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Advanced Biofuels Study

Strategic Directions for Australia

Appendix

14 December 2011

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1. INTRODUCTION

The Advanced Biofuels Study was commissioned by the Department of Resources, Energy and Tourism, funded through the Australian Centre for Renewable Energy (ACRE), to inform the priorities of the Australian Biofuels Research Institute (ABRI). The Study will also inform the development of the Government's Alternative Transport Fuels Strategy.

This Appendix contains a summary of detailed research and analysis from the Advanced Biofuels Study, and covers advanced biofuel (ABF) technologies, feedstock options and economics.

This Appendix is intended to be read in conjunction with a Summary Report which summarises findings from the Advanced Biofuels Study, identifies priority pathways for the industry and recommends the role Government should undertake in order to facilitate the establishment of an ABF industry.

Chapter two of the Appendix describes the existing biofuels landscape in Australia, including the state of the current biofuels industry and government policies. International policies are also explored, as are Australia's comparative ABF advantages.

Chapter three identifies sectors in the Australian economy that have the greatest need and ability to switch to ABF, and provides information on the fuel types that will be required.

Chapter four identifies advanced biomass sources and assesses their potential as feedstock for an advanced biofuels industry of scale in Australia.

Chapter five describes the technologies for transforming biomass into a refined fuel, prioritising feedstock and technology combinations into a set of most attractive ABF pathways for Australia.

Chapter six presents the economics of these pathways in more detail, discussing potential cost competitiveness at commercial deployment and further in the future.

In this Study, advanced biofuels are defined as liquid fuels derived from sustainable sources of organic matter that do not typically compete with food production, such as wood residues, certain oilseeds, and algae.

2.	THE AUSTRALIAN BIOFUELS LANDSCAPE

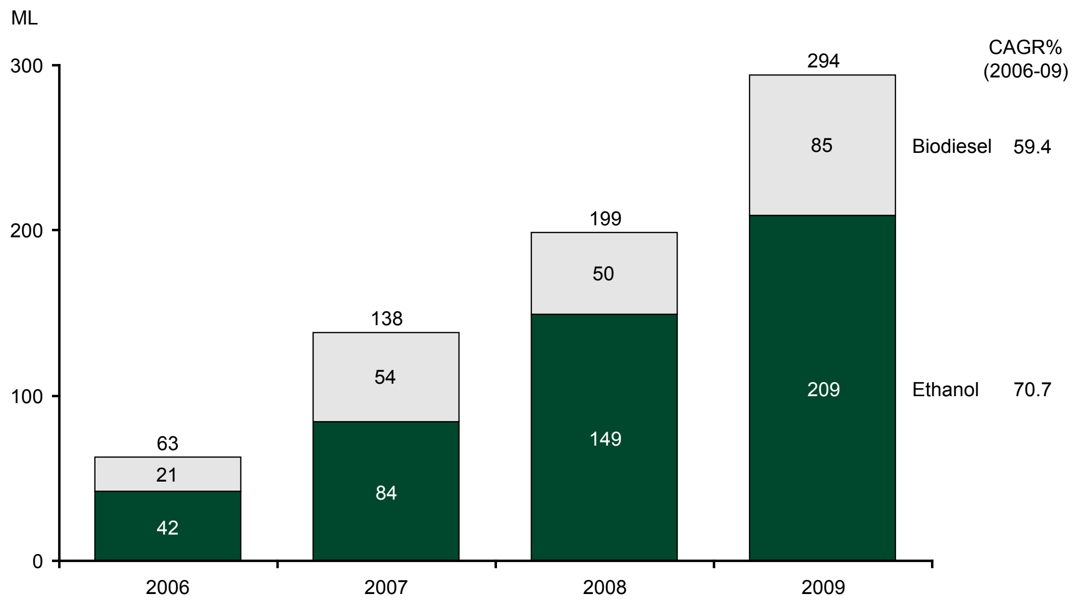
2.1. Introduction

The purpose of this section of the Appendix is to outline the key features of the existing biofuels landscape in Australia, briefly summarise international activity, and outline potential sources of Australian comparative advantage.

2.2. The current Australian biofuels industry

The current Australian biofuels industry produces small but material volumes, accounting for c.1% of fuel consumption. Ethanol and biodiesel are the major products (Figure 1) and are typically blended into gasoline and diesel respectively. Ethanol is most commonly blended with regular unleaded petrol to produce E10 while biodiesel is typically used in B5 and B20 blends.

Figure 1: Australian biofuel production (FY2006-09)



Source: ABARES

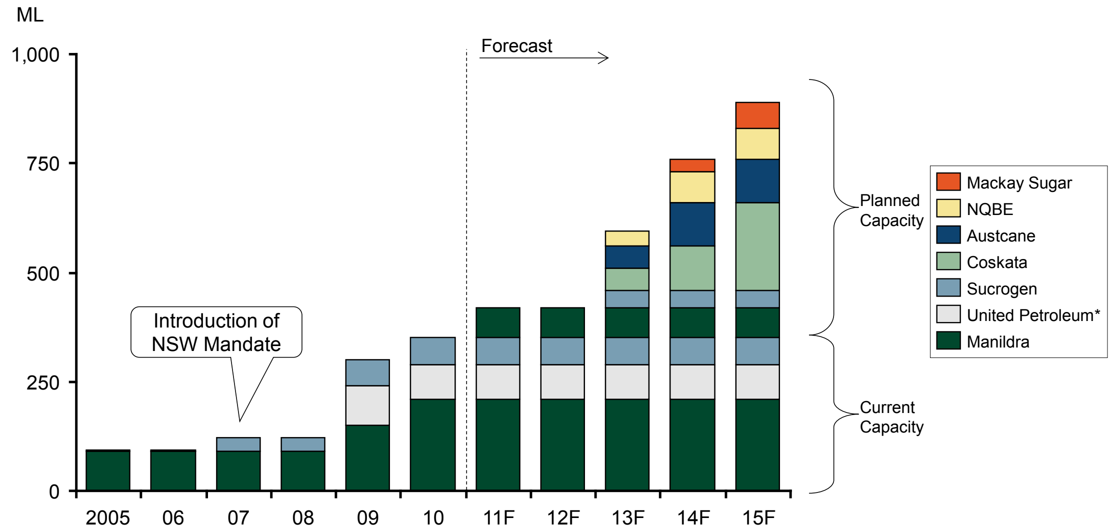
Recently, industry players have also exhibited interest in advanced biofuels (e.g. BP have produced renewable diesel and NQBE plan to construct a lignocellulosic ethanol plant).

2.2.1. The Australian ethanol industry

Australian ethanol production capacity is concentrated, with only three players currently in operation. Of the 350ML of production capacity available in 2010, the Manildra ethanol plant in NSW accounted for over two thirds (Figure 2). To date, ethanol production has predominately utilised waste wheat, molasses and sorghum feedstocks (Figure 3) with profitability very dependent on feedstock price.

The ability to divert residues and outputs to ethanol production provides grain and sugar producers with opportunities to maximise profit. ACCC reports an expected doubling in the number of ethanol players by 2015, with production capacity forecast to grow to 890 ML. This is consistent with ongoing potentially favourable production economics and expectations of growing future demand.

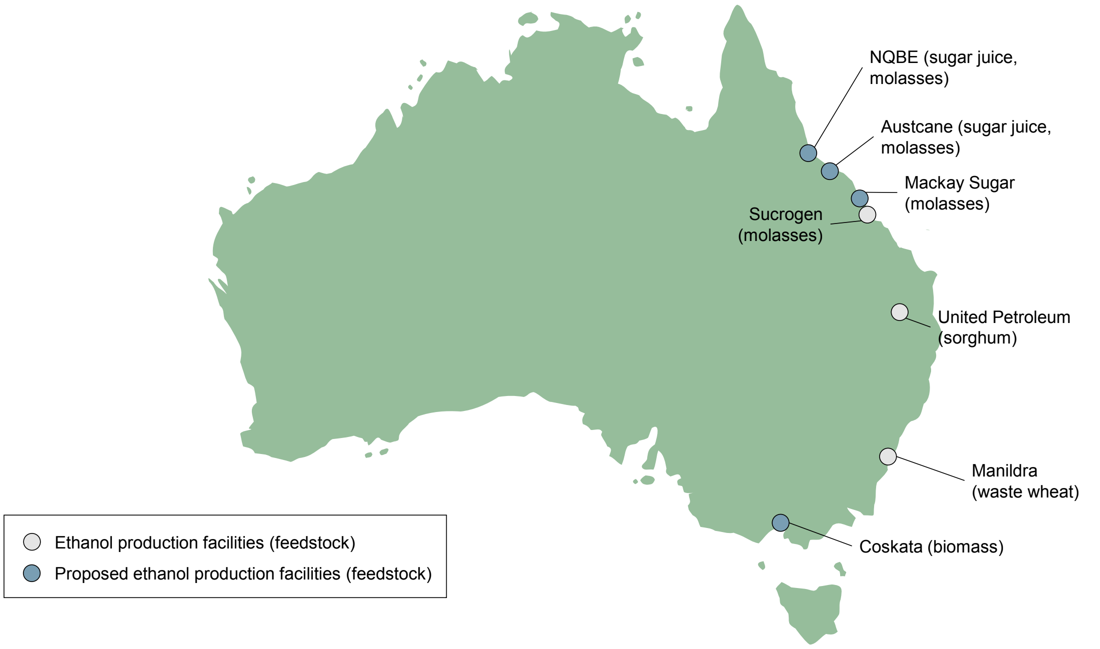
Figure 2: Australian ethanol maximum production capacity (CY2005-15F)



Note: * Previously Dalby Bio

Source: ACCC

Figure 3: Australian ethanol production facilities

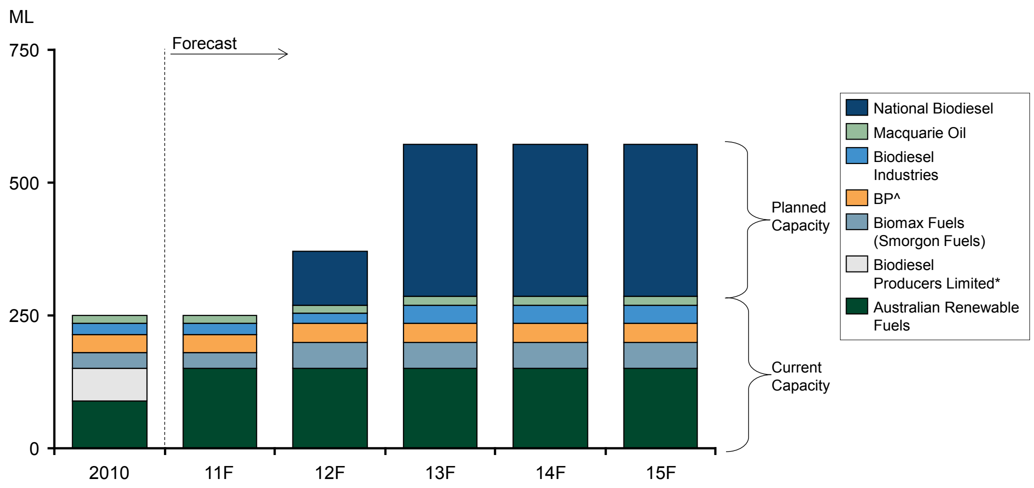


Source: ACCC

2.2.2. The Australian biodiesel industry

There are currently five biodiesel producers in Australia, with a combined production capacity of c.250ML. In recent years, a number of players have placed production capacity on stand-by, with actual 2010 production estimated at c.130ML. Australian Renewable Fuels accounts for over 50 per cent of domestic production capacity. The remaining 50 per cent is fragmented across four players (Figure 4). The industry is centred in Victoria, which accounts for c.70 per cent of production capacity (Figure 5). First generation biodiesel production in Australia has predominantly utilised tallow feedstock. The ACCC reports strong capacity growth, driven by National Biodiesel's planned soybean processing and biodiesel production facility.

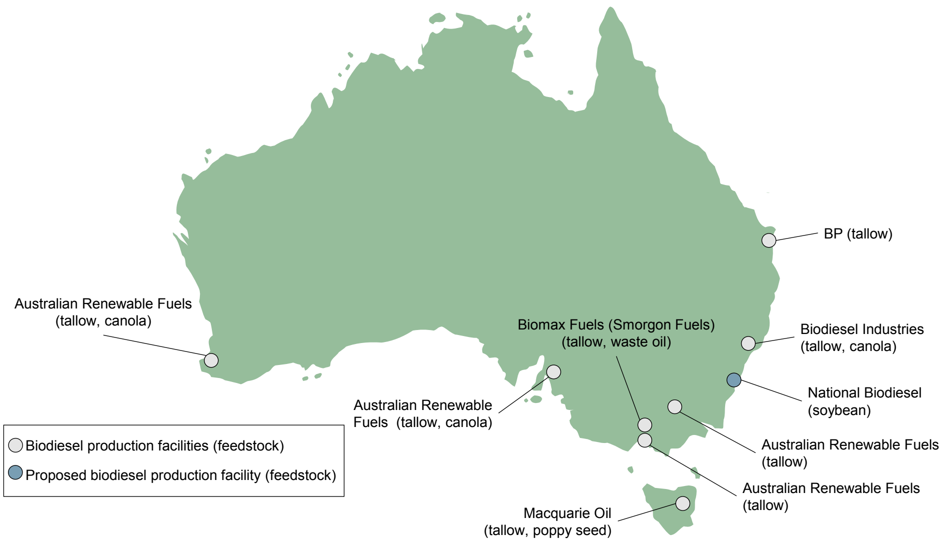
Figure 4: Australian biodiesel maximum production capacity (CY2010-15F)



Note: ^ Renewable diesel, *Acquired by Australian Renewable Fuels in 2011

Source: ACCC; L.E.K. Analysis

Figure 5: Australian biodiesel production facilities



Source: ACCC

2.2.3. Recent industry challenges

In recent years, challenges facing the Australian biofuels industry have included regulatory uncertainty, supply constraints, end user acceptance and cost competitiveness. However, industry capacity continues to expand where production economics allow and in line with expectations of growing demand.

Industry participants have reported that regulatory uncertainty at both a State and Federal level has contributed to low investor confidence, limiting investment in new ethanol and biodiesel production plants and constraining available supply. In 2010, the NSW Government held back planned increases in its ethanol mandate and the Queensland Government deferred introducing an ethanol mandate, citing federal uncertainty and supply shortage concerns. Retailers of blended fuels have also cited supply shortage concerns following the recent Queensland floods.

End user acceptance for biofuels has also curbed uptake. Specifically, one commonly cited example is motorists' concern that ethanol blends can damage vehicle engines. Stakeholder discussions suggest that this has been compounded by an absence of consumer knowledge of the potential environmental and fuel security benefits of biofuels and a desire for a more cost competitive option. These factors contributed to Shell's decision to withdraw its E10 product from sale in Victoria in mid-2010. Progress continues to be made however, with Coskata, Holden and Caltex partnering to introduce higher ethanol blends into the Victorian market.

The economics of biofuel production has presented significant challenges to the biodiesel sector, with import pressures and high feedstock prices resulting in a number of plants being closed or placed on stand-by. In 2009/10 the domestic industry struggled to compete with United States imports due to high local feedstock prices and United States subsidies for biodiesel producers. Following this, the Australian Government announced an import duty would be applied on U.S. biodiesel in 2011.

2.3. Australian biofuels policy

Australia's biofuels policy sits at the intersection of energy, environmental and regional development policies and as a result should not be viewed in isolation. Recent moves to introduce a price on carbon, the proposed establishment of the $10b Clean Energy Finance Corporation, the $800m Clean Technology Investment Program, the $200m Clean Technology Innovation Program, and the $3.2b Australian Renewable Energy Agency (ARENA) are all relevant policy decisions. The focus here is on summarising specific Australian biofuels policies currently in place.

Biodiesel, renewable diesel and domestic ethanol are all subject to a concessionary excise regime through the Energy Grants (Cleaner Fuels) Scheme and Ethanol Production Grants Program. Producers are able to receive grants of 38.143cpl which has the effect of fully offsetting fuel tax paid. These provisions were recently extended for another 10 years, with concessional treatment to be next reviewed in 2021.

Different end users are subject to different excise treatment, which may impact upon biofuels adoption. The fuel tax credit scheme, for example, provides a full excise credit for fuel used in certain mining, agriculture and forestry activities. This may reduce the incentive to take up biofuels in these sectors. Certain transport fuels and uses will also be treated differently under the proposed carbon pricing scheme. Carbon price exemptions for household and light on-road business use, and off-road agriculture, forestry and fishing use may diminish incentives for switching to low emission alternatives.

At the national level, Australia does not have a binding biofuels target. New South Wales has escalating 4% ethanol and 2% biodiesel blending mandates in place as legislated in the NSW Biofuels Act 2007, which has helped to drive Australia's conventional biofuels consumption to date. Queensland has also considered but not yet introduced an ethanol blending mandate. In 2001, a voluntary national target was set for 350ML by 2010, but this has not been replaced or extended.

A number of investments have been made in biofuels-related R&D. For example, the Australian Centre for Renewable Energy (ACRE) was recently set up to manage over $690m of committed renewable energy funding. This includes several programs outlined in Figure 6. As at Sep 2011, the relationship between these programs and ARENA is still being defined.

Figure 6: ACRE biofuels-related research and investment programs*

Program	Focus	Description
Australian Biofuels Research Institute (in progress)	Biofuels specific	Established with $20m of ACRE funding to focus on reducing the costs of next generation biofuels. This includes a $5m foundation project via James Cook University in Townsville
Second Generation Biofuels R&D Program (in progress)	Biofuels specific	$13m allocated to 6 research, pilot and demonstration projects across: algae; mallee; sugarcane; bagasse; and lignocellulosics
Emerging Renewables Program (in progress)	General (may include biofuels)	$126m grant funding across two categories: Projects (technology and infrastructure development); and Measures (feasibility and preparatory studies, guidelines, skills etc.)
Renewable Energy Venture Capital Fund (pending)	General (may include biofuels)	$100m funding for the commercialisation of early-stage renewable energy technologies. Expected to be in operation early 2012

Note: * Other ACRE programs exist in areas such as solar, geothermal, energy storage and wind

Source: ACRE

Previous Government funding programs have also included the Biofuel Capital Grants Program, the Ethanol Distribution Program and pilot/demonstration funding via the National Collaborative Research Infrastructure Strategy. Other relevant yet indirect policies have focussed on consumer education, vehicle testing, health studies, and labelling.

Any new advanced biofuel policy initiatives will need to take account of this existing policy foundation.

2.4. International biofuels policy

Globally, Australia is not alone in its interest in the potential of an advanced biofuels industry. A number of countries are in the process of strengthening their advanced biofuels focus and considerable activity is already underway.

The approach taken by other key markets has been assessed to identify drivers, common barriers, interventions and insights relevant to Australia. This has also included consideration of conventional biofuels activities where applicable.

While specific policy objectives vary by geography, government interest in biofuels is typically driven by a combination of energy security, emission reduction and rural and industrial development goals. In the United States for example, energy independence has been a key driver of recent biofuels activity, whereas Europe has placed greater focus on emission reduction goals.

Common areas for government intervention include improving certainty of biofuels demand, supporting production economics, and addressing technology and feedstock research and development (R&D) funding needs.

Several jurisdictions have adopted mandates and standards for biofuels consumption as they look to drive uptake and increase certainty of demand. The United States' revised Renewable Fuel Standard, for example, requires the use of 136 GL of biofuels in transportation by 2022. Europe's Renewable Energy Directive includes a binding requirement of 10% renewables in transport by 2020, with biofuels a major contributor. India, Brazil and parts of China also have explicit biofuels targets.

Governments are also providing a range of incentives to support production economics in the absence of cost-competitive biofuels supply. Mechanisms include preferential tax treatment for biofuels (e.g. USA, Europe, Brazil), production subsidies (e.g. Canada), and minimum price guarantees (e.g. India). Several countries are also using tariffs to protect domestic biofuel producers, even though this may not lead to lowest cost outcomes for end fuel consumers.

Technology and feedstock R&D is receiving considerable attention in line with the early-stage of many advanced biofuel pathways. Governments are deploying a number of interventions including R&D funding allocations, capital grants, loans and loan guarantees. The US American Recovery and Reinvestment Act 2009, for example, directed $800m towards new research on biofuels, including a number of advanced bio-processing projects. Other US initiatives include loan guarantees to fund the development of commercial-scale advanced biofuel technologies, competitively awarded funding for biomass R&D, and projects via the Department of Energy's Advanced Research Projects Agency.

Notably, the US is also focussing on defence procurement as it looks to reduce fuel costs, improve energy independence and create pull-through biofuels demand. This includes coordinated government investment of up to $510m over the next three years to produce advanced drop-in aviation and marine biofuels to power military and commercial transportation, and includes substantial alternative energy commitments. The Department of Navy's Great Green Fleet initiative, for example, aims for 50% of total Department energy consumption to come from alternative sources by 2020 and targets demonstration sailings of a Green Strike Group for 2012 (domestically) and 2016 (overseas).

Importantly, a number of other countries are also shifting their focus towards advanced biofuels as they look to mitigate sustainability and food price concerns associated with conventional biofuels supply. Practically, this can be observed not only through R&D emphasis, but in the increased adoption of explicit sub-targets and biofuels sustainability criteria. For example, the US Renewable Fuel Standard includes differentiated 2022 obligations for corn-based, non-corn, cellulosic, and bio-based diesel fuels, in addition to life-cycle emission reduction requirements. The EU Renewable Energy Directive requires biofuels to meet tightening life-cycle emission reduction thresholds while ensuring they do not come from sensitive land areas. Certification can also be via approved third party schemes (e.g. Roundtable on Sustainable Biofuels), supporting the emergence of international biofuel sustainability criteria. The Australian Government has also committed to developing ISO Sustainability Criteria for Bioenergy, although this process has not yet commenced.

Governments are generally taking a portfolio approach, diversifying their focus across multiple feedstocks and technologies as they look to manage uncertainties around the development of advanced biofuels. At the same time, governments are also considering opportunities for comparative advantage and recognising local feedstocks with particular regional potential (e.g. India's stated interest in Jatropha).

The barriers and actions discussed in the Advanced Biofuels Study draw on insights from other jurisdictions. Overseas activity should also help inform the potential dimensions of Australia's biofuels aspiration. International linkages will be of benefit to Australia in continuing to draw upon lessons from global biofuels policy, experience and expertise.

2.5. Australia's comparative advantage

Going forward, Australia should prioritise opportunities that play to its comparative advantages.

Australia has world-class agricultural R&D capabilities in the areas of plant breeding and genetic modification. It also possesses world-class agricultural science and agronomy capabilities that support well managed agricultural production systems. This has been supported by strong research organisations such as the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES). Australia also already has some R&D activity relevant for advanced biofuels, mostly focussed on feedstocks (e.g. plant breeding, yields, drought tolerant species).

In the area of feedstock, Australia has attractive natural conditions suitable for growing dedicated energy biomass. For lignocellulosic or oilseed crops Australia offers abundant land, suitable climate and advanced capabilities in crop production. For algae, Australia has abundant land and sunlight as well as significant waste streams of CO_2 and supplies of saline / brackish water. However, these conditions do not always overlap in the same geographical location.

By global standards Australia is considered an attractive country to do business. Underlying this is its transparent rule of law, rigorous regulatory and compliance systems, democratically elected government, strong public institutions and triple-A credit rating. Looking forward, compliance systems may be particularly attractive in the context of a biofuels industry where, subject to the development of further standards, environmental rigour could be attractive to overseas companies and countries looking to import advanced biofuels and concerned about sustainability.

Australia has exhibited strengths in industry-building and is able to capitalise on natural resource advantages, as evidenced through the building of Australia's LNG industry. There may also be opportunities to extend existing skills (e.g. engineering, construction) into areas of value in the global biofuels value chain (e.g. algal pond construction). Expertise may also, for example, be able to be built around stubble harvesting on the back of existing wheat expertise.

Australia is also well placed to leverage strong political and trading alliances with international countries that have made significant biofuels development investment (e.g. the USA defence sector) and regional neighbours which have significant growing transport fuel demands (e.g. China). Australia's geographical positioning also suggests it is well placed to access existing and emerging biorefining capacity in regions such as Singapore and India.

2.6. Summary and conclusions

Australia has a small but growing biofuels industry and policy foundation on which to build an advanced biofuels industry. Drawing on the experience, expertise and challenges faced by international countries and the domestic industry to date will also help to inform and shape the ABF industry going forward. Australia should also prioritise opportunities to play to its comparative advantages, which are material.

3. END-USE SECTOR NEEDS

3.1. Introduction

The purpose of this section of the Appendix is to explain the methodology used to prioritise key end-use sectors for an advanced biofuels industry in Australia. This section outlines the considerations and rationale at each stage of the framework.

3.2. Overview of end-use sector needs

Potential end-use demand is a key consideration when looking to develop an advanced biofuels industry in Australia. End-use sectors with the greatest need to find alternative fuels will provide the highest level of market demand, helping to establish the advanced biofuels industry. This section of the Appendix identifies the sectors:

- with the greatest need for fuel alternatives; and
- where advanced biofuels compare favourably to other options.

The main types of fuel used by industry sector are shown in Figure 7 below.

Figure 7: Industry sectors and major end uses of fuel

	Major end uses of fuel						
Industry sector	Light vehicles	Heavy vehicles	Equipment & machinery	Marine	Aviation	Remote generation	Heating
Agriculture		✓	✓			✓	
Aviation					✓		
Commercial & services	✓	✓					✓
Construction	✓	✓	✓			✓	
Defence	✓	✓		✓	✓		
Freight road transport	✓	✓					
Manufacturing			✓				
Marine				✓			
Mining		✓	✓			✓	
Private transport	✓						
Passenger road transport	✓	✓					
Rail		✓					
Residential (non-transport)							✓

Source: ABS; L.E.K. analysis

Advanced biofuels are potential substitutes for liquid fuels across many end-uses as depicted in Figure 8 below.

Figure 8: Advanced biofuels substitutes by end-use

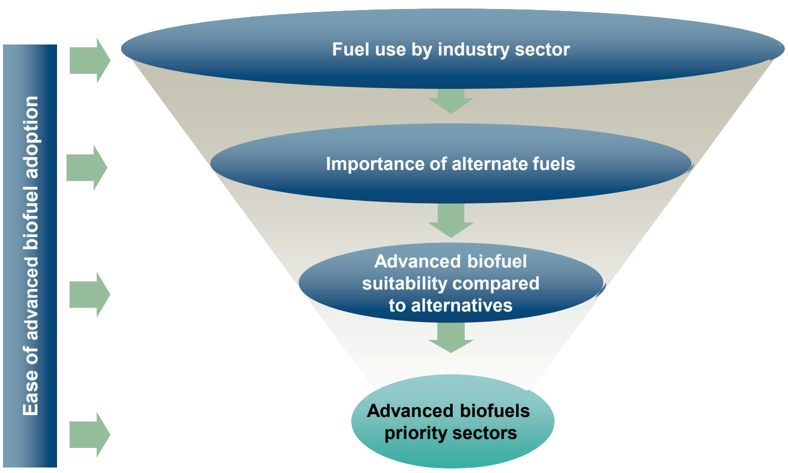
Current fuel usage *(primary fuels by end use)*		Potential biofuel substitute (*blend or drop-in*)
Light vehicles	Gasoline / diesel / LPG	Ethanol Biodiesel Renewable gasoline Renewable diesel Other fuels and additives
Heavy vehicles	Diesel	Biodiesel Renewable diesel
Equipment / machinery	Diesel	Biodiesel Renewable diesel
Marine	Diesel / fuel oil	Biodiesel Renewable diesel
Aviation	Aviation fuel	Renewable aviation fuel
Remote generation	Diesel / natural gas	Biodiesel Renewable diesel Bio-synthetic gas

Source: CSIRO; IEA; L.E.K. interviews

3.3. Prioritisation framework

A three-stage prioritisation process has been used to identify the sectors that offer the greatest potential end-use demand for a biofuels industry in Australia (Figure 9).

Figure 9: Prioritisation framework



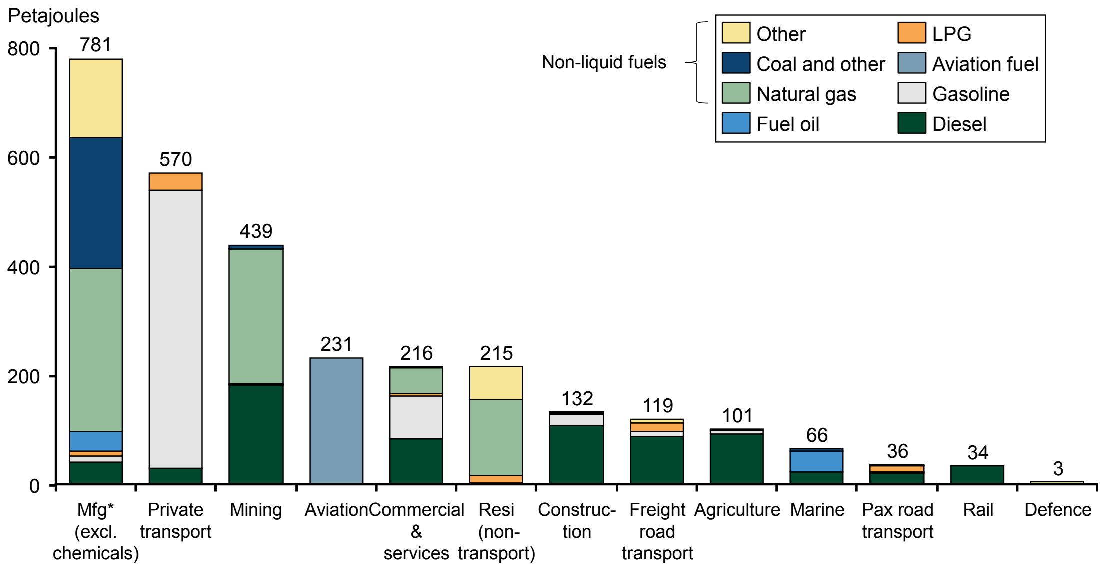
Source: L.E.K. analysis

3.4. Fuel use by industry sector

The first step in prioritisation considers fuel use by industry sector. According to the ABS and ABARES, the key energy sources in Australia (excluding electricity) are diesel (24% of final energy consumption), gasoline (22%), aviation fuels (8%) and natural gas (25%). Consumption of aviation fuel and diesel has been growing at 3-4% pa over the last 20 years, while gasoline consumption has remained broadly stable.

The manufacturing sector is the highest consumer of energy, followed by private transport, mining and aviation (Figure 10). However, across these sectors, energy use by fuel type varies significantly. Manufacturing uses predominantly natural gas and coal. Private transport is largely gasoline based, with diesel and LPG making a small but growing contribution.

Figure 10: Total fuel use by fuel type and industry sector, excluding electricity (FY2009)



Note: * Manufacturing excludes chemical manufacturing, as this largely relates to petroleum refining activities which are not considered an end use

Source: ABS; ABARES; Defence Material Organisation; L.E.K. analysis

There are seven industry sectors with significant consumption of conventional non-renewable liquid fuels. These sectors typically consume a large amount of one or two fuel types:

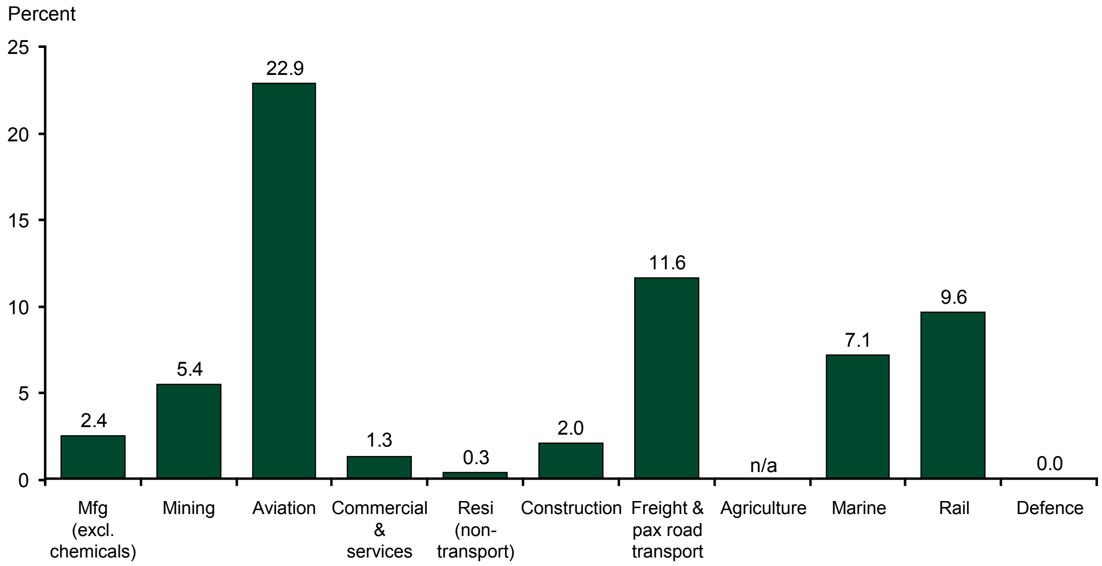
- agriculture (diesel);
- aviation (aviation fuels);
- commercial and services (diesel, gasoline);
- construction (diesel);
- freight road transport (diesel);
- mining (diesel); and
- private transport (gasoline).

3.5. Importance of alternative fuels

The second step in prioritisation is the need for alternative fuels. The main reasons for customers to consider alternative fuels are rising fuel costs and pressure to reduce the environmental impacts of non-renewable fuel combustion.

Sectors with high relative intensity of energy expenditure are likely to be more motivated to reduce fuel consumption or switch to alternative fuels (Figure 11). These sectors include aviation, road transport, rail, marine and mining.

Figure 11: Relative energy expenditure intensity by sector, excluding electricity (FY2009)



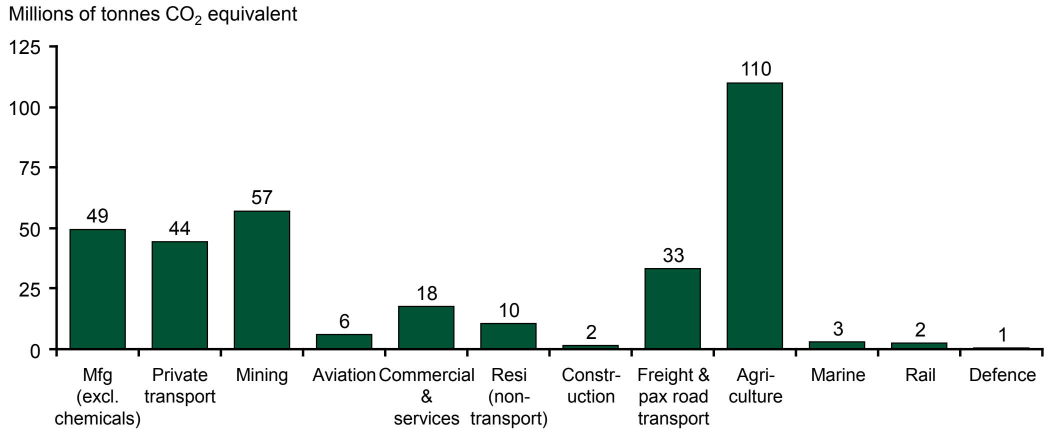
Source: ABS; ABARES; Defence Material Organisation; L.E.K. analysis

Sectors with high greenhouse gas (GHG) emissions are under greater pressure to reduce their environmental impact. For sectors where fuel is a major source of these emissions, deploying lower impact fuel alternatives has become a priority.

The sectors that generate the greatest direct GHG emissions are agriculture[1], mining, manufacturing, private transport and road transport (mainly freight road transport) (Figure 12). Mining and road transport all have combustion of liquid fuels as the major source of their emissions.

[1] A significant proportion of agricultural emissions relate to land use change and livestock. Similarly, a sizeable share of direct emissions from manufacturing relates to the use of coal products for steel and other metals.

Figure 12: Direct greenhouse gas emissions by sector (FY2009)



CAGR% (1990-09)	(0.1)	1.1	2.6	3.9	(0.2)	1.6	(2.5)	2.9	(3.6)	(0.0)	1.7	-

Note: Direct emissions exclude emissions from consumed grid-based electricity

Source: Australian National Greenhouse Accounts National Inventory by Economic Sector 2009; L.E.K. analysis

External pressure to reduce GHG emissions can also be influenced by public perception. Certain sectors such as mining, aviation, and private vehicles are more visible in the public domain and as a result face increased pressure to demonstrate tangible efforts to reduce their impact on the environment.

Strategies to reduce fuel consumption and GHG emissions can include:

- improving fuel efficiency through better engine technology;
- reducing weight through use of lighter materials;
- changing operating practices (e.g. flight paths, operating procedures); and
- switching to alternative fuels.

While all of these can make a contribution, consideration of fuel alternatives is important (if not key) for many of these sectors.

Four sectors therefore demonstrate a tangible need to consider fuel alternatives due to concerns over high fuel costs and GHG emissions:

- aviation (aviation fuel);
- mining (diesel, natural gas);
- freight road transport (diesel); and
- private transport (gasoline).

3.6. Advanced biofuel suitability compared to alternatives

The third prioritisation step is to identify end-use sectors with limited alternatives. Advanced biofuels will be more suitable for sectors where they meet fuel performance requirements and compare favourably to other fuel alternatives on a cost-benefit basis. However, the full costs and benefits (including GHG performance) of advanced biofuels and other alternative fuels are quite uncertain today.

Some fuel alternatives will require significant modification to engines or distribution infrastructure before they can be used (e.g. charging infrastructure for electric vehicles, distribution infrastructure for hydrogen fuel cell technology). These costs are likely substantial and in addition to direct costs of fuel production, and will depend on a range of factors including scale of take-up and technology development. The impacts of these types of changes on full life-cycle economics and emissions are also very uncertain. Given these unknowns, a pure cost-benefit assessment is not presently the most appropriate method to compare long term fuel alternatives. It is, however, reasonable to expect that advanced biofuels will be relatively more important for sectors with fewer long term alternatives that meet performance requirements (Figure 13).

Figure 13: Availability of fuel alternatives

		Major fuel alternatives						
		Biofuel options				Non biofuel options		
End use	**Current fuel used**	Ethanol (blend)	Biodiesel (blend)	Renewable drop in fuels	Other fuels & additives	CNG / LNG	Electricity	Hydrogen
Light vehicles	Gasoline / diesel / LPG	✓	✓	✓	✓		✓	✓
Heavy vehicles	Diesel		✓	✓	✓	✓		
Equipment / machinery	Diesel		✓	✓		✓		✓
Marine	Diesel / fuel oil		✓	✓				
Aviation	Aviation fuel			✓				
Remote generation	Diesel / natural gas		✓	✓		✓		✓

Source: IEA; CSIRO

Aviation has no known alternatives for traditional aviation fuel (other than biofuels). Heavy vehicles, equipment and machinery, remote generation and marine vessels have few fuel alternatives that can fully substitute for current diesel use. While CNG / LNG / natural gas can substitute for diesel in some applications, their lower energy content (and density) constrains range and ultimately reduces attractiveness for heavy duty use and / or use in remote locations.

3.6.1. Private transport considerations

The private transport sector (passenger vehicles, light vehicles) is the largest absolute consumer of gasoline. This sector, however, has a number of existing and promising long term alternatives in addition to advanced biofuels.

Electric vehicles are particularly promising, with a wide range of global and local efforts underway. Many large challenges still need to be overcome, including the need to transition the car fleet and establish necessary charging, battery-switching and potentially home-based infrastructure. To deliver material GHG emission reductions, electricity generation will also need to be from renewable sources such as wind or solar. In the long-term, however, electricity may become a viable private transport fuel alternative.

Other alternatives for private vehicles include LPG (and possibly, but to a far lesser extent CNG/LNG), but they are currently not widely used. A key barrier to the large scale deployment of these alternatives is the requirement for significant investment in distribution infrastructure and refuelling points. Additionally, motor vehicle engines need to be substantially modified to take these alternatives, adding costs to end users. These alternatives are also of lower volumetric energy densities relative to gasoline or diesel, requiring more space for fuel tanks or a reduced driving range.

Ethanol is also an option, but due to its relatively low volumetric energy density and corrosiveness, it is only usable in low blends (e.g. up to 10%) in most conventional engines. Higher blends require partial modification to engines, which has not been widely undertaken in Australia to date. Furthermore, as ethanol remains a non-core fuel in many markets, there are fewer incentives for car manufacturers to develop and market modified car models. Assuming estimated gasoline demand of c.20GL in 2030, an E10 blend would suggest a total market for fuel ethanol of 2GL per annum.

In this context, advanced biofuels are only one of a number of private transport fuel alternatives. The development of cost competitive ‘drop-in’ advanced biofuels that are compatible with existing engines and infrastructure (e.g. renewable gasoline, renewable diesel) would, however, be conducive to large scale private transport sector adoption.

3.7. Ease of adoption

Some important practical factors will affect the ease of adoption of advanced biofuels, including:

- ease of access to a viable supply chain;
- ability to meet fuel certification requirements; and
- industry concentration.

3.7.1. Ease of access to a viable supply chain

There is currently a complex supply chain governing the production and distribution of refined oil products in Australia. For many end sectors, key components of the supply chain infrastructure are owned or operated by the major oil companies (i.e. terminals, pipelines, trucking and petrol stations). These sectors includes private transport, freight road transport, aviation, mining, commercial and services, agriculture and manufacturing. Complete replication of this network would be impractical and therefore, the involvement by major oil companies will be critical for development of an advanced biofuels industry.

Biofuels such as biodiesel and ethanol present significant challenges for supply chains, due to their different molecular composition and physical properties versus non-renewable fossil fuels. These biofuels cannot be distributed through the current infrastructure networks and generally require new dedicated distribution infrastructure (i.e. ethanol may require new pipelines as its corrosiveness and hydrophilic properties render it largely incompatible with existing infrastructure). Even where these fuels are blended with non-renewable fuels, additional infrastructure such as tank and blending infrastructure may be required at either the refinery or terminal stage.

On the other hand, 'drop-in' advanced biofuels such as renewable diesel are largely compatible with existing infrastructure, as they have a very similar molecular composition to their non-renewable equivalents. This would allow for integration into the existing supply chains with very limited modification to distribution networks.

3.7.2. Ability to meet fuel certification requirements

Fuel certifications and standards may constrain a sector's ability and motivation to replace its current fuel with an advanced biofuel alternative, particularly in the short-term. For most end users there are standards which affect whether new fuels can be adopted. For example, the road transport sector must adhere to national fuel standards, defined by the Fuel Quality Standards Act 2000, while in the aviation sector standards are set by the American Society for Testing and Materials (ASTM).

Generally, changes to standards and adoption of alternative fuels can be accelerated with industry co-operation and support for alternative fuels. For example, the aviation sector has relatively stringent fuel certification requirements. Strong airline support for biofuels (and subsequent trialling) has seen the revision of ASTM standards to allow airlines to accept aviation fuel that blends up to 50 percent biofuels.

Lack of standards can be a significant hurdle to adoption of advanced biofuels. For example, some road transport operators suggest that biodiesel adoption has been limited because there is no well-defined standard and OEM's have not been very active in testing and certifying a wide range of biofuel blends.

3.7.3. Industry concentration

Sectors with smaller groups of influential decision makers should be more able to adopt new fuels and standards across shorter timeframes. From this perspective, industries with significant levels of government involvement are also potentially attractive (e.g. defence). Similarly, industry sectors with a higher concentration of fuel end-users, such as aviation and mining, are also potentially attractive.

3.8. Tax and excise considerations

Different taxation regimes need to be considered when looking at end user adoption of advanced biofuels. Under the carbon tax as currently proposed, transport fuel for households, light on-road business use, off-road agriculture, forestry and fisheries will be exempt from a carbon price. End-use sectors that are shielded from a carbon price will see less advantage in switching to lower carbon fuels relative to other sectors that may not be exempt (e.g. mining, domestic aviation and marine).

Similarly, different excise treatment across end-use sectors may also impact upon incentives for advanced biofuels use. For example, under the fuel tax credit scheme, certain mining, agriculture and forestry activities are entitled to a credit which offsets fuel excise. This diminishes the effect of concessionary excise treatment afforded to biofuels.

At the margin, these differences in taxation will impact the attractiveness of advanced biofuels to a specific industry sector, and may also be subject to change from time to time. If advanced biofuels become more cost competitive with non-renewable fuels, then excise and carbon tax regimes could have a significant bearing on attractiveness.

3.9. Summary and conclusions

End-use sectors with the greatest need to find alternative fuels will provide the highest level of market demand, helping to establish the advanced biofuels industry. Sectors with the greatest need for alternative fuels are those:

- that demonstrate high absolute consumption of liquid fuels;
- that are under pressure to reduce their GHG emissions from combustion of liquid fuels; and
- that have high advanced biofuel suitability compared to alternative fuels.

Based on these considerations, the most likely sectors to lead the adoption of advanced biofuels are:

- **aviation**;
- **mining**;
- **freight road transport**;
- **marine**; and
- **defence**.

In each case, drop-in fuels are much more likely to succeed than fuels requiring separate distribution infrastructure or new engine technology. The **private transport sector** may therefore also offer significant potential if drop-in biofuels can be developed.

Figure 14: Summary of priority sectors

Industry sector	Liquid fuel consumption (PJ)*	Prioritisation framework				
		Three stage prioritisation			Strategic overlay	Prioritised sectors
		Fuel use by sector	Importance of alternative fuels	Biofuel suitability vs alternatives	Ease of adoption	Major fuel types
Aviation	231	✓	✓	✓	✓	Aviation fuel
Mining	185	✓	✓	✓	✓	Diesel
Freight road transport	113	✓	✓	✓	✓	Diesel
Marine	61				✓	Diesel
Defence	3				✓	Assorted
Private transport	570	✓	✓		✓	Diesel / gasoline
Commercial & services	165	✓				
Construction	129	✓				
Agriculture	101	✓				
Manufacturing	97					
Passenger road transport	34					
Rail	34					

Note: * Substantially lower than total fuel consumption for some sectors

Source: ABARES; L.E.K. analysis

L.E.K.

4. FEEDSTOCK OPTIONS

4.1. Introduction

The purpose of this section of the Appendix is to identify advanced biomass sources and assess their potential as feedstock for an advanced biofuels industry of scale in Australia.

Biomass is organic matter or waste that can be used as an energy source, and includes materials such as wood, straw, and oilseeds. It is a renewable source that can be converted into other forms of energy including electricity and biofuels. Conventional biomass is food biomass such as sugar, starch and edible vegetable oil. This report focuses on advanced biomass, which is derived from inedible crops, edible crops not typically consumed as food, or other biomass sources that do not displace food production. Feedstock is the term for biomass that is used to produce biofuel.

According to the IEA, most of the world's biofuel (99%) is currently derived from conventional feedstocks. The majority comes from food crops, such as sugar cane in Brazil and corn in the United States. However, advanced biomass is receiving increased research and investment worldwide; the IEA projects that advanced biomass will supply more than 50% of feedstock required for biofuel production by 2030.

Australia has an abundance of potential biomass which could potentially be used as feedstock for an advanced biofuels industry. These feedstocks can be categorised into three broad groups based on their downstream processing and conversion requirements:

- lignocellulosic sources: basic plant biomass, found in large quantities in the cell walls of herbaceous and woody plants;
- oil based sources: fats and oils, typically from specific plants; and
- algae biomass sources: plant matter and oils produced by aquatic plant species (algae).

Within these categories, a further distinction can be drawn between existing or currently available sources such as animal tallow, and potentially available sources such as new crops like pongamia.

This section reviews the advantages and disadvantages of existing and potential new supply across key dimensions of availability, affordability, and sustainability:

- availability examines the abundance and scalability of the feedstock, and its estimated energy yield. This underpins the size and timeframe of the industry which could be developed using each feedstock;
- affordability is critical as feedstocks make up 30-50% of biofuel production costs. This Appendix considers the opportunity costs and farm-gate costs including cultivation, harvest and transportation; and

- sustainability examines complex issues such as food security and environmental impacts including soil, air (including GHG emissions), and water. Community and biodiversity issues are also considered.

Importantly, feedstock comparisons need to be considered alongside the relevant downstream processes which convert these feedstocks to biofuel.

4.2. Lignocellulosic feedstock options

Lignocellulosic biomass refers to plant matter comprised of cellulose, lignin and hemicellulose and is one of the most abundant biomass sources on earth. Agricultural and forestry residues make up most of Australia's current lignocellulose supply base. Over time, dedicated energy crops (e.g. grasses, short rotation coppice) can be cultivated to supplement current supply.

4.2.1. Existing lignocellulosic options

The major existing lignocellulose options in Australia are agriculture residues (bagasse and crop stubble); wood and forest residues; and landfill wastes.

Figure 15: Existing sources of lignocellulosic biomass in Australia

Bagasse	Crop stubble	Wood & forest residues	Landfill wastes
			
The stem residue remaining after crushing to remove sugar-rich juice from sugar cane	The residue remaining after the harvest of crops such as wheat, barley and lupins	Bark, sawdust, pulpwood (wood used for processing into paper and related products) and harvest residues	Includes municipal, commercial and industrial solid wastes, as well as construction and demolition wastes

Agricultural residues

Australia's large land mass, topography and diverse range of climatic zones provide opportunity to grow a range of crops, many of which produce residues. Australia is a top ten producer on a global scale of wheat and sugar (and a top five exporter), and the volume of residues resulting from these cropping systems is significant.

Agricultural residues can typically be made available at a reasonable cost as they side-step the need for dedicated cultivation and its associated costs (e.g. labour, land, inputs). While residues, particularly bagasse, have alternate uses such as electricity generation, the opportunity costs of these uses are relatively small. Furthermore, the production system for agricultural residues is relatively straightforward and requires limited infrastructure investment to supply biofuel plants. Some residues, such as bagasse and sawmill residues offer logistical advantages because they tend to be concentrated in one place.

Agricultural residues are typically considered sustainable from a food security perspective because they are inedible and do not require additional land. Incremental environmental impacts are also limited (provided soil carbon and fertility levels are maintained) as the residues are available without additional cultivation and farming inputs and hence rate well in terms of life-cycle GHG emissions.

Wood and forest residues

Wood residues include primary waste from forestry such as cleared bark and sawn branches as well as pulp logs. Secondary residues from sawmills include chips, sawdust and shavings. These residues are generally found in abundance in the southern and eastern coasts, and in south western WA, with supply being available year round. With the exception of pulp logs, which have an alternate use in paper production, and some harvesting issues with forest residues, wood wastes can generally be obtained at affordable costs.

Sustainability issues around the use of wood residues for biofuels are complex. Environmentally, collection of forest residues may help prevent forest fires, but it also reduces soil carbon. There is also debate about using sawmill by-products as this could drive demand for more wood and thus contribute to clearing of native forests.

Landfill wastes

Landfill wastes are tertiary residues which include:

- municipal solid waste;
- commercial and industrial waste; and
- construction and demolition waste.

At present, there is limited knowledge of the exact sub-components available. Landfill wastes rate highly in terms of sustainability (e.g. reduce impact of landfill, and rate well in terms of life-cycle GHG). However, separation challenges and contamination issues can make the collection of useful residues from landfill potentially costly.

4.2.2. Potential new lignocellulosic options

An alternative to using crop and waste residues for feedstock is to develop dedicated lignocellulosic crops. These are fast growing plant species that are harvested entirely for biofuel production and, ideally, do not vie with food crops for land use or fresh water.

Figure 16: Potential new sources of lignocellulosic biomass in Australia

Short Rotation Coppice (SRC)	Grasses
	
Short rotation tree species (eg poplar, willow and eucalyptus) that regenerate quickly via coppicing (via shoots from the stump of cut down trees).	Various varieties – wild sorghum, kangaroo grass, tall fescue, perennial ryegrass.

Short rotation coppice (SRC)

A range of woody energy crops are currently in commercial production for generation of biomass, primarily for burning to generate power. They are typically densely planted, high yielding varieties of poplar, willow and eucalyptus that regenerate quickly after harvesting via coppicing (shoots from the stump of cut down trees).

Short rotation coppice (SRC) offer a number of advantages when it comes to feedstock production:

- limited energy or fertilizer is required and they can grow on poor soils not suited for plantations. SRC systems can also be integrated into existing cropping areas via strip and block planting;
- species native to Australia (e.g. Eucalyptus, Mallee) can be scaled to cover large regions in the Eastern states or in South West WA without impinging on farming land;
- they can be harvested year-round to supply a stable stream of biomass; and
- wood harvesting and processing methods are well established, thus SRC can be harvested and transported at a relatively low cost.

However, SRC as a feedstock will take significant time and cost to reach scale. While SRC trees take only approximately three years to grow to harvest maturity, historical establishment rates have not exceeded 100,000 hectares per annum (ABARES, 2011). If this trend persists, it would take many years to establish a scale resource. There is some investment interest in this area; Virgin Australia has recently partnered with the Future Farm Industries Co-operative Research Centre, Renewable Oil Corporation and Dynamotive Energy Systems Corporation to develop bio-derived jet fuel from coppice eucalypt trees.

Grasses

While grasses are available in plentiful supply throughout Australia, the development of a grass feedstock industry of scale requires the cultivation of a dedicated grass field, using premium grass species. Grasses are a relatively prospective feedstock option, offering several advantages as a dedicated energy crop:

- highly scalable in Australia as grasses grow rapidly on large areas of marginal grazing land and semi-arid climate zones, and would not compete with food production or intensive grazing;
- grasses have beneficial soil effects particularly when introduced on degraded land. GHG emissions to farm gate are also relatively good given limited inputs are required; and
- grasses have good agronomic properties, making them relatively affordable to cultivate. They are hardy and drought tolerant, can be harvested within a year using existing cropping equipment, and elite varieties can be high yielding.

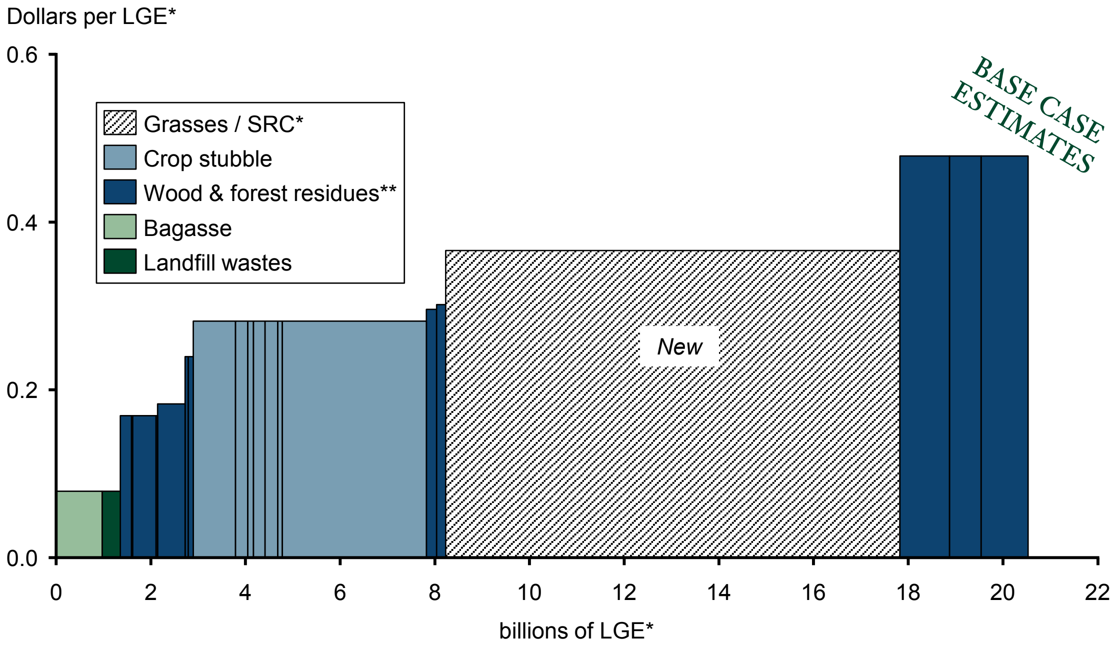
The establishment of dedicated grasslands, however, particularly in remote areas with limited infrastructure, may require significant set up time and costs. Furthermore, there may be environmental and legal impediments in clearing existing land for dedicated production. Care must also be taken in species selection to limit biodiversity issues.

4.2.3. Overall assessment

Overall, the lignocellulosic options described above appear attractive from a sustainability perspective. They are readily available at reasonable cost and do not result in diversion of food supply, nor a substantial displacement of food crops. Their GHG emissions to farm gate are also relatively small, particularly when compared to conventional biomass.

Bagasse and some forms of wood residues are very inexpensive, however these are constrained in terms of availability (see chart below). SRC and grasses rank among the most promising of lignocellulosic feedstock options from the perspective of scale. Grasses grow rapidly on semi-arid and marginal land, and once scaled, can be relatively cheap to cultivate and harvest. SRC grows at a slower rate on infertile soil, but can be grown alongside traditional crops and grazing land in strip plantations which are logistically easier to establish.

Figure 17: Farm gate supply curve: lignocellulosic feedstocks (2011E)^



Note: * LGE = Gasoline equivalent litres, SRC = Short rotation coppice; ** Wood and forest residues consists of forest residues, pulp log and sawmill residues, which are further classified into their respective source location (i.e. native managed forest, softwood plantations, hardwood plantations). Each category of wood & forest residues has a unique cost-quantity profile, as illustrated in the supply curve above; ^ Key assumptions: i) for bagasse: efficiency gains at current co-generation plants releases 50% for biofuel production, ii) for wood & forest residues: harvestable rates are 100% for stems and 0% of branch and foliage, diversion rates are 100% for residues, export fraction for pulp log and 0% of sawn timber, iii) for crop stubble: 50% harvestable, after which 100% divertible, iv) for landfill wastes: only 70% of urban wood waste is technically harvestable, all other forms not harvestable due to contamination issues, v) for grasses / SRC: cultivation on 1% of total grazing land

Source: Bureau of Rural Services; ABARES; CSIRO; L.E.K. research, interviews and analysis

The supply curve above is based on supportable assumptions. These assumptions do not include some potential improvements that are less certain. Sensitivity analysis to some of these key assumptions is shown at the end of this chapter.

It is also important to note that accurate estimates of biofuel competitiveness with fossil fuels must be undertaken at a regional level. CSIRO has done this analysis for the Green Triangle and other regions.

4.3. Oil based feedstock options

Oil based feedstocks contain various forms of fats and oils which can be extracted as inputs for biofuels production. Current sources of oil based feedstocks include animal tallow and waste cooking oil, while future sources include species of inedible oilseed crops (e.g. jatropha, pongamia, juncea, carinata and camelina).

4.3.1. Existing options

Tallow & waste oils

Existing sources of waste oils and fats include animal tallow (primarily from abattoirs) and waste oil mixtures from restaurants and food processing plants. While tallow and waste oils are a high energy density biomass, supply is relatively decentralised and their availability is limited. They are also relatively expensive due to competing demand for use in lubricant and oleochemical production. Their limited current scale and growth potential means tallow and waste oil are likely to represent only niche opportunities for smaller biofuel plants.

Vegetable oils which are residues of other agricultural processes may also provide a source of biomass, although this is an area to be treated with some caution. For example, soybean oil in Australia is primarily a residue from soy protein meal production and will be the feedstock for a significant biodiesel production facility in NSW. However, outside of Australia, soybean oil has widespread use as cooking oil and, like canola oil, is considered a food product.

4.3.2. Potential new options

New oilseed crops have significant potential for development as a dedicated biomass source. Jatropha, pongamia and rotational oilseed crops appear particularly promising: they rate well from a food security perspective as they are largely inedible, and their cultivation does not require displacement of traditional crops.

Figure 18: Potential new sources of oil based biomass in Australia

Jatropha curcas	Pongamia pinnata	Rotational oilseed crops
		
Small tree, native to central America, that produces seeds containing inedible oil content of 30-40% seed weight.	A medium-sized oil-yielding legume tree, indigenous to the Indian subcontinent and south-east Asia.	Various varieties of annual perennial crops within the crucifer family, in particular brassica juncea, brassica carinata and camelina sativa.

Jatropha

Jatropha curcas is a tall shrub or small tree growing to about 6 meters, producing oil-rich seeds. It is native to Central America, and is currently being grown commercially in India, Africa and South America for biofuels production, where it is seen as a promising feedstock option for further development for several reasons:

- it does not typically compete for food supply or arable land as the oilseeds are inedible, and the plant can be grown on marginal land;

- it is a relatively high yielding crop, producing seeds with oil content of 30-40% of seed weight; and
- it requires only 1 to 2 years of cultivation before harvesting.

However, there are a number of factors that are likely to limit the large scale production of jatropha in Australia:

- it is more suited to grow in the temperate tropics and tropics;
- jatropha seeds ripen in an asynchronous manner, requiring harvesting by (costly) manual means; and
- jatropha has been classified as a noxious weed in NT and QLD where its cultivation is prohibited.

Overall, Australia lacks the appropriate climatic and labour market conditions for the competitive development of jatropha as a dedicated biomass, and its cultivation is banned in two states. It is not recommended as a priority for further development.

Pongamia

Pongamia pinnata is a medium-sized tree indigenous to the Indian subcontinent and south-east Asia, and has been successfully introduced to humid tropical regions of the world as well as parts of Australia, New Zealand, China and the United States. Pongamia shows some promising characteristics as a future source of biomass:

- it has the potential for high oilseed production and has an oil content as high as 40% when grown under ideal conditions;
- it is inedible and its cultivation does not typically compete with food production. The plant can tolerate saline, sandy and rocky soils (with lower yields);
- its fertilizer and water requirements are low although irrigation is required in the initial years;
- it does not pose a significant biosecurity / invasive threat to native vegetation; and
- it has attracted R&D and investment interest from a number of industry players including Ergon Energy, R.M. Williams and BioEnergy Plantations Australia.

There are a range of supply chain issues, however, relating to the commercial establishment of large-scale plantations of pongamia in Australia:

- domestic yields are poorly understood as Australian trials of P. pinnata plantations to date have been undertaken on a relatively small scale;
- time to maturity may be lengthy, however this may decrease with advancements in plant breeding (currently 4 – 8 years);
- the plants tend to self-pollinate, which may result in inconsistent output;
- its seeds tend to mature in an asynchronous manner, which may make harvesting relatively labour intensive; and
- its cultivation is likely to be in relatively remote tropical and sub-tropical regions which may require significant investment in infrastructure.

Rotational oilseed crops

There are a number of annual and perennial oilseed crops which may be particularly prospective feedstock options:

- Brassica juncea (Indian mustard);
- Brassica carinata (Ethiopian mustard); and
- Camelina sativa (false flex).

These are all members of the Brassicaceae family, like canola. They have similar agronomic properties to canola but are more tolerant to drought and cold temperatures. The use of rotational oilseed crops as a dedicated feedstock option has several advantages:

- as dry land crops they can be scaled up to grow as break / supplementary crops across Australia's dry, marginal agricultural land;
- oilseed meals left after crushing for oil can be used as livestock feed;
- existing harvest technologies and infrastructure for primary crops can be leveraged to produce rotational oilseed crops at low cost; and
- biomass to biofuels technologies are well established. Smorgan Fuels are already producing biodiesel from dryland juncea in Australia and US companies such as Great Plains and Sustainable Oils are producing biofuels derived from camelina oil at commercial scale.

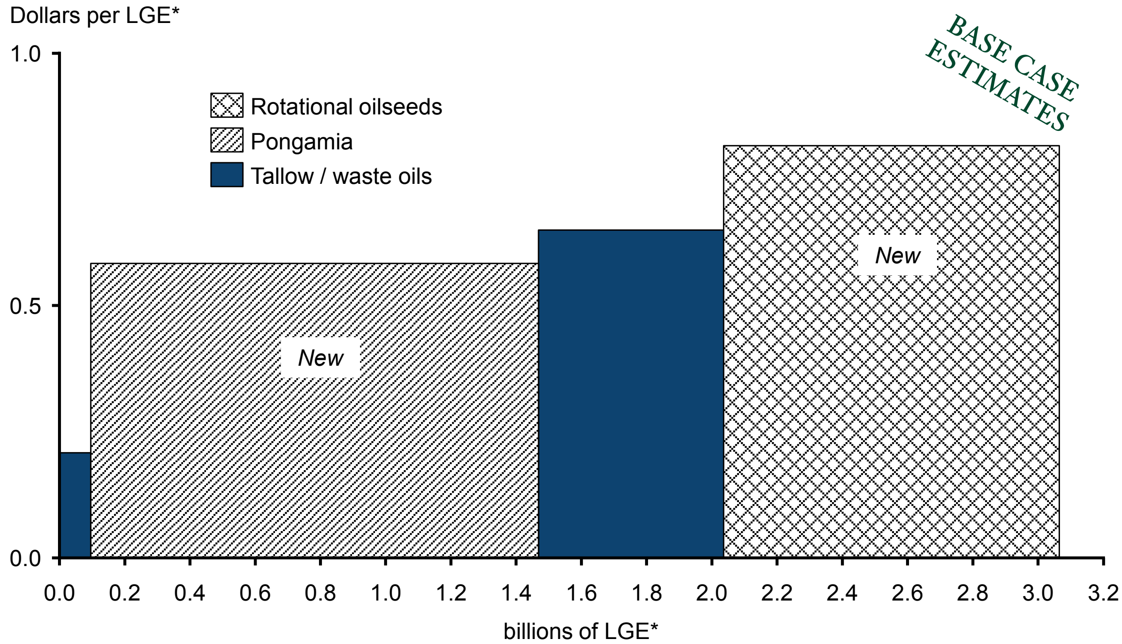
There are relatively few significant drawbacks to using these oilseed crops as biomass sources. However their scale up potential is constrained to available cropping land and pastures, and demand from alternative use as health food supplements may elevate opportunity costs. The agroeconomy will benefit from their cultivation, and many regions already have the necessary institutional and supply chain maturity to scale up the industry. Over time, production could also be expanded to more marginal land.

4.3.3. Overall assessment

Pongamia and rotational oilseeds rate relatively well across the dimensions of scalability, affordability and sustainability. Pongamia can be grown on sandy, rocky or saline soils with little need for nutrient inputs. Dry land oilseeds (e.g. juncea, camelina and carinata) can be cultivated either as break crops in existing cropping regions, or as dedicated crops in marginal agricultural land that is too dry to support other mainstream crops. The availability of tallow and waste oils appears limited. Jatropha has been eliminated due to its classification as a noxious weed in two states.

Relative to lignocellulosic feedstocks, oil based feedstocks are small in scale (< 5 GL combined under base case in Figure 19), with a high cost per litre. That said, the cultivation of dedicated oilseed crops to open up a new biofuels industry has some attractions. For example, extracted oilseed feedstocks can leverage downstream processes which are mature, unlike lignocellulose.

Figure 19: Farm gate supply curve: oil based feedstocks (2011E)^



Note: * Gasoline equivalent litres; ^ Key assumptions: : i) waste oil & tallow: fully diverted, ii) rotational oilseeds are grown on 5% cropping land, iii) pongamia is grown on 5% of land within the "41-60% productivity zone" (as per CSIRO) without irrigation, iii) jatropha is not cultivated due to regulatory prohibitions in various Australian states

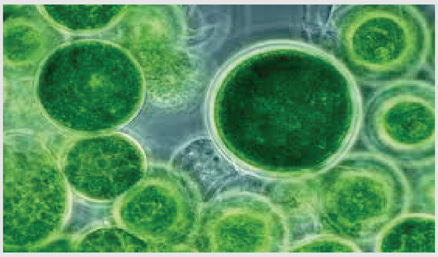
Source: Bureau of Rural Services; ABARES; CSIRO; L.E.K. research, interviews and analysis

The supply curve above is based on supportable assumptions. These assumptions do not include some potential improvements that are less certain. Sensitivity analysis to some of these key assumptions is shown at the end of this chapter.

4.4. Algae feedstock options

Algae represent a broad group of primitive plant species, ranging from small, single-celled organisms (microalgae) to multi-cellular organisms (macroalgae), some with fairly complex and differentiated forms.

Figure 20: Types of algal biomass

Microalgae	Macroalgae
	
Microalgae are microscopic, aquatically grown plant species which, in addition to lignocellulosic matter, also produce algal oils which can be utilised for fuel production.	Unlike their microscopic counterparts, macroalgae are multi-cellular and may possess plant-like structural features. They have low lipid content as a general rule but are high in carbohydrates that can be converted to various fuels.

4.4.1. Microalgae

Microalgae are small aquatic plant species which, in addition to lignocellulosic matter, produce algal oils which are ideal for conversion into liquid fuels. Microalgae are microscopic and therefore require unique cultivation, harvesting and other downstream processing techniques.

Key advantages

Microalgae are a potentially attractive biomass option for several reasons:

- their productivity offers high biomass yields per hectare of cultivation (yields are higher than terrestrial plants) meaning low total land requirements;
- cultivation strategies can minimise or avoid competition with arable land and nutrients used for conventional agriculture. In addition, microalgae can utilise waste water and saline water, thereby reducing competition for limited freshwater supplies;
- some species can recycle carbon from CO_2-rich emission streams from sources including power plants and other industrial emitters; and
- microalgae biomass is capable of being converted into a variety of fuels and a number of other valuable products (in some cases, these products may be more valuable than algal oils, and may be the economic and production focus for some microalgae players).

Key challenges

As a relatively new biomass option, there are challenges inherent in each step of the production system.

The selection / breeding of elite strains requires careful consideration as it has practical implications downstream, particularly in cultivation and harvest. A number of industry experts suggest that improvement of strains through selective breeding techniques and genetic modification may be the key to achieving scale in the industry. There are a number of companies currently adopting selective breeding techniques but the use of genetically modified algae species in Australia is untested and will require further research before deployment is possible. In addition, a single strain may be vulnerable to contamination in an open pond system, though a number of strains (called a 'polyculture') can be grown together to make the algae more resistant to invasions. Identifying strains that are particularly suited to Australia will be important for creating effective production systems. Biodiversity issues related to the importation and cultivation of strains need to be addressed, as do royalty costs for proprietary strains developed elsewhere.

Like other plants, microalgae require both an energy and a carbon input to grow. Most microalgae are strictly photosynthetic and therefore grow in phototrophic cultures, i.e. they need light and preferably a dedicated CO_2 source as inputs for high yielding commercial production (microalgae can also grow, but at lower yields, without a concentrated CO_2 source). Some algae species, however, are capable of growing in heterotrophic conditions, i.e. in darkness, using organic carbons (such as glucose or acetate) as energy and carbon sources. From a scalability perspective, the need for sugar may be a constraining factor in heterotrophic cultivation as sugar inputs, if demanded in large quantities to feed a large scale algae industry, may be costly to obtain.

Phototrophic cultivation can take place either in an open pond or in a photo-bioreactor. Open ponds are favoured by some companies because they are simpler to establish and operate, but the resulting culture is less concentrated (potentially translating to lower yields) and is more susceptible to pests. In contrast, photo-bioreactors provide a more controlled and protected environment in which a highly concentrated / yielding culture can grow, but the facilities are both capital and operator intensive.

The harvest, dewatering and separation steps necessary to process microalgae are inextricably linked to its downstream technologies; hence these are discussed in further detail in Chapter 4. At this stage, it is sufficient to note that there remain some challenges in harvest, dewatering and separation. Nonetheless, there is substantial R&D momentum to bring these processes to commercial viability.

Overall assessment

With a large land base, plentiful sunlight and an abundant supply of concentrated CO_2 streams, Australia has a natural comparative advantage in phototrophic algae cultivation. Microalgae production facilities are typically suited to flat land located near a waste CO_2 stream from an industrial facility such as coal fired power plants. High yielding native strains may also provide an added source of comparative advantage for Australia.

The successful production of algae biomass requires further development before it is proven at a commercial scale. There are a number of companies in the private sector, both locally and internationally, developing commercial operations who will be key to developing the sector in Australia.

4.4.2. Macroalgae

Macroalgae represent a broad group of photosynthetic marine organisms that grow in both fresh and saltwater, some varieties of which are known as seaweeds. They possess plant-like structural features, have low lipid content as a general rule but are high in carbohydrates that can be converted to various fuels. Macroalgae rate well in the food security debate and have several other advantages:

- many species are inedible or not consumed in significant quantities, hence use as biofuel feedstock poses no direct threat to food supply;
- they do not require arable land or fresh water to grow, and therefore do not compete for these inputs with food production;
- they can be beneficial to the aquatic system in which they grow, by providing a protected and natural habitat for other marine organisms;
- their yields in terms of energy content per tonne of biomass are generally higher than terrestrial plants (although lower than microalgae); and
- they can be harvested relatively simply (e.g. raising a net), although mechanised collection will be required at scale.

The key drawback is that effective cultivation of macroalgae remains a challenge. Prototypes for offshore and land-based growth are still in developmental stage. While commercial scale production facilities exist in China and Japan, they are almost entirely focused on producing high valued species for human consumption. Cultivation methods require further work before they can be deployed at a low cost, commercially viable scale for biofuels.

4.5. Summary and Conclusions

When these feedstock options are assessed against the key criteria of availability, affordability and sustainability, several conclusions can be drawn.

First, **lignocellulosic biomass** is found quite abundantly and readily in the current production system, and has relatively low farm gate costs and low GHG emissions. Preliminary evidence suggests that currently divertible quantities could support a significant advanced biofuels industry (c.10 GL) although investments in harvesting, densification and transport infrastructure would be important. A larger scale biofuels industry utilising lignocellulosic feedstock will require new feedstocks to be cultivated in large quantities. Of these, grasses and short rotation coppice appear most promising, although these will take time to develop to scale. Depending on the assumptions used, estimates of fuel production from new lignocellulosic feedstocks range from 10-30 GL per annum.

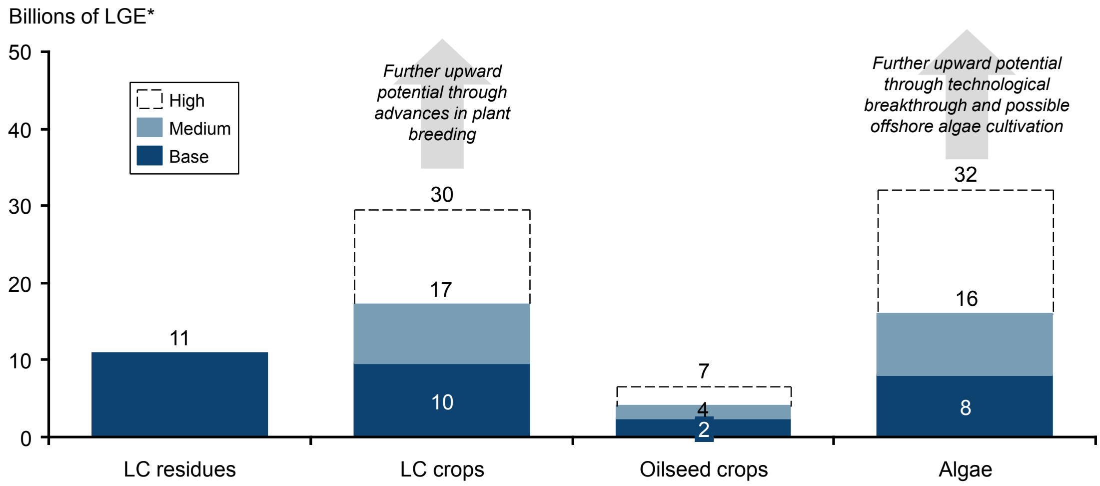
The current agricultural system provides only limited quantities of **oil based biomass**. However, a dedicated oilseed industry could be developed relatively quickly, leveraging annual oilseed species such as juncea, camelina and pongamia. New oilseeds are slightly more costly with less attractive GHG emissions than new lignocellulose feedstocks, and production quantities likely to be <10 GL. Nonetheless once established, these production systems are easy to maintain, and harvested oilseeds can be easily fed into established technology pathways.

Algae biomass has the potential to provide significant production scale with more limited land use. In addition, those production systems that use CO_2 emissions have very attractive GHG emission reduction benefits. However, all algae systems are reliant on technologies which are unproven on a commercial scale, so technology learning curves will be critical to how this can be best positioned within an Australia biofuels industry over time. Depending on assumptions made about CO_2 sources, land, water and growth rates, production estimates range from 8 GL to as high as 32 GL.

Additionally, there is the potential to explore other feedstock options (e.g. cyanobacteria, yeast, offshore macroalgae cultivation) in the medium to long run. These very early stage biomass sources provide further upside scalability potential for Australia.

The potential ranges of fuel production from existing and potential new biomass sources are shown below (Figure 21). Ranges are derived by sensibly adjusting assumptions around key input constraints such as availability and yields, and illustrate that new LC crops and algae have significantly higher scale potential than either LC residues or oilseed crops.

Figure 21: Scalability of feedstock: sensitivity analysis (2011E)^



Note: Waste oils (e.g. tallow) not shown in diagram; * LGE = gasoline equivalent litres; ^ Key assumptions: i) LC residues: mass after applying structural, environmental, and technical feasibility constraints (all cases), ii) LC crops: grown on 1% of grazing land (base case) to 4% of grazing land and lower average land utilisation (high case), iii) Oilseed crops: grown on 2.5% of cropping land without displacing food crops (base case) to 10% of cropping land without displacing food crops and lower average land utilisation (high case), iv) Algae: utilisation of 5% of total Australian emissions (base case) to 20% of total Australian emissions (high case)

Source: L.E.K. research, interviews and analysis

5. CONVERSION TECHNOLOGIES

5.1. Introduction

This section of the Appendix provides an overview of the key conversion technologies for producing advanced biofuels. These technologies can be combined with feedstocks to form 'pathways' for biofuels production, which are then assessed for their relative attractiveness. This assessment and prioritisation is considered beneficial in helping industry and government focus on areas most prospective in the Australian context.

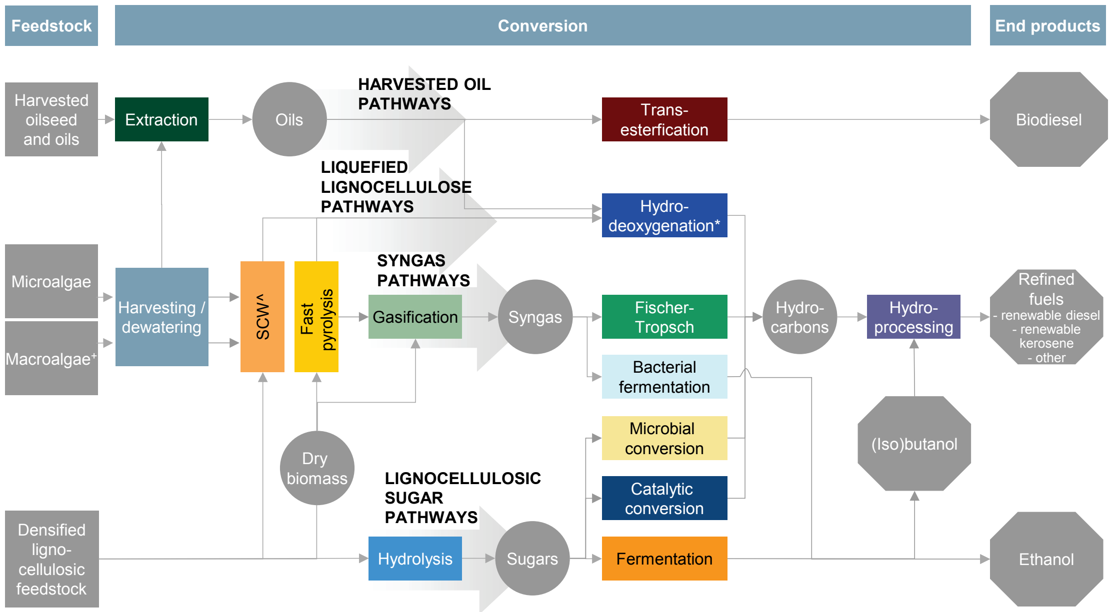
Each pathway comprises a complete set of processes necessary to convert a harvested feedstock into a biofuel. For the purpose of this section, the processes within a pathway are called technology steps. The output of technology steps that do not result in the final end biofuel are called intermediary products; these are necessary to produce the end product, but may also have standalone uses. Similar pathways have been grouped into groups ('pathway groups'). These typically take the same harvested feedstock and produce the same end biofuel, and / or share common intermediary products.

Feedstock can be converted into an advanced biofuel through a number of different pathways. Conversion technology pathways considered in this section have active players driving their development (in whole or in part) towards commercialisation.

There are four pathway groups considered:

1) the **harvested oils** pathway group covers the conversion of vegetable and algal oils into either biodiesel or refined fuels;
2) the **liquefied lignocellulose** pathway group describes the conversion of lignocellulosic materials into intermediary oil products that are further upgraded to refined fuels;
3) the **syngas** pathway group involves the conversion of lignocellulosic materials to synthesis gas (syngas) that can be further converted into refined fuels or ethanol; and
4) the **lignocellulosic sugars** pathway group includes the extraction of sugars from lignocellulosic materials and the conversion of these sugars to either ethanol or refined fuels.

Figure 22: Advanced biofuel conversion pathway groups



Note: There are a number of companies developing microorganisms capable of biologically producing substances similar to refined fuels, which may bypass the conversion steps in the diagram above. * The processing of different oils via this conversion process are at different levels of maturity and there may be technical processing differences depending on the source of the oil; ^ Supercritical water treatment, or similar thermochemical liquefaction processing, produces a green crude that has properties different to that derived from fast pyrolysis, in particular lower oxygen content. + Macroalgae can also be processed using fast pyrolysis technology

Source: L.E.K. interviews, research and analysis

Each conversion technology pathway is made up of a number of technology steps, which can be at differing levels of development status. A pathway is only considered commercial when all its requisite technology steps are considered commercial.

5.2. Conversion technologies

The conversion technology pathways within each pathway group are considered in turn. Each one has been assessed in terms of attractiveness against three key criteria:

- **Produces drop-in fuel:** Pathways that produce fuels that can be used with existing end-user and fuel supply infrastructure will be most attractive. This means that pathways that produce drop-in equivalent fuels (e.g. via 'green crude') have been prioritised above those that produce ethanol and biodiesel, which typically must be blended with refined fuels for compatibility with existing infrastructure.
- **Leverages Australia's comparative advantages:** Pathways that utilise Australia's key comparative advantages, in agricultural science and research, abundance of flat land and sunlight, and suitable climate for growing dedicated energy crops, have been prioritised. By corollary, pathways that play to Australia's comparative disadvantages have been deprioritised. For example, Australia does not have a large scale established conventional biofuel industry so pathways relying on retrofitting conventional plants are considered less attractive.

- **Logistical compatibility within the Australian context:** Key components required to build a successful advanced biofuels industry exist in Australia, however, these components are not always co-located. For instance, ideal cultivation land may not be located near existing supply chain or processing infrastructure. Pathways that overcome costly logistical challenges are more attractive.

The discussion in this section is based on a synthesis of available public information from a range of sources including leading research and industry bodies (e.g. CSIRO, IEA, RIRDC), interviews with key domestic and international industry players and researchers across the different steps in the technology tree, peer-reviewed journals, company websites and press releases.

Information deemed potentially commercially sensitive has been excluded from this section.

Given the early stage of development of some technologies, the above criteria cannot currently be assessed with complete certainty, and conclusions should therefore be treated with caution. Where there are major uncertainties, these have been noted.

Figure 23: What is "green crude"

Green crude is the term used to describe the renewable equivalent of crude oil. It is a crude substance derived from current biomass sources and can be refined in a similar way to crude oil.

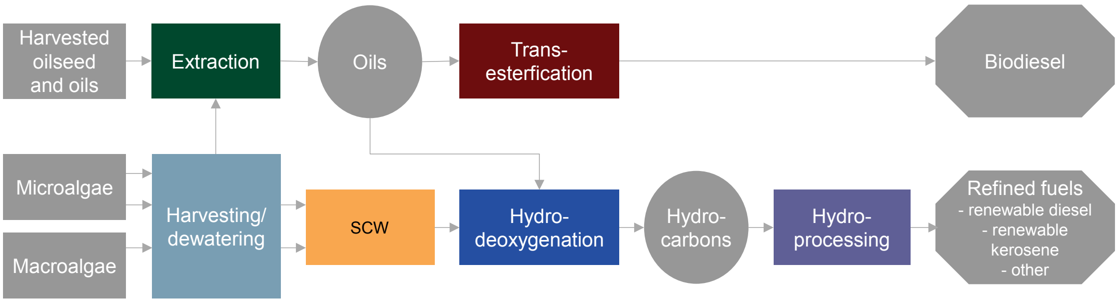
Like crude oil, there are different varieties of green crude with different characteristics and pre-processing requirements.

By this definition, intermediary vegetable oils, intermediary algal oils, pyrolysis bio-oils and SCW bio-crudes are all varieties of green crude.

5.2.1. Harvested oils pathway group (Pathway Group 1)

The harvested oils pathways group includes the conversion of extracted oils from oilseed crops or algae to produce biodiesel through transesterification, or the conversion of these oils to refined fuels through hydrodeoxygenation and hydroprocessing.

Figure 24: Harvested oils conversion technology pathways



This group covers five specific conversion technology pathways:

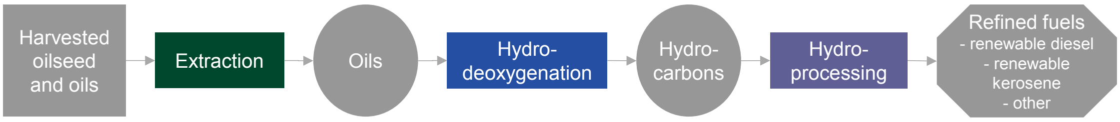
- oilseed to refined fuel via oil extraction (pathway 1a);
- algae to refined fuel via oil extraction (pathway 1b);
- algae to refined fuel via SCW treatment[2] (pathway 1c);
- oilseed to biodiesel via transesterifcation (pathway 1d); and
- algae to biodiesel via transesterifcation (pathway 1e).

Pathway 1a: Oilseed to refined fuel via oil extraction

Technology description:

Harvested oilseeds can be processed into refined fuels through a multi-stage conversion process. Intermediary vegetable oils are extracted from oilseeds of harvested oilseed crops, such as pongamia and juncea. Waste oils can also be used with appropriate pre-processing.

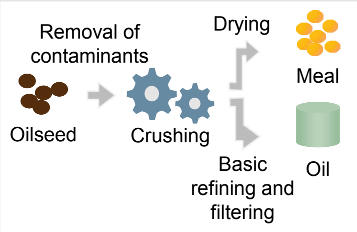
Figure 25: Oilseed to refined fuel via oil extraction (Pathway 1a)



[2] While pathway 1c does not require the harvesting / extraction of oil from algal biomass (instead using the entire biomass in the conversion process), it has been included in the 'harvested oils' pathway group for ease of comparison with pathway 1b, as both pathways share the same inputs and end products.

Figure 26: Technology step summary - Extraction

Extraction – *the extraction of vegetable oils from harvested oilseeds*

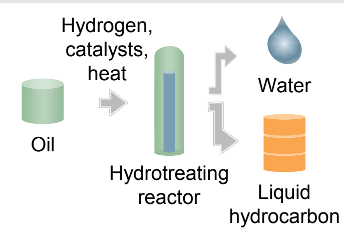


Technology description: Mechanical extraction: the seed is pressed, separating the oil from the meal (c.65-80% recovery). Solvent extraction: solvent is applied to prepressed material; the solvent bonds to the oil and an oil laden solvent solution is separated. This solution is then processed to separate the oil from the solvent (c.95% recovery)

Hydrodeoxygenation for intermediary vegetable oils involves treating the oils with heat and hydrogen to remove unwanted oxygen. This step for intermediary vegetable oils is well understood and the process can be performed at a standalone unit or co-located with refinery infrastructure. However, it may be more economical to co-locate the process with refinery infrastructure, which may provide access to a lower cost source of hydrogen.

Figure 27: Technology step summary - Hydrodeoxygenation

Hydrodeoxygenation – *conversion of intermediary oil products to hydrocarbon chains*

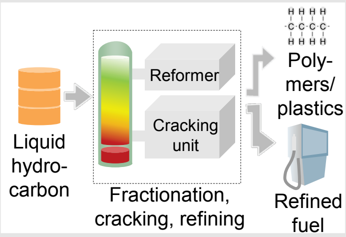


Technology description: Processed oils are heated to high temperatures and a catalyst is added. Hydrogen is bubbled through the liquid to displace oxygen and other impurities. The mixture is then filtered, leaving liquid hydrocarbons

The upgraded oils (post hydrodeoxygenation) can then be processed into refined fuels through hydroprocessing. This is similar to the process used for crude oil and requires similar refinery infrastructure and technology. For crude oil, refinery processing involves fractional distillation that separates the crude into component fractions. The fractions are typically hydrotreated to stabilise them and remove unwanted elements such as sulphur and nitrogen. Depending on desired end product, fractions may then undergo cracking and / or reforming. Green crudes require limited, if any, distillation, but appear likely to need a hydrocracker (rather than only a fluid catalytic cracker) to achieve acceptable end product yields. Finally, output can be further processed to remove impurities and to meet product specifications and standards. For intermediary vegetable oils, the specific process will depend on the chemical composition of the particular vegetable oil and the desired end product.

Figure 28: Technology step summary - Hydroprocessing

Hydroprocessing – *conversion of hydrocarbon chains to renewable fuels*



Technology description: Key hydroprocessing steps include fractionation, cracking, and reforming. Fractionation involves separating the different lengths of hydrocarbon chains in a crude mixture on the basis of differences in boiling points. Cracking involves the application of hydrogen and / or catalysts to break longer chains into shorter chains. Reforming involves joining or rearranging chains. Hydroprocessing also includes hydrotreating to remove contaminants (e.g. sulphur) and blending (e.g. additives) to give desired properties to end products. The combination of steps used depends on input mixture and desired output

Discussion

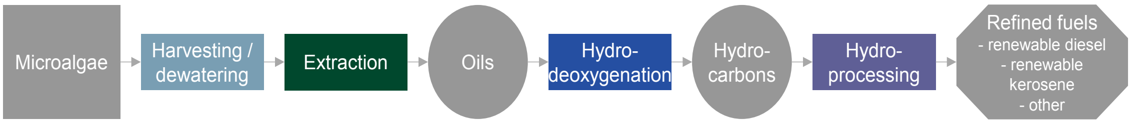
This pathway is attractive. It has potential to produce refined fuels via technology that is relatively proven. Key issues are scale related, around ensuring stable supply volumes to enable integration with existing refineries, or alternatively, securing significant upfront capital investment and engineering capability for new processing infrastructure.

Pathway 1b: Algae to refined fuel via oil extraction

Technology description:

Refined fuels can be produced through a multi-stage process from algae harvested in a controlled environment.

Figure 29: Algae to refined fuel via oil extraction (Pathway 1b)

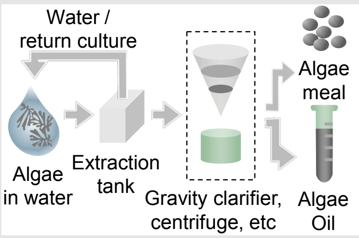


This conversion pathway involves the extraction of algal oil from harvested algal biomass (typically only microalgae for its higher oil content), followed by conversion into a refined fuel. The algal oil can be extracted from the harvested algal biomass using a range of techniques at the cultivation site. Algal oils are often triglyceride-based and have a similar composition to vegetable oils from oilseeds (see pathway 1a). The remaining algal biomass, or algal meal, can be considered a co-product.

Following extraction, the process is similar to pathway 1a, and the oils may be converted to an end fuel through hydrodeoxygenation and hydroprocessing. The remaining algal meal may contribute ancillary revenues with applications for animal feed, nutraceuticals and pharmaceuticals.

Figure 30: Technology step summary – Harvesting & oil extraction (algae)

Harvesting & Oil extraction – *removal of algae from growth medium and extraction of oils*



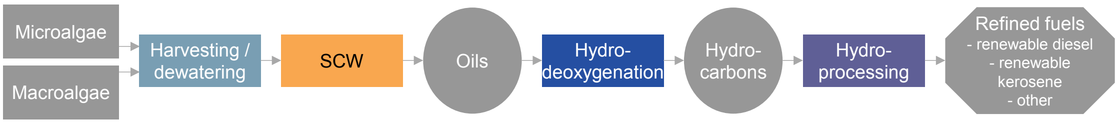
Technology description: There are numerous approaches to obtaining oil from cultivated algae. One approach has been to harvest and dewater prior to the separation of oils. Harvesting and dewatering involves removing the algae from its growth medium. Examples of technologies used to perform this include centrifugation, flocculation, filtration and flotation. Separation of oils from the remaining biomass can then be achieved by mechanical and / or solvent based techniques. Alternative approaches have focused on the separation of oils with less or no dewatering, for example using ultrasonic waves to break down algae cell walls

Pathway 1c: Algae to refined fuel via SCW treatment

Technology description:

Refined fuels can be produced from algal crude derived from algae harvested in a controlled environment.

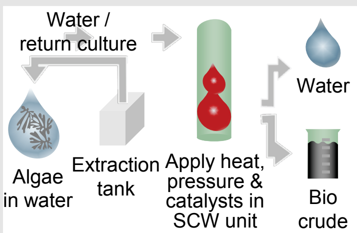
Figure 31: Algae to refined fuel via SCW treatment (Pathway 1c)



This pathway involves the liquefaction of harvested algal biomass, to create algal crude, followed by conversion into a refined fuel. Liquefaction of the algal biomass can be achieved through supercritical water treatment (see pathway 2b) or a similar thermochemical process. The use of the entire biomass can result in relatively high yields, and an intermediary product that may be more similar to fossil-derived crude oil than the triglyceride-based algal oil through oil extraction (see pathway 1b). As the entire biomass is required, however, this process does not produce algal meal, which may be a relatively valuable co-product.

Figure 32: Technology step summary – Harvesting & SCW treatment

Harvesting & SCW treatment – *removal of algae from growth medium and SCW treatment*



Technology description: Algal crude can be obtained from cultivated algae through a multi-stage process. Harvesting and dewatering techniques, like those used in algae harvesting and oil extraction, are first used to remove the algae from its growth medium. The algal biomass is then liquefied using thermochemical processes, such as supercritical water, which involve subjecting the biomass to controlled temperature and pressure conditions in the presence of appropriate catalysts. This process creates a crude mixture different to oil extraction processes described earlier.

Discussion

Overall, both pathways 1b and 1c are attractive, with significant potential to substitute for fossil fuels. Within the range of different algal technology options, the most attractive will be those that have the ability to scale and can do so in a cost competitive way.

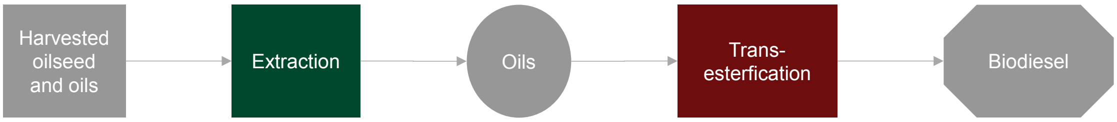
The key challenges for the pathways relate to developing cost effective approaches at large scales for algae cultivation and the production of algal oil / algal crude. R&D momentum appears to be high around these challenges. In addition, depending on the chosen technology, these pathways have potential to capitalise on Australia's abundance of flat land and high solar irradiance, which are beneficial for phototrophic algae cultivation.

Pathway 1d: Oilseed to biodiesel via transesterification

Technology description:

This pathway involves the extraction of intermediary vegetable oils from harvested oilseeds to produce biodiesel through transesterification. Oils can be separated from harvested oilseed crops using various extraction techniques, or waste oils can be used with appropriate pre-processing, similar to pathway 1a. The extraction / pre-processing step may be performed at the biomass source or at the biodiesel production facility.

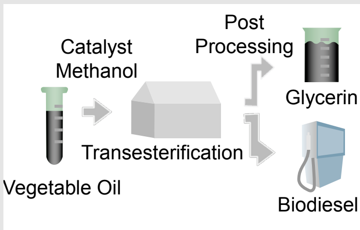
Figure 33: Oilseed to biodiesel via transesterification (Pathway 1d)



Biodiesel is produced through the transesterification of intermediary vegetable oils, which involves the removal of glycerine (that can be sold as a co-product) through a chemical process, leaving the fatty acid biodiesel product. This process does not require refinery infrastructure.

Figure 34: Technology step summary - Transesterification

Transesterfication – *conversion of plant derived oils to biodiesel*



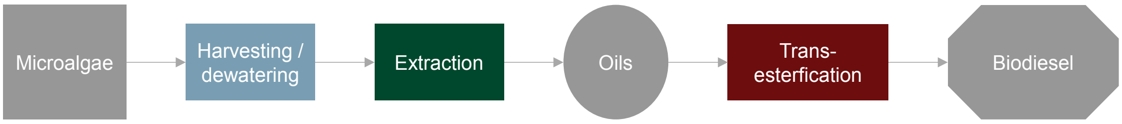
Technology description: This process involves the neutralisation of fatty acids in triglyceride molecules, the removal of glycerin and the creation of an alcohol ester. This is accomplished by mixing methanol and a catalyst with the vegetable oil. After settling, glycerin is left on the bottom and biodiesel on top

Discussion

This pathway uses mature technology. Industry experience suggests, however, that unless low cost feedstock can be consistently sourced (with minimal price fluctuations) production may not be economically viable. In addition, the end fuel produced, biodiesel, is not a drop-in fuel which limits its end-use applications.

Conversion pathway 1e: Algae to biodiesel via transesterification

Figure 35: Algae to biodiesel via transesterification (Pathway 1e)

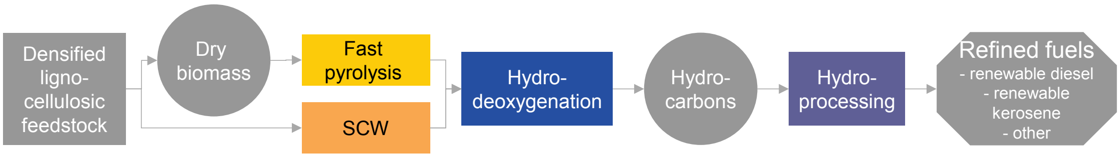


Extracted algal oil from harvested algal biomass (typically only microalgae for its oil content) can be processed into biodiesel in a way similar to oil from oilseeds (pathway 1d), rather than upgraded to a refined fuel (pathways 1a and 1b). This process can be used for triglyceride oils extracted from the algae. However, most algae producers are focused on developing refined fuels (pathway 1b) and/or high value products, and this pathway does not produce a drop-in fuel which limits its end-use applications.

5.2.2. Liquefied lignocellulose pathway group (Pathway Group 2)

The liquefied lignocellulose pathway group includes the conversion of lignocellulosic feedstock to a refined fuel through hydrodeoxygenation and hydroprocessing.

Figure 36: Liquefied lignocellulose conversion technology pathways



Two liquefaction pathways are covered in this pathway group:

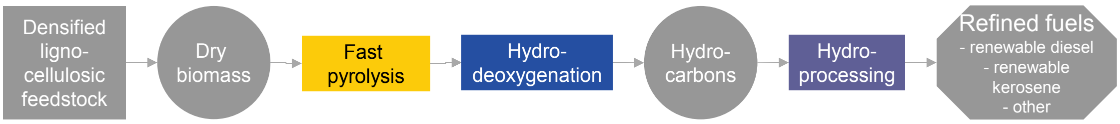
- lignocellulose to refined fuel via fast pyrolysis (pathway 2a); and
- lignocellulose to refined fuel via SCW treatment (pathway 2b).

Pathway 2a: Lignocellulose to refined fuel via fast pyrolysis

Technology description:

This conversion pathway involves liquefaction of lignocellulosic materials through fast pyrolysis into bio-oil, followed by upgrading to a refined fuel through hydrodeoxygenation and hydroprocessing.

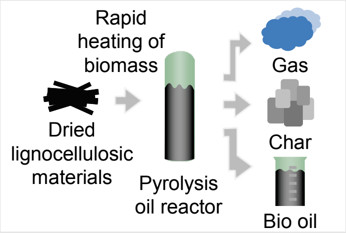
Figure 37: Lignocellulose to refined fuel via fast pyrolysis (Pathway 2a)



Lignocellulosic materials, such as agricultural or forest residues, are first liquefied to create a bio-oil using fast pyrolysis. Char and gas are co-products also produced from the process. The char can be sold and the gas used for heating purposes.

Figure 38: Technology step summary - Fast pyrolysis

Fast pyrolysis – conversion of lignocellulosic materials to bio-oil



Technology description: Dried and ground biomass is heated rapidly in the absence of oxygen, releasing volatiles that are rapidly condensed into a dark liquid bio-oil. Residuals from the process are gases that cannot be condensed, and solids (char) that contain carbon

Fast pyrolysis is a modular technology that may be located at the biomass source. Despite the produced bio-oil having a high oxygen content (similar to the woody feedstock it is created from), as a liquid it is significantly less bulky compared to the raw lignocellulosic feedstock. This reduces the logistics costs of transport for downstream processing.

Hydrodeoxygenation for bio-oil is similar to the process used for vegetable oils (pathway 1a), but is more complex because of the high oxygen content of bio-oil and a consequent hydrogen requirement and need for catalyst optimisation. A producer may choose to either perform hydrodeoxygenation at a standalone facility, or to co-locate with a refinery. The advantage of co-locating is the potential access to a low cost source of hydrogen. Alternatively, bio-oil can be used in low grade industrial fuel applications, for example as a replacement for fuel oil.

Similar to non-renewable crude oil, the hydrocarbon produced from the hydrodeoxygenation step can be upgraded into a refined fuel at a refinery. The required hydroprocessing steps will depend on the properties of the input and desired end product.

Discussion

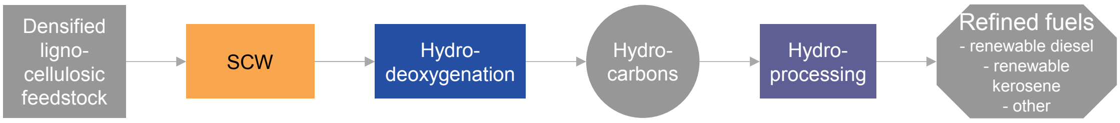
This pathway is attractive because it can produce refined fuels and its modular nature complements the dispersed nature of Australia’s current and potential lignocellulosic feedstock sources. Fast pyrolysis technology is also mature; however, challenges include scale deployment of processing plants and the optimisation of the bio-oil hydrodeoxygenation process. R&D momentum appears to be high around these challenges.

Pathway 2b: Lignocellulose to refined fuel via SCW treatment

Technology description:

This pathway involves liquefying lignocellulosic materials through supercritical water (‘SCW’) treatment, then upgrading the intermediary oil into refined fuels through hydrodeoxygenation and hydroprocessing.

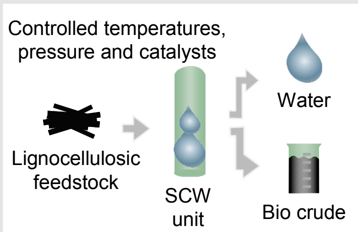
Figure 39: Lignocellulose to refined fuel via SCW treatment (Conversion pathway 2b)



SCW treatment produces a stable form of bio-crude from lignocellulosic materials, which can have a significantly lower oxygen content compared to pyrolysis bio-oil. The bio-crude can also be converted into refined fuels via an upgrading process involving hydrodeoxygenation and hydroprocessing.

Figure 40: Technology step summary - Supercritical water ('SCW') treatment

Supercritical Water treatment – conversion of lignocellulosic materials to liquid bio-crude



Technology description: Lignocellulosic feedstocks are liquefied by the application of water and / or appropriate catalysts in a controlled temperature and pressure environment. This selectively cuts chemical bonds leaving a low-oxygen bio crude

A key difference between fast pyrolysis and SCW treatment is that the latter does not require the biomass to be dried, which may significantly reduce pre-processing requirements depending on the feedstock. However, there may be issues with co-locating SCW processing plants close to biomass sources, as the technology requires high-pressure equipment that has strict operating conditions and potentially may create safety hazards.

Bio-crude derived from SCW treatment also has a lower oxygen content compared to pyrolysis bio-oil, making it denser (on an energy content basis) and therefore less costly to transport. This also makes the hydrodeoxygenation step potentially more straightforward, as there is less oxygen to remove and it allows for the use of existing catalyst technologies. Commentators believe this may make SCW derived bio-crude more attractive for a refinery to process compared to pyrolysis derived bio-oil.

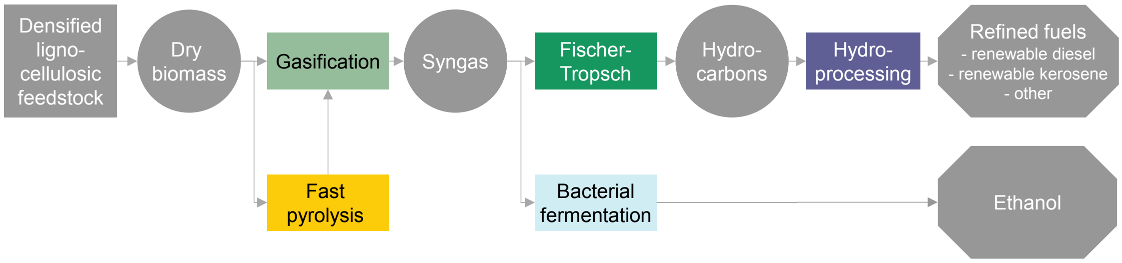
Discussion

This conversion pathway is attractive. This conversion pathway provides a route to refined fuels from a variety of lignocellulosic sources. The relatively lower oxygen content of bio-crude (compared to bio-oil derived via fast pyrolysis) may reduce the complexity of upgrading to end fuels. However, the SCW technology and upgrading processes are unproven at significant scale, which remains a key challenge for the pathway. In addition, R&D momentum and investment in the conversion pathway remains limited compared to fast pyrolysis (see pathway 2a).

5.2.3. Syngas pathway group (Pathway Group 3)

The syngas pathway group involves the conversion of lignocellulosic materials into synthesis gas (syngas). This is followed by either upgrading to refined fuels through Fischer-Tropsch (FT) synthesis and hydrocracking, or bacterial fermentation to ethanol.

Figure 41: Syngas conversion technology pathways



This pathway group covers two pathways:

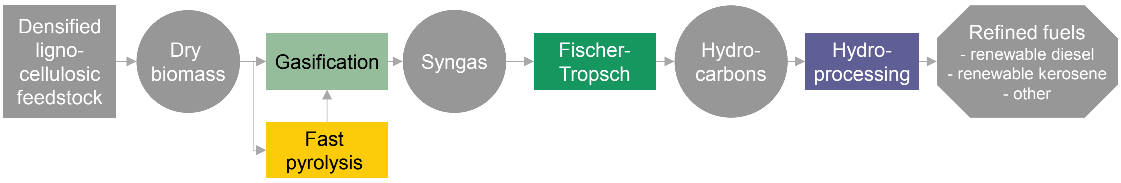
- lignocellulose to refined fuel via gasification and FT (pathway 3a); and
- lignocellulose to ethanol via gasification and bacterial fermentation (pathway 3b).

Pathway 3a: Lignocellulose to refined fuel via gasification and FT

Technology description:

Lignocellulosic feedstock can be converted to refined fuels through gasification and downstream processing.

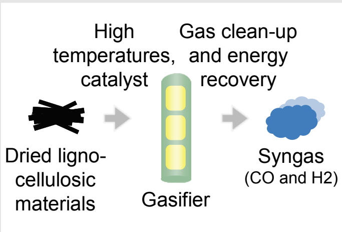
Figure 42: Lignocellulose to refined fuel via gasification and FT (Conversion pathway 3a)



The gasification process converts dried finely ground lignocellulosic materials to syngas. This process is potentially highly feedstock flexible, with even municipal waste considered a possible feedstock source. Alternatively, the biomass may be liquefied prior to gasification using liquefaction techniques, such as fast pyrolysis (see pathways 2a and 2b). The primary motivation for this additional step is to reduce logistics costs of transporting bulky dry biomass, though the trade-off is additional processing costs. The liquefied biomass may also be more amenable to gasification.

Figure 43: Technology step summary - Gasification

Gasification – *conversion of lignocellulosic materials to synthesis gas (syngas)*

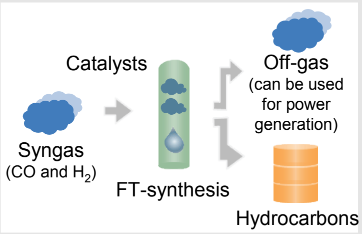


Technology description: Dried biomass is decomposed by heating it to very high temperatures, breaking molecular bonds in the material while controlling the amount of oxygen present in the mix to produce a synthesis gas (syngas)

The syngas is converted through FT synthesis, which involves heat, pressure and catalytic reactions to create hydrocarbon chains (in particular waxes). The hydrocarbon chains can be processed into refined fuels in a manner similar to heavy paraffinic fractions of crude oil.

Figure 44: Technology step summary - Fischer-Tropsch

Fischer-Tropsch – *conversion of syngas to liquids*



Technology description: High heat and pressure is applied to syngas, and a catalyst is introduced. The catalyst triggers a chemical reaction between the hydrogen and carbon monoxide, creating long chains of hydrocarbons. Different catalysts can produce different hydrocarbon structures

Discussion

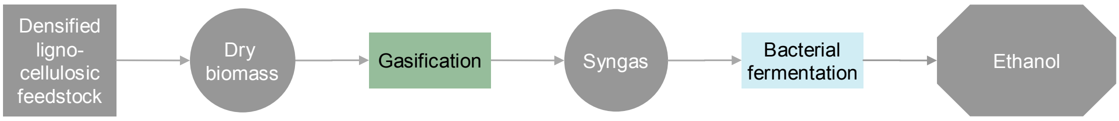
This process is moderately attractive. At scale, FT is an efficient process that produces high quality fuels and is feedstock flexible. The extreme conditions required for the process, however, lead to high capital and maintenance costs. This implies large-scale production may be required to achieve cost efficiency. The corollary is that biomass densities within a given radius of production facilities need to be sufficient, or else logistics costs may become prohibitive.

Pathway 3b: Lignocellulose to ethanol via gasification and bacterial fermentation

Technology description:

This conversion pathway involves the conversion of lignocellulosic materials or municipal and other waste streams to syngas. The syngas is converted through microorganisms that consume carbon monoxide and hydrogen, producing ethanol.

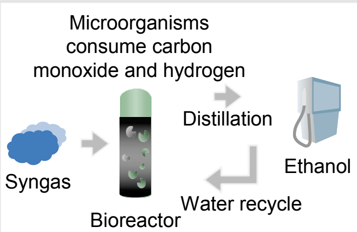
Figure 45: Lignocellulose to ethanol via gasification and bacterial fermentation (Conversion pathway 3b)



This conversion pathway can produce ethanol for blending with fossil fuel derived petroleum, with the potential for higher blends with appropriate engine technology. While some companies are currently focused on ethanol, in the long-run there also may be opportunities to produce chemicals (such as butanol), which could be sold directly or converted to refined fuels.

Figure 46: Technology step summary - Bacterial fermentation

Bacterial fermentation – *conversion of syngas to ethanol using microorganisms*



Technology description: Microorganisms covert syngas by consuming the carbon monoxide and hydrogen in the gas stream. Following the gas-to-liquid conversion, the resulting ethanol is recovered using well established distillation processes

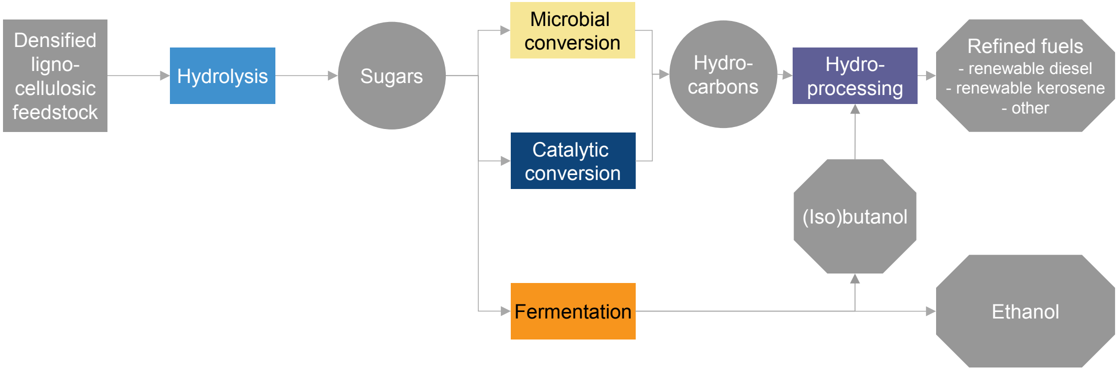
Discussion

This conversion pathway has the potential to be highly feedstock flexible and does not require potentially costly pre-treatment and hydrolysis of feedstock, which some other ethanol conversion pathways do (see pathway 4a and 4b). However, the end fuel produced, ethanol, is not a drop-in fuel which limits its end-use applications.

5.2.4. Lignocellulosic sugar pathway group (Pathway Group 4)

The lignocellulosic sugars pathway group includes the conversion of extracted sugars from cellulosic biomass to produce ethanol or refined fuels using biological or catalytic upgrading of sugars to hydrocarbon products. These products can be processed into refined fuels through refinery hydroprocessing steps or distillation to ethanol.

Figure 47: Lignocellulosic sugar conversion technology pathways



This pathway group covers four conversion pathways:

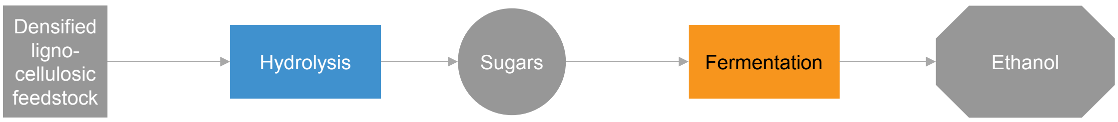
- lignocellulose to ethanol via fermentation (pathway 4a);
- lignocellulose to refined fuel via microbial conversion (pathway 4b);
- lignocellulose to refined fuel via catalytic conversion (pathway 4c); and
- lignocellulose to refined fuel via fermentation and hydroprocessing (pathway 4d).

Pathway 4a: Lignocellulose to ethanol via fermentation

Technology description:

Ethanol can be produced by hydrolysis of lignocellulosic materials to extract sugars, which are fermented to produce cellulosic ethanol.

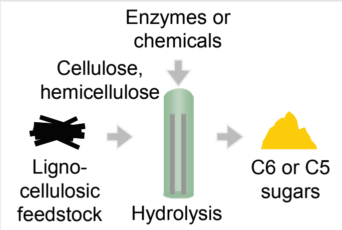
Figure 48: Lignocellulose to ethanol via fermentation (Pathway 4a)



Following the pretreatment of lignocellulosic materials, the cellulose and hemicellulose can be separated into sugars using enzymatic hydrolysis. Alternatively, the lignocellulose can be hydrolysed directly using chemical methods. Enzymatic methods are predominately used for this step however some companies are developing chemical (acid) hydrolysis processes for biomass dissolution. Both these approaches are the subject of further research: chemical hydrolysis requires strong acids and potentially suffers from a number of inhibitory by-products, while the slower enzymatic process may require further optimisation to improve economics.

Figure 49: Technology step summary - Hydrolysis

Hydrolysis – *extraction of sugars from lignocellulosic materials*

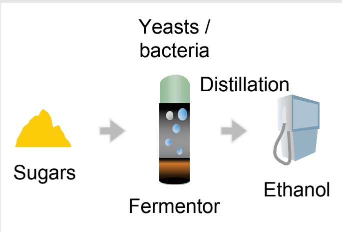


Technology description: This process involves recovering sugars from lignocellulosic materials. Lignocellulose consists of three main components: lignin, cellulose and hemicellulose. Sugars come from cellulose and hemicellulose. The process can be performed using enzymes on pre-treated feedstock (with pre-treatment procedures used to remove lignin), or directly using chemical methods.

Cellulosic sugars can be converted into ethanol and water by fermentation with yeasts and bacteria. Distillation can then be used to separate the cellulosic ethanol, which has the same properties as conventional ethanol. The hydrolysis and fermentation steps are generally co-located.

Figure 50: Technology step summary - Fermentation

Fermentation – *the conversion of sugars into alcohols*



Technology description: Fermentation refers to the conversion of sugars to alcohols and water by yeasts and bacteria, often under anaerobic conditions, though the specific process differs between organisms. The conversion takes place through a series of transformation steps within the organisms. Distillation is then used to separate ethanol from the water produced

Discussion

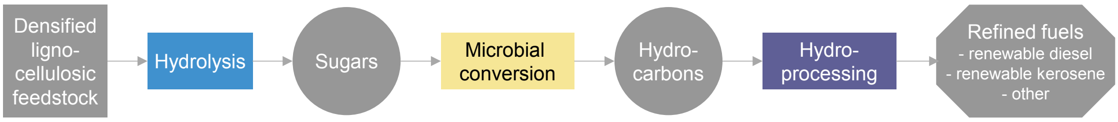
This conversion pathway is currently under development, with substantial R&D momentum, particularly in the US. The key challenge for the conversion pathway is improvement of hydrolysis technologies. If this is overcome the pathway may be attractive, however, the end fuel produced, ethanol, is not a drop-in fuel which limits its end-use applications.

Pathway 4b: Lignocellulose to refined fuel via microbial conversion

Technology description:

Refined fuels may be produced from lignocellulosic materials through the microbial conversion of cellulosic sugars.

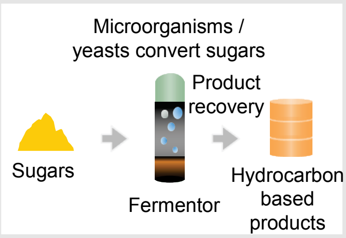
Figure 51: Lignocellulose to refined fuel via microbial conversion (Pathway 4b)



Pre-treated lignocellulosic materials are first hydrolysed using either chemical or enzymatic methods to extract the cellulosic sugars (see pathway 4a). The extracted sugars are next fermented with tailored microorganisms to produce intermediary hydrocarbons, which may then be upgraded to a refined fuel by hydroprocessing with refinery infrastructure and technology. The intermediary hydrocarbons produced by fermentation may also be suitable for processing into high value chemicals. For this reason, some companies in the space appear to be focusing their efforts on chemicals and non-fuel products.

Figure 52: Technology step summary - Microbial conversion

Microbial conversion – *conversion of sugars to hydrocarbons*



Technology description: The process uses engineered yeasts or microorganisms to convert sugar into hydrocarbon products. The hydrocarbon output forms a separate phase and floats on top of the fermentation broth. The recovery and purification of the hydrocarbon is therefore relatively straight forward

Discussion

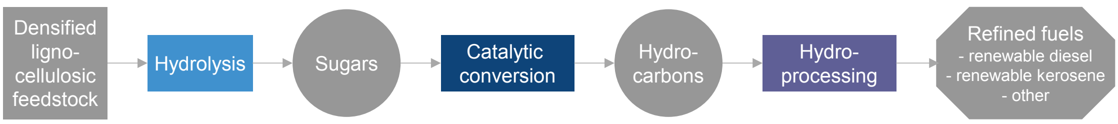
This pathway to refined fuels is at an early stage of development and there are uncertainties regarding large-scale production. In addition, there appears to be limited R&D momentum across the full pathway from lignocellulose. Current efforts have focused on utilising conventional sugars as feedstock, and fuel has not been the priority by all players active in the space. This makes the pathway less attractive in the Australian context until full pathway development gains more momentum.

Pathway 4c: Lignocellulose to refined fuel via catalytic conversion

Technology description:

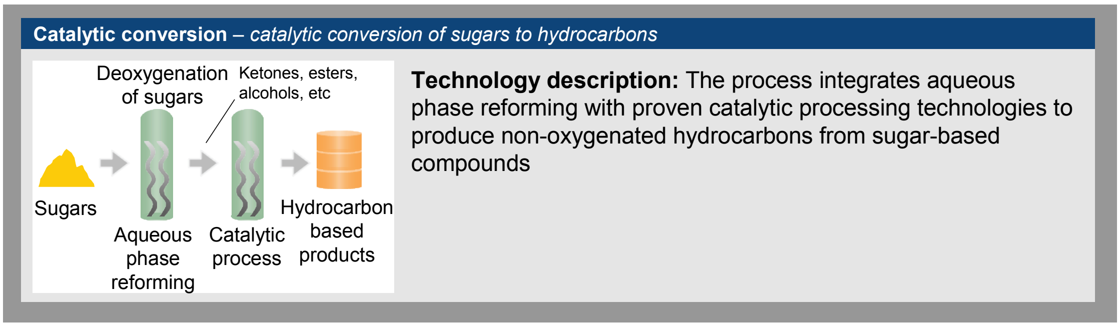
This pathway involves the catalytic conversion of cellulosic sugars into refined fuels.

Figure 53: Lignocellulose to refined fuel via catalytic conversion (Pathway 4c)



Similar to pathway 4b, pre-treated lignocellulosic materials are first hydrolysed to extract cellulosic sugars. The extracted sugars are then converted using chemical catalysts to form intermediary hydrocarbons, which may then be upgraded to a refined fuel by hydroprocessing with refinery infrastructure and technology.

Figure 54: Technology step summary - Catalytic conversion



Discussion

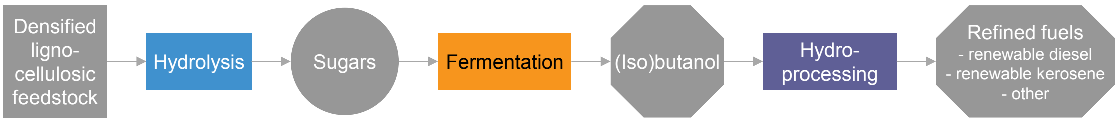
Similar to pathway 4b, this conversion pathway is at an early stage of development and there are uncertainties regarding large-scale production. Activity to date has utilised conventional sugars as feedstock, but there is some R&D focus on using lignocellulosic sugars as feedstock. Key challenges include optimising catalysts and further developing the full end-to-end pathway. The pathway is currently less attractive in the Australian context, but should be observed for future developments.

Pathway 4d: Lignocellulose to refined fuel via fermentation and hydroprocessing

Technology description:

Lignocellulosic materials can be converted into (iso)butanol through hydrolysis and fermentation, similar to cellulosic ethanol.

Figure 55: Lignocellulose to refined fuel via fermentation and hydroprocessing (Pathway 4d)



Following the hydrolysis of lignocellulosic materials, extracted cellulosic sugars can be fermented, using tailored organisms, to (iso)butanol and water. The (iso)butanol can be separated from the water using distillation. While butanol and isobutanol are currently sold in the chemicals market, they can be potentially upgraded to refined fuels using appropriate hydroprocessing techniques. It is expected that hydrolysis and fermentation steps could be co-located, but technology to date has focused on retrofitting existing ethanol plants and using conventional sugars as feedstock.

Discussion

This pathway to refined fuels is attracting some particular private sector attention. Key challenges are technology related and include the final upgrading step of (iso)butanol to refined fuels as well as hydrolysis of lignocellulosic feedstocks. While there has been renewed R&D interest in this pathway in recent months, this pathway may be less attractive in the Australian context. The development of this pathway is somewhat dependent on leveraging substantial existing infrastructure and technology, where Australia is at a comparative disadvantage relative to other countries, such as the US and Brazil, which may be natural developers of this pathway given their ability to build on significant conventional ethanol industries.

5.3. The next generation of advanced biofuels

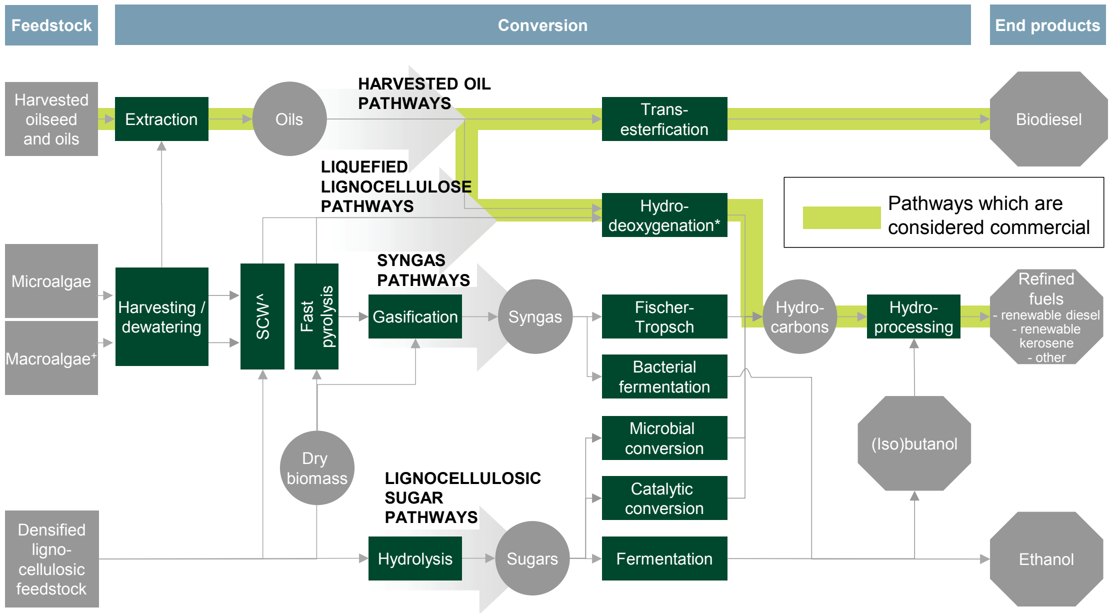
A number of companies are developing microorganisms capable of biologically producing substances similar to refined fuels, removing the need for a number of intermediary technology steps. The main benefit of these technologies is they promise to deliver refined fuels at a significantly lower cost by reducing the need for external refinery processing. This represents an attractive longer term prospect for countries without a comparative advantage in refinery infrastructure.

These technologies are at various stages of development and have different levels of engineering aspiration, with some players aiming to completely bypass the need for refining infrastructure by targeting near drop-in fuel production from microorganisms. Key challenges revolve around organism design, but also include many scale up issues faced by other pathways utilising microorganisms (see pathways 1b and 1c).

5.4. Summary and conclusions

Most of the conversion pathways analysed are at varying early stages of development, with the exception of a small number of pathways that are commercial (illustrated by green arrows in the diagram on the following page).

Figure 56: Advanced biofuel conversion pathways currently considered commercial



Note: The technology progression in the above diagram refers to the full technology conversion pathways. While individual parts of a particular conversion pathway may be commercial in isolation, this does not necessarily mean a conversion pathway from feedstock to fuel is commercial; * The degree of commerciality depends on the source of the intermediary oil fed into this step; + Macroalgae can also be processed using fast pyrolysis technology

Source: L.E.K. interviews, research and analysis

This makes prioritisation difficult, as the precise timing of technology breakthroughs cannot be estimated with accuracy. Complicating this fact is that some companies appear to be also focusing on alternative (non-fuel) products, or are working on only specific steps within conversion pathways.

Furthermore, a final assessment of attractiveness needs to incorporate all aspects of the value chain from feedstock through to end user adoption. Chapter Six of this Appendix will review production economics and scale, including the availability and cost of feedstock, conversion and refining costs.

These difficulties notwithstanding, some conversion pathways appear inherently more attractive than others. The key factors influencing this assessment include:

- produces “drop-in” fuel;
- leverages Australia’s comparative advantages; and
- logistical compatibility within the Australian context.

Most attractive conversion pathways

On the basis of available information, the following conversion pathways emerge as being the most attractive in the Australian context:

- oilseed to refined fuel via oil extraction (Conversion pathway 1a);
- algae to refined fuel via oil extraction (Conversion pathway 1b);
- algae to refined fuel via SCW treatment (Conversion pathway 1c);

- lignocellulose to refined fuel via fast pyrolysis (Conversion pathway 2a); and
- lignocellulosic to refined fuel via SCW treatment (Conversion pathway 2b).

These conversion pathways are discussed in turn below.

Oilseed to refined fuel via oil extraction (Pathway 1a)

This pathway is attractive for a number of reasons. First, it produces refined fuels, such as renewable diesel and aviation fuel, which are drop-in fuels and compatible with existing infrastructure. Second, the pathway is at a commercial stage of maturity and has proven capability to produce large quantities of drop-in fuels. Furthermore, production costs on a per litre basis have clear potential to improve as a result of improvements to the upgrading steps and economies of scale from higher production volumes.

The biggest challenge for this conversion pathway is the optimisation and capital cost incurred in upgrading the intermediary oils derived from oilseed crops. Traditional refineries may require expensive tuning and reconfiguration to process the intermediary oils and need scale volumes to justify the necessary adjustments. The alternative is to construct a purpose built plant, which can require significant capital outlay. In addition, investment in upstream cultivation of non-food oilseed crops is necessary for this conversion pathway to develop in Australia.

Algae to refined fuel via oil extraction (Pathway 1b)

This pathway is attractive. Like the oilseed to refined fuel via oil extraction pathway (pathway 1a), it produces refined fuel as an end product. In addition, the potential scalability of algae as a feedstock means it could supply significant quantities of fuel. The pathway could also leverage Australia's comparative advantages: particularly Australia's abundance of flat land and sunlight if phototrophic algae cultivation is utilised.

The technology is currently at pilot stage with key players investing in demonstration plants and facilities. Current costs appear high, but are expected to reduce significantly if projected advances in cultivation and oil extraction can be achieved at larger production scales. R&D and investment momentum appears to be high around these key steps. An additional challenge is the optimisation of upgrading algal oil to refined fuels.

Algae to refined fuel via supercritical water ('SCW') treatment (Conversion pathway 1c)

This pathway is similar to the above pathway in that it produces refined fuels. The pathway utilises the entire algal biomass to create an intermediary algal crude. Compared to algal oil extraction (pathway 1b), the use of the entire biomass can result in relatively higher yields, and produces an intermediary output which may be more similar to fossil-derived crude oil (e.g. potentially lower low oxygen content). As the entire biomass is used, however, this process does not produce algal meal, which may be a relatively valuable co-product. The pathway faces similar challenges of cost effective cultivation at large scales as pathway 1b.

Lignocellulose to refined fuel via fast pyrolysis (Conversion pathway 2a)

This is an attractive pathway to produce refined fuels because the fast pyrolysis step is modular and has relatively low capital requirements. The technology also allows feedstock to be pyrolysised at the biomass source enabling the relatively less bulky oils (compared to raw lignocellulosic feedstock) to be transported for downstream processing. This lends well to the distributed and often disaggregated nature of Australia's current and potential lignocellulosic feedstock sources.

The key issue facing this pathway relates to the final upgrading step of pyrolysis bio-oil. Bio-oil produced through pyrolysis has a high oxygen content and therefore requires complex processing to enable production of end fuels. High oxygen content (with limited energy value) also leads to higher logistics costs when transporting bio-oil. Scaling up by tuning existing refinery infrastructure to upgrade bio-oil, and / or constructing cost effective dedicated plants, therefore remains a challenge for large scale production.

Lignocellulose to refined fuel via supercritical water ('SCW') treatment (Conversion pathway 2b)

SCW treatment has similar benefits to the above pathway (pathway 2a), in improving transportability of dispersed lignocellulosic feedstock in Australia, though minimum plant sizes may be larger than fast pyrolysis units due to greater technical complexity of the SCW process. This conversion pathway also has potential for additional cost benefits as it does not need biomass to be dried for processing. Furthermore, SCW derived bio-crude has a lower oxygen content compared to pyrolysis derived bio-oil, which means it has a higher energy density and is therefore more economical to transport. This also makes the hydrodeoxygenation step more straightforward, as there is less oxygen to remove and is likely to be compatible with existing catalyst technologies.

Many of the challenges for commercialisation are focused on the bio-crude upgrading steps of the process. Companies expect that the upgrading process will require ongoing research and development, and cooperation from refineries for large scale output. Additionally, R&D momentum and investment in the conversion pathway remains limited (compared to fast pyrolysis).

Other potentially attractive conversion pathways

Lignocellulose to refined fuel via gasification and FT (Conversion pathway 3a)

This conversion pathway is at pilot stage, with some companies intending to move to a commercial stage in the near to medium term. A key challenge for the process is the sourcing of adequate feedstock volumes and gasification at large scales. If this technology proves it can accommodate municipal waste with minimal pre-handling at scale, the conversion pathway may be attractive for its ability to utilise an otherwise unusable feedstock.

Some companies have also flagged developing smaller, more modular FT technologies as a potential path to commercialisation. However this may be a significant challenge in practice given the fundamentals of the FT technology.

Disruptive technologies (next generation of advanced biofuels)

There are a number of potentially disruptive technologies that aim to create molecular substances similar to those of refined fuels through a biological medium, such as algae and bacteria. These are in very early stages of development and far too early to prioritise. They offer significant benefits if successfully commercialised, and should be observed closely.

A number of companies are developing heterotrophic or photosynthetic microorganisms capable of biologically producing substances similar to refined fuels. The main benefit of these technologies is that they may deliver refined fuels at a lower cost by reducing the need for refining processes and infrastructure.

These deserve to be monitored for future development.

Conversion pathways that appear less attractive

Oilseed to biodiesel via transesterification (Conversion pathway 1d) and Algae to biodiesel via transesterification (Conversion pathway 1e)

These conversion pathways produce an end fuel that is less desirable from feedstocks that could be used to produce refined fuels. Additionally, cost reductions in their conversion technologies are expected to be limited.

Lignocellulose to ethanol via fermentation (Conversion pathway 4a), Lignocellulose to refined fuel via fermentation and hydroprocessing (Conversion pathway 4d) and Lignocellulose to ethanol via gasification and bacterial fermentation (Conversion pathway 3b)

These conversion pathways are less attractive because they produce an end fuel which is less desirable, and are somewhat dependent on leveraging substantial existing industry (infrastructure and / or technology), where Australia has a comparative disadvantage relative to other countries, such as the US and Brazil.

Although some of these conversion pathways may have potential to produce isobutanol, which may ultimately be converted into refined fuels, there is currently uncertainty around the economics of the full conversion pathways from lignocellulosic sugars.

Lignocellulose to refined fuel via microbial conversion (Conversion pathway 4b) and Lignocellulose to refined fuel via catalytic conversion (Conversion pathway 4c)

These conversion pathways may be attractive in the longer term, but at present appear to have a less clear path to commercial scale. The additional requirement of improving the hydrolysis step to create sugars from lignocellulosic feedstock poses an additional technology hurdle. It therefore appears that these conversion pathways present more opportunity for countries with significant conventional biofuels industries, which can leverage existing conventional feedstocks until hydrolysis of lignocellulosic feedstock becomes viable.

L.E.K.

6. ECONOMICS

6.1. Introduction

The purpose of this section of the Appendix is to outline the methodology underpinning estimates of the relative costs of advanced biofuel production. This assessment has been undertaken from two perspectives: expected economics if there were commercial deployment today, and potential future costs accounting for possible improvements over time.

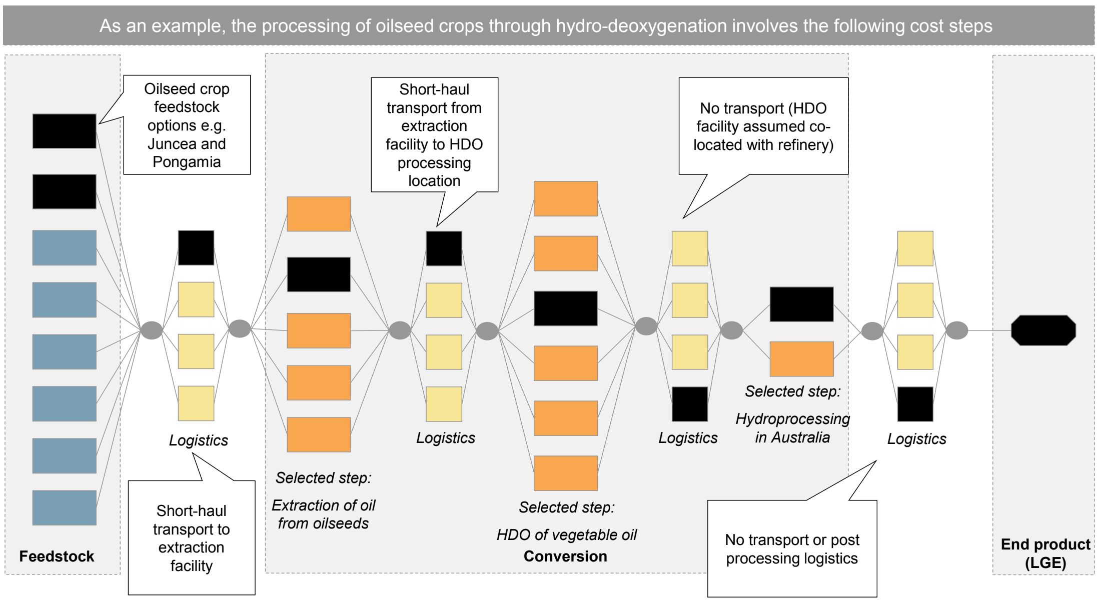
GHG reduction potential for advanced biofuels, Australia's refining options for green crude and the potential for job creation are also discussed in this section.

6.2. Estimated production costs at commercial deployment

6.2.1. Methodology

To estimate end to end pathway costs of advanced biofuels, individual costs were modelled as a number of discrete steps, from feedstock to refinery / terminal gate. These steps are connected by assumptions about input-output yields and potential logistics requirements to transport intermediary product to processing facilities. Pathway cost estimates are pre-distribution to end use markets, and do not include biofuel producer margins. All costs were normalised to litres per gasoline equivalent. This allows for fuels of varying energy content to be compared on a consistent energy basis.

Figure 57: Model schematic

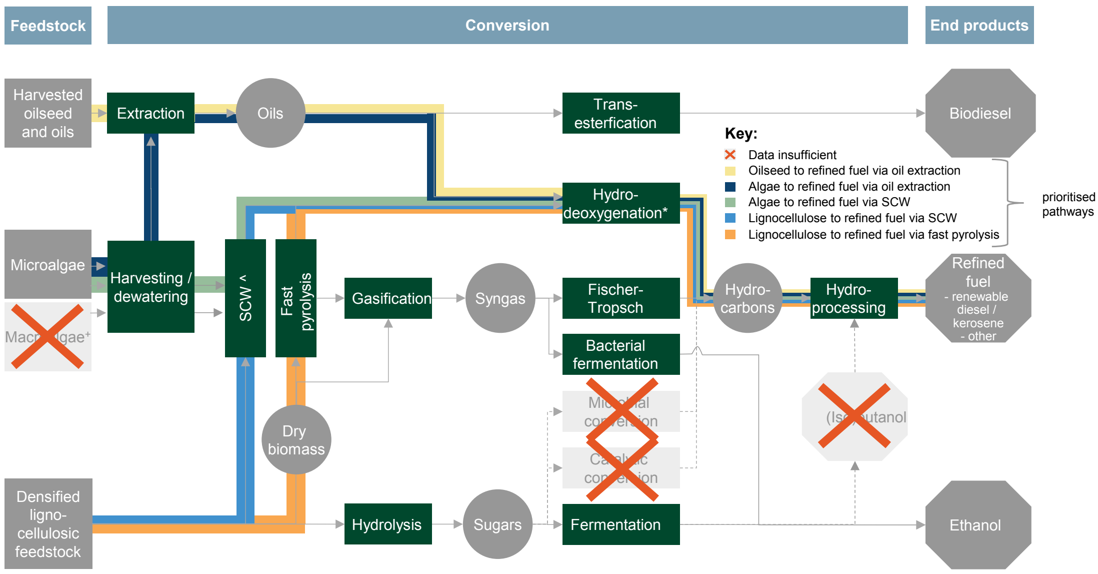


Inputs for each step were derived from a wide range of sources including interviews with leading technology players, published company reports, academic journal articles and research institutions[3]. Production costs at commercial deployment were estimated across all pathways where data was available. Demonstrated costs and yields at commercial scale were sought but where these could not be obtained, estimates of cost and yield at commercial scale were used. This sometimes involved adjusting capital costs to account for underutilised equipment and other efficiency gains that could plausibly be made from larger scale (i.e. non-pilot / non-demonstration scale) production.

The prioritised pathways described in Chapter 5 were examined in more detail:

1) Oilseed to refined fuel via oil extraction (pathway 1a);
2) Algae to refined fuel via oil extraction (pathway 1b);
3) Algae to refined fuel via SCW treatment (pathway 1c);
4) Lignocellulose to refined fuel via SCW treatment (pathway 2a); and
5) Lignocellulose to refined fuel via fast pyrolysis (pathway 2b).

Figure 58: Technology tree and prioritised pathways



Note: * The processing of different oils via this conversion process are at different levels of maturity and may vary depending on the source of the oil; ^SCW = supercritical water treatment or similar thermochemical liquefaction process; + Macroalgae can also be processed using fast pyrolysis technology

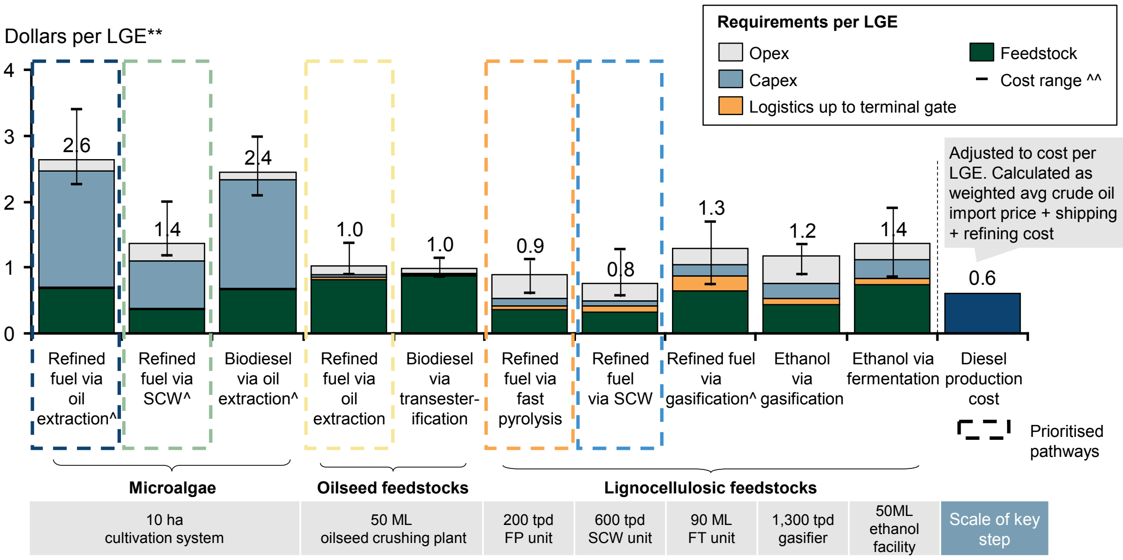
As outlined in Chapter Five, these have been selected on the basis of their attractiveness against key criteria which include producing drop-in fuels, potential to leverage Australia's comparative advantage and upside scalability potential.

[3]Cost inputs were collated over the period of July 2011 – September 2011.

6.2.2. Cost estimates

Estimated production costs show that the pathways of interest would not yet be at parity with non-renewable (diesel) fuels (Figure 59). The cost of diesel production in this analysis has been estimated at $0.60 per LGE, which is based on the weighted average crude oil import cost for FY2011, plus estimated shipping and refining costs.

Figure 59: Estimated production cost of selected pathways (not adjusted)

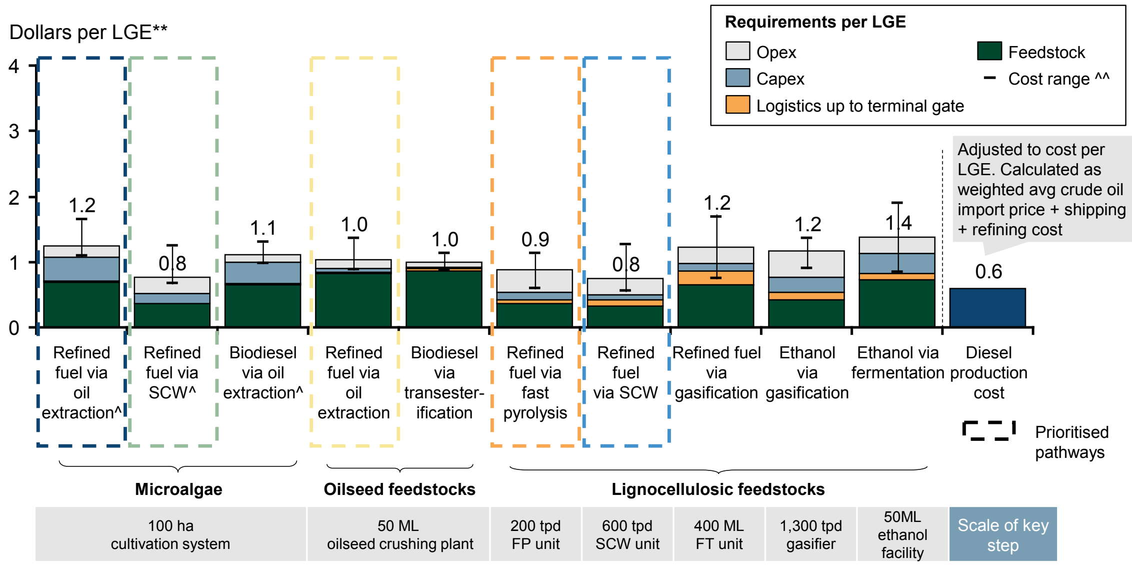


Note: ** LGE = Litres of Gasoline Equivalent; ^Estimates of cost not at commercial scale; ^^Range of cost estimate for overall pathway, Feedstock cost is based on most prospective option for pathway

Source: Company reports; Academic journals; Research institutions; ABS; AIP; L.E.K. interviews and analysis

Estimated production costs are based on the most recently available demonstrated costs for a given pathway. However, some pathways are currently being demonstrated only at sub-scale volumes which may not reflect scale at commercial deployment. When adjusted for scale, the algal pathways are expected to benefit significantly from potential efficiency improvements achievable when commercial scale facilities are available reducing unit costs (Figure 60).

Figure 60: Estimated production cost of selected pathways (adjusted to commercial scale)



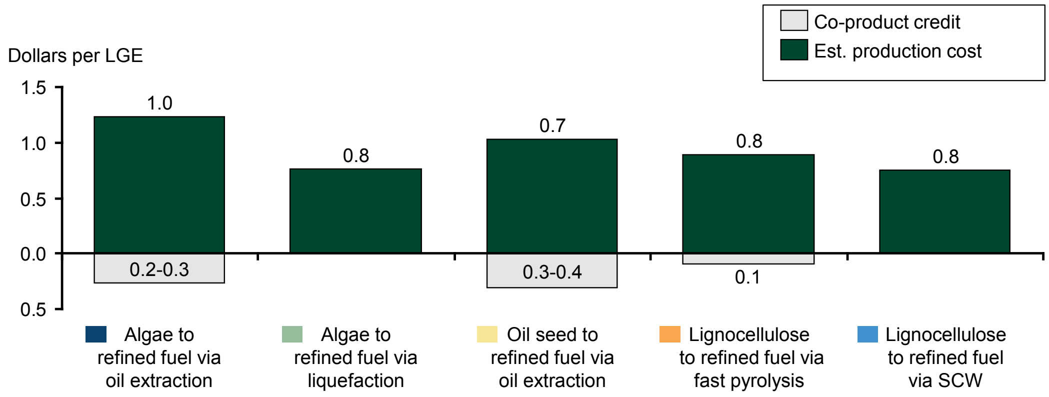
Note: **LGE = Litres of Gasoline Equivalent; ^Costs from demonstrations significantly higher than estimated costs at commercial scale; ^^Range of cost estimate for overall pathway, Feedstock cost is based on most prospective option for pathway

Source: Company reports; Academic journals; Research institutions; ABS; AIP; L.E.K. interviews and analysis

6.2.3. Co-products

Co-products have the potential to improve the economics of a number of prioritised pathways by providing ancillary revenue that can partially offset the costs of production. Co-products are defined as products made in addition to the desired end fuel. Key identified co-products are oilseed meal, algal meal and char. This is different to alternative products which are made instead of producing an end fuel. Alternative products are not considered in this study. Given the aspirations for large scale fuel production, the volume of co-product quantities is potentially large. Only co-products with sufficient end-use demand are therefore relevant to the economics assessment.

Figure 61: Estimated production costs of prioritised pathways (adjusted to commercial scale, including co-products)



Potential co-products	**Algal Meal:** Meal is the remaining de-oiled algae. It is rich in protein and carbohydrates, and may be sold as animal feed or used for electricity generation	No significant co-products identified, but given infancy of pathway, opportunities may exist	**Oilseed meal**: Oilseed meal is the remaining de-oiled seed. Oilseed meal can be used in animal feed and sold in existing markets	**Char:** Char is the residual from biomass after volatile gases and liquids are condensed into pyrolysis oil. It can be used as fertiliser or combusted to generate electricity	No significant co-products identified, but given infancy of pathway, opportunities may exist

Source: Company reports; Academic journals; ABARES; ABS; AEMO; Australian Oilseeds Federation; Bureau of Rural Services; CSIRO; FIFA; Food & Agriculture Organisation, OECD data; Melbourne Water; L.E.K. interviews and analysis.

Oilseed meal is produced during the crushing and oil extraction step for oilseed. Similarly, algal meal is produced during the process of extracting oil from algae. Both of these residual products are rich in protein and have potential use in animal feed. This is a substantial global (commodity) market. The assumed co-product credit from meal is conservative, to allow for fuel production optimisation (e.g. through improved algal oil yields and / or recycling of algal biomass for nutrients), which may reduce the amount or quality of saleable meal.

Char is produced during the fast pyrolysis of lignocellulose (c. 20% of original biomass). It is the residual from biomass after volatile gases and liquids are condensed into pyrolysis oil. Char is high in carbon and has a range of applications including agriculture and power generation. At large scale production levels, it is unclear whether agricultural requirements will be sufficient to absorb expected supply while maintaining prices, so energy equivalent pricing (i.e. use in power generation) has been assumed.

6.3. Potential future costs

6.3.1. Methodology

The cost of producing advanced biofuels is expected to improve over time. Improvements will be largely driven by cost reductions in conversion technologies and feedstock. Logistics and refining costs are not expected to materially improve. The quantum of potential reduction has been estimated using analogous reductions in other industries.

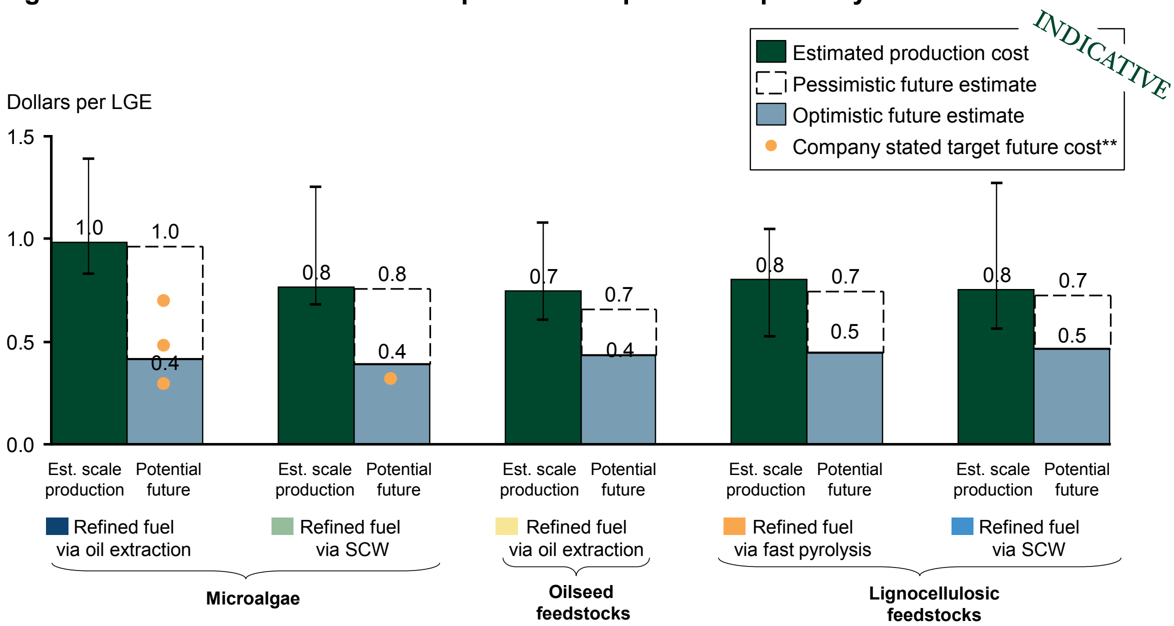
Conversion technology costs reductions can be estimated by looking at other industries. Empirical evidence indicates that new technologies tend to be deployed along standard S-shaped diffusion curves (with increasing rates of deployment in the early years, and a gradual tapering off as the technology matures). Full deployment typically takes 30 to 60 years from the first commercial facility. Experience from other energy technologies suggests material cost reductions can be achieved as this deployment occurs. The reduction in technology cost for every doubling of capacity is referred to as a technology learning rate. Observed technology learning rates suggest a range from 5% to 22% could be applied to estimate cost reduction potential for advanced biofuels.

Feedstock cost reductions can be estimated by looking at historical Australian experience. Total factor productivity improvements have been observed in Australian agriculture over the long term, in the order of c. 0.5% to 2% per annum. This is expected to positively impact agricultural feedstock costs, particularly those relying on new crops (as opposed to waste products and residues).

6.3.2. Cost estimates

The potential for cost reduction in the future is significant.

Figure 62: Estimated cost reduction potential for prioritised pathways

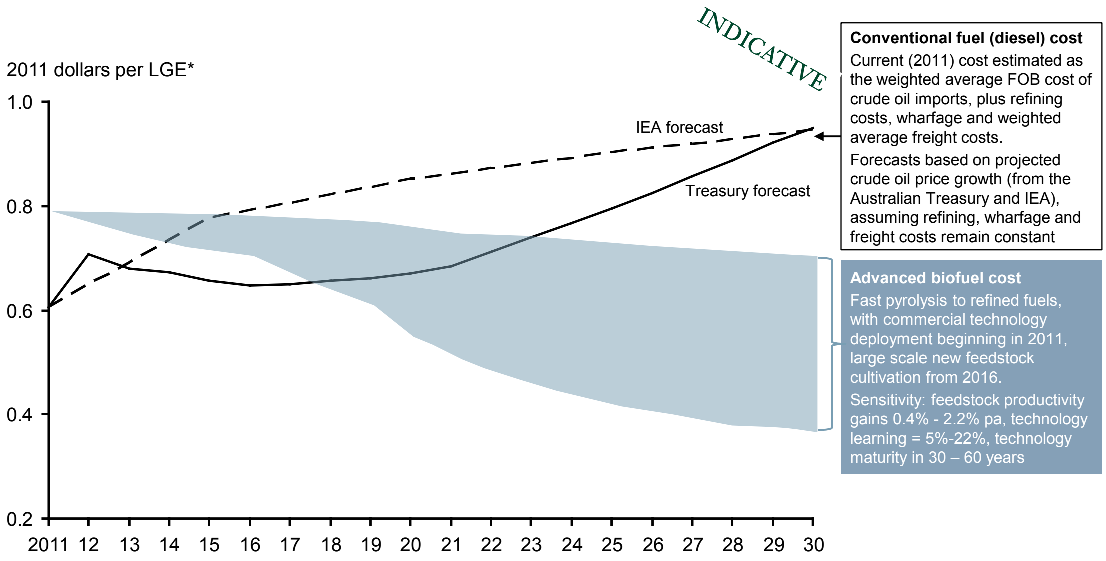


Note: * Includes co-product credits and logistics costs up to terminal gate; **Company targets adjusted to 2030 using analogous learning curves

Source: Company reports; Academic journals; Research institutions; ABS; L.E.K. interviews and analysis

Depending on assumptions about diffusion and learning rates, more advanced technologies could become commercially viable in as soon as 5 to 10 years (Figure 63). However, projections of future costs are contingent on pathways overcoming a number of key challenges, which remains highly uncertain given the early stage of development of a number of conversion processes.

Figure 63: Possible evolution of conventional fuel vs biofuel costs



Note: Values are in real 2011 dollars; *LGE = litres of gasoline equivalent

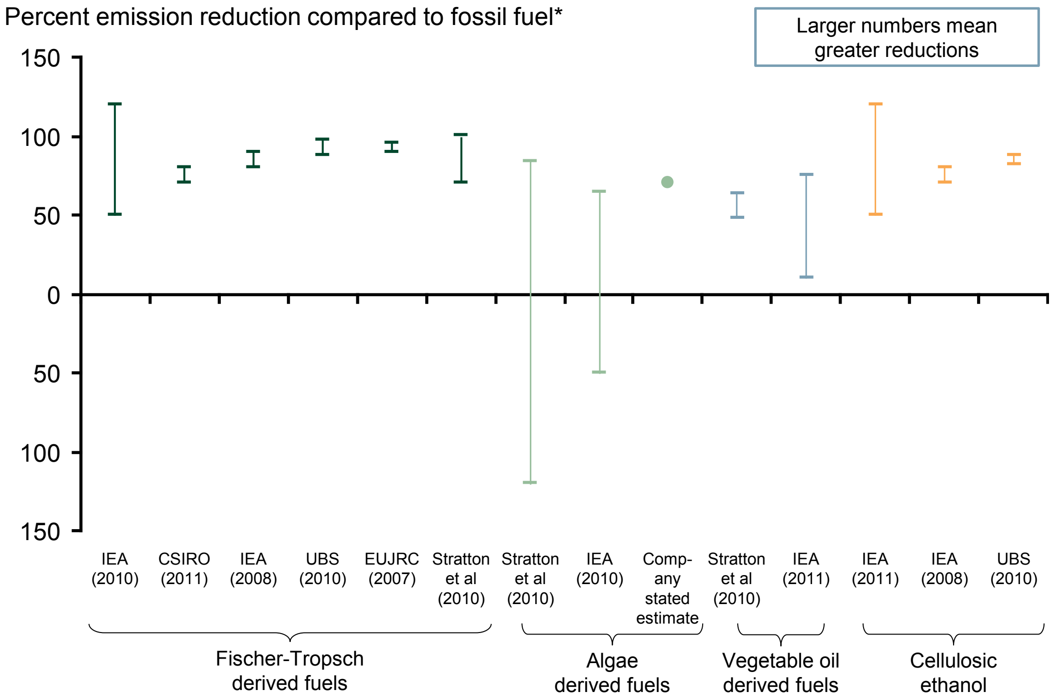
Source: IEA; ACCC; AIP; Australian Treasury; L.E.K. interviews and analysis

6.4. Other advanced biofuel considerations

6.4.1. GHG reductions

GHG emission reduction is a key potential benefit of advanced biofuels. Estimates show that advanced biofuels could offer material potential for GHG reductions, although the quantum may vary depending on feedstock and conversion technology used (Figure 64). Not surprisingly, more accurate GHG reduction estimates are available for the more developed pathways, whereas estimates are less certain for pathways in earlier stages of technology development.

Figure 64: Life-cycle GHG balance of selected advanced biofuel pathways



Note: *Some advanced biofuels may offer greater than 100% emission reductions compared to fossil fuel due to co-products (e.g. for power generation)

Source: IEA; EUJRC, UBS, Partnership for Air Transportation Noise and Emissions Reduction

6.4.2. Refining

Refining is a necessary step in all prioritised advanced biofuel pathways. Refining green crude will leverage technology currently used in traditional crude oil refining, but also require some new equipment.

It is likely that refining in Australia would ultimately be cheaper than shipping to Singapore to refine. However, Australia has limited refinery infrastructure capable of processing green crude today. There are three options that could be considered.

- **Retrofit an existing refinery**: This would require a complex and potentially costly retrofit, including new equipment (such as a hydrocracker), up-front configuration, and additional on-going operating expenses (including more frequent catalyst replacement and additional hydrogen) depending on the type of green crude and end fuel produced;
- **Construct a purpose-built 'biorefinery'**: This would involve a large upfront cost in the order of $1bn, and given their smaller scale compared to traditional refineries, multiple plants will be required. Sites with access to key inputs and downstream infrastructure are also required. High O_2 content oils would incur greater costs;
- **Refine overseas (e.g. ship to Singapore)**: This would further increase Australia's reliance on overseas refineries, and add costs to logistics to ship and return product. However until refining infrastructure investment is made, it may be more economical to ship to a regional refinery in Singapore from most parts of Australia.

Refining therefore presents a particular challenge in the development of advanced biofuels through the priority pathways identified for Australia. This is not considered insurmountable, however, given the potential to export for regional refining in the absence of local investment. Efforts to explore the feasibility of domestic biofuel refining could also be integrated into broader industrial biotechnology activity. This includes a recent proposal for the establishment of a Biorefinery Research Institute in Australia to support wider Pulp and Paper Industry interest in biomass-based products (e.g. bio-chemicals and bio-materials).

6.4.3. Job creation

Potential for regional development is one of the benefits of establishing an advanced biofuel industry. An aspect of this is the direct creation of new jobs.

The early stage nature of technology development means there is little in the way of published data on job creation. Company estimates also vary, and depend on feedstock choice and technology (e.g. labour intensity and level of automation). Collating estimates of labour requirements across feedstock production, conversion plants and refining facilities, suggest that between 1,000 to 1,500 full time employees (‘FTEs’) could be required per gigalitre of advanced biofuel produced. These jobs may be located in vastly different areas (depending on feedstock and plant locations), and will cover a range of roles from farming to supervisory positions.

The scale of jobs created will depend on the scale of the industry. For example, a substantial industry of 15 GL per annum could create 15,000 to 25,000 jobs; an industry of 30GL could create 30,000 to 45,000.

6.5. Summary and conclusions

Based on estimated costs of production at commercial deployment, priority pathways would not yet be at parity with non-renewable fuels. This could change in the future, as crude oil prices continue to rise and ABFs are expected to benefit from learning improvements across both feedstock cultivation and technology conversion. Depending on assumptions, more advanced ABF technologies could become commercially viable in the next 5-10 years and are likely to be significantly more cost competitive with fossil fuels over the longer term.

The ABF industry is expected to provide substantial employment opportunities. Given the nature of the feedstock location, it is also sensible to assume many of these jobs could also be in regional and rural areas.

ABF can also delivery significant GHG reductions, depending on the type of feedstock. Technology maturity is expected to improve certainty around the quantum of this benefit.

The availability of refining infrastructure will be an important consideration for ABF. It is likely that refining in Australia would ultimately be cheaper than shipping to Singapore to refine. However, Australia has limited refinery infrastructure capable of processing green crude today. Until refining infrastructure investment is made, it may be necessary to ship to a regional refinery (Singapore).

7. REFERENCES

In addition to the key references below, L.E.K. would like to acknowledge the contributions of the ABRI Establishment Council and CSIRO in providing input to the Advanced Biofuels Study.

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Data and statistics

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Australian Bureau of Statistics (ABS)

Commonwealth Scientific and Industrial Research Organisation (CSIRO)

Food and Agriculture Organisation of the United Nations (FAO)

Geoscience Australia

OECD Statistics

Industry participants interviewed as part of the Advanced Biofuels Study

International technology players (21)

Algenol
Amyris
Avantium
BTG-BTL
Chemrec
Coskata
DuPont Danisco Cellulosic Ethanol (DDCE)
Dynamotive
Ensyn
Gevo
Joule Unlimited
KiOR
LanzaTech
Neste Oil
Origin Oil
Rentech
Sapphire Energy
Solena
Solix BioSystems
Verenium
Virent Energy Systems

Local technology players (7)

Ethtec / North QLD Bioenergy
GenetiFuel
Hydrodec Australia
Ignite Energy Resources
MBD Energy
Microbiogen
Renewable Oil Corporation

Fuel distributors (5)

BP Australia
Caltex
Exxon Mobil Australia
Freedom Fuels
Shell Australia

Local biofuel producers, feedstock developers & research institutions (6)

ANU Centre for European Studies
Biofuels Association of Australia
Bioenergy Plantations Australia
Biomax Fuels
Curtin Centre for Advanced Energy Science & Engineering
University of Sydney's Plant Breeding Institute

End users & industry associations (11)

Australian Automobile Association
Centennial Coal
Defence Materiel Organisation
Ergon Energy
L.Arthur Transport
Linfox
Mediterranean Shipping Company
National Road Transport Operator Association
Qantas Airways
Truck Industry Council
Virgin Australia

OEMs and equipment distributors (2)

Energy Power Systems
GM Holden

Investors (3)

Cornerstone Capital
General Catalyst
TPG

8. GLOSSARY OF KEY TERMS

Advanced biofuel	A liquid fuel derived from sustainable sources of organic matter that do not typically compete with food production, such as wood residues, certain oilseeds, and algae
Advanced biomass	Biomass that is non-food, or is not typically consumed as food, and can be cultivated without displacing food crops Examples include municipal waste, agricultural residues and inedible oils
Advanced feedstock	Advanced biomass used for the production of advanced biofuel
Alcohol ester	Output resulting from the condensation of an acid with an alcohol
Algae	A broad group of primitive, aquatic plant species
Algal meal	The carbohydrates and proteins that remain after lipids (oils) have been extracted from the algae
Alternative product	Products produced from biomass instead of biofuel [cf. co-product]
B20	Liquid fuel consisting of 20% biodiesel and 80% diesel
B5	Liquid fuel consisting of 5% biodiesel and 95% diesel
Bagasse	The stem residue remaining after the crushing of sugar cane to remove sugar-rich juice
Biodiesel	Fatty acid based biofuel with properties similar, but not identical, to non-renewable diesel
Biofuel	A liquid fuel derived from biomass
Biofuel blends	A liquid fuel consisting of a mix of biofuels and non-renewable fuels (such as E10, B5 and B20)
Biomass	Biological or organic matter derived from recently living organisms (such as plant matter, wood, waste and oilseeds) that can be converted into electricity or fuels
Biorefining	The refining of green crude
Brassica carinata	A species of rotational oilseed crop. Commonly known as Ethiopian mustard
Brassica juncea	A species of rotational oilseed crop. Commonly known as Indian mustard
Break crops	[See rotational crops]
Butanol	Also known as butyl alcohol. Any of the four isomeric alcohols of the formula C_4H_9OH: n-butanol, isobutanol, sec-butanol and tert-butanol
Camelina sativa	A species of rotational oilseed crop. Commonly known as false flex
Catalytic conversion	A process which uses chemical catalysts to convert sugar into hydrocarbon products

Cellulose	A linear polymer of glucose linked by B-1,4 bonds. The bonds form crystalline structures that give plants structural strength
Char	A residual form of charcoal produced from the fast pyrolysis of biomass
Chemical hydrolysis	Hydrolysis using acids
Compressed natural gas (CNG)	A fossil fuel substitute to gasoline or diesel which is made by compressing natural gas to less than 1% of the volume it occupies at standard atmospheric pressure
Conventional biofuel	Biofuels derived from conventional biomass
Conventional biomass	Biomass that is typically consumed as food, or which if cultivated displaces food crops Examples include corn and edible vegetable oil
Conventional feedstock	Conventional biomass used for the production of conventional biofuels
Conversion technology	A technology or process required to convert (partially or fully) a harvested biomass or an intermediary product into a biofuel
Conversion technology pathway	The aggregate of all processes necessary to convert a harvested biomass into a biofuel
Conversion technology pathway group	Similar conversion technology pathways, which typically take the same harvested biomass to produce the same end biofuel
Conversion technology step	A process within a conversion technology pathway
Co-product	Products produced in addition to biofuel as part of the biofuel production process [cf. alternative product]
Cracking	The chemical process of breaking longer hydrocarbon chains into shorter ones
Crop stubble	The residue remaining after the harvest of grain crops such as wheat, barley and lupins
Dedicated energy crops	Crops purposely cultivated and harvested for biomass production
Dewatering (of algae)	Process of removing excess water from algae biomass
Distillation (for ethanol)	Process used to separate ethanol from non-ethanol compounds (mainly water) in a mixture
Diversion rate	Quantity of biomass used as feedstock for biofuels production as a proportion of quantity of biomass harvested
Drop-in fuel	Fuel which has been processed (e.g. refined) to a form that can be used in a variety of applications without the need for modifications to fuel distribution infrastructure or equipment (e.g. engines)

E10	Liquid fuel consisting of 10% ethanol and 90% gasoline
End biofuel	Final output produced by a biofuel production pathway. Can also be referred to as renewable refined fuel
Enzymatic hydrolysis	Hydrolysis using enzymes
Ester	A chemical compound formed by condensing an acid with an alcohol
Ethanol	Also known as ethyl alcohol; a chemical compound with the formula C_2H_5OH. When used as a biofuel, it has properties similar, but not identical, to conventional gasoline
Extraction (of oil)	The process of removing or separating oils from oilseeds or algae, by pressing, crushing or by using a solvent
Fast pyrolysis	Rapid heating of dried and ground plant matter in the absence of oxygen, followed by rapid condensation to produce oil
Fatty acids	A chemical compound, comprised of a carboxylic acid with a long unbranched aliphatic tail
Feedstock	Biomass used for the production of biofuel
Fermentation	A biological process in which sugars are converted into alcohols and water by microorganisms including yeasts and bacteria
Fischer-Tropsch synthesis	A set of chemical reactions that converts syngas into liquid hydrocarbons. This process is triggered when heat and pressure is applied to syngas in the presence of catalysts
Fluid catalytic cracking	Cracking via the application of catalysts
Fractionation	The process of separating different-length hydrocarbon chains in a crude mixture on the basis of differences in boiling points
Fuel oil	A heavy fraction obtain from crude oil distillation
Gasification (of biomass)	The chemical decomposition of dried plant matter using heat (in a limited oxygen environment) to produce a synthetic gas
Glycerin	Also known as glycerine or glycerol; a co-product of the production of biodiesel via transesterification. It is a simple alcohol compound, taking the form of a colourless, odourless and viscous liquid
Green crude	The renewable equivalent of crude oil; a crude substance derived from biomass that can be refined in a way similar to crude oil It covers a range of intermediary oils, including fast pyrolysis derived bio-oil, bio-crude derived via supercritical water treatment, intermediary vegetable oil and intermediary algal oil
Harvest rate	Quantity of biomass collected as a ratio of the quantity of biomass cultivated

Harvested oils conversion technology pathway group	Conversion pathway group which describes the conversion of vegetable and algal oils into either biodiesel or refined fuels
Harvesting (of algae)	The collecting of wet algae biomass from an algae culture
Hemicellulose	A highly branched polymer composed primarily of five-carbon sugars. It is chemically bonded to lignin and serves as an interface between the lignin and cellulose.
Heterotrophic algae culture	An algae culture which uses sugars as inputs [cf. phototrophic algae culture]
Hydrocracking	Cracking via the application of hydrogen
Hydrodeoxygenation	The process of removing unwanted oxygen from intermediary oils by pumping heated hydrogen through the oils in the presence of catalysts
Hydrolysis (of biomass)	The decomposition of plant matter to recover sugars through a chemical reaction with water
Hydrophile	Tending to dissolve in, mix with, or be wetted by water
Hydroprocessing	A combination of chemical processes which may include fractionation, cracking, reforming and treating
Intermediary algal oil	Green crude extracted from algae
Intermediary oil	[See green crude]
Intermediary vegetable oil	Green crude extracted from oilseeds
Jatropha curcas	A small tree, indigenous to central America, which produces oilseeds
Lignin	A polymer of phenyl propane units linked primarily by ether bonds; it acts as “glue” in the lignocellulose substance
Lignocellulose	A substance typically found in cell walls of woody plants; it comprises of three major components: cellulose, lignin and hemicellulose
Lignocellulosic sugars conversion technology pathway group	Conversion pathway group which describes the conversion of lignocellulosic materials into intermediary oil products that are further upgraded to refined fuels
Liquefaction	The process of making a liquid from a gas / solid
Liquefied lignocellulose conversion technology pathway group	Conversion pathway group which describes the conversion of lignocellulosic materials to synthetic gas (syngas) that can be further converted into refined fuels or ethanol

Liquified natural gas (LNG)	Natural gas that has been converted temporarily to liquid form, typically for ease of storage or transport
Liquified petroleum gas (LPG)	A flammable mixture of hydrocarbon gases used as a fuel in heating appliances and in some vehicles
Macroalgae	Multicellular algae, commonly known as seaweeds
Methanol	Also known as methyl alcohol; a chemical compound with the formula CH_3OH
Microalgae	Microscopic algae
Microbial conversion	A process which uses engineered yeasts or microorganisms to convert sugars into hydrocarbon products
Molasses	A viscous by-product of the processing of sugar cane, grapes or sugar beets into sugar
Monoculture	A culture which contains only one strain/species of the cultivated organism [cf. polyculture]
Oilseed meal	The carbohydrates and proteins that remain after lipids (oils) have been extracted from oilseeds
Photobioreactor	A reactor that incorporates a light source in which algae or other organisms can be cultivated
Phototrophic algae culture	An algae culture which uses sunlight and carbon dioxide as inputs [cf. heterotrophic culture]
Polyculture	A culture which contains more than one strain/species of the cultivated organism [cf. monoculture]
Pongamia pinnata	A medium-sized legume tree, indigenous to the Indian subcontinent and south-east Asia, which produces oilseeds
Pyrolysis bio-oil	Green crude extracted from plant matter via the pyrolysis process
Refined fuel	Fuel produced through refining processes, such as diesel and gasoline
Reforming	The chemical joining or rearranging of hydrocarbon chains
Remote generation	Off grid electricity generation
Renewable fuel	Fuel derived from renewable sources
Retrofitting	The addition of new technologies to existing production systems such that a new output can be produced
Rotational crops	A crop which is typically grown in the off season of the mainstream / primary crop, in order to provide supplementary income or to replenish soil carbon or nutrient levels
Self-pollination	Transfer of pollen from an anther to a stigma of the same flower
Separation (of oil)	[See extraction]

Short rotation coppice	A variety of tree species (e.g. poplar, willow and eucalyptus) that regenerate quickly via coppicing via shoots from the stump of cut down trees
Sorghum	A genus of numerous species of grasses, typically cultivated for grain
Supercritical water treatment (of biomass)	A biomass liquefaction process by the application of water and / or appropriate catalysts in a controlled temperature and pressure environment
Supercritical water bio-crude	Green crude extracted from biomass via the supercritical water process
Syngas conversion technology pathway group	Conversion pathway group which describes the extraction of sugars from lignocellulosic materials and the conversion of these sugars to either ethanol or refined fuels
Synthetic gas (syngas)	A gas mixture that contains varying amounts of carbon monoxide and hydrogen
Tallow	A hard fatty substance made from rendered animal fat
Technology diffusion rate	Rate at which a given technology is being deployed / adopted in a given market
Technology learning rate	Percent cost reduction from every doubling of production capacity
Total factor productivity	A measure of total output produced as a proportion of a measure of total inputs consumed
Transesterification	A process involving the neutralisation of fatty acids in triglyceride molecules, the removal of glycerin and the creation of an alcohol ester
Triglyceride	An ester derived from glycerol and three fatty acids
Upgrading (of oils)	The process of converting an intermediary oil into a refined fuel
Volatiles	A group of compounds with low boiling points