domestic market. The impact that availability has on price is illustrated in Figure 32.

Figure 32: Domestic feedstock pricing and availability (elasticity)



At a more detailed level, the price point and reasoning of each commodity is outlined in Table 6. Price build-up data is provided in Appendix E.

Table 6: Commodity pricing rules

Commodity	Price Formula	Reasoning
Jet fuel (conventional)	IPP	Net imported product into Australia
Naphtha	IPP	Net imported product into Australia
Diesel	IPP	Net imported product into Australia
Gas	-	Domestic gas prices are not currently linked to the international crude oil market
Tallow (NSW/Vic)	Min (EPP + transport + elasticity, IPP)	Domestic product with net export, entry into market likely to lift price
Tallow (Qld)	Min (EPP + transport + elasticity, IPP)	Domestic product with net export, entry into market likely to lift price
Export and available crushed Canola	Min (EPP + transport, IPP)	Increase demand will induce supply therefore price to stay at EPP
Additional crushed Canola	IPP	Additional crushing would require investment by crushers with low meal demand. IPP price is used as proxy for higher price
UCO	Min (EPP + transport + elasticity, IPP)	Domestic product with net export, entry into market likely to lift price
Sustainable palm	IPP	Net imported product into Australia

Source: SKM analysis (2013)

8.3.1.5 Feedstock scenario and volumes

The economic viability of the project was tested under five feedstock scenarios to inform a broader project assessment framework that includes external factors, such as political, technological and environmental constrains. The five feedstock scenarios assessed are based around feedstock availability and production capacity, as outlined in Section 4.3. The domestic first scenario was chosen as the base case for the analysis.

8.3.2 Economics

8.3.2.1 Discount rates

To provide a discounted cash flow analysis of the project, a variety of discount rates were used. Discount rates are used to calculate the economic viability of the project[107] and reflect a number of assumptions, including cost of capital, commercial risk of the investment and "commercial hurdle rate". In particular, a discount rate reflects the risk of the investment decision compared to other investment decisions available. In this study, a HEFA refinery for aviation fuel is considered to be riskier since none exist in Australia at present and inputs are based on agricultural commodities which are generally more volatile than crude oil. The study selected a discount rate of 15% as the base case.

8.3.2.2 Willingness to pay a renewable premium

The economic analysis assumes that purchasers of SAF would not be willing to pay a premium on top of the conventional jet fuel price on a cents-per-litre basis. While SAF and renewable diesel have higher energy content than their conventional equivalents this benefit was not included in the economic study due to the challenge for purchasers of renewable fuel capturing the benefit (especially monitoring and calculating the benefit for each fuel batch). However, over time, this benefit may be captured, so sensitivity to the inclusion of this variable was tested.

8.3.2.3 Exchange rates

An appropriate exchange is required to convert commodity prices and capital expenditure[108] from US dollars into Australian dollars. Two approaches were used in determining a forecast exchange rate. The first approach, the one adopted in the base case in this analysis, uses exchange rate forecasts from an institutional bank from 2013 to 2017, with the 2017 exchange assumed to continue forwards. The second approach is based on a regression analysis which was used to identify a correlation between exchange rates and the price of crude oil. US Energy Information Agency (EIA) crude oil forecasts were then used as a sensitivity to forecast the exchange rate forward.

8.3.2.4 Forecast price for crude oil

Crude oil forecasts used in the analysis were based on EIA forecasts for Brent Crude in 2012 US dollars. A sensitivity of constant real Brent crude prices from US$90 through to US$120 were tested in the analysis. The mean EIA forecast shows crude oil prices falling in real terms over the medium term before increasing again as conventional oil stocks deplete and oil demand continues to grow.

8.3.3 Technical

8.3.3.1 Bio-refinery location

The analysis was carried out with the presumption that the bio-refinery would be co-located with a brownfield refinery. Both Greater Melbourne and Greater Brisbane locations were considered as conventional brownfield refinery sites exist in both these locations. All feedstock and product pricing has been calculated for these two locations.

[107] The approach of using the discount rate as the metric for economic valuation does not necessarily reflect how the project partners would set a hurdle rate for financial evaluation. For scenarios where there is an operating loss, using a high discount rate will result in anomalous outcomes.

[108] Manufacturing plant costs are provided in 2012 USD

8.3.3.2 Bio-refinery volume capacity

The analysis considers a bio-refinery capable of refining 3,000 tonnes of bio-feedstock per day, with a 1,000 tonnes per day bio-refinery considered as an alternative scenario. The facility sizes were selected to compare with Nesté Oil's operational 2,100 tonnes per day renewable fuel facility in Singapore.

8.3.3.3 Bio-refinery operating time

Both the base case of 3,000 tonnes per day of feedstock and the reduced scale of 1,000 tonnes per day were modelled with two levels of refinery operating time used (i.e., proportion of time the refinery is operating versus shut down for maintenance). A low case of 90% 'up time' and an industry average of 95% 'up time' were used in this study.

8.3.3.4 Bio-refinery output yields

While this study is primarily focused on the feasibility of the production of SAF in Australia, as discussed in Section 6, the techno-economic reality of bio-refining is that hydroprocessing of bio-feedstock naturally produces diesel molecules. The economic study therefore looked at both ends of the techno-economic spectrum by examining the 'maximum diesel case' (e.g., nil cracking) and the 'maximum SAF (kerosene) case' (e.g., max cracking). The maximum diesel case results in approximately 10% SAF from the bio-product slate, while the maximum kerosene case, results in approximately 55% SAF from the bio-product slate. The base case used a mid-point that is representative of the jet fuel yields from a modern petrochemical complex. The base case therefore assumed SAF at 30% of the bio-product slate, with renewable diesel, naphtha and natural gas comprising the remainder of the slate.

8.3.3.5 Capital Expenditure

The capital costs used in the assessment, provided by Shell Australia, included costs for the construction of a combined aggregation and pre-treatment facility, a hydroprocessing unit and a Hydrogen Manufacturing Unit (HMU). Directional costs also include the construction and modification of distribution infrastructure. The capital cost of a 3,000 tonnes per day facility was approximately A$1 billion (2012). Per Section 6, this figure is consistent with industry values. The assessment assumes that construction of the refinery would be spread over three years with the bulk of the costs expended in the second year of construction. A sensitivity analysis of the costs was conducted for both plus and minus 30% of the directional costs.

8.3.4 Policy

8.3.4.1 Energy grants

A grant, under the *Energy Grants (Cleaner Fuels) Scheme Act 2004,* provides a 38c per litre benefit equivalent to the level of excise for the domestic production and import of bio-diesel and renewable diesel.[109] Under the Ethanol Production Grants Program, the same 38 cpl benefit is also provided for domestic production of ethanol. The Energy Grants (Cleaner Fuels) Scheme is expected to be reviewed in 2021; however this review is not legislated. The other renewable fuel products produced in the renewable fuel refining stage (i.e. SAF, naphtha and natural gas) studied in this report are not legislated to receive any benefit. The development of a SAF refinery may require a change in legislation to recognise the other renewable fuel products. In the legislation's current state, the production of renewable diesel is further favoured due to the grant[110].

The economic analysis is initially undertaken on the basis that no grants are received for any of the renewable fuel products produced by the refinery. This is done to test the economic conditions for viability in the absence of any government support. As an alternative, other scenarios were explored to assess the impact on economic viability for a range of potential government support initiatives. Ten additional government grant scenarios are examined and are outlined in Section 8.9.3.

[109] The Energy Grants (Cleaner Fuels) Scheme Act 2004 provides excise relief for producers and importers of renewable diesel and biodiesel whereby excise is first paid and then reimbursed in the form of a grant. The level of excise applied to aviation fuel in Australia is 3.5 cpl.

[110] Note, as discussed in the results section, renewable diesel production is favoured regardless of the grant as renewable oil feedstock when processed naturally produces diesel molecules. Cracking these molecules in the refining process to produce SAF results in loss of middle distillate yield, which has a higher economic value.

8.3.4.2 Government contribution

The ability to select a level of direct government financial assistance was also included as a variable in the economic model. The nature of government assistance was either a direct upfront grant or low-interest loan for capital expenditure on the project. Four amounts (A$) were considered – no assistance, $100 million, $500 million and $1 billion to reflect zero, low, medium and high assistance. This was considered a wide but reasonably representative range of government assistance scenarios, given the current policies and funding programs in place or announced across both political parties for carbon abatement programs.

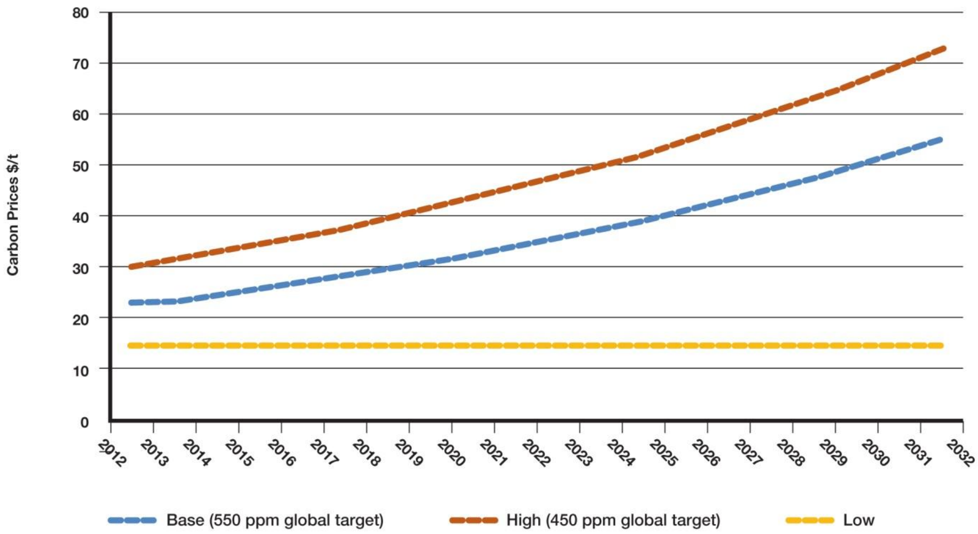
8.3.4.3 Carbon price

Petroleum products, including jet fuel, diesel, naphtha and refinery gas, produce carbon emissions when combusted. Under the current government legislation all these products, except naphtha, can incur a cost, either directly to the emitter (based on the carbon price and direct emissions) or indirectly through an equivalent charge levied through the excise or taxation systems. Heavy on-road transport use of diesel is currently exempt, but is to be reviewed in 2014. Renewable versions of these products would not incur any cost because the feedstock is deemed renewable, in that the carbon dioxide emissions are effectively recycled via growth in the feedstock[111].

The economic benefit of the reduced carbon emissions – equal to the value of reduced carbon cost – is a benefit to the overall value chain. For modelling simplicity, a carbon price is applied to conventional jet fuel, diesel, naphtha and gas. However, as it is challenging to assign the economic benefits to the supply chain participants, the economic benefit of reduced carbon emissions is presented ‘below the line’, unless otherwise stated. The study partners recognise it is highly unlikely that all products will be subject to a carbon price.

The base carbon price adopted in the assessment uses the legislated carbon price[112] until 2015 followed by a 4.5% real increase per annum; this is representative of a 550 ppm global CO_2 target. The high case starts with a $30 per tonne price of carbon with a 4.5% increase each year, which is representative of a 450 ppm target. The low case starts at A$15 per tonne with no real increase going forward, which is representative of the current uncertainty of global carbon prices. The forecast carbon prices adopted in the analysis are presented in Figure 33.

Figure 33: Forecast carbon prices



Source: SKM analysis (2013)

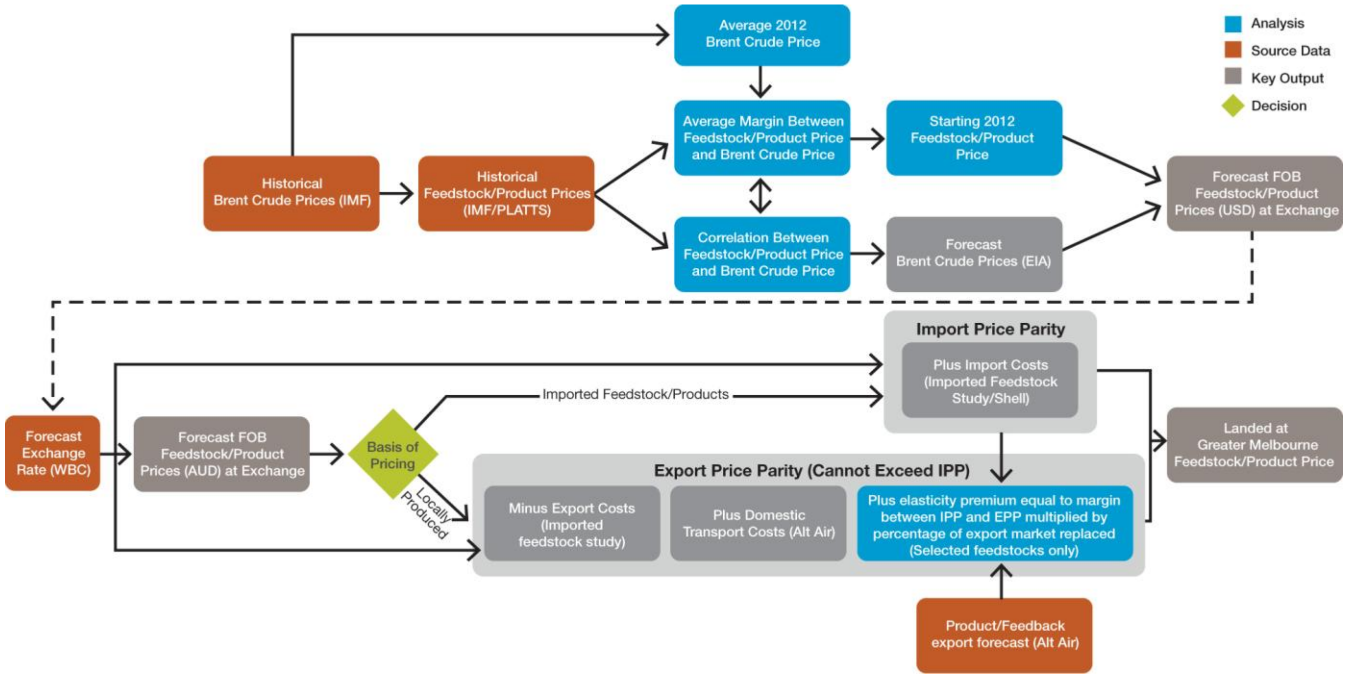
[111] Sustainable aviation fuels and some other renewable fuels have yet to be zero rated for the carbon impost as part of the Clean Energy Futures Legislation and associated regulations. It is assumed that this will occur sometime in the future.

[112] Viewed February 2013, <http://www.cleanenergyfuture.gov.au/transport-fuels/>

8.3.5 Pricing methodology summary

The inputs, pricing assumptions and methodologies detailed in this section have been layered together to provide an overall inputs and pricing methodology approach. Detailed consideration and assumptions have been outlined in this section to evaluate a market and value chain that does not currently exist and cannot be readily observed in operation. The summary and inter-relationships of the inputs and pricing methodology is outlined in Figure 34.

Figure 34: Summary of inputs and pricing methodology



Source: SKM Analysis (2013)

8.4 Economic evaluation of the base case scenario

This section presents the findings of the economic analysis. Uncertainties in the key findings are outlined and discussed through the use of sensitivity analysis.

8.4.1 Base case scenario

The base case envisages construction of a bio-refinery facility at a brownfield site, with feedstock sourced from the domestic market to the point where intervention does not significantly affect feedstock price. The balance of feedstock is imported. This strategy is referred to as the 'domestic first' scenario as all feasible and competitive domestic sources are exhausted before looking offshore (Section 4.3). The facility processes 3,000 tonnes per day of feedstock through hydroprocessing, with approximately 30% SAF product output. Construction is assumed to occur over 2013 to 2015. Operation is assumed from 2016 until 2035.

8.4.2 Base case variables

A sensitivity analysis was carried out on the variables to provide net present values and levelised costs[113] as shown in Figure 35, with the base case variables highlighted.

Figure 35: Detailed variables of each scenario

				Base Case			
Feedstock	Feedstock scenarios	Low cost	Aggressive	Domestic first	Tallow only	Reduced scale	
Economics	Forecast Price Spread		Low	Average	High		
	Discount Rate (Real)	7%	11%	15%	20%		
	Capex		-30%	Base	+30%		
	Renewable Premium			Parity to jet	Premium		
	Crude Oil Price	$90/bbl	$100/bbl	EIA forecast	$110/bbl	$120/bbl	$130/bbl
Technical/ Ops	Capacity		1000T/day	3000T/day			
	% Cracking		0% (max diesel)	45%	100% (max jet)		
	Forecast Forex		Low	Base	High		
	Forex Approach			Inst. Banks	Linked to crude		
	Operating Time		90%	95%			
Policy	Cleaner Fuels Scheme (value)			None	Low	Medium	High
	Cleaner Fuels Scheme (timing)			Terminate	Short	Medium	Long
	Carbon Price (Inclusion)			Out	In		
	Carbon Price (Value)		$15/T	$23/T	$30/T		
	Govt Contribution			No	$100m	$500m	$1bn

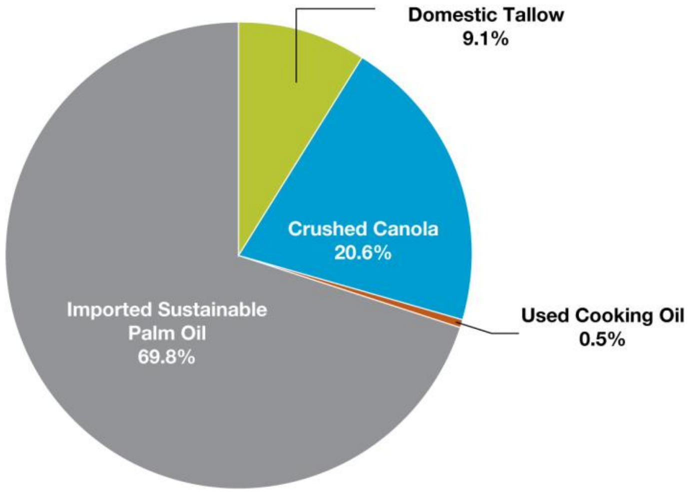
Source: SKM analysis (2013)

8.4.2.1 Feedstock requirements

Feedstock requirements for this facility are shown in Figure 36. Due to the lack of availability of domestic feedstock, close to 70% of the requirement comes from imported oils (sustainable palm oil is assumed). Of the domestic feedstock, about 20% comes from high-priced, domestically produced Canola oil, with the remainder from by-products (tallow 9.1%) and used cooking oil (UCO 0.5%). All the feedstock used in this scenario is sourced from currently available and commercial feedstock.

[113] On a A$ per litre basis. This can then be compared to the imported price of conventional jet fuel

Figure 36: Base case feedstock split (%)



Source: SKM analysis (2013)

8.4.2.2 Costs

Feedstock forms the major cost component and are predicted to rise in real terms from A$874 million per annum in 2016 to approximately A$1,067 million in 2025 and ultimately A$1,300 million in 2035. This represents an average per annum rise of 1.8%. The cost of each feedstock is expected to rise, with the cost of high-value natural oil (whether produced domestically or imported) expected to experience the most rapid rate of growth. The increase in cost is due principally to the expectation of rising global commodity prices for these food commodities.

Estimated annual operating costs by component are broken down in Table 7. Clearly, feedstock costs comprise the largest component, starting at around 88% of total costs. Costs for feedstock are expected to increase at a faster rate than other cost components, increasing to around 90% of total costs. Refinery operating costs comprise a minor and declining proportion of total costs. Most refinery operating costs are expected to stay constant or fall over time with the exception of gas used in the HMU process. Natural gas is expected to rise rapidly over the period to 2020 due to a forecast increase in domestic gas prices.

Capital costs for construction were identified in Sections 5 to 7 at approximately A$1 billion, spread over three years, with the bulk of the costs expended in the second year of construction.

Table 7: Breakdown of operating costs, base case scenario

	2016	2020	2025	2030	2035
Operating costs, $m (2012)					
Feedstock	874	969	1,067	1,176	1,300
Refinery operating					
Aggregation & Pre-treatment	6	6	6	6	6
Manufacturing	107	114	117	117	116
Distribution	3	3	3	3	3
Carbon charges	7	9	11	13	17
Total	997	1,100	1,203	1,315	1,442
% of total opex					
Feedstock	88	88	89	89	90
Refinery operating					
Aggregation	1	1	0	0	0

	2016	2020	2025	2030	2035
Pre-treatment	0	0	0	0	0
Manufacturing	11	10	10	9	8
Distribution and other	0	0	0	0	0
Carbon charges	1	1	1	1	1

Source: SKM analysis (2013)

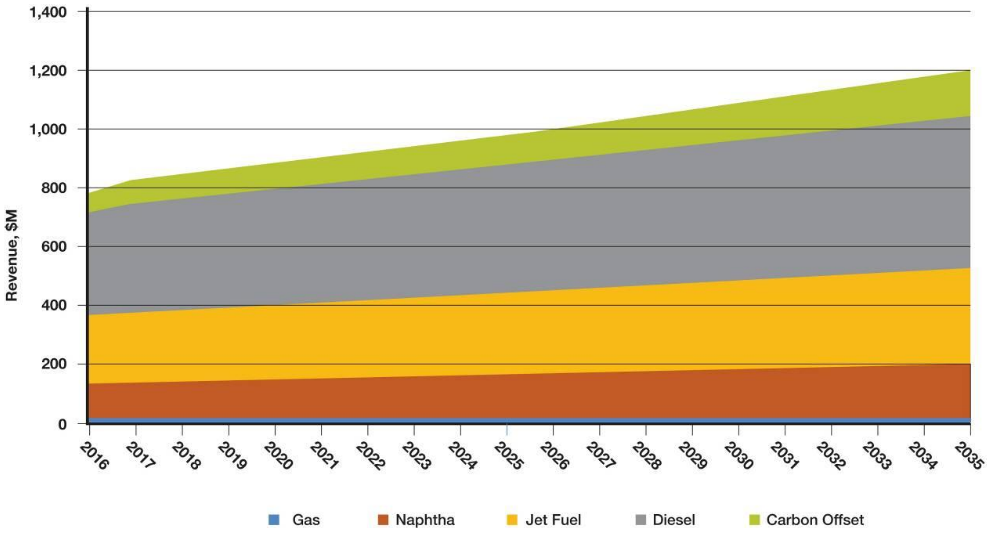
8.4.2.3 Output and revenue

The output mix of the plant as configured for the base case scenario is favoured towards production of renewable diesel and SAF. Thirty per cent of the product slate comprises SAF and around 46% comprises renewable diesel. Low-value naphtha comprises 20% with the remainder being refinery gases.

Annual revenue from the product mix (in real 2012 dollars) is shown in Figure 37. Revenues start at approximately $793 million in 2016, reaching around $977 million in 2025 and $1,212 million in 2035. Revenues grow at a slightly faster rate than costs, mainly due to the assumed high rate of growth in revenues from the carbon benefits inherent in renewable fuels. If there is no value attributed to carbon benefit, the revenue stream grows at a rate commensurate with operating costs.

Revenue from renewable diesel sales comprises over 40% of total revenue. SAF sales comprise around 27% of product revenue. Naphtha comprises around 17% of revenue. No grant schemes (e.g., Cleaner Fuels Scheme) were included in this analysis.

Figure 37: Annual revenue stream from renewable product mix, real 2012 dollars A$ – base case

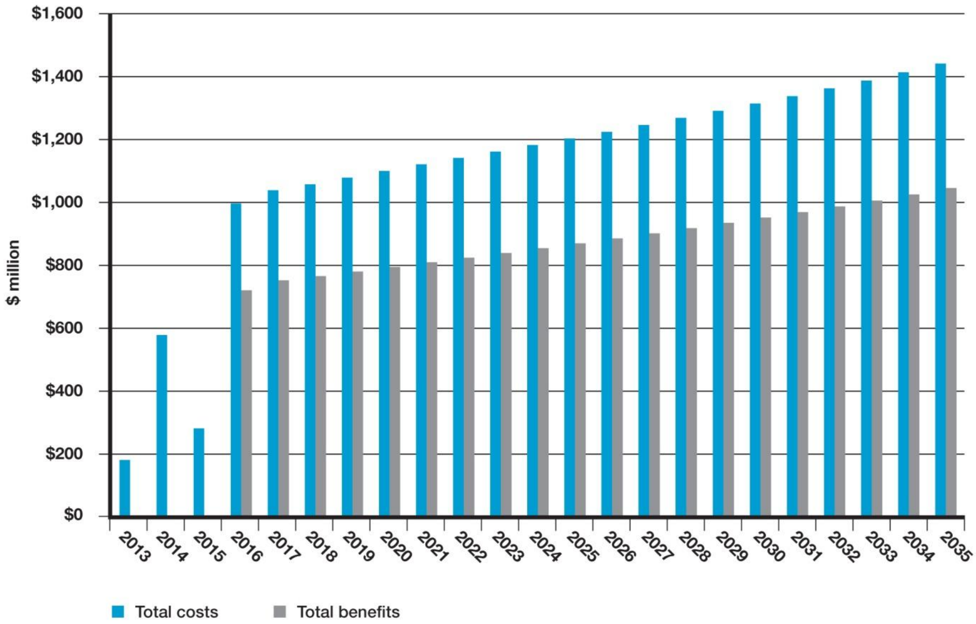


Source: SKM analysis (2013)

8.4.2.4 Economic appraisal

The estimated cash flows for this scenario are shown in Figure 38. The analysis indicates that at no time do the projected revenues exceed the projected costs, assuming that there is no price differential between SAF and conventional jet fuel (or the other renewable and conventional products). The difference each year is approximately $300 million during the early operating phase of the project increasing to $400 million by 2035.

Figure 38: Comparison of estimated cost and revenues – base case (A$ 2012)

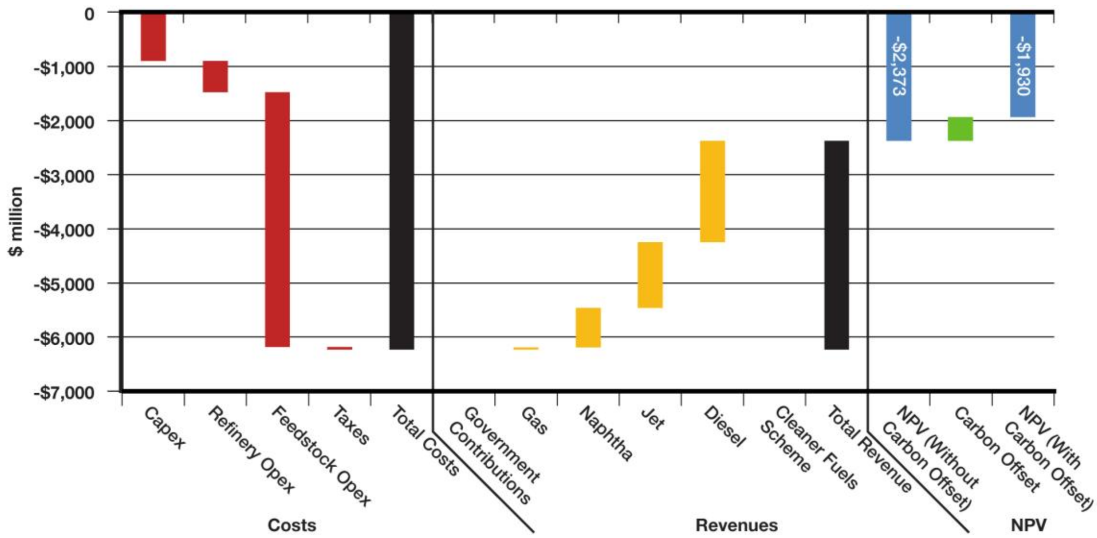


Source: SKM analysis (2013)

A summary of the cost and revenue components is presented in Figure 39. The net present value of the costs is around $6 billion, whilst the net present value of the revenues is approximately $4 billion. The largest cost component is the cost of feedstock, accounting for approximately $4.5 billion or around 70% to 80% of total costs. A key point is that the annual cost of feedstock exceeds the annual revenue earned by the project. This is based on the key assumption of price parity between renewable and conventional products.

This cost arises as the modelled prices for the bulk of the feedstock exceed the prices for most of the end products of the refinery process. Therefore, a lower cost mix of feedstock is required to make the process viable. Ultimately, even with the carbon offset benefit included, the NPV on the base case is A$1.9 billion and the LRMC is A$1.94 per litre SAF.

Figure 39: Cost and revenue composition – base case scenario(A$ 2012)



Source: SKM analysis (2013)

8.5 Economic evaluation of alternative feedstock scenarios

Based on the feedstock strategies outlined in Section 4, the conditions under which the project could be commercially viable were re-evaluated. Results are in real 2012 Australian dollars.

8.5.1 Low cost scenario

This scenario sources the lowest cost feedstock in the market, regardless of origin (Section 4.3). In this case, the projected revenues still do not exceed the projected costs. The difference each year is approximately $260 million during the early operating phase of the project. Losses are projected to increase to $380 million per annum by 2035. The net present value of the costs is around $6 billion, whilst the net present value of the revenues is estimated to be $4 billion. The feedstock operating cost in the low cost feedstock scenario is improved by approximately $100 million (present value at 15%) compared to the base case scenario. In this scenario the NPV is -$1.8 billion and the LRMC of SAF is $1.92 per litre (including carbon benefits).

While more expensive domestic feedstock, such as Canola, are replaced by sustainable palm oil, the cost of feedstock does not reduce significantly. Since the sustainable palm oil needs to be imported, its price discount on the international market is lost to importing costs. The reduction in feedstock operating costs is not significant at approximately 1% or $13 million per annum. Other than the minor change in feedstock costs, the composition of the costs and benefits in the low cost feedstock scenario are very similar to those in the base case scenario.

8.5.2 Aggressive domestic scenario

This scenario assesses the economic impact of increasing the volume of domestic feedstock to supply approximately half of the bio-refinery demand, thereby offsetting imported feedstock. However, such a large intervention into the domestic market for natural oils not only increases the average price of feedstock, but relies further on food-related feedstock. The analysis shows that this option, with increased operating costs, is not feasible, with an operating loss in the order of $300 million each year, increasing to $430 million by 2035. The increased usage of domestic feedstock increases the feedstock operating costs by approximately 3% ($24 million per annum) compared to the base case strategy. Other than the change in feedstock costs, the composition of the costs and benefits are similar to those in the base case scenario. In this scenario the NPV is -$2.1 billion and the LRMC of SAF is $1.99 per litre (including carbon offsets).

8.6 Economic evaluation of alternative capacity scenarios

An appraisal of a smaller scale plant at 1,000 tonnes per day of feedstock processed was undertaken.

8.6.1 Reduced scale scenario

This scenario assesses the economic impact of reducing the size of the bio-refinery to 1,000 tonnes per day to better match the domestic feedstock volumes. This scenario makes an operating loss of approximately $110 million per annum during the early stage operating phase of the project. Losses are projected to increase to $150 million by 2035. The scenario is the least economically viable of the five cases analysed. This is because the plant suffers from classic diseconomies of scale such that, while the production volume reduces by two-thirds, the capital costs only reduce by half to approximately $500 million (see Sections 5-7). Therefore, the unit capital costs tend to be the highest of all the options.

While this scenario presents a higher net present value than the other scenarios, it has a higher proportion of capital costs at 16% of total costs. In this scenario the NPV is -$892 million and the LRMC of SAF is $2.26 per litre compared with $1.94 per litre for the base case scenario (including carbon).

8.6.2 Reduced scale: Tallow / UCO scenario

To find a scenario that utilises domestic *and* non-food feedstock, an analysis was performed on a ‘reduced scale tallow/UCO-only’ scenario. This scenario has the same scale of production as the reduced scale scenario, but uses close to 100% tallow feedstock (1.4% of the feedstock is UCO), with any domestic shortfall met by imported tallow (65%). This scenario presented the prospect of low unit costs because of the potential to utilise low cost non-food sources of feedstock.

However, the predicted annual costs and revenues are similar to the reduced scale scenario. Costs are slightly higher in the short term and slightly lower in the long term due to differences in feedstock costs. In summary, while it is the most attractive scenario from a sustainability perspective, the NPV for this scenario is -$890 million and the LRMC of SAF is $2.26 per litre compared to base case LRMC of $1.94 per litre (including carbon).

8.7 Economic results

The key economic indicators of net present value and LRMC of producing SAF are provided in Table 8 (results include carbon benefits). While the reduced scale scenario produces the best net present value result, this is a result of the project making less of an operating loss in each year of operation. The results for the LRMC of SAF show that the low cost or base case scenarios provide the least cost production option. LRMC results should be compared to the cost of imported jet fuel.

Table 8: Scenario summary (A$ 2012); including carbon benefits

	NPV ($million)	LRMC ($/litre)
Discount rate	**15%**	**15%**
Base case	-1,930	1.94
Low cost	-1,821	1.92
Aggressive domestic	-2,064	1.99
Reduced scale	-892	2.26
Tallow / UCO	-890	2.26

Source: SKM analysis (2013)

The quantity of Australian jet fuel demand supplied by blended SAF is presented in Table 10.[114]

Table 9: Proportion of Australian fuel demand met by blended SAF (50:50)

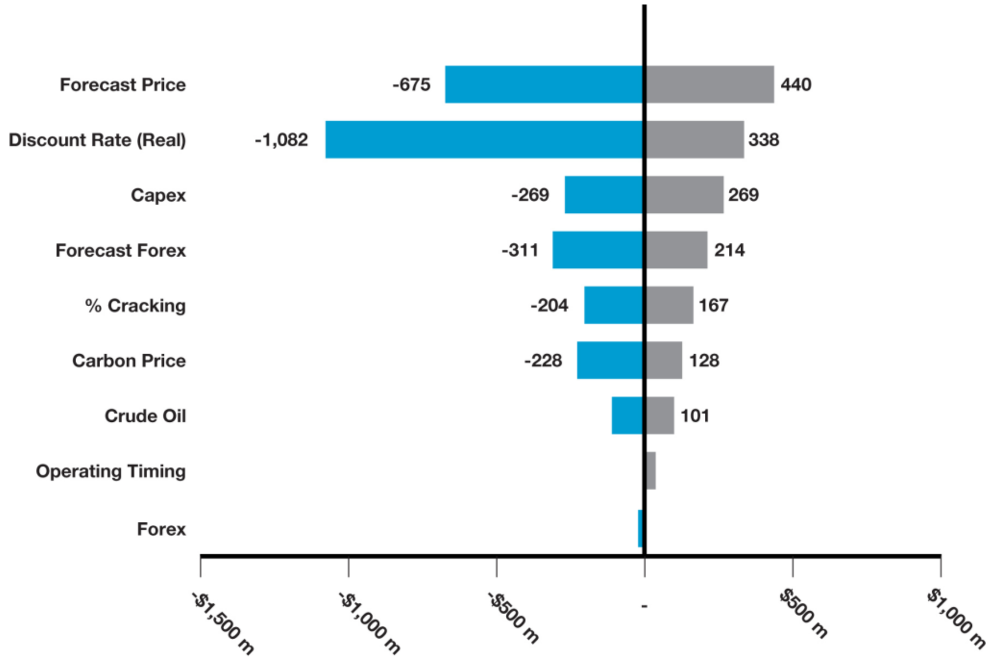
	Total Australian jet fuel demand %		
Year / Discount rate	**2016**	**2020**	**2030**
Base case	9	8	7
Low cost	9	8	7
Aggressive domestic	9	9	7
Reduced scale	3	3	2
Tallow / UCO	3	3	2

8.8 Sensitivity analysis results

Key sensitivities tested reflect the structure of the economics model outlined in Section 8.2. A sensitivity analysis was carried out on the variables (Figure 35), providing NPV and levelised costs for each variable. The tornado chart in Figure 40 represents the change in the base case NPV when testing sensitivities on the key variables of interest – i.e. discount rate, forecast price, forecast forex, and capex. Percentage cracking and carbon price also have a material impact. The forecast price variable, which impacts the crude price and the coefficient assumptions between crude and each of the feedstock and products, can significantly improve and worsen the net present value of the project. As the future price of the feedstock and products are uncertain this presents a risk to the project. The variables tested and the sensitivities applied are described in more detail in Appendix F.

[114] Jet Fuel Demand Study Group (2011)

Figure 40: Tornado chart of sensitivity of key variables, base case scenario (NPV)



Source: SKM analysis (2013)

A benefit of the HEFA refinery is the potential to generate carbon benefits from the production of renewable fuel products, which offsets the use of conventional fuel in various end uses. The value of carbon offsets, in NPV terms, varies from $314 million to $671 million depending on carbon price assumptions. Although the inclusion of carbon offsets could be a valuable source of revenue for the project, the magnitude of the revenue is insufficient to make up the shortfall required to make the project economic. Reducing the scale of the plant reduces the carbon benefits in a linear correlation. The carbon offset benefits are about one-third the benefit of the large scale plant, in line with size of the plant relative to the larger size.

8.9 Strategies to mitigate operating losses

Three levers were examined to mitigate projected operating losses (e.g. Figure 38):

- Reduce feedstock costs
- Maximise renewable diesel production
- Equalise production grants for all renewable products

In some cases, strategic application of these levers was found to produce a positive NPV; thereby representing the combination of conditions that would need to exist in order to develop a SAF industry in Australia. However, the practicality of these levers must be considered in a wider context.

8.9.1 Feedstock costs

The cost of natural oil and tallow feedstock significantly impacts the economic viability of the HEFA pathway. Analysis identified that the modelled feedstock scenarios have minimal impact on project NPV; with feedstock operating costs exceeding product revenues for all modelled strategies. Access to feedstock below the market price is a critical leaver to improve the project NPV. However, this represents an opportunity loss for the producer.

Applying the feedstock leaver in isolation, Table 10 presents the average feedstock price required for the project to breakeven. In the price calculation the feedstock cost is de-coupled from the crude oil and end product prices. Practically, de-coupling this correlation will require either the saturation of alternate markets with low cost feedstock and/or the development of emerging feedstock that have limited alternate use.

Table 10: Required feedstock price for base case scenario to breakeven

Feedstock Scenarios	Modelled feedstock price (A$/t, 2012)	Feedstock price required (A$/tonne)
Base case	1,011	566
Low cost	993	570
Aggressive domestic	1,040	566
Reduced scale	1,048	452
Tallow / UCO	1,045	457

Source: Qantas, SKM analysis (2013)

8.9.2 Targeting renewable diesel

Production analysis (Section 6.4) identified that hydroprocessing natural oils and tallow feedstock naturally produces renewable diesel. Converting these diesel molecules into SAF reduces the economic value of the bio-refinery product slate. The economic impact of hydrocracking is demonstrated in Table 11.

Table 11: Hydrocracking economic impact

Case (A$ million)	Maximum Diesel	Base Case	Maximum SAF
Cost/Revenue 2016	-247	-277	-312
Project NPV	-1,764	-1,930	-2,134

Source: SKM analysis (2013)

Targeting renewable diesel maximises NPV, however, the facility still produces a net loss of 1.8 billion over the project lifetime. In this configuration, the plant produces minimal SAF and must compete against the lower cost bio-diesel pathway (see Box 1). The latter presents a more economic pathway for converting natural oils and animal fats in a bio-fuel that is compatible with diesel engines. The hydrocracking lever alone is therefore insufficient to mitigate projected NPV losses.

8.9.3 Government support

8.9.3.1 Cleaner Fuels Grant

Several support cases were explored in relation to the form of a grant (*Energy Grants (Cleaner Fuels) Scheme Act 2004)*, as presented in Table 12 and explained in Section 8.3.4.1.

Table 12: Cleaner fuels scheme grant scenarios (A$ 2012)

		2012 – 2021		2022 onwards	
No	**Support cases**	**Diesel value**	**Jet, naphtha & gas**	**Diesel value**	**Jet, naphtha & gas**
1	High and long grant	38c/L	38c/L	38c/L	38c/L
2	High and medium grant	38c/L	38c/L	19c/L	19c/L
3	High and short grant	38c/L	38c/L	-	-
4	Medium and long grant	38c/L	19c/L	38c/L	19c/L
5	Medium and medium grant	38c/L	19c/L	19c/L	9.5c/L
6	Medium and short grant	38c/L	19c/L	-	
7	Low and long grant	38c/L	-	38c/L	-
8	Low and medium grant	38c/L	-	19c/L	-

		2012 – 2021		2022 onwards	
9	Low and short grant	38c/L	-	-	-
10	No grant	-	-	-	-
11	Excise match	38c/L	3.8c/L for jet only	-	-

Source: SKM analysis (2013)

The results of this analysis are shown in Table 13. It is only when a grant of 38c per litre is applied to all products equally[115] for the life of the plant (case 1 – high and long grant support case) do the base case and low cost scenarios produce a positive NPV. In all other scenarios, with varying levels of government assistance, the project does not reach an economic NPV level.

Table 13: Net present value with government support, $million, 15% discount rate and real 2012 A$ terms

Support case	Base case	Low cost	Aggressive	Small scale	Tallow/UCO
1	121	229	- 12	- 208	- 205
2	- 285	- 176	- 418	- 343	- 341
3	- 690	- 582	- 823	- 478	- 476
4	- 442	- 324	- 584	- 404	- 402
5	- 737	- 620	- 877	- 500	- 498
6	- 1,031	- 916	- 1,169	- 597	- 595
7	- 1,006	- 876	- 1,156	- 600	- 598
8	- 1,188	- 1,063	- 1,336	- 658	- 656
9	- 1,371	- 1,250	- 1,515	- 716	- 714
10	- 1,930	- 1,821	- 2,064	- 892	- 890
11	- 1,337	- 1,216	- 1,479	- 703	- 701

Source: SKM Analysis (2013).
Note that Case 9 is representative of the current state and Case 10 is the base case with no Cleaner Fuels Scheme from government. These scenarios assume 30% SAF.

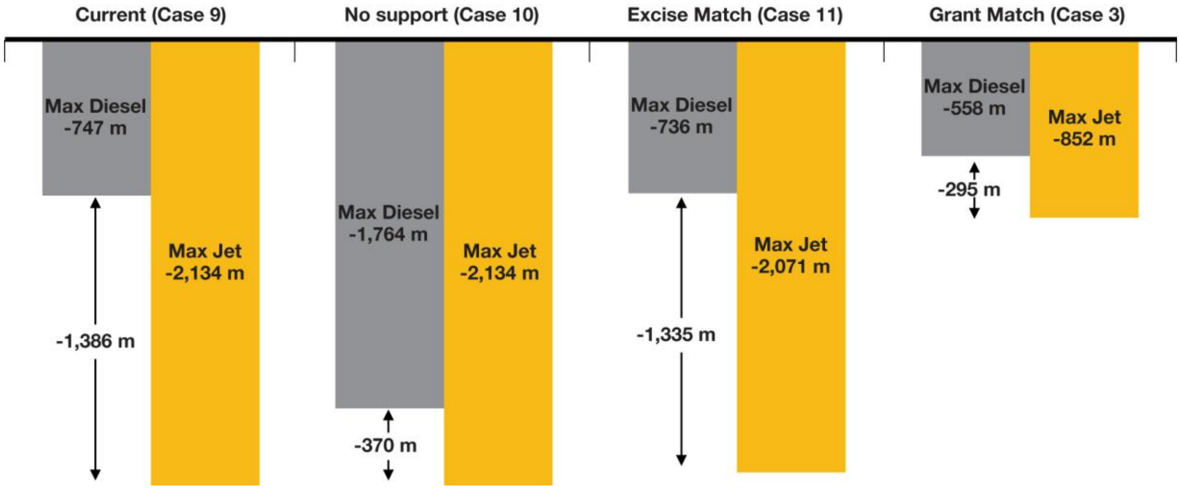
An important observation from these results is the incentive provided to producers of bio-diesel and renewable diesel. This has a flow on effect for investment in SAF. In addition to the techno-economic preference in refining to produce diesel as outlined in Section 6, the Cleaner Fuels Scheme increases the incentive to produce renewable diesel. Figure 41 provides a comparison of the current state (case 9) and a case where no grant is applied to any bio-products (case 10). This analysis shows that the NPV for a bio-refinery is improved by approximately $1 billion with a grant to renewable diesel when the refinery is configured to produce maximum diesel (i.e. 0% cracking). This provides a significant incentive for any supplier to maximise renewable diesel over SAF when contemplating investment of capital. In addition, the hydroprocessing pathway does not represent the best economic method for producing a bio-fuel compatible with diesel engines. The same natural oil and tallow feedstock can be used to produce bio-diesel through transesterification, at significantly less capital cost, and is being produced commercially today. Therefore, not only do investment and production choices tend towards renewable diesel over SAF as described above, but they also tend towards bio-diesel over renewable diesel. The Cleaner Fuels Scheme therefore reinforces a techno-economic tendency towards diesel, and thus away from SAF.

A comparison of the current state (case 9) and a case where the Scheme is applied to all bio-products (case 11; i.e. a 3.5 cent per litre grant for SAF) shows that the NPV of providing this benefit to SAF is approximately $74 million when the refinery is configured to produce maximum jet (i.e. 100% cracking). While the NPV improvement is small, the relief mitigates the strong preference for renewable diesel, thereby increasing the

[115] While aviation fuel is not subject to a 38c per litre excise, several support cases for all refinery products were modelled to understand the impact on project viability

prospects for production of SAF from the same refining process relative to renewable diesel. A producer would be more incentivised to produce SAF in the scenario of a grant match (case 3) where all bio-products received a flat 38-cent benefit. However, even in this case, the techno-economic reality of hydroprocessing Australian natural oils means a refiner would choose to produce renewable diesel over SAF (e.g., case 10 demonstrates a $370 million advantage). The incentivising nature of the Scheme is shown in Figure 41.

Figure 41: Impact of the Cleaner Fuels Scheme



Source: SKM analysis (2013)

8.9.3.2 Government contribution

The ability to select a level of direct government financial assistance was also included as a variable in the economic model. The nature of government assistance was either a direct upfront grant or a low-interest loan for capital expenditure on the project. In practice, any direct government assistance would contribute towards reducing a negative NPV result and move the project towards a positive NPV.

Given the majority of NPV results in Table 13 are worse than -$1 billion, direct government assistance would need to be at least A$500 million to make a significant impact on the project under current base case assumptions.

8.10 Summary

The development of a HEFA based SAF industry in Australia has significant economic challenges. Based on current assumptions a HEFA industry is not commercially viable. Revenue collected from the project is less than the costs of purchasing available feedstock. The magnitude of the losses is such that even a A$0.38 per litre benefit on all renewable products (i.e., adapted Cleaner Fuels Scheme; benefit applied until 2021) would not be enough to recover costs.

The cost of conventional jet fuel (at the refinery gate based on IPP) is predicted to be around A$0.65 to A$0.95 per litre in the projection period, which is approximately A$1.00 to A$1.50 per litre less than the cost of SAF production. Closing the gap will be difficult as higher crude prices (reflecting higher jet fuel prices) paradoxically lead to higher costs. This is principally because of the observed short-to-medium term correlation between crude oil and bio-feedstock prices. Therefore, a higher crude oil price not only leads to higher market jet fuel prices, but also to higher input costs through increased bio-feedstock prices, assuming no supply chain integration.

Non-pecuniary benefits are not large enough to compensate for the revenue deficit. The valuation of carbon mitigation (A$443 million; applied to all products) does not provide sufficient benefit to mitigate against the A$2,370 million deficit. Applying a premium to SAF based on the higher energy content relative to conventional jet fuel was considered. However, in practice this premium is difficult to obtain in the supply chain and would only amount to an additional 1% cost reduction for airlines, which is clearly not enough to cover the project gap.

The combination of conditions required to mitigate operating losses and thereby provide a positive NPV are:

- **Reduce feedstock input costs**: access to feedstock below the market price is imperative. However, this represents an opportunity loss for the producer. If the crude-natural oil feedstock correlation is weakened, the market price for feedstock needs to be reduced by approximately 50% for the project to breakeven.
- **Target renewable diesel**: maximising renewable diesel production (which is generally the case in conventional oil refineries) will result in lower losses and optimise the gains. However, increasing the production of higher value renewable fuels in isolation does not overcome the main problem of high feedstock prices relative to end product prices.
- **Equalised production grants**: a financial benefit of around A$0.38 per litre applied across all the bio-products (not just SAF and renewable diesel) during the life of the project (e.g., beyond 2021) is likely to provide a positive net present value for the project.

Importantly, the above represents a combination of conditions that would need to exist in Australia in order to make the HEFA SAF pathway commercially viable. Assessment of similar HEFA based project overseas demonstrates that such combinations exist in certain markets.

Finally, the economic results were robust to changes in the key assumptions. A decrease of one percentage point in the discount rate led to a decrease in LRMC of less than A$0.02 to A$0.04 per litre, depending on the feedstock scenario. In addition, the higher the carbon price, the lower the LRMC; however, a high price of carbon[116] leads to a reduction of LRMC by only $0.10 per litre.

In conclusion, the HEFA based pathway faces significant economic challenges in Australia based on the current understanding of HEFA feedstock pricing structures and capital costs. Revenue collected from the project is generally less than the costs of purchasing key feedstock under a range of reasonable assumptions on key input values. In addition, the price of SAF is not competitive, with the LRMC higher than the projected average conventional jet fuel price range over the next two decades.

[116] High price of carbon based on a carbon price that is derived from a strict global target of 450 parts per million.

9. Fischer Tropsch

9.1 Introduction

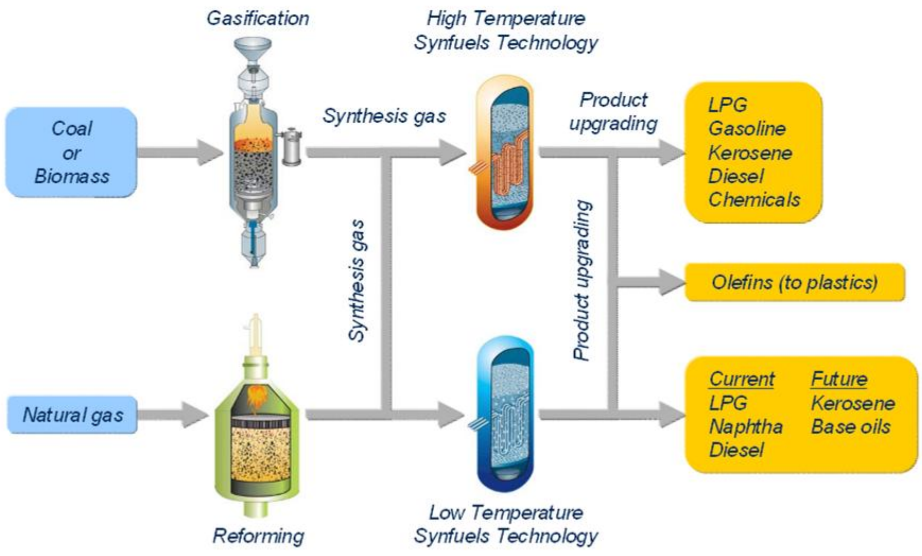
The Fischer Tropsch (FT) process refers to the process of turning a mixture of carbon monoxide and hydrogen into hydrocarbons using catalysts for liquid fuel use.

The FT process was developed in Germany in the 1920s by Franz Fischer and Hans Tropsch. Its purpose was to ensure steady supplies of energy for Germany during World War II while energy imports were blocked. The FT process was again used in apartheid South Africa when isolation and trade embargoes reduced the ability of South Africa to import its energy needs. Instead, the South African government turned to its abundant and cheap supplies of coal to produce liquid transport fuels via the FT process.[117]

Broadly speaking, the FT process involves two primary steps. The first step is gasification (biomass or coal feedstock) or reforming (natural gas feedstock), which converts a feedstock into a synthesis gas, or syngas. This syngas consists of a mixture of carbon monoxide and hydrogen. In the second step, the FT process takes the syngas and exposes it at temperature to a metallic catalyst, which reconstitutes the syngas into a crude FT hydrocarbon wax which is subsequently upgraded into ASTM-certified fuels. Low-temperature FT is used primarily for natural gas feedstock between 150-300°C and high-temperature FT is used primarily with coal feedstock at temperatures of 300-350°C. Common FT catalysts include nickel, cobalt and iron.

The most common FT feedstock used to date in commercial volumes has been coal and natural gas. The technology is often referred to as coal-to-liquids (CTL) or gas-to-liquids (GTL) depending on the feedstock used. Recent developments have focused on using existing biomass such as ligno-cellulosic (LC) or municipal solid waste (MSW) as a feedstock, referred to as biomass-to-liquids (BTL).

Figure 42: Sasol synthetic fuels process – CTL, BTL and GTL



Source: www.sasol.com

As a result of the development and use of CTL during apartheid, South Africa has become the world leader in development of commercial-scale, coal-based FT plants, further extended through national oil company, Sasol. The first Sasol commercial CTL plant was opened in 1955 in Sasolburg. Sasol has been able to leverage the abundant coal reserves in South Africa to mitigate its traditionally low access to crude oil. Sasol uses both coal and natural gas as feedstock and produces a variety of products, including a significant portion South Africa's diesel fuel.[118]

Examples of current FT plants include:

[117] Sasol History, http://www.sasol.com/sasol_internet/frontend/navigation.jsp?navid=700006&rootid=2

[118] Sasol History, http://www.sasol.com/sasol_internet/frontend/navigation.jsp?navid=700006&rootid=2

- Sasolburg I and II CTL plants – Sasol, South Africa
- Bintulu GTL plant – Shell, Malaysia
- Pearl GTL plant – Shell, Qatar
- Louisiana GTL plants – Sasol, United States
- Escravos GTL plant – Chevron & Sasol, Nigeria

As outlined in the CSIRO and L.E.K reports, FT plants are capital intensive and, therefore, expensive to build relative to the liquid fuels produced.[119] The high capital cost is required to avoid diseconomies of scale associated with down-scaling the gasification or reforming stages of the FT process. To be economically viable, the high capital costs must be balanced by cheap feedstock costs. In the case of FT plants in South Africa, coal has traditionally been a cheap and plentiful source of feedstock for CTL plants. The exploitation and expansion of cheap natural gas reserves has also led to the economic viability of GTL plants. A cheap and plentiful feedstock is therefore a fundamental requirement for successful FT plants.

9.2 FT pathway for aviation

The FT process is the first alternative fuel pathway to successfully navigate its way through the ASTM process for certification in a jet engine. The process to carve out exceptions or additions to the ASTM process has traditionally been expensive and time consuming, involving significant investment in multiple chemical, mechanical, aeronautical and safety testing processes. Sasol was the pioneer in driving an alternative fuels pathway out of necessity – approximately 25-30% of South African fuel is derived from coal, and synthetic jet fuel blends have been in commercial use in South Africa since 1999.[120]

In February 1999, an exception application to the UK Defence standard, Def Stan 91-91, was approved, allowing Sasol to supply FT-derived, semi-synthetic coal-based jet fuel. In August 2009, the ASTM committee approved the first Annex to ASTM D7566 in the form of generic FT-derived, semi-synthetic jet fuel, including using biomass feedstock. The product is known as FT-SPK (synthetic paraffinic kerosene) which does not have aromatics. Therefore, a blend limit of 50% exists as removal of aromatics, for example, has been demonstrated to have adverse effects on aircraft fuel system seals. The approval of FT-derived fuels was followed in July 2011 by the HEFA-derived jet fuel approval in ASTM D7566 Annex 2, also up to 50% blend.[121]

The key commercial feedstock to date have been coal and natural gas. These feedstock are commercially viable for producing *alternative* aviation fuels, but do not produce *sustainable* aviation fuels. In other words, the FT process to produce jet fuel using coal or natural gas does not result in significant reductions in greenhouse gas emissions. In the case of a coal-based FT process, manufacturing emissions are considerably worse than a conventional petrochemical complex. [122]

9.3 The Solena model – waste feedstock

Solena Fuels Corporation is a US-based company seeking to commercialise the FT process using biomass feedstock (BTL) to produce low-carbon SAF.[123] There are several attractive aspects to the Solena model.

Firstly, the feedstock proposed by Solena is urban waste normally destined for land fill. Given the high capital cost of FT plants per litre of product output, the economics of FT will be more achievable with very cheap or negative cost feedstock. Since FT can use syngas made from a variety of feedstock, urban waste can be used to "recycle" the hydrocarbons already present in waste. Many countries have significant waste levies that put a price on landfill per tonne deposited. For example, in London, the landfill levy is £110 per tonne (approximately A$170). Solena will source its waste at a price that incentivises waste companies to pay Solena to take away the waste at a cost per tonne that is lower than the landfill levy. The waste company therefore reduces its cost of disposal, and Solena is paid to take away a valuable feedstock input for its BTL process.

[119] Sustainable Aviation Fuels Road Map: Flight path to sustainable aviation, CSIRO, 2011, p25; Advanced bio-fuels study: strategic directions for Australia - Appendix, L.E.K Consulting, Dec 2011, p46

[120] "An Overview of Sasol's Jet Fuel Journey", Dec 2011, Presentation to the 20th World Petroleum Congress, http://www.sasol.com/sasol_internet/downloads/The_synthetic_jet_fuel_journey_WPC_PMorgan_Sasol_1323236837470.pdf

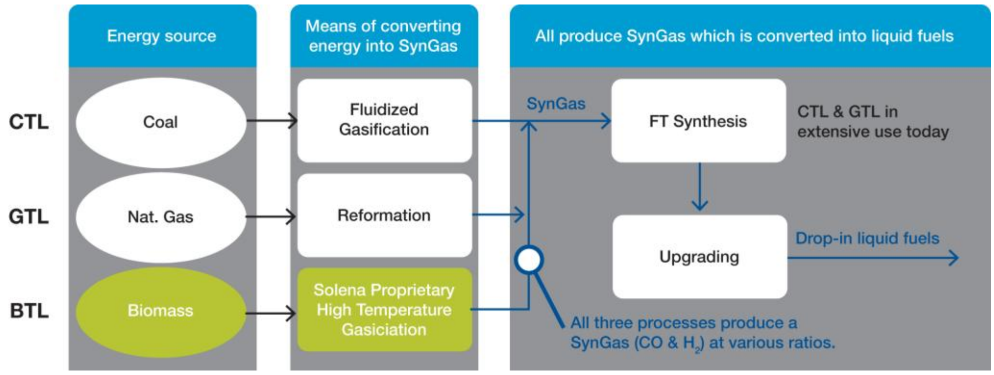
[121] "An Overview of Sasol's Jet Fuel Journey", Dec 2011, Presentation to the 20th World Petroleum Congress

[122] Sustainable Aviation Fuels Road Map: Flight path to sustainable aviation – Data assumptions and modelling, CSIRO, 2011, p27

[123] www.solenafuels.com

Solena offers an end-to-end integrated process that includes all the elements of feedstock, gasification, FT process and hydroprocessing to meet the jet fuel specification. Like the HEFA study in this report, this has the advantage of aggregating the value chain together under one umbrella operation and avoiding gaps in the SAF value chain.[124] Figure 43 shows a simplified version of the end-to-end integrated value chain in the Solena model.

Figure 43: FT process



Source: Solena (2012)

As described, the Solena process utilises urban waste feedstock with an average of 16 mega joules of energy and processes it through the gasification stage. Out of the gasification comes a bio-syngas, which is then put through the FT reactors and upgraded using traditional hydroprocessing. As outlined in the refining section, the product split from the hydroprocessing stage is generally diesel, kerosene, naphtha and gas. Solena's optimised hydrocracking produces approximately 40% renewable diesel, 40% SAF and 20% bio-naphtha.

9.4 Solena-British Airways GreenSky London project

In November 2012, British Airways (BA) announced it had signed an off-take agreement to receive 100% of SAF product from a Solena plant. British Airways has committed to a 10-year, off-take agreement, at market competitive prices, for the jet fuel produced by the plant which equates to US$500 million at today's prices.[125]

The plant is planned to convert approximately 500,000 tonnes of waste per annum normally destined for landfill into 150 million litres of fuel product (~2,500 barrels per day[126]), including 60 million litres of SAF (40%), 60 million litres of renewable diesel (40%) and 30 million litres of bio-naphtha (20%).

The London project requires approximate capital expenditure of US ~$500 million, assuming a brownfield site. In terms of the end-to-end integrated process, it is proposed that Solena Fuels will provide the high-temperature gasification process that converts waste matter into synthesis gas and the overall integrated solution. Oxford Catalysts Group/Velocys will supply the FT reactors and catalyst which will convert the cleaned synthesis gas into liquid hydrocarbons. Fluor has been named the project's engineering partner.[127]

One of the advantages of London as a BTL site is the high landfill levies in London at £110 per tonne or approximately A$170. The waste feedstock therefore generates an income stream for the project, rather than a cost burden, which balances the comparable high capital cost of the gasification and FT plant. In addition, the EU has in place a price on carbon for aviation, which is driving airlines to invest in SAF volumes to mitigate carbon cost.[128]

While the final project details are still being assembled and full commercial scale production is yet to be proven, if successful, the GreenSky London project would be ground breaking in launching the global SAF market. The project would be the most advanced commercial scale BTL project in the world, and the first commercial-scale plant capable of producing commercial volumes of SAF.

[124] FT process however makes a waxy hydrocarbon rather than a bio-crude.

[125] "British Airways commits $500M to fuel from GreenSky London plant", Bio-fuels Digest, 3rd Dec 2012

[126] By comparison, the size of the facility modelled for the HEFA component of the study is 20,000 barrels per day.

[127] BA Press Release, "GreenSky London Bio-fuel Plant Preparing for Lift-off", 30th Nov 2012, http://press.ba.com/?p=2533

[128] At the time of writing the EU had passed 'stop the clock' legislation in relation to aviation

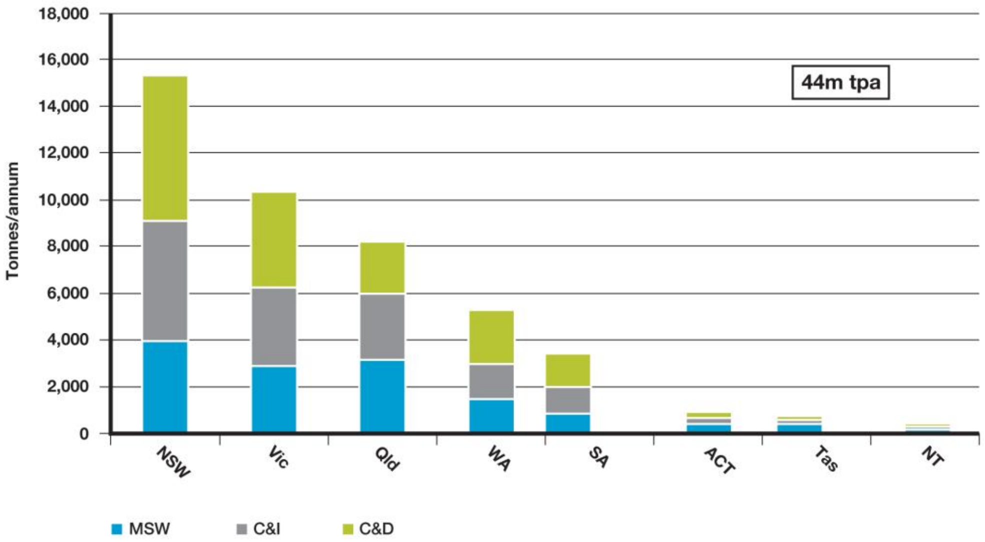
9.5 FT in the Australian context

9.5.1 Waste market

Central to the concept of a BTL Solena plant in Australia is the viability of Solena having access to significant volumes of very cheap or negative cost waste feedstock with the appropriate minimum level of energy content.

As Figure 44 shows, Australia's total waste volume in 2010 was approximately 44 million tonnes comprising of construction and demolition or C&D (~37%), commercial and industrial waste or C&I (~33%) and municipal solid waste or MSW (~30%). The states generating the highest waste volumes are New South Wales (~30%), Victoria (~26%) and Queensland (~18%).[129]

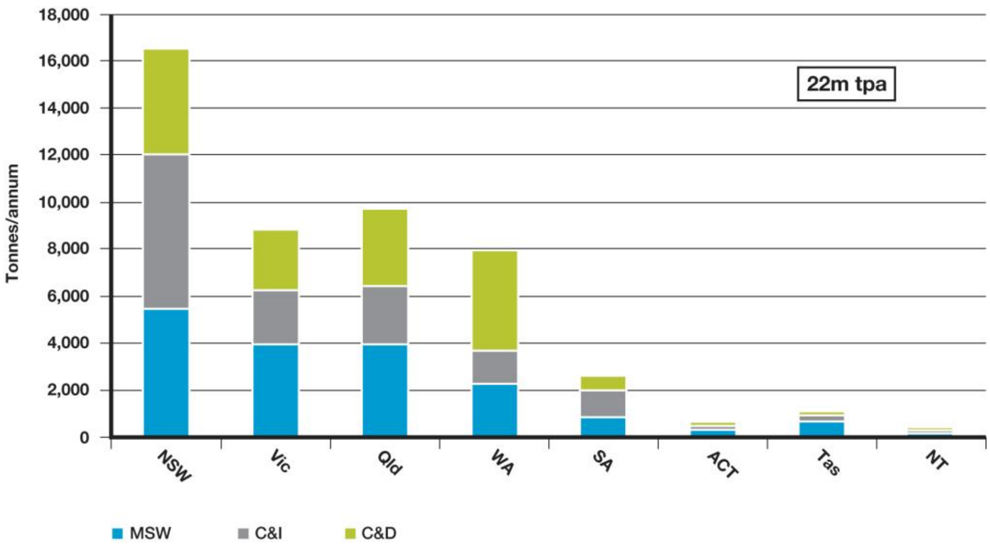
Figure 44: Total waste generation by state (2010)



Source: National Waste Report (2010)

As Figure 45 demonstrates, approximately 22 million tonnes are landfilled, implying a landfill versus recycling ratio in Australia of 50%.

Figure 45: Total waste landfill by state (2010)

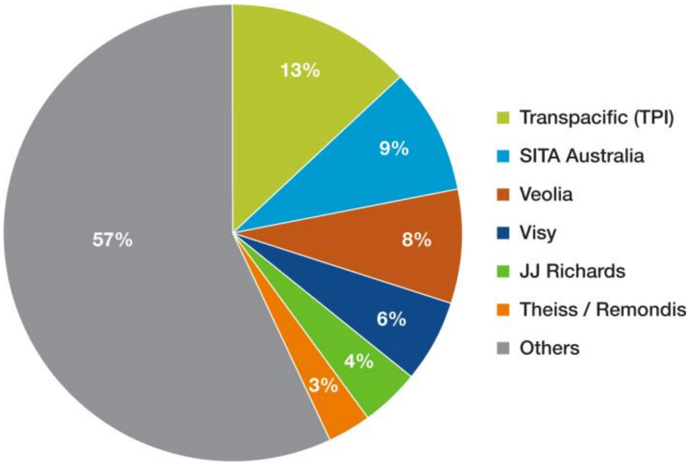


[129] National Waste Report 2010, http://www.ephc.gov.au/taxonomy/term/89; SITA analysis

Source: National Waste Report (2010)

This high-level market data suggests there is enough relevant waste in Sydney or Melbourne to feed a Solena plant requiring 500,000 tonnes per annum. New South Wales produces approximately 3.9 million tonnes per annum of MSW alone, and Victoria produces approximately 2.7 million tonnes per annum.[130] Some of these volumes would not meet the required energy content; however, waste from other categories such as C&I and C&D might possess the required energy content. Also, a ~20% intervention into the New South Wales MSW market or a ~30% intervention into the Victorian MSW market from Solena would still be a significant market intervention and an attractive supply contract for waste. This is compounded by the fact that while the waste industry in Australia has recently been consolidating, it is still relatively fragmented across companies and geographies, as reflected in Figure 46.

Figure 46: Major players in Australian waste market (2013)



Source: IBIS World

In addition, landfill levies are appropriately high enough in New South Wales (~$95.20 per tonne) and Victoria ($48.40 per tonne) to allow Solena to offer a cheaper alternative to waste disposal from waste aggregators. One issue is the fact that Queensland does not have a landfill levy, potentially providing firms with a cheap interstate landfill alternative (subject to interstate waste regulations). Table 14 outlines the current landfill levies operating from 1 July 2012.

Table 14: Current landfill levy from 1 July 2012

Jurisdiction	Current Landfill levy (from 1 July 2012)	Announced price path	Source
NSW	$95.20/t[1]	• Increase of $10/t + CPI every year until 2015/16	• Department of Environment and Heritage (NSW); and Protection of the Environment Operations (Waste) Regulation 2005
Vic	$48.40/t[1]	• From 1 July 2013; $53.20 • From 1 July 2014; $58.50	• EPA Victoria; • http://www.epa.vic.gov.au/your-environment/waste/landfills/landfill-and-prescribed-waste-levies
Qld	Nil	• C&I waste levy for $35/t was put in place from Dec 2011 but then repealed 1 July 2012	• Department of Environment and Heritage Protection; http://www.ehp.qld.gov.au/waste/index.html
WA	$28/t	• na	• Waste Authority (WA); http://www.wasteauthority.wa.gov.au/about/levy/
SA	$42/t[1]	• Signalled increases 'up to at least	• Zero Waste SA; http://www.zerowaste.sa.gov.au/about-us/waste-

[130] National Waste Report 2010, http://www.ephc.gov.au/taxonomy/term/89

		$50/t'	levy
ACT*	na	• na	• Waste Minimisation (Landfill Fees) Determination 2012 (No 1)
Tas**	$2/t	• na	• na
NT	na	• na	• na

Source: Source: Various

Notes: [1] Reflects metro area rates

* Landfill disposal rates are regulated by the ACT Government. From 1 July 2012, C&I disposal rates are $121.90/t (incl. GST)

** Northern Tasmania Waste Management Group prescribe a voluntary levy of $5/t. The Tasmanian LGA has endorsed a proposal to introduce a levy of $10/t, however this is currently being considered by the Tasmanian EPA

However, several questions still remain to make the concept viable. A key issue is whether a long-term feedstock supply agreement can be negotiated at a reasonably cheap or negative cost. Key variables include current market conditions, regulatory risk of landfill levy changes and supply market dynamics with consolidation amongst suppliers. In addition, the cost of sorting technology will need to be borne at some point in the supply chain to ensure the appropriate level of energy content in the waste feedstock (i.e., average of 16 mega joules per tonne).

9.5.2 FT plant analysis

An FT plant in Australia utilising biomass feedstock has potential, but key assumptions are as yet unproven in the Australian market.

Capital expenditure of FT and gasification technology is historically very high compared to HEFA pathways, and therefore requires very low or negative-priced feedstock to balance the significant capital expenditure. Municipal solid waste is therefore the ideal feedstock from an economic perspective for FT, since those who require MSW for feedstock are generally paid to take the feedstock away, rather than to pay for it.

A Solena plant in Australia would be of similar scale and technology to the GreenSky London BA-Solena plant, built to maximise SAF production, and likely be located in Sydney or Melbourne to access sufficient waste volumes. The plant requires a long-term contract for approximately 500,000 tonnes per annum of waste feedstock with an energy content of average 16 mega joules per tonne.

While there is likely to be sufficient waste volume in the major capital cities of Sydney and Melbourne (although further detailed work is required on the volume and energy content of relevant waste), the model relies on Solena being paid to take waste feedstock, as an alternative to landfill disposal (where the customer pays disposal and levy costs) or other competing resource recovery options.

There is also a significant technology risk associated with the plant, since there is, as yet, no successful commercial-scale BTL plant anywhere in the world. The world's first commercial BTL plant was under construction in Frieberg, Germany by Choren using wood feedstock. However, Choren Industries filed for insolvency in July 2011. In February 2012, Choren's BTL technology was sold to Linde Engineering, who will develop the technology only.[131]

The EU has been actively supporting BTL plants at both demonstration and commercial level. NER300 is a large-scale funding program for innovative, low-carbon energy demonstration projects. It is a catalyst for the demonstration of environmentally safe carbon capture and storage (CCS) and innovative renewable energy (RES) technologies on a commercial scale within the EU.[132] At the commercial level, two projects recently received funding under the EU NER300 program.

In December 2012, the UPM Stracel project in France was awarded counterpart funding of €170 million under the NER300 funding program. This project aims to construct and operate a BTL plant on the Strasbourg site of the UPM Group, which already owns and operates a paper mill on the same site (Stracel). The plant will be integrated into the paper and pulp production line and will use about 1 million tonnes of woody biomass, with an annual output of 105,000 tonnes of bio-fuel – renewable diesel (80%) and bio-naphtha (20%). It was also

[131] European Bio-fuels Technology Platform – BTL projects, http://www.bio-fuelstp.eu/btl.html

[132] European Commission, NER300 Policy, http://ec.europa.eu/clima/policies/lowcarbon/ner300/index_en.htm

announced that the AJos BTL project in Finland was to receive counterpart funding of €88.5 million to design, construct and operate a BTL plant in northern Finland. Its targeted annual output is 115,000 tonnes of bio-fuel comprising of renewable diesel and bio-naphtha, using close to 950,000 tonnes per annum of woody feedstock.[133]

Despite these planned BTL facilities, there is no commercial-scale BTL plant, which increases the potential cost, risk and required return. Capital expenditure for a Solena plant is approximately US$500 million (2012), assuming a brownfield site, which would produce approximately 40% SAF, 40% renewable diesel and 20% naphtha.

However, such a plant would produce the equivalent of 60 million litres of SAF. When blended in a certified 50:50 blend, this would be approximately 120 million litres blended or 5-7.5% of Qantas Group domestic flying per annum.

9.6 Summary

A similar project may have potential in Australia but the following conditions would need to be satisfied for the Solena technology to be viable:

1. **Technology scale up:** Successfully scale up the waste-to-liquid-based FT pathway from laboratory to commercial scale
2. **Waste supply:** Ability to negotiate with Australian waste companies to receive payment for long-term waste supply agreements
3. **Appropriate site:** Ability to utilise a brownfield site with appropriate utilities in relative proximity to waste source in Sydney or Melbourne

[133] European Commission, "NER300 - Moving towards a low carbon economy and boosting innovation, growth and employment across the EU" http://ec.europa.eu/clima/news/docs/2012071201_swd_ner300.pdf

10. Policy implications

10.1 Role of government

The inability of the market to date to establish a SAF industry, despite large demand from end users such as airlines, suggests that opportunity exists to introduce policy measures to correct this position. There are various forms of government intervention in this space.

Firstly, a key role of government is to create a policy landscape that removes market distortions and encourages appropriate private sector investment and development. Secondly, government can provide limited direct financial assistance in the form of grants, loans, guarantees, etc., where there is no capital forthcoming from the market in a strategically important industry. Thirdly, the government can use its spending and purchasing power to stimulate demand in markets that require a kick-start.

In the case of SAF, there are three fundamental structural gaps in the supply chain where the government could play a role. In the feedstock section of the supply chain for the HEFA pathway, there is a lack of sustainable, non-food feedstock for domestic consumption. Despite Australia's competitive advantage in land and agriculture, there is insufficient sustainable feedstock to maintain even a moderate SAF industry. Part of the role of the government could be to encourage Australian farmers to grow sustainable feedstock, potentially on marginal land, to increase feedstock volumes, establish an additional revenue stream for Australian farmers and break the bio-fuel 'chicken and egg' cycle to encourage capital expenditure on bio-fuel plants. This could break the link between rising fuel prices and rising natural oil prices if emerging feedstock have fewer alternative uses.

In the refining section of the supply chain for the HEFA pathway, there is a fundamental lack of refining infrastructure that can process natural bio-oils. Even if sustainable domestic feedstock were ramped up to appropriate levels, and relevant technology providers utilised this volume, there is nowhere to refine the bio-feedstock into renewable diesel or SAF. Part of the role of the government might be to explore options with industry for bio-refinery locations and supply chains in Australia.

The benefits from government assistance to establish key parts of the SAF value chain include:

- Gaining an early mover advantage over other parts of the world in an emerging and growing industry
- Leveraging Australia's world-leading R&D in innovative agriculture and bio-fuels technology
- Sustaining a commercial advantage for business based on Australia's comparative advantage in land for feedstock
- Creating a new "green" industry with significant employment in skilled areas of innovative agriculture and refining, primarily focused on rural and regional areas
- Maintaining the value adding steps of this new industry in Australia
- Supplementing the energy security needs of Australia's energy landscape
- Reducing carbon emissions in domestic aviation.

10.2 Policy issues

The study identified the importance of a supportive policy environment in facilitating the development of the SAF industry in Australia. Constructing such an environment has to be carefully considered and be complementary to other policy imperatives at Federal and State government levels.

While the intent of the study was not to conduct an in-depth analysis of government policy, a number of the challenges that were identified do identify potential opportunities for government.

Firstly, the lack of existing non-food feedstock for the HEFA pathway opens up the possibility for Australia to **ramp up emerging feedstock** to commercial scale at competitive prices, in order to fill the gap in domestic sustainable supply. Such assistance might take the form of a targeted agricultural program in rural and regional areas, which has the potential to encourage the development of promising feedstock alternatives, improve the productivity of marginal land without displacing existing land use and, ultimately, weaken the link between natural oil and crude oil prices. On a broader scale, such incentive-based programs have the potential to facilitate the development of a new industry and related jobs in rural and regional areas. By way of example, programs run by the United States Department of Agriculture illustrate how agricultural policy and assistance is being used to help develop a local biofuels industry.

Secondly, consideration could be given to exploring policy options that provide a **level playing field** in terms of fiscal incentives for production of all sustainable renewable transport fuels– not just bio-diesel, renewable diesel and ethanol. In this regard, approaches taken by other leading global economies, such as the United States, provide examples that the Australian Government could draw upon to help shape domestic policy,

10.3 Opportunities

The short-term opportunities for SAF in Australia are to focus on improvements in the feedstock economics of the HEFA pathway and the technology readiness of the waste-to-fuel FT pathway. In addition, in the medium term, there is a significant opportunity to explore the feasibility of next-generation pathways that are likely to be certified by the global standards organisation ASTM[134] in the near future. As identified by this report and previous reports, emerging pathways have the potential to involve feedstock that are cheaper, more plentiful and more sustainable than natural oil feedstock that have lower capital expenditure than FT, and in which Australia has a significant advantage compared to the rest of the world.

In a similar manner to this study, future studies (e.g., supported by the Australian Initiative for Sustainable Aviation Fuels or AISAF)[135] might involve key players in the supply chain to assess the practical and commercial conditions under which emerging pathways can lead to the establishment of viable SAF value chains.

[134] www.astm.org

[135] www.aisaf.org.au

References

Industry and research organisations interviewed

Australian Agricultural Crop Technologies, August 2012, <http://www.aacroptech.com/>

Australian Oilseeds Federation, August 2012, <http://www.australianoilseeds.com/>

Australian Renderers Association, Aug 2012, <http://www.ausrenderers.com.au/>

Bio-fuels Association of Australia, July 2012, August 2012, <http://www.bio-fuelsassociation.com.au/>

Biomax Fuels, July 2012, <http://biomaxfuels.com/home.html>

Cargill Australia, July 2012, <http://www.cargill.com.au/en/index.jsp>

Colyer Fehr, July 2012, <http://www.colyerfehr.com.au/>

International Air Show and Aerospace and Defence Exposition February 2013

Northern Agricultural Research Station Interview Data, 21 July, 2010, <http://ag.montana.edu/narc/>

University of Adelaide Australian Plant Phenomics Facility, Australian Centre for Plant Functional Genomics July 2012, <http://www.plantphenomics.org.au/>

University of Adelaide FoodPlus Research Centre, August 2012, <http://www.adelaide.edu.au/foodplus/>

Secondary Sources

ACIL Tasman 2009, *Petroleum import infrastructure in Australia*, Prepared for the Department of Resources, Energy and Tourism, Canberra.

American Society for Testing and Materials (ASTM International) 2013, ASTM International, West Conshohocken, viewed September 2012, <http://www.astm.org/>.

Applied Research Associates 2013, Applied Research Associates, Albuquerque, viewed September 2012, <http://www.ara.com>.

Asia Pacific Equity Research 2011, *Australian Carbon Pricing – Quantifying the Impacts on Company Earnings Under Various Carbon Pricing Scenarios,* JP Morgan.

Australian Agricultural Crop Technologies n.d., Australian Agricultural Crop Technologies, Wee Waa, viewed September 2012, <http://www.aacroptech.com/>.

Australian Bureau of Agricultural Economics and Sciences 2012, Department of Agriculture, Fisheries and Forestry, Canberra, viewed September 2012, <http://daff.gov.au/abares>.

Australian Competition and Consumer Commission (ACCC) 2012, *Monitoring of the Australian petroleum industry—Report of the ACCC into the prices, costs and profits of unleaded petrol in Australia*, ACCC, Canberra.

Australian Oilseeds Federation 2010, *Annual Report 2009-2010*, Australian Oilseeds Federation, Sydney, viewed September 2012, <http://www.australianoilseeds.com/__data/assets/pdf_file/0006/7719/2009-10_AOF_Annual_Report.pdf>.

Australian Plant Phenomics Facility n.d., University of Adelaide, Adelaide, viewed September 2012, <http://www.plantphenomics.org.au/>.

Australian Renderers Association 2013, Australian Renderers Association, Warwick, viewed September 2012, <http://www.ausrenderers.com.au/>.

Beer T, Grant T, & Campbell PK 2007, *The greenhouse and air quality emissions of bio-diesel blends in Australia*. CSIRO, Aspendale.

Bio-fuels Association of Australia 2011, *NSW Government suspends bio-diesel mandate increase*, media release, Bio-fuels Association of Australia, 22 December.

Bio-fuels Association of Australia 2012, *Bio-diesel production facilities in Australia*, Bio-fuels Association of Australia, viewed September 2012, <http:// www.bio-fuelsassociation.com.au>.

Biomax Fuels 2008, Biomax Fuels, Chennai, viewed September 2012, <http://biomaxfuels.com/home.html>.

British Airways 2012, “GreenSky London bio-fuel plant preparing for lift-off”, media release, British Airways, London, 30 November.

Brown, N (US Federal Aviation Administration) 2012, “Sustainable alternative jet fuels”, paper presented to the Industry Roundtable on Update on ASTM Approval, 18 May 2012.

Cargill 2012*, Canola oil*, Cargill, viewed September 2012, <http://www.cargill.com/products/industrial/bioindustrial-index/Canola-oil/index.jsp>.

Clean Energy Future 2012, *Clean Energy Fact Sheet,* Australian Government, Canberra, viewed September 2012, <http://www.cleanenergyfuture.gov.au/wp-content/uploads/2011/11/fact-sheet-16-transport-fuels-2-PDF.pdf>.

Clean Energy Future 2013, Australian Government, Canberra, viewed September 2012, http://www.cleanenergyfuture.gov.au/>.

Cobalt Technologies 2013, Cobalt Technologies, Mountain View, viewed September 2012, <http://www.cobalttech.com>.

Colyer Fehr Group n.d., Colyer Fehr Group, Mount Druitt, viewed September 2012, <http://www.colyerfehr.com.au/>.

Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council, National Academy of Engineering 2004, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs,* The National Academies Press, Washington DC.

CSIRO 2011, *Flight path to sustainable aviation towards establishing a sustainable aviation fuels industry in Australia and New Zealand*, CSIRO, Melbourne.

Darby, M 2012, *Australia Bio-fuels Annual: Gain Report AS1211,* US Department of Agriculture, Foreign Agriculture Service, Washington DC.

Department of Resources, Energy and Tourism 2012, *Energy White Paper 2012: Australia’s Energy Transformation,* Australian Government, Canberra, viewed December 2012, <http://www.ret.gov.au/energy/Documents/ewp/2012/Energy_%20White_Paper_2012.pdf>.

Ecoinvestor 2013, ‘Largest biodiesel plant to open’, *Eco Innovation,* 10, viewed May 2013, < http://www.ecoinvestor.com.au/Eco_Innovation/Apr_2013/Largest_Biodiesel_Plant_to_Open.htm>.

Environment Protection and Heritage Council 2010, *National waste report 2010,* Department of the Environment, Water, Heritage and the Arts, Adelaide, viewed September 2012, <http://www.ephc.gov.au/taxonomy/term/89>.

European Bio-fuels Technology Platform 2012, European Bio-fuels Technology Platform, Newbury, viewed September 2012, <http://www.bio-fuelstp.eu/btl.html>.

European Commission 2012, “NER300 ‘Moving towards a low carbon economy and boosting innovation, growth and employment across the EU’”, Commission Staff Working Document, Brussels, viewed September 2012, <http://ec.europa.eu/clima/news/docs/2012071201_swd_ner300.pdf>.

European Commission 2012, NER300 Policy, European Commission, Brussels, viewed September 2012, <http://ec.europa.eu/clima/policies/lowcarbon/ner300/index_en.htm>.

Ewijk, FV (Qantas Airways Limited) 2013, "Rising to the SAF Challenge in Australia: The Qantas View", Presentation at the Australian International Air Show and Aerospace and Defence Exposition, Lara, 26-27 February 2013.

Ewing, R 2013, "Analysis: Big crop, policy revive Brazil's sugar-ethanol mills*", Reuters*, 11 February 2013.

FOODPlus Research Centre 2013, University of Adelaide, Adelaide, viewed September 2012, <http://www.adelaide.edu.au/foodplus/>.

Furimsky E, 1998, "Selection of catalysts and reactors for hydroprocessing", *Applied Catalysis A: General*, 171, pp. 177-206.

Gevo 2013, Gevo, Englewood, viewed September 2012, <http://www.gevo.com>.

Ghosh, S & Nanda, R 2010, "Venture capital investment in the clean energy sector", *Harvard Business School Entrepreneurial Management Working Paper 11-020*, Boston, pp 11-20.

Graham, P et al 2011, *Sustainable Aviation Fuels Road Map: Data assumptions and modelling*, CSIRO, Newcastle.

Haritos, V & Warden, A 2008, "Future Bio-fuels for Australia–Issues and opportunities for conversion of second generation lignocellulosics", *Publication No. 08/117*, Rural Industries Research and Development Corporation, Barton.

Herndon, A 2013, "Tesoro Is First Customer for Sapphire's Algae-Derived Crude Oil", *Bloomberg News*, 21 March 2013.

International Air Transport Association (IATA) 2009, *A Global Approach to Reducing Aviation Emissions*, IATA, Geneva, viewed September 2012, <http://www.iata.org/SiteCollectionDocuments/Documents/Global_Approach_Reducing_Emissions_251109web.pdf>.

International Air Transport Association (IATA) 2013, *Directive on the deployment of alternative fuels infrastructure*, Proposal 2013/0012(COD).

International Air Transport Association, *Carbon Neutral Growth by 2020*, media release, International Air Transport Association, Kuala Lumpur, 8 June 2009.

ISTA Mielke GmbH, Hamburg, Germany, <www.oilworld.de>

KiOR 2013, KiOR, Pasadena, viewed September 2012, <http://www.kior.com/>.

Lane, J 2012, "Aviation and military bio-fuels: new thinking on finance and fuels", *Bio-fuels Digest,* 8 February.

Lane, J 2012, "Boeing, COMAC partner to develop bio-fuels from gutter oil for China market", *Bio-fuels Digest,* 16 August.

Lane, J 2012, "British Airways commits $500M to fuel from GreenSky London plant", *Bio-fuels Digest,* 3 December.

Lane, J 2012, "Cobalt: Bio-fuels Digest's 5-Minute Guide", *Bio-fuels Digest,* 25 October.

Lane, J 2012, "The Solyndra Effect, or why alcohol-to-jet fuel is a tough sell", *Bio-fuels Digest,* 16 November.

Lane, J 2012, "Whatever happened to algae and bio-fuels?", *Bio-fuels Digest,* 23 April.

Lane, J 2013, "Blue Sun Energy and ARA partner for isoconversion demonstration facility", *Bio-fuels Digest*, 21 January.

Lane, J 2013, “Brazilian ethanol prices fall below value of sugar for first time in two years”, *Bio-fuels Digest,* 4 March.

Lane, J 2013, “Camelina on the move: Global Clean Energy Holdings acquires Sustainable Oils”, *Bio-fuels Digest,* 14 March.

Lane, J 2013, “Crazy 8s: Algae’s 8 crazy-fast cores of innovation”, *Bio-fuels Digest,* 6 May.

Lane, J 2013, “Gevo: Bio-fuels Digest’s 5-Minute Guide (Q1 2013 update)”, *Bio-fuels Digest,* 8 January.

Lane, J 2013, “Jatropha Loves to Fly and It Shows”, *Bio-fuels Digest,* 29 January.

Lane, J 2013, “KiOR now shipping world’s first cellulosic diesel from its first commercial plant”, *Bio-fuels Digest,* 20 March.

Lane, J 2013, “ZeaChem Begins Production of Cellulosic Chemicals and Ethanol, Advances Toward Commercialization”, *Bio-fuels Digest,* 12 March.

LanzaTech 2010, Lanzatech NZ, Auckland, viewed September 2012, <www.lanzatech.com>.

L.E.K Consulting 2011, Advanced Bio-fuels Study: Strategic Directions for Australia, Appendix, report to the Department of Resources, Energy and Tourism, Sydney.

Licella 2011, Licella, North Sydney, viewed September 2012, <http://www.licella.com.au>.

Lim, R 2013, “Nesté's bio-fuels back in black for Q1”, *Business Times,* Singapore, 27 April.

Maron, DF 2010, “The Race to Make Fuel Out of Algae Poses Risks as Well as Benefits”, *ClimateWire/NYT,* 22 July.

Matlack, C 2012, “Jatropha: A Green Fuel Awash in Red Ink”, *Bio-fuels Digest,* 15 March.

McCrone, A 2012, “Some aviation bio-fuels could be competitive by 2020”, *Bloomberg New Energy Finance*, 13 February.

McVay, KA & Lamb, PF 2008, “Camelina production in Montana”, *Field Crops Extension Report No. D-16.* Montana State University, Bozeman.

Melbourne Jet Fuel Demand Study Group 2011, *Melbourne Airport jet fuel demand study for the period to 2028*, Prepared for the Minister for Resources and Energy, Canberra.

Minister for Resources and Energy 2011, *Budget: Australian Bio-fuels Research Institute,* Australian Government, Canberra, viewed September 2012, <http://minister.ret.gov.au/mediacentre/mediareleases/pages/budgetaustralianbio-fuelsresearchinstitute.aspx>.

Monteiro, N, Altman, I, & Lahiri, S 2012, “The impact of ethanol production on food prices: The role of interplay between the US and Brazil”, *Energy Policy*, *41*, pp 193-199.

Morgan, P 2011, “An Overview of Sasol’s Jet Fuel Journey”, *Presentation at 20th World Petroleum Congress*, Doha, 4-8 December 2011.

Murphy, H et al 2012, “A common view of the opportunities, challenges, and research actions for Pongamia in Australia”, *BioEnergy Research, 5 (3)*, pp 778-800.

National Academy of Engineering and National Research Council (US) Committee on Alternatives and Strategies for Future Hydrogen Production and Use 2004, *The hydrogen economy: opportunities, costs, barriers, and R&D needs*, National Academies Press, Washington DC.

Northern Agricultural Research Station 2007, Montana State University, Montana, viewed September 2012, <http://ag.montana.edu/narc/>.

Norton, R, Burton, WW, & Salisbury, P 2005, “Agronomy for Canola quality *Brassica juncea* in modern cropping systems” in: Potter, T (ed), *Australian Research Assembly on Brassicas 14*, pp 111-115, South Australian Research and Development Institute (SARDI), Port Lincoln.

O’Brien, RD et al 2005, “Chapter 5: Cottonseed Oil” in Shahidi, F (ed), *Bailey’s Industrial Oil and Fat Products, Volume 2: Edible Oils and Fat Products: Edible Oils,* John Wiley & Sons, Hoboken.

O’Sullivan, M 2012, “Qantas Puts Carbon Tax in Frame for Fare Increases”*, Sydney Morning Herald,* Sydney, viewed February 2012, <http://www.smh.com.au/travel/travel-news/qantas-puts-carbon-taxes-in-frame-for-fare-increases-20120202-1qvo1.html>.

Potter, T (ed) 2005, “Australian Research Assembly on Brassicas”, 14, pp 111-115, proceedings of the South Australian Research and Development Institute (SARDI), Primary Industries and Resources, Port Lincoln.

Potter, T 2011, “Development of Brassica juncea as a bio-diesel feedstock in low rainfall areas of Australia”, *Proceedings of the 13th International Rapeseed Conference*, Prague, 5-9 June 2011.

Potter. TD, Ludwig, I & Kay, JR 1997, “Brassica crops for low rainfall environments in South Australia”, *Proceedings of the 11th Australian Research Assembly on Brassica’s,* Perth, 6-10 October.

PR Newswire 2012, “JOil says science can triple jatropha yields”*, Bio-fuels Digest,* Singapore, 18 January.

Przybyksji, T et al 2005, “Chapter 2: Canola Oil” in Shahidi, F (ed), *Bailey’s Industrial Oil and Fat Products, Volume 2: Edible Oils and Fat Products: Edible Oils,* John Wiley & Sons, Hoboken, viewed September 2012, <http://uqu.edu.sa/files2/tiny_mce/plugins/filemanager/files/4281709/84607_17.pdf>.

Reals, K 2011, “Tarom, Airbus partner for camelina aviation bio-fuels”, *Bio-fuels Digest,* 24 March.

Rye, L. Blakey, S. et al 2010, “Sustainability of supply or the planet: a review of potential drop-in alternative aviation fuels”, *Energy & Environmental Science*, 3, pp. 17-27.

Sapp, M 2012, “Nesté Oil to produce renewable jet fuel from Spanish camelina”, *Bio-fuels Digest,* December 24.

Sasol n.d., Sasol, Johannesburg, viewed September 2012, <http://www.sasol.com>.

Schuster, A & Friedt, W 1998, “Glucosinolate content and composition as parameters of quality of Camelinaseed”, *Industrial Crops and Products, 7(2)*, pp 297-302.

SkyNRG 2013, SkyNRG, Amsterdam, viewed September 2012, <http://skynrg.com/the-opportunity/SAF-fuel-supply/>.

Small, Top 100 Food Plants, 2009, National Research Council of Canada

Solena Fuels 2012, Solena Fuels Corporation, Washington DC, viewed September 2012, <http://www.solenafuels.com>.

Spolaore, P, Joannis-Cassan, C, Duran, E & Isambert, A 2006, “Commercial Applications of Microalgae”, *Journal of Bioscience & Bioengineering,* 101 (2), pp 87-96.

Spooncer, P, "Export Markets Vital to Australian Renderers", RENDER Magazine August 2012

Starck et. al. ‘New Route for Increasing the Aviation Alternative Fuels Production and Optimizing the Biomass Usage: Focus on HRJ’, IASH, 2011

United Airlines Press Release, “United Airlines and AltAir Fuels to Bring Commercial-Scale, Cost-Competitive Biofuels to Aviation Industry”, June 4, 2013.

US Energy Information Administration 2010, “The Ethanol Blend Wall”, *This Week in Petroleum,* 8 July, viewed September 2012, <http://www.eia.gov/oog/info/twip/twiparch/100708/twipprint.html>.

Virent 2013, Virent, Madison, viewed September 2012, <http://www.virent.com>.

Wahl, N et al 2013, *Insights into Jatropha Projects Worldwide – Key Facts & Figures from a Global Survey*, Centre for Sustainability Management, University of Lüneburg, Lüneburg.

Weeds Australia Database 2012, *Noxious weeds,* Australian Weeds Committee, Melbourne, viewed September 2012, <http://www.weeds.org.au/noxious.htm>.

Whitty, J 2013, “Inside the Military’s Clean Energy Revolution”, *Atlantic Monthly*, 27 February.

Williams, J 2012, “Who’s in the lead? Algae around the world”, *Bio-fuels Digest,* New Mexico, 12 January.

ZeaChem 2011, ZeaChem Inc., Lakewood, viewed September 2012, <http://www.zeachem.com>.

Zubr, J 2003, “Qualitative variation of *Camelina sativa* seed from different locations”, *Industrial Crops and Products,* 17 (3), pp 161-169.

List of abbreviations

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
AISAF	Australian Initiative for Sustainable Aviation Fuels
bbl	Barrel
Bio-SPK	Bio-Synthetic Paraffinic Kerosene
EIA	Energy Information Agency (operating under the US Department of Energy)
EPP	Export price parity
E10	A blend of 90% unleaded petrol and 10% fuel ethanol
FOB	Free-on-board
FT	Fischer Tropsch
HEFA	Hydroprocessed Esters and Fatty Acids
HMU	Hydrogen (H_2) Manufacturing Unit
HRJ	Hydrotreated Renewable Jet
IPP	Import price parity
L	Litres
LC	Lignocellulosic
LNG	Liquefied natural gas
LRMC	Long-run marginal cost
kT	Kilo tonnes
NPV	Net present value
ppm	Parts per million
PV	Present value
SAF	Sustainable Aviation Fuel
SEA	South East Asia
SPK	Synthetic Paraffinic Kerosene
UCO	Used cooking oil
ULS	Ultra low sulphur
WTI	West Texas Intermediate

Glossary of terms

Aggregation	Provides the receipt and storage of various feedstock types
Anthropogenic	Human impact on the biophysical environment, biodiversity and other resources
ASTM D7566	ASTM standard specification for Aviation Turbine Fuels Containing Synthesised Hydrocarbons. This certification permits the use of sustainable aviation fuels in commercial flights. The specification limits the fraction of SAF to 50 per cent (by volume)
Autotrophic algae	Refer to algae that absorb (fix) carbon from the atmosphere via photosynthesis. Autotrophic algae can either be “microalgae” or “cyanobacteria”, or “blue-green algae”
Bio-diesel	Alternative diesel fuel produced through the transesterficiation of natural bio-oils or animal fats. Bio-diesel is not a hydrocarbon
Bio-fuel	A fuel derived from biomass
Brown grease	Waste fats, oils, and greases collected from grease traps and gravity interceptors in wastewater treatment equipment
Camelina	An annual oilseed crop *Camelina sativa* believed to be native to the temperate regions of Northern and Eastern Europe and South-Western Asia, especially in areas along the Mediterranean Sea
Canola	An annual oilseed crop primarily grown for cooking oil and animal feed protein meal and is an edible cultivar of rapeseed (*Brassica napus L.)*
Canola (crude)	Crude Canola oil is produced after Canola seed is crushed at a facility which extracts the oil by slightly heating and then crushing the seed. Approximately 43% of a seed is oil
Canola (finished)	Canola oil that has been “finished” by further refining using water precipitation and organic acid, "bleaching" with clay, and deodorizing using steam distillation
Canola (meal)	By-product from crushing Canola seed and is used as animal feed
Catalysis	Material used to increase the rate of a chemical reaction
Cleaner Fuels Grant cSheme	A grant programme designed to encourage the manufacture or importation of fuels that have a lower impact on the environment. The scheme functions by paying a grant equal to the fuel excise
Cottonseed oil	A premium edible oil produced as a co-product of cotton fibre production. Primary species are *Gossypium hirsutum* and *Gosssipium herbaceum*
EURO5	The European emission standards that define the acceptable limits for exhaust emissions of new vehicles sold in EU member states. The EURO5 diesel standard has been adopted in Australia. The standard limits sulphur in diesel fuel to 10ppm
Finished feedstock	Natural oils and fats that have been part processed or “finished” to remove some contaminants (e.g., phosphorus)
Fischer Tropsch	A manufacturing process the converts synthesis gas (carbon monoxide and hydrogen) into liquid hydrocarbons; usually waxes
Hydrocracking	Describes a hydroprocess used to breakdown carbon chain lengths, thereby producing lighter, more valuable molecules. Specific to bio-oil hydroprocessing,

	hydrocracking is used to convert diesel range molecules into SAF
Hydroprocessing	Generic term used to describe a range of refinery processes that use hydrogen, along with an appropriate catalyst, to remove undesired components from refinery streams. The technology is core to a modern petrochemical refinery
Hydrotreatment	Process used to removal undesirable materials, including nitrogen, sulphur and residual metals from refinery streams
Isomerisation	Process that reshapes the structure of simple molecules. The process is required when hydroprocessing natural oil to improve the cold weather performance of intermediate product
Jatropha	*Jatropha curcas*, a perennial tree that produces inedible oil-bearing seeds and is capable of growing on marginal land
Lignocellulosic biomass	A biomass feedstock that can be derived from plant matter such as grasses, shrubs and trees (e.g., coppice eucalyptus), crop stubble, sugar cane bagasse offcuts and forest residues
Mustard	*Brassica juncea* is a small scale crop producing mustard seed. Primary use is as a spice and condiment crop
Naphtha	Blend component used to manufacture high octane gasoline
Pongamia	*Pongamia pinnata* is a leguminous, inedible oilseed-producing tree that is capable of giving naturally high oil yields in marginal conditions
Pre-treatment	A process used to remove material (e.g., metals, free fatty acids, water, insolubles etc) for bio-feedstock before upgrade in a bio-refinery
Sustainable aviation fuel	Fuel blend component recognised as having the potential to make a significant contribution to mitigating aviation carbon emissions. The SAF component is limited to 50% (by volume), with the balance made up from conventional jet fuel
Synthetic Paraffinic Kerosene	Synthesised blending component that is comprised of essentially kerosene molecules. Once certified per ASTM D7566, SPK sourced for sustainable feedstock is referred to in this report as SAF.
Tallow	Rendered fat from the meat and livestock processing industry
Used cooking oil	Used cooking oil (or waste vegetable oil), is the spent vegetable oil from a deep-fryer that is recovered and stored for removal

Appendix A. Emerging certification pathways

A.1 Alcohol-to-Jet

A.1.1 Current state and key issues

An emerging pathway of genuine interest for SAF production is the alcohol-to-jet pathway or ATJ. As the name implies, this pathway utilises a variety of feedstock (e.g., LC, sugars, industrial waste gases) to make alcohol (i.e. ethanol, butanol or isobutanol) that can then be upgraded into a variety of bio-products including SAF. In general, the conversion from alcohol to jet fuel involves catalytic dehydration, oligimerisation and hydrogenation steps.

ATJ processes are not currently certified under the ASTM process for use in jet engines. However, there are two sub-pathways currently well advanced in the ASTM process. The first is known as the Bio Synthetic Paraffinic Kerosene (Bio-SPK) pathway pursued by companies such as LanzaTech, ZeaChem, GEVO, Cobalt and their partners. This pathway focuses on converting alcohols to SAF but without aromatics. The other pathway currently in the ASTM process is the Bio Synthetic Kerosene containing Aromatics (Bio-SKA) which, as the name implies, produces SAF with high levels of aromatics. Examples of firms pursuing this route include the consortium of LanzaTech and Swedish Bio-fuels. A variety of interviews with key industry players suggest that at least one of the ATJ pathways could be certified by mid to end 2014.

There are several advantages of the ATJ pathway. First, the feedstock is generally plentiful and cheap since it is LC biomass, and is especially convenient in the Australian context if the product is a by-product from a more sophisticated commercial agricultural process (e.g., wheat straw or sugar bagasse). Some pathways also use low cost and plentiful waste gases from existing industrial processes.

Second, Australia has significant history and experience in the commercial production, blending and distribution of ethanol, primarily due to blend mandates with petrol. The largest volume of ethanol blended petrol is sold in NSW due to the NSW ethanol mandate introduced in October 2011. This mandate requires that 6% of the total volume of petrol sold in NSW should be ethanol. This has resulted in the product E10 which is a maximum of 10% ethanol blended with petrol. Similar regulations around E10 product exist in the United States.[136] NSW accounts for over 80 per cent of the Australian ethanol market. The NSW Independent Pricing and Regulatory Tribunal assessed current and projected levels of ethanol supply and demand and concluded in March 2012 that there would not be enough demand for ethanol to meet the 6% mandate. In January 2012, the New South Wales Government amended its ethanol mandate by removing the requirement for E10 to fully replace regular ULP from July 2012 in recognition of the limited demand for ethanol.[137]

While the conversion technology may be different for ATJ and the Australian ethanol market has had its ups and downs, the Australian market is familiar with how to price, blend, store and transport alcohol-based fuels.

However, there are several key disadvantages of ATJ. First, the ethanol blend mandates for petrol (e.g., in NSW) mean that there is a policy driver to produce ethanol for road transport as opposed to jet fuel. In addition to these mandates, the production grant of 38 cents per litre, equivalent to the level of excise, is available for producers of ethanol. In the absence of similar fiscal relief for SAF, the mandated demand and producer grant provide an incentive to produce ethanol over SAF.

Second, at a broader level, ATJ suffers from higher value alternative uses for the intermediate product of alcohol. This is also referred to as the “curse of the intermediate products”.[138] The general principle is that if the price of a product further down the value chain of a manufacturing process (in this case SAF) is *lower* than the price of an alternative intermediate product that requires less manufacturing processes and therefore less cost to produce (in this case ethanol for motor vehicles[139] or high value alcohol-based consumer products), the rational firm will always choose to produce that intermediate product.

[136] US Energy Information Administration, 8th July 2010, http://www.eia.gov/oog/info/twip/twiparch/100708/twipprint.html

[137] Monitoring of the Australian petroleum industry—Report of the ACCC into the prices, costs and profits of unleaded petrol in Australia, 2012, Chapter 5, http://transition.accc.gov.au/content/index.phtml/itemId/1092497

[138] “The Solyndra Effect, or why alcohol-to-jet fuel is a tough sell”, Bio-fuels Digest, 16th Nov 2012

[139] Australian ethanol producers receive a 38 cent per litre production grant

Third, while often cheap and plentiful, ATJ base feedstock are not necessarily sophisticated; this drives up aggregation and supply prices. As discussed elsewhere in this section, LC biomass can be difficult to aggregate at volume, and modern agricultural techniques are not necessarily applied to these feedstock. Raw sugar as a commodity tends to be somewhat volatile and price levels are impacted by the food market and the demand for ethanol blends in petrol. It is likely that waste products from existing commercial agricultural or industrial processes would be the best LC feedstock for ATJ.

Suppliers of ATJ respond to these challenges in three ways. Firstly, they contend that the combination of cheap and plentiful feedstock, combined with advanced conversion technologies, can bring down significantly the cost of production of the alcohol product. If the cost of production for the alcohol is low enough based on waste feedstock, then the cost of the upgraded SAF product could be competitive with conventional jet.

Secondly, ATJ suppliers argue that the size of volume demand for SAF from a large aviation customer is attractive when compared with ethanol blended petrol or consumer products customers. A large customer with security of demand diversifies risk across customer and product bases. Locking in large and long-term volume provides certainty of revenues and more confidence to financiers.

Thirdly, the mandate for ethanol in petrol can only go so far. The NSW mandate for ethanol at 6% is equivalent to approximately 300 mega litres of demand per annum. However, as described, there is generally not enough demand for E10 product to reach this mandate – in 2011/12 only around 3.6% of the volume of petrol sold in NSW was ethanol.[140] In addition, the maximum ethanol blend with petrol before engine modification is required is currently set at 10%. This is often called the “blend wall” as production cannot generally move past the limit of 10% of the total market, thereby creating a barrier to accommodating additional ethanol supply. Thus the combination of lack of demand and a limit on supply makes the production of ethanol somewhat tricky in the Australian context.

ATJ advocates argue that as supply increases up to the blend wall, production of ATJ is likely to come on line as an additional revenue stream. This scenario may be true in the United States where production of ethanol is getting close to the blend wall at approximately 9% of production.[141] However, in the largest Australian ethanol market of NSW, 2011/12 production was only 3.6%, with the blend wall a long way off. The counter-argument is that there is still a long way to go to the blend wall in the Australian market. In addition, firms may not risk installing additional capacity without clear alternative and secure demand for alcohol-based products. Given that ATJ is not yet approved through the ASTM process, firms are unlikely to be able to rely on SAF demand in the short term.

A.1.2 Suppliers of interest

The suppliers listed are primarily US-based, but with some projects and links to Australia and New Zealand.

LanzaTech is a leader in the ATJ space with gas-to-liquid technology that utilises waste gases as feedstock.[142] In this process biological microbes are used to convert industrial waste gases into alcohol. LanzaTech can engineer its microbes to produce either alcohols or chemicals, utilising both fermentation and separation processes. The base alcohol product of ethanol can then be upgraded to bio-products such as diesel, gasoline and aviation fuels using catalytic conversion. The process can also use syngas produced from biomass to create alcohols or chemicals. LanzaTech was originally started in New Zealand and now partners with Swedish Bio-fuels to upgrade their alcohol to SAF.[143] As Figure 47 shows, the base products from the process are alcohol products.

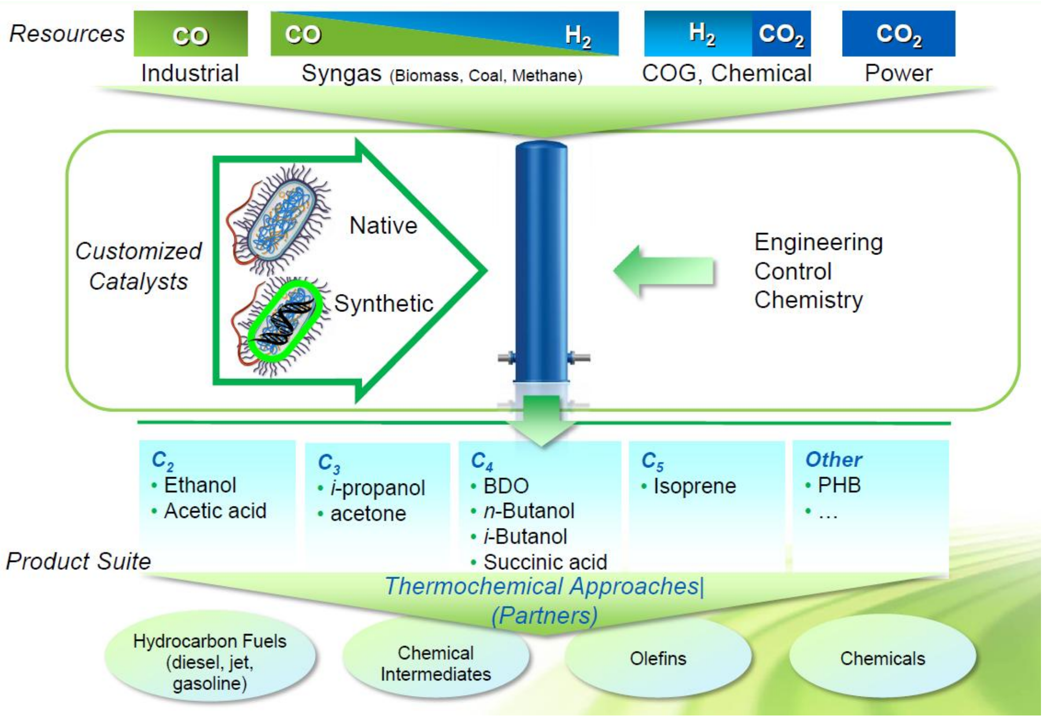
[140] Monitoring of the Australian petroleum industry—Report of the ACCC into the prices, costs and profits of unleaded petrol in Australia, 2012, Chapter 5, http://transition.accc.gov.au/content/index.phtml/itemId/1092497

[141] US Energy Information Administration, 8th July 2010, http://www.eia.gov/oog/info/twip/twiparch/100708/twipprint.html

[142] www.lanzatech.com

[143] “LanzaTech: Bio-fuels Digest’s 5-Minute Guide (Q1 2013 update)”, Bio-fuels Digest, 8th Jan 2013

Figure 47: LanzaTech gas-to-liquid platform



Source: LanzaTech (2012)

The advantage of the LanzaTech process is that it utilises abundant and cheap (waste) feedstock. Sources of feedstock include waste industrial flue gases from steel mills, processing plants and refineries; syngas generated from any biomass resource (such as municipal bio-waste, organic industrial waste, and agricultural waste); coal-derived syngas; and reformed natural gas.

LanzaTech is one of the most advanced bio-fuel companies in commercialisation. In 2008 LanzaTech established a pilot plant utilising waste gases from the BlueScope Steel plant in Wollongong, Australia. Following the successful pilot demonstration, LanzaTech established a commercial demonstration plant with Bao Steel in Shanghai, China in 2011. This plant has been operational since 2012 and is currently producing 30 million gallons (110 million litres) of ethanol per annum. Several other LanzaTech commercial demonstration plants are currently in the design phase including Freedom Pines Biorefinery in the US, Concord Enviro Biorefinery in India and a further plant in China with Shougang Group.

ZeaChem is another potential ATJ producer that utilises LC biomass to produce advanced bio-fuels and specialty chemicals. Like LanzaTech, ZeaChem uses both biochemical (fermentation) and thermochemical (gasification) processes. The feedstock used is plentiful and cheap LC biomass such as wood, grasses and agricultural residues. The process generally produces ethanol and has a high yield relative to other bio-refineries.[144]

ZeaChem has taken an integrated approach to the bio-refinery value chain. A demonstration facility in Boardman, Oregon of 250,000 gallons per annum (~1 million litres per annum) was completed in 2010 and has recently produced cellulosic ethanol from the facility.[145] The primary feedstock at present is woody biomass and agricultural residues from Oregon. ZeaChem has signalled its intention to further expand the Oregon plant to convert cellulosic ethanol into SAF and bio-diesel fuels. In addition, ZeaChem is developing its first commercial bio-refinery to be located adjacent to the demonstration plant with capacity of 25 million gallons per annum (~100 million litres per annum). The US Department of Agriculture (USDA) has provided a conditional loan guarantee scheduled to begin 2013.[146]

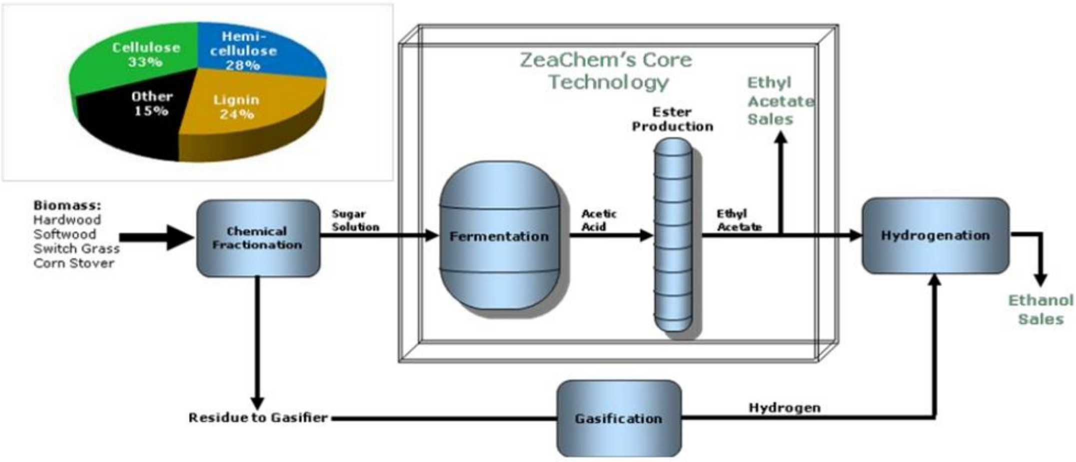
---

144 www.zeachem.com

145 "ZeaChem Begins Production of Cellulosic Chemicals and Ethanol, Advances Toward Commercialization", Bio-fuels Digest, 12th March 2013

146 "ZeaChem: Bio-fuels Digest's 5-Minute Guide (Q1 2013 update)", Bio-fuels Digest, 8th Jan 2013

Figure 48: ZeaChem technology overview

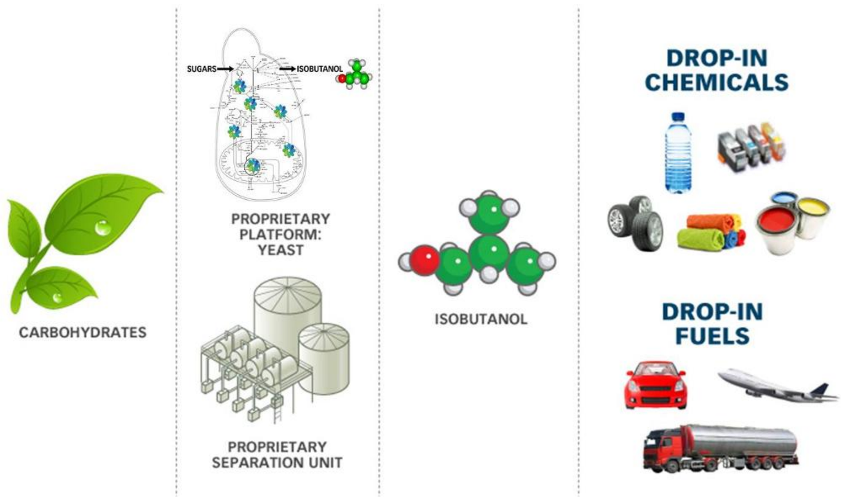


Source: ZeaChem.com (2013)

Gevo is another ATJ company that has the potential to utilise LC biomass, but with a focus on producing isobutanol. The current process uses simple sugars in preference to LC biomass and is based on a proprietary fermentation method using a biocatalyst and separation of isobutanol. These two processes are used in combination to enable retrofit of existing ethanol plants for isobutanol production. The advantage of isobutanol over ethanol is that it has the potential to be used in existing infrastructure, i.e., transported in pipelines and dispensed in existing retail pumps. Isobutanol also has 30% more energy content than ethanol and can be blended into gasoline without modifying automobile engines.[147] However, the cost of production for isobutanol can be higher than for ethanol and therefore alternative intermediate products for isobutanol can be especially attractive compared to SAF.[148]

In September 2010 Gevo acquired a 22 million gallons per annum (83 million litres) ethanol plant owned by Agri Energy in Luverne, Minnesota for retrofitting. Gevo started commercial production in mid-2012 in Minnesota and plans to increase capacity by 100-200% in the short-to-medium term, including plans for retrofitting of the Redfield Ethanol Plant, South Dakota.[149] Given existing ethanol plants in Australia, the ability to retrofit ethanol plants could be a significant advantage in the Australian context, however, the higher cost of production of isobutanol could make production of SAF difficult.

Figure 49: GEVO process



Source: www.gevo.com (2013)

147 www.gevo.com

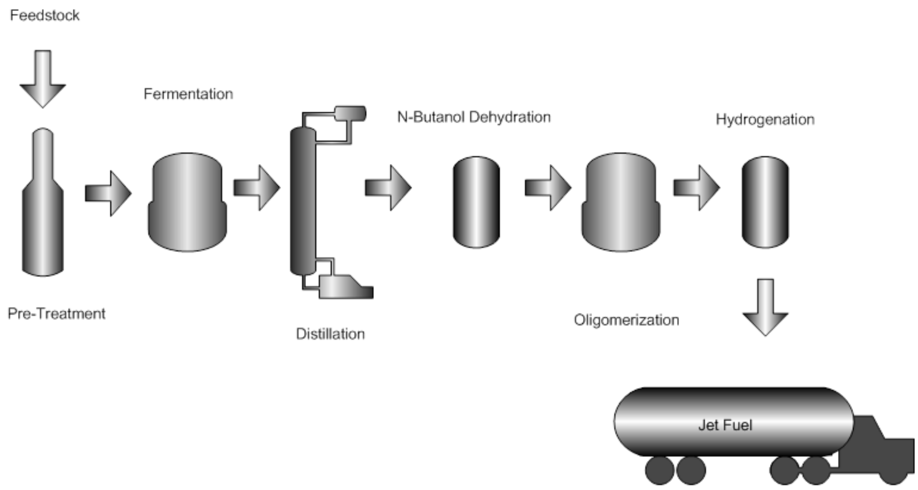
148 "The Solyndra Effect, or why alcohol-to-jet fuel is a tough sell", Bio-fuels Digest, 16th Nov 2012

149 "Gevo: Bio-fuels Digest's 5-Minute Guide (Q1 2013 update)", Bio-fuels Digest, 8th Jan 2013

Cobalt is a US-based, bio-fuels company that uses LC biomass to focus on production of butanol as the base product for fuel and chemical production.[150] Cobalt's process uses low cost LC biomass feedstock such as woody biomass, pulp & paper and sugar bagasse, and combines them with advanced biocatalyst organisms. It then puts the material through a biomass pre-treatment process, an accelerated fermentation system in a proprietary bio-reactor and a distillation process. Cobalt's butanol production costs are claimed to be 30%-60% less than the cost of petroleum-based butanol.

Cobalt is active in the ATJ space where it is collaborating with a division of the US Navy to produce SAF from butanol. Sample SAF produced from the Cobalt-Navy process has passed early stage Navy fuel certification.[151] Cobalt also has plans to build a commercial scale bio-butanol refinery in Michigan with American Process, and has a strategic partnership with chemicals company Rhodia to develop bio-butanol refineries in Latin America.[152]

Figure 50: Cobalt technology



Source: Cobalt (2013)

A.2 Catalytic cracking

The catalytic cracking pathway is also known as Hydroprocessed Depolymerised Cellulose Jet (HDCJ) fuel derived for synthetic kerosene with aromatics (SKA) or the HDCJ-SKA pathway. This pathway converts LC biomass utilising a proprietary refining platform and standard refining equipment to produce renewable crude. The key advocate of this pathway in the ASTM process is Nasdaq listed company **KiOR**.

KiOR converts cellulosic biomass through a one-step catalytic process called Biomass Fluid Catalytic Cracking (BFCC).The technology platform combines a proprietary catalyst system with a process based on existing Fluid Catalytic Cracking (FCC) technology, a standard process used in oil refining. The renewable crude is refined and upgraded into gasoline and diesel blend stocks that are "drop-in" i.e., utilise existing transportation fuel infrastructure. The process is similar to pyrolysis but results in a low oxygen bio-crude (compared to pyrolysis which is high in oxygen).

KiOR processes its renewable crude oil in a conventional hydrotreater, which is also a standard process unit used in oil refineries. The utilisiation of current refining technology lowers the novelty and capital cost of this system. [153] KiOR is therefore in a good position as an alternative candidate to ATJ for SAF.

The major advantage of KiOR's technology is that it produces "drop in" cellulosic hydrocarbon gasoline and diesel (as opposed to ethanol or bio-diesel) at commercial scale. It has 80% lower greenhouse gas emissions than conventional fuel, feedstock flexibility with all types of sustainable, non-food biomass and has experience in the development, construction, commissioning and operation of the Columbus, Mississippi facility, KiOR's first commercial scale cellulosic fuel production facility. Feedstock for this plant is pine wood chips previously

[150] www.cobalttech.com

[151] www.cobalttech.com/press-releases

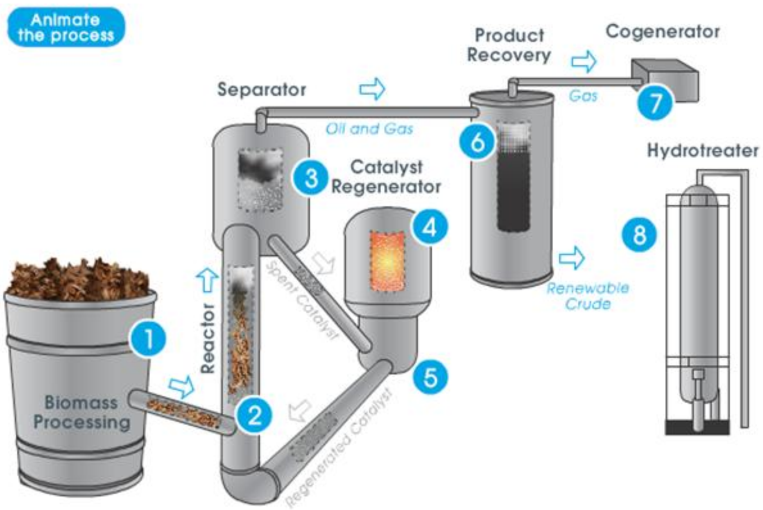
[152] "Cobalt: Bio-fuels Digest's 5-Minute Guide", Bio-fuels Digest, 25th Oct 2012

[153] www.kior.com

feeding a shutdown paper mill in Ohio. The facility produces renewable gasoline and diesel. In March 2013 KiOR announced the first shipments of cellulosic diesel from the commercial scale facility.[154]

In theory, KiOR could form a pathway for general catalytic cracking certification in the ASTM process in a similar manner to the broad categories of HEFA and FT. However, recent interviews conducted by the study suggest that certification for the KiOR process will likely have very limited application to other company processes. For example, KiOR incorporate an in situ catalytic process which upgrades the crude coming out of their process. This makes their product different chemically to other fast pyrolysis processes and different again to, for example, Licella's products. In other words, it is likely the KiOR ASTM certification would be applicable to the KiOR proprietary process only.

Figure 51: KiOR technology process



Source: www.kior.com (2013)

A.3 Thermochemical – super critical water

One area of interest that does not fit neatly into the leading ASTM pathways is the technology from Australian company **Licella**. The company uses proprietary supercritical water technology. Under elevated heat and pressure, water approaches a fourth state of matter called the 'supercritical state'. Licella's process centres on using supercritical water technology to break down pulverised biomass.[155]

Licella currently has a demonstration plant in Somersby, NSW where Radiata Pine sawdust (a saw mill by-product), and other LC biomass energy crops, have been processed.[156] In March 2013 Licella received a grant of $5.5 million to assess the feasibility of constructing its first pre-commercial bio-fuel plant with expected completion by end 2014. Such a plant is estimated to produce 20 million litres of bio-crude per annum, which could be used as a drop in fuel for the aviation industry. The advantage of the Licella process is that it utilises feedstock that fit well with what is known about potential current and future stocks in Australia.[157]

The closest pathway to the Licella process is the KiOR sponsored pathway which is well advanced in ASTM, and indeed Licella is on the working party for this pathway in ASTM. However, through private interviews conducted by this study, the Licella process does not fit neatly into this pathway for the purposes of certification. Due to the unique nature of the Licella thermochemical pathway and the pre-commercial stage of the company, as well as the incentives for bio-diesel production in Australia, it is difficult to see how the Licella process could be certified for use in jet engines via the ASTM process in the short-to-medium term.

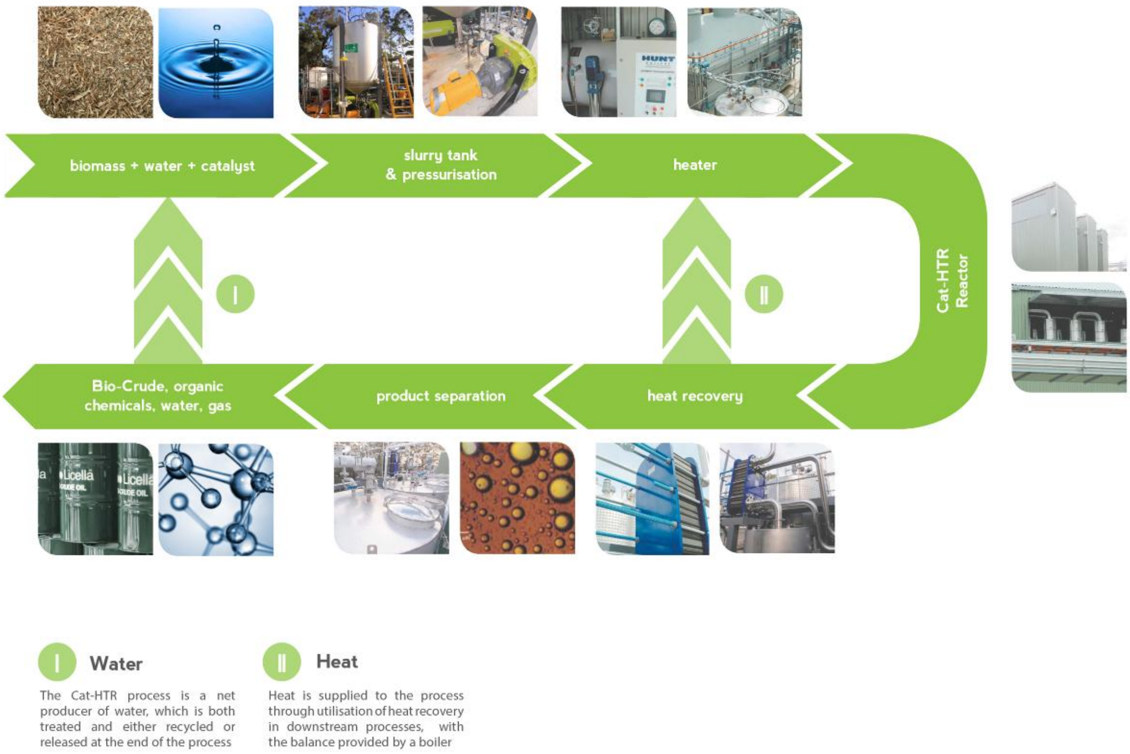
[154] "KiOR now shipping world's first cellulosic diesel from its first commercial plant", Bio-fuels Digest, 20th Mar 2013

[155] www.licella.com.au

[156] www.licella.com.au

[157] Haritos, V & Warden, A 2008, Future Bio-fuels for Australia – Issues and Opportunities for Conversion of Second Generation Lignocellulosics, Rural Industries Research and Development Corporation, Canberra.

Figure 52: Licella process flow



Source: Licella (2013)

A.4 Catalytic conversion using hydrothermolisis

Applied Research Associates (ARA) has developed renewable and aromatic "drop-in" jet and diesel fuels using a patented technology called Catalytic Hydrothermolysis (CH). ARA uses an isconversion process to convert triglyceride oils (i.e., natural oils as in the HEFA pathway) into a bio-crude. It then utilises a partnership with Chevron Lummus Global (CLG) for hydroprocessing technology to refine into diesel, jet or other products.[158] CLG is a joint venture between Chevron and Lummus Engineering which provides an integrated source for hydroprocessing technologies and services.

The process uses water to reduce hydrogen consumption compared to HEFA and FT fuels, while also reducing catalyst consumption, and carbon footprint relative to alternative fuel conversion processes. The feedstock used is any non-edible oil (lipid/triglyceride) with conversion directly into high-density aromatic, cycloparaffin, and isoparaffin hydrocarbons that are ideal for drop-in jet (JP-5, JP-8 and Jet A) and diesel (ASTM D 975 and F-76 Naval Distillate) fuels.[159]

ARA has demonstrated their process at lab-scale and small pilot scale (100 gallons per day). ARA also teamed up with Blue Sun Energy in January 2013 to develop and market the products. Blue Sun is building a commercial scale pilot plant that will produce 100 barrels a day (4,200 gallons per day or 5 million litres per annum) adjacent to its Missouri bio-diesel plant to further prove the ARA process.[160] To date ARA has produced fuel for a number of companies and organisations for testing to qualify and certify as a drop-in jet fuel in the ASTM process.

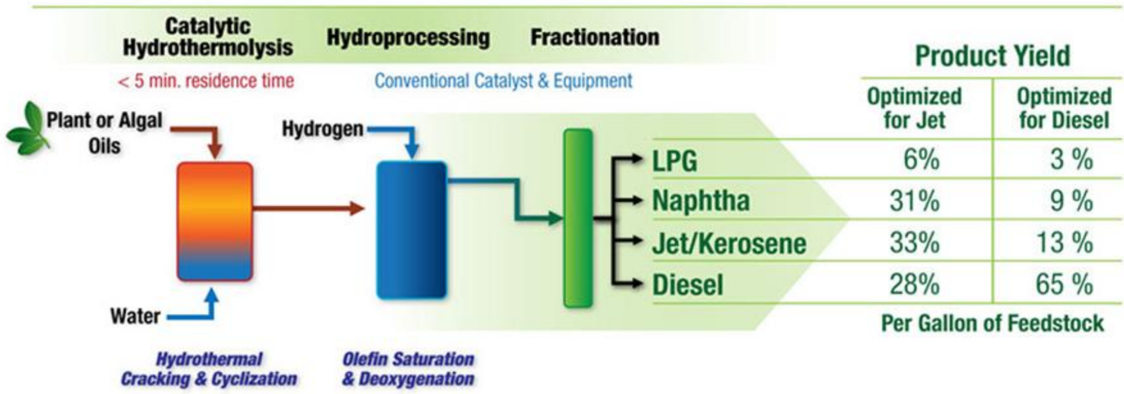
---

[158] www.ara.com

[159] www.ara.com

[160] "Blue Sun Energy and ARA partner for isoconversion demonstration facility", Bio-fuels Digest, 21st Jan 2013

Figure 53: ARA technology process



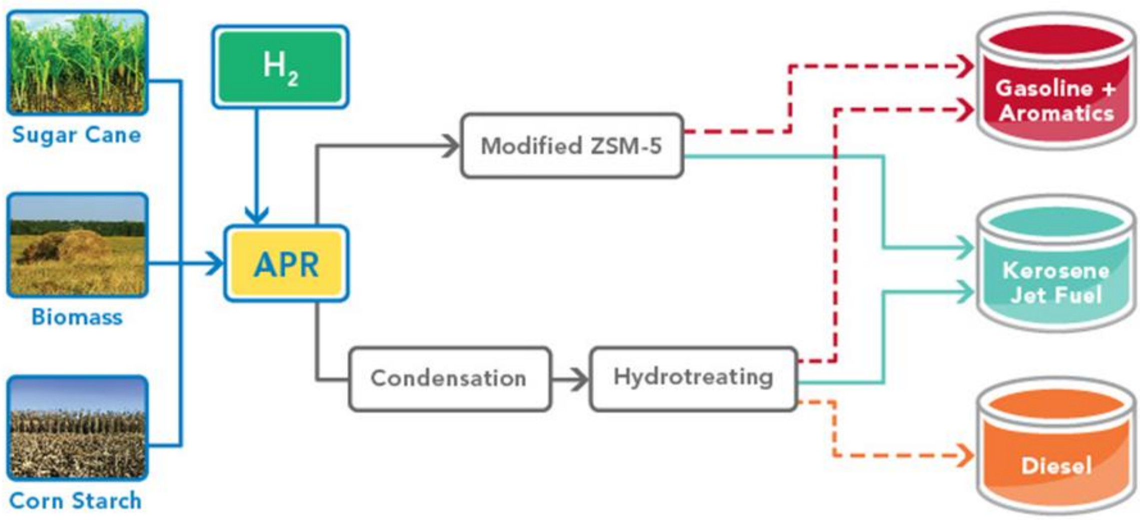
Source: www.ara.com (2013)

A.5 Catalytic conversion using aqueous phase reforming

Virent's patented technology uses catalytic chemistry to convert plant-based sugars into products such as gasoline, diesel, jet fuel and chemicals.[161] The patented technology is aqueous phase reforming combined with catalytic processing which uses carbohydrate feedstock and removes oxygen to form hydrocarbons and aromatic compounds for production of aviation fuel. which is a form of hydro de-oxygenation. Virent operates a demonstration plant in Madison, Wisconsin under a $1.5 million award received in 2011 from the Federal Aviation Administration and U.S. Department of Transportation. It has capacity to produce up to 5,000 gallons (20,000 litres) of fuel per annum. Design, engineering and construction were performed in-house by Virent employees. This is the second operating demonstration plant built by Virent with the Madison facility also housing a 10,000 gallon (40,000 litres) per annum system that is optimised to produce gasoline and aromatic chemicals. Strategic partners and investors include Royal Dutch Shell, Coca-Cola, Cargill and Honda.

In May 2013 Virent announced the delivery of 100 gallons of its bio-based jet fuel to the U.S. Air Force Research Laboratory (AFRL) for testing purposes. The testing is to validate Virent's SAF against ASTM certification standards. This testing is in the very early stages, however, with significant investors such as Shell and Honda, there is potential for this novel conversion technology to be utilised for SAF in the medium term.

Figure 54: Virent technology process



Source: www.virent.com (2013)

[161] www.virent.com

Appendix B. Marginal land identification methodology

To identify potential marginal land for crop utilisation, a six-step process was followed:

Step 1: Define marginal lands

a. Bare and herbaceous areas

b. Lands with moderate and steep slopes (8-30%)

c. Lands with soil problems: shallow soils; poorly drained soils; soils with low to moderate natural rainfall; coarse textured or sandy soils; soils with a gypsic horizon; acid soils (pH<5,5); soils with high calcium levels (calcisols); and peat soils

Step 2: Exclude unusable lands

a. Deserts, cold regions and ice or glacier areas

b. Protected areas

c. Water features as lakes, wetlands and swamps.

d. Forests, agricultural areas, urban areas and herbaceous lands under intensive pastoralism

Step 3: Define boundary and introduce correction

a. At least 0.5 millionhectares of marginal land available

b. Availability of the required maps

c. 25% safety net reduction on available lands

Step 4: Determine selection criteria

a. Ability to grow on marginal land and in the climate conditions present in the selected countries

b. Oil yield per hectare on arable land

c. Experience with crop production on a commercial scale (at least 5000 hectares for five years)

Step 5: Calculate inputs & yields

a. Intermediate inputs: using moderate fertilizer input, use of machines, but not a high tech operation

b. Rain fed scenario, so no irrigation

c. The type of marginal land will determine the potential yield. All yield scenarios come from the Food and Agricultural Organisation of the United Nations (FAO) databases

Step 6: Combine map data

a. Combined marginal land maps with oil crop yield maps

b. Calculation of the potential oil crop production on marginal land in selected countries and/or regions

Source: SkyNRG (2013)

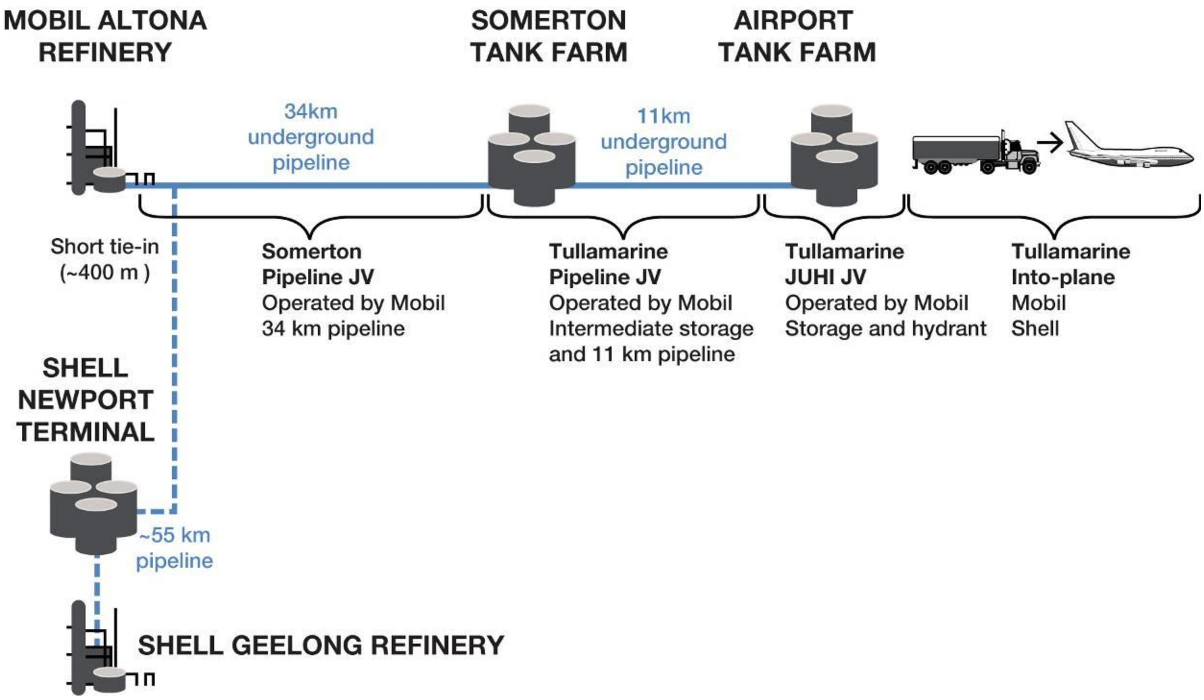
Appendix C. Supply case study

The following text has been adapted from the “Sydney Jet Fuel Infrastructure Working Group – Final Report” and the “Melbourne Jet Fuel Demand Study Group – Final Report”.

Melbourne Airport is 22 kilometres north-west of Melbourne and is owned and operated by Australia Pacific Airports Melbourne Pty Limited (APAM). The jet fuel supply infrastructure to Melbourne Airport is shown in Figure 55.

Mobil Oil Australia Pty Ltd (Mobil) operates the Somerton Pipeline Joint Venture which is a 34-kilometre underground pipeline from Mobil’s Altona refinery to Somerton. Mobil also operates the Tullamarine Pipeline Joint Venture which includes the Somerton tank farm and the 11-kilometre underground pipeline from Somerton to the Tullamarine JUHI. Pipeline supply is supplemented by product trucked to Melbourne Airport from three industry terminals in Melbourne’s inner-west. The Tullamarine JUHI is operated by ExxonMobil on behalf of the joint venture participants, consisting of Mobil, Shell, BP and Caltex. Fuel supply within the airport is dependent on hydrant infrastructure which the JUHI has stated has sufficient available capacity to accommodate demand growth.

Figure 55: Melbourne Jet Fuel Supply Chain



Source: Melbourne Jet Fuel Demand Study Group – Final Report (2011)

Appendix D. Regression analysis coefficients

A regression analysis of historical prices for each feedstock or refined product and Brent crude was carried out to determine the relationship of prices across these commodities. This enabled a forecast of the feedstock and refined product prices to be linked to a published forecast of the crude oil price. Results from the natural-crude oil regression analysis are shown in Table 8. The P50[162] estimate of the coefficient is adopted for the analysis, with the P90 and P10 used in the sensitivity analysis. Coefficients above one mean that as crude oil prices increase, the price of the natural oil feedstock increases by a greater amount. Conversely, if crude oil prices decrease, the price of the bio-feedstock decreases relatively more. Coefficients below one imply that a bio-feedstock price increases less (and decreases less) than an increase (decrease) in the crude oil price.

Table 15: Regression analysis results: natural oil feedstock

Feedstock	Goodness of fit (R^2 statistic)	Starting reference price $US	$US 2012 price	Coefficient (P10)	Coefficient (P50)	Coefficient (P90)
Tallow	0.79	891	829	0.69	0.81	0.93
Crude Canola	0.90	1,140	1,106	1.14	1.26	1.37
UCO	0.79	717	655	0.69	0.81	0.93
Palm	0.84	984	1,006	0.98	1.12	1.26

Source: SKM analysis (2013)

162 The coefficient is defined as a distribution of values between an upper and lower point. The 50th percentile, the point to which 50% of values are above and below, is used as the base coefficient in the analysis and is referred to as the P50.

Appendix E. Feedstock price build-up

The IPP and EPP prices require an estimate of both import and export prices for each product and feedstock. The import and export price is specific to the location that the commodity would be imported or exported from or to. Shell provided SKM with world-scale data as well as published data for insurance and wharfage costs to estimate the import cost of petroleum products. The cost calculation is summarised in Table 16.

Table 16: Petroleum product import cost

Import costs	A$/tonne
Shipping cost	$30/t
Insurance & loss	$4/t
Landed cost	$6/t
Total	$40/t

Source: The Shell Company of Australia, SKM analysis (2013)

The import cost of $40 per tonne is consistent with high-level estimates provided by AltAir. For domestic feedstock, the indicative export price provided by AltAir has been used in the regression analysis. The price for imported bio-feedstock has been provided by SkyNRG. A summary of each commodity and their respective assumed import or export country used for pricing is represented in Table 17.

Table 17: Commodity import and export price benchmarks

Commodity	Trade orientation	Source / Destination country	Import / Export cost
Jet fuel (conventional)	Import	Singapore	$40/t
Naphtha	Import	Singapore	$40/t
Diesel	Import	Singapore	$40/t
Tallow	Export	Singapore	$40/t
Export Canola	Export	Rotterdam	$100/t
Crushed Canola	Export	Rotterdam	$100/t
UCO	Export	Singapore	$40/t
Sustainable palm	Import	Malaysia	$40/t

Source: AltAir, SkyNRG, SKM analysis (2013)

Appendix F. Economic sensitivity analysis

No	Variable	Base scenario	Scenarios tested	Comments
1	Forecast price	Base	Base, high and low	Crude forecast and commodity coefficients with crude are adjusted for both feedstock and product pricing. The Base forecast is determined by the historical P50 value of the historical correlation between the crude oil price and the output or feedstock price. The low is based on the P10 value of the historical correlation coefficient. The P90 is 90th percentile value of the historical correlation coefficient of the relationship between crude oil price and related product or feedstock price.
2	Discount rate (Real)	15%	7%,11%, 20%	For scenarios where there is an operating loss, using a high discount rate will result in anomalous outcomes. Need to interpret the values appropriately. The discount rate is a proxy used in this analysis to determine economic viability.
3	Capital costs	Base	Base, +30%, -30%	A sensitivity to capital costs is tested
4	Forecast exchange rate	Base	Base, high and low	High and low are equal to the P10 and P90 of the historical values of the exchange rate. The base is the P50 value of the historical relationship.
5	% Cracking	Selective (base)	Nil, base and maximum	The cost and yield relationship with percent cracking has been provided by Shell
6	Carbon price	Base ($23/T, 550 ppm target)	High ($30/T, 450 ppm target), Low ($15/T with no increase)	Change in global carbon goals
7	Crude oil price	EIA forecast	EIA, $90/bbl., $100/bbl., $110/bbl., $120/bbl., $130/bbl.	A common measure of a project's feasibility. Crude price impacts both feedstock and product pricing
8	Manufacturing operating time	95%	95%, 90%	A low operating time case is tested
9	Exchange rate approach	Institutional forecast	Institutional forecast, linked to crude	Forecasting the exchange rate using an institutional forecast of the exchange rate or by linking to the crude oil price forecast using a derived historical relationship with crude (based on the notion that Australia's exchange rate is a commodity driven exchange rate and therefore the link to crude will ensure a consistent set of assumptions)