LPG ASSOCIATION NZ

Pathway to 70 / 100% renewable LPG

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Synopsis

This study explores the appropriate journey for decarbonisation of the New Zealand LPG sector, and demonstrates that maintaining existing LPG distribution assets and progressively displacing conventional LPG with renewable LPG can support growth of a biofuels industry whilst supporting jobs, fuel security and energy supply diversity.

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Pathway to 70 / 100% renewable LPG

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Executive summary

This study explores the opportunities for decarbonisation of the New Zealand LPG sector, and demonstrates that maintaining existing LPG distribution assets and progressively displacing conventional LPG with renewable LPG can support growth of a biofuels industry whilst supporting jobs, fuel security and energy supply diversity.

Liquified Petroleum Gas (LPG) is a flexible, high density fuel that provides a range of commercial and residential heating services. This fuel is a by-product of domestic natural gas and light condensate production and is valued because it can be readily transported / stored and has much cleaner burn properties than solids and other liquid fuels. The most familiar form of this fuel are the 9 kg and 45 kg “LPG bottles” used in commercial kitchens, in homes for heating and cooking, and classic kiwi BBQs.

The journey to reduce the greenhouse gas footprint of New Zealand will naturally challenge the value of LPG services relative to the emissions that the combustion of conventional LPG (cLPG) yields. It is thus appropriate to consider alternative low carbon mechanisms for delivering LPG services. Electrification is unlikely to be a favoured substitution approach since LPG is primarily used where the high burn temperature or mobility value is prized and providing this service with electricity is very expensive and often impractical. Substitution with biomass pellets and biofuels is possible, but will likely be limited by availability of supply, cost of transition, and concerns around poorer burn properties. The hurdles associated with indirect substitution suggest that the alternative of retaining the existing LPG infrastructure and sourcing substantial volumes of renewable LPG (rLPG) could be the most effective decarbonisation route.

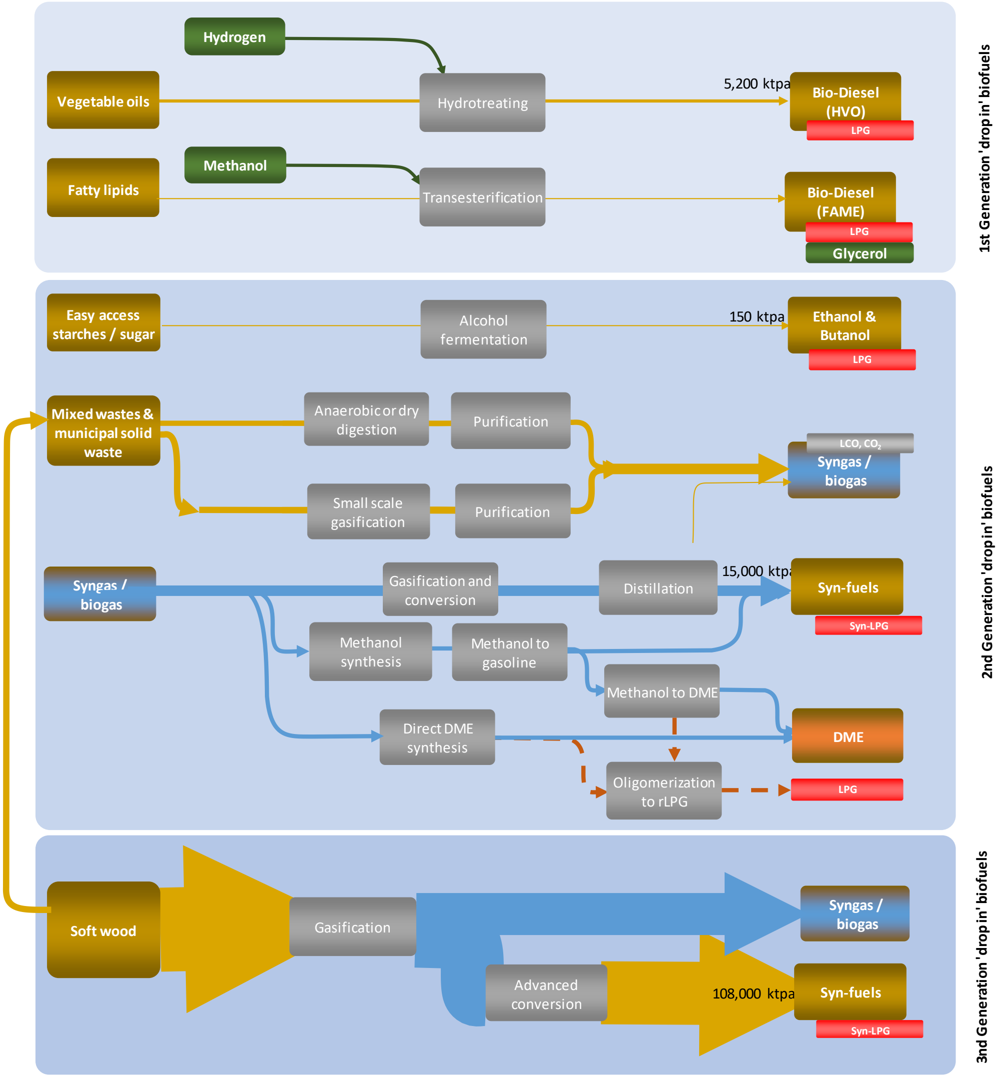
Renewable LPG is chemically identical to conventional LPG so it can be used as a “drop in” fuel i.e. it can be used within existing distribution systems (bottles and pipelines) and appliances. There are a number of different supply routes for rLPG which will be explored in this study, all of which have a much lower greenhouse gas footprint (some are strongly negative) than the cLPG counterpart. The ultimate source of energy for all the rLPG pathways is basically biomass derived or established waste streams, and the relative availability and cost of different sources of biomass will ultimately dictate the preferred routes to rLPG.

A huge range of rLPG production pathways have been distilled into three (3) generations of biofuel technology.

In this analysis we have distilled a huge range of biofuel / rLPG production pathways into four (4) groupings that represent comparable feedstocks and levels of technical / commercial maturity. These groups are characterised in Figure 1 and listed below:

1. 1st generation "drop-in" rLPG
2. 2nd generation "drop-in" rLPG
3. 3rd generation "drop-in" rLPG
4. "Blended" components

Figure 1 – Simplified Sankey diagram forecast of world LPG production in 2050



Renewable LPG (rLPG) is a natural co-product of first-generation biofuel (i.e. HVO/HEFA and FAME) pathways and is likely to be the source of the first tranche of rLPG. The production capacity from this pathway is limited by the availability of low-cost vegetable oils and animal fats that are needed for these pathways.

The biofuel production trends witnessed in Europe and North American provide promise that New Zealand will have a second generation of biofuel pathways based on recovery and utilisation of municipal and agricultural sector waste streams, successfully operating prior to 2035. For this tranche of technologies, dry digestion and gasification pathways will yield biogas precursors that can be oligomerised to yield either renewable dimethyl ether (rDME) or rLPG, both of which can be substituted into the LPG pool.

The exploitation of soft wood cellulosic to yield biofuels has been heavily researched yet is still considered to be a 3rd generation technology due to competitive use of feedstock and scale that is required to achieve a commercial outcome. New Zealand has comparative feedstock advantages that could drive the commercialisation of this pathway prior to 2050.

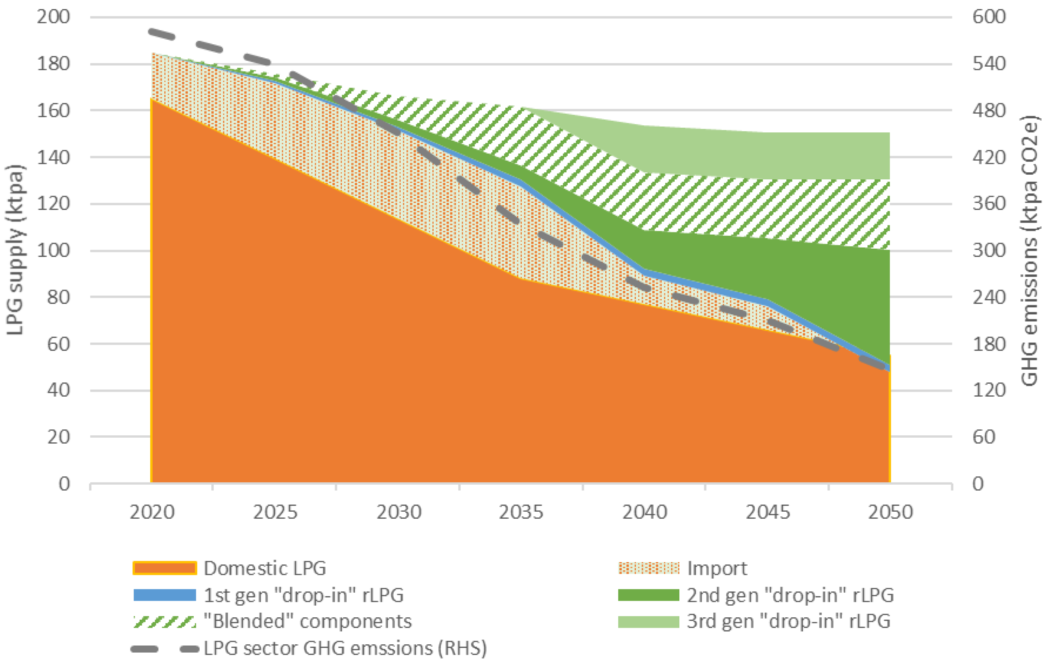
We find that decarbonisation of LPG contribution to heating sector can be achieved through 70% rLPG substitution.

In response to the Climate Change Commissions challenge to fully decarbonise the heating sector, the LPGA has suggested a phased decarbonisation approach, aligned to the Commission's pathway analysis. This phased approach undertakes:

- Enabling actions prior to 2025;
- Leveraging 1st and 2nd generation biofuel / rLPG technologies, as well as substitution with "blended" components to achieve 30 ktpa LPG substitution between 2025 and 2035, and
- Leveraging 3rd generation biofuel / rLPG technologies to achieve 70% rLPG substitution prior to 2050.

The overall outcome is summarised in Figure 2 below. The Sankey diagram for this scenario can be found in Appendix C.

Figure 2 – LPG market projection for 70% rLPG substitution scenario



In this projection of the LPG sector, it is anticipated that New Zealand's natural gas industry will continue to evolve and deliver conventional LPG up to and beyond 2050. To balance the decline in cLPG production, a healthy rLPG production industry will progressively evolve, with the following developments expected:

- Reinstatement of ZBioD at full capacity – yielding 1.6 ktpa rLPG before 2035;
- A further HVO or FAME plant adding a further 1.6 ktpa rLPG before 2035;
- Two mixed waste gasification to rLPG developments – yielding 6 ktpa rLPG before 2035;
- A further mixed waste gasification to rLPG developments – yielding 3 ktpa rLPG before 2050;
- Multiple wastewater / manure to rDME facilities yielding 25 ktpa LPG equivalent (as rDME) before 2035;
- Direct biogas to rLPG capability yielding 40 ktpa before 2050;
- One softwood to biofuels plants to add 20 ktpa rLPG capacity prior to 2050.

It is anticipated that rLPG production will not be able to match the decline in cLPG production, hence a proportion of the demand will be met through import of LPG / rLPG. Prior to 2035 it is assumed that majority of imports will be cLPG, but after 2035 rLPG will be imported.

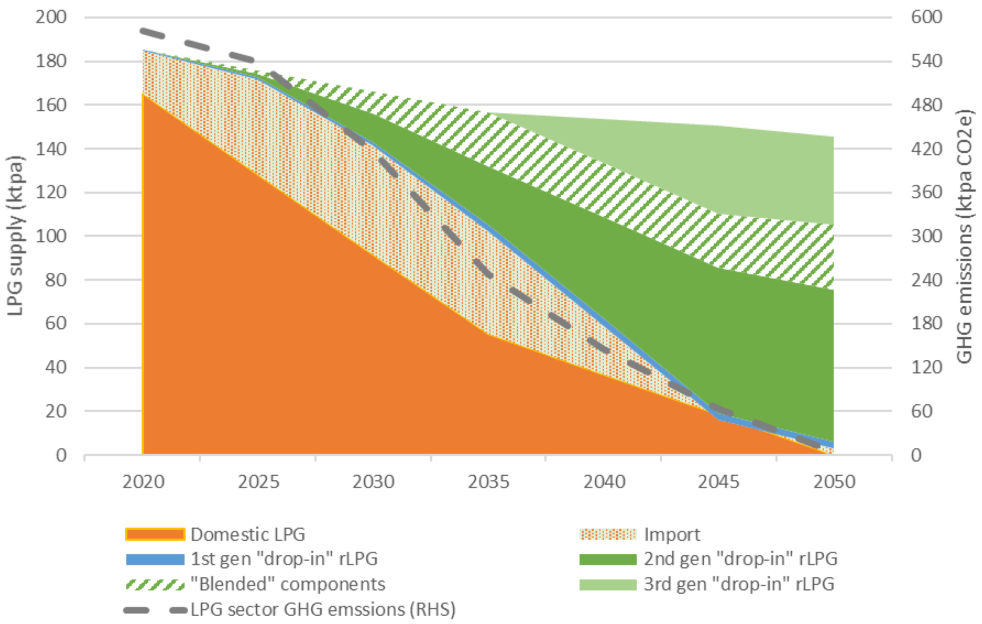
This production scenario is founded on conservative interpretations of technology development and feedstock utilisation. We believe that this is a realistic projection which can yield greater resilience and economic value than a ban on new connections.

The emissions reduction identified for this scenario was ~434 $ktCO_2e$ and therefore exceeds the GHG emissions reduction target set by the CCC for the heating sector.

A more aspirational, 100% rLPG substitution scenario was characterised to reveal key challenges.

Some energy market analysts suggest that New Zealand's natural gas production sector will collapse prior to 2050, with commensurate demise of cLPG production. We characterised a hypothetical LPG sector response to this outcome based on the same phased approach that was used for the 70% substitution scenario, but with acceleration of key production elements. The overall outcome is summarised in Figure 3 below.

Figure 3 – LPG market projection for 100% rLPG substitution scenario



In this projection of the LPG sector, it is anticipated that New Zealand's natural gas industry will be sustained until 2035, but rapidly decline thereafter. To balance the decline in cLPG production, an rLPG production industry must aggressively evolve to fill the shortfall. The following developments above what would already be required by the 70% rLPG scenario are:

- An additional 20 ktpa rLPG via biogas conversion;
- A second softwood to biofuel plant yielding an additional 20 ktpa of rLPG.

The primary uncertainties associated with the 100% rLPG substitution scenario are tabled in Section 7.2, and mostly relate to:

- Inconsistency between demise of the natural gas sector, and benefits of biogas as a biomass energy delivery vector;
- rLPG market signals and prospective LPG price that is required to accelerate development.

The 100% rLPG pathway is technically plausible but faces numerous commercial challenges which will require considered messaging regarding the sustained operation of the natural gas / biogas industry.

rLPG provides a promising forward path.

This report has undertaken a holistic interpretation of the relationship between the decline of cLPG production and potential to substitute with renewable LPG. New Zealand certainly has the feedstock resources to take advantages of the technical advancements that are occurring in this area. The report identifies that rLPG (and blend components e.g. rDME) can be both co-products and targeted products of a burgeoning biofuels industry.

The energy density and transportability of LPG / rLPG and cost-effective production make it an ideal energy carrier for the future. The capacity to realistically achieve 70^{+}% rLPG substation with emissions reductions comparable or in excess of the CCC targets suggest that sustaining the current LPG delivery infrastructure and distribution mechanisms is likely to provide considerable benefit to New Zealand.

In order to sustain the promise of a rLPG supported economic growth requires continued engagement of the LPG industry with industry players who are prepared to support investment in biofuels (including biogas and rLPG) production facilities, and research groups that are enabling the advancement of new / novel production pathways.

1. Context

Conventional Liquified Petroleum Gas (termed cLPG in this report) is a flexible, high density fuel that provides niche energy services within New Zealand's energy ecosystem. This fuel currently accounts for ~185 ktpa (~9 PJ/a) of energy demand. The combustion of cLPG like all fossil fuels contributes to climate change through the release of greenhouse gases. The combustion of LPG in New Zealand is considered to contribute nearly 560 ktCO_{2eq}/year.

1.1 Accelerated decarbonisation policy

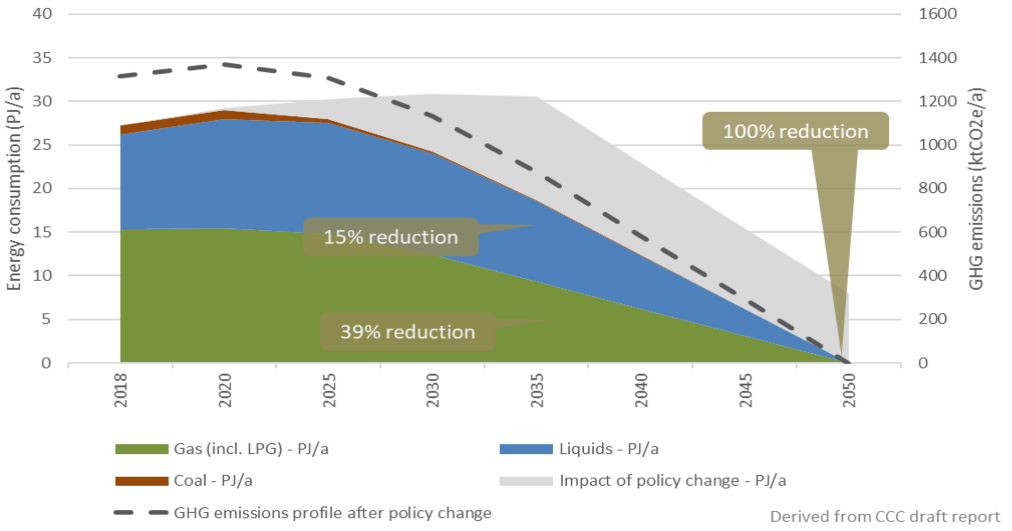
In late 2019, the New Zealand Climate Change Commission (CCC), formed as part of the Climate Change Response (Zero Carbon) Amendment Act 2019, was tasked with defining a pathway towards decarbonisation of the NZ economy by 2050. In their "Advice to Government" (31 Jan 2021 Draft) the CCC targeted the phase out of fossil fuel based heating systems in existing buildings prior to 2030. The implications for the current LPG industry were captured under necessary action 9c, namely:

> "Setting a date by when no new natural gas connections are permitted, and where feasible, all new or replacement heating systems installed are [to be] electric or bioenergy [based]. This should be no later than 2025 and earlier if possible".

The interpretation of this advice from the CCC is that there will be no new LPG or gas connections or new builds after 2025, followed by an active phase out of existing LPG and gas infrastructure post 2030. Based on the assumption that LPG and gas infrastructure has a lifespan of 20 years, it is inferred that there will be no LPG or gas consumption in buildings post 2050. In the view of the Commission, the phase out of LPG (& natural gas) should not add costs beyond normal asset lifecycle costs. Although these lifespans are suggested for residential infrastructure only, and not the distribution networks which are longer.

The energy consumption trend and greenhouse gas advantage of the proposed actions from the Commission is summarised below. The Climate Change Commission seeks to fully decarbonise the ~320 tCO_{2eq} attributed to current LPG use in the heating sector. It should be noted the LPG is considered to be part of the "liquids" stream.

Figure 4 – Forecast impact of CCC policy change on heating sector



Derived from CCC draft report

The overall decarbonisation strategy nominated by the CCC, which is comparable to other international jurisdictions who are now setting strong decarbonisation strategies, involves high levels of electrification complimented by biofuel & hydrogen developments. The biofuels aspirations for New Zealand are captured under necessary action 4a, namely:

> "Set a target and introduce polices so that at least 140 million litres [per year] of low carbon liquid fuels are sold in Aotearoa by 31 December 2035".

This level of biofuel production represents less than 2% of current liquid fuel demand, but the concomitant quantity of C3/C4 by-products would yield nearly 3% of the current LPG demand.

Conventional LPG has an emission density (on HHV basis) of 62 $ktCO_{2eq}/PJ$[1], which is lower in contrast to diesel (70 $ktCO_{2eq}/PJ$), coal (90-106 $ktCO_{2eq}/PJ$ depending on grade), and ethanol (~68 $ktCO_{2eq}/PJ$ depending on feedstock)[2]. Fugitive emissions of LPG do not contribute to global warming i.e. Global Warming Potential is 0[3].

1.2 International LPG production trends

Renewable LPG production worldwide is predominantly a co-product of HVO/HEFA manufacture of sustainable aviation fuel. The World LPG Association[4] estimates current renewable LPG production to be 460 ktpa[5].

The demand for biofuels is immense however increasing production from the HVO/HEFA pathway is limited by the availability of low-cost vegetable oils. In Europe and North America, alternative (2nd generation) biofuel pathways are already emerging and there is high expectation that a third generation of biofuel pathways will emerge circa 2030 - 2040.

Key observations regarding the state of the world biofuel production include:

- The "easy access sugar fermentation" pathway is emerging now with several alcohol-to-jet/LPG facilities under construction / slated for development in the near term;
- Biogas production from mixed wastes is a mature market in Europe and parts of North America;
- Recovery of residue biomass and municipal waste for syngas and synthetic liquids are, after years of struggling to commercialise, finally gaining some traction;
- Technologies for upgrading biogas to rDME and BioLPG are reaching commercial maturity now
- Small refineries are looking to reconfigure operations to support either HVO processing or catalytic cracking of bio-oils and bio-pyrolysis oils;
- The carbon footprint of rLPG is significantly lower than cLPG, often lower than biodiesel and bioethanol and their fossil counterparts. Sometimes the emissions intensity of rLPG is lower than wood pellets, depending on the feedstock (wood residue or whole trees) and the method used to dry pellets.

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[1] www.mfe.govt.nz/sites/default/files/media/Climate%20Change/voluntary-ghg-reporting-summary-tables-emissions-factors-2015.pdf

[2] www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf

[3] https://cip-glob-cdn.azureedge.net/-/media/sites/greatbritain/pdfs/atlanticconsultingscientificreviewcarbonfootprinted2009.pdf

[4] www.wlpga.org

[5] "BioLPG - The Renewable Future", Atlantic Consulting, 2020 V2

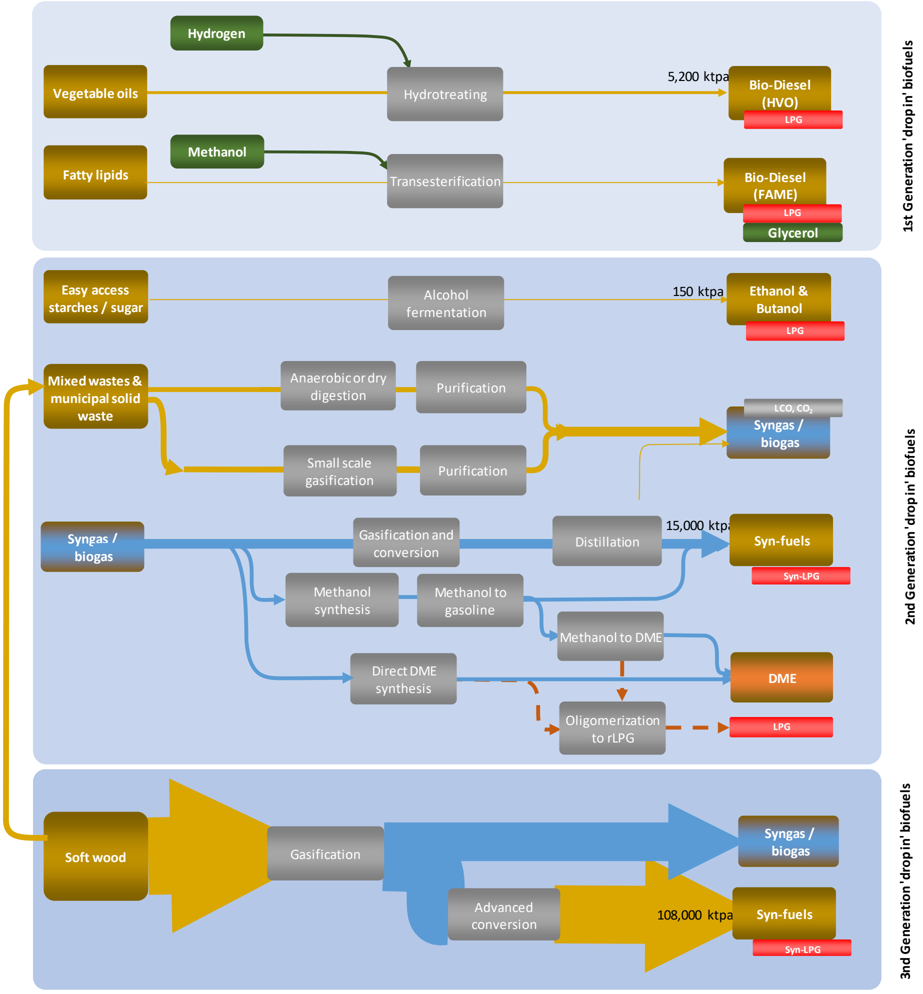
Whilst public sentiment for rLPG is strong, regulatory policy is weak with as yet no specific mandates at jurisdictional level; limited guidelines for benchmarking different supply routes / application, and regulatory gaps. In Europe these issues are being addressed and it is likely that these omissions will be rectified I the near to medium-term.

The World LPG Association production forecast for rLPG is summarised in tabular and simplified Sankey diagram formats below.

Table 1 - Forecast world LPG production profiles (ktpa)

Pathway	Technology wave	2020	2030	2050
Hydrotreated vegetable oils	Current	450	3,300	5,200
Easy access sugar fermentation	Emergent now	15	150	150
Mixed waste digestion + gasification	2nd gen	0	15,000	15,000
Cellulosic / Softwood synfuels	3rd gen	0	94,000	108,000
TOTAL		465	112,450	128,350

Figure 5 – Simplified Sankey diagram forecast of world LPG production in 2050



1.3 Decarbonising pathway

The LPGA have suggested a three (3) step pathway for decarbonising the LPG industry which follows the same time steps at the Climate Change Commission's phasing – see Figure 6 below.

Figure 6 – Suggested LPG decarbonisation transition roadmap

The phased approach provides clear business targets and a framework for measuring progress.

The first step involves accessing easy wins in rLPG production, through facilitating reinstatement, modification and expansion of existing biofuel production assets which co-yield rLPG.

The second step introduces and incentivises well established global pathways that exploit existing waste and residue streams to yield rLPG and rDME. This phase leverages 1st and 2nd generation biofuel / rLPG technologies, as well as substitution with "blended" components.

The final step seeks to totally replace or offset cLPG by 2050. It is expected that this will leverage a significant New Zealand softwood to biofuels industry. This phase leverages 3rd generation biofuel / rLPG technologies.

1.4 Acceptance of dimethyl ether (DME) in New Zealand

It is widely understood that dimethyl ether (DME) is a competitive LPG substitute up to a 20% v/v blend limit.

DME is a methanol derivative, which is produced globally both for use as a fuel servicing automotive heating and small-scale power generation markets. World production of DME today stands at approximately 9,000 ktpa (5,600 ktpa LPG equivalent)[6]. China has actively pursued the production and use of methanol and DME as an automotive fuel, because it enables the utilisation of marginal / poor coal assets to contribute to economic resilience. The USA has advanced small scale developments of DME as a mechanism of contributing to the pool of liquid heating fuels.

As an automotive fuel, blends of up to 30% DME / 70% LPG, can be used to fuel diesel engines. Further, 100% DME can be consumed in a diesel engine with only modest modifications, and it is interesting to note that numerous manufacturers of heavy vehicles are building vehicles with DME as the preferred fuel. DME has a cetane rating between 55 – 60, which yields stable combustion characteristics and significant advantages from a clean air perspective.

As a heating fuel, DME is a flammable, thermally stable liquid like LPG and can be handled like LPG with similar safety guidelines and codes as cLPG. For domestic heating and similar services, the use of up to 20% DME / 80% LPG is acceptable with minimal (if any) modifications.

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[6] https://aboutdme.org/FAQ#:~:text=World%20production%20of%20DME%20today,or%20through%20natural%20gas%20reforming.

The use of 100% DME is common for small-scale power generation markets, since the supporting diesel gensets are easily modified to support this fuel.

New Zealand fuel specifications address ethanol and methanol blends with petrol, biodiesel and fatty acid methyl esters. LPG use in vehicles are addressed but with little comment on the associated specification. DME is neither an ester nor an alcohol and thus DME is not specifically allowed for. It could potential be treated as an LPG component but would limit opportunities. Ideally, this omission should be addressed to improve regulatory certainty.

1.5 Emissions intensity evaluation

The emissions intensity nominations for key biofuel production pathways assessed in this report have been assumed modest emission reductions from waste to biogas pathways in line with similar applications globally – generally IEA references. The emissions intensity for each pathway will be highly dependent upon which feedstocks are recovered, the point of ownership transition and value of offsets attributed to diversion of waste streams.

1.6 Acronym list

The following acronyms are used in this report.

Table 2 – List of acronyms

Acronym	Short descriptor	Long descriptor
Biogas	Biological methane	Methane produced not from fossil fuels
C3	Propane	Constituent of LPG
C4	Butane	Constituent of LPG
CCC	Climate change commission	An independent advisory body on climate change
cLPG	Liquified petroleum gases	Conventional / fossil LPG
CO_2	Carbon dioxide	Greenhouse gas
DME	Dimethyl ether	Simple chemical - used as feedstock for production of other compounds
FAME	Fatty acid methyl esters	Category of feedstock used to produce biofuels
FT	Fischer - Tropsch	Process to convert gas mixtures into liquid hydrocarbon using a chemical catalyst
Gasification		Process to produce gas by heating (not burning) a substance
GHG	Greenhouse gas	Gas which contributes to heating of the atmosphere.
HHV	Higher heating value	Energy released upon combustion of a product
HVO	Hydrogenated vegetable oil	Feedstock for many existing biofuels products
LPGA	LPG association	NZ association representing LPG producers and users
Pyrolysis		Process to decompose a substance, usually organic, via heating
rLPG	Renewable LPG	LPG made via renewable / low GHG emission process
synLPG	Synthetic LPG	LPG made via synthetic gas processes

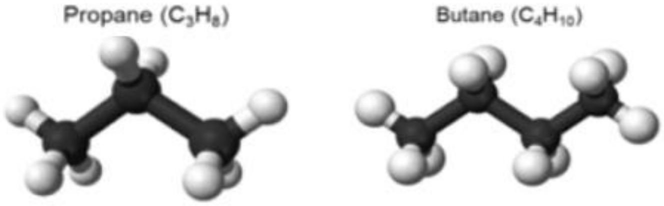
2. Fossil LPG and substitutes

Liquefied petroleum gas (LPG) describes hydrocarbon mixtures in which the main components are propane (C3), butane (nC4), isobutane (iC4), propene and butenes. Most commonly this term is applied to mixtures of propane and butane- see Figure 7. In the New Zealand market, the propane to butane ratios are typically 55:45, with minimal olefin volume. The vast majority (>99%) is used in the heating sector, with <1% used as autogas.

Conventional (or fossil) LPG is a by-product of domestic natural gas and light condensate production and is valued because it can be readily transported / stored and has much cleaner burn properties than solids and liquid fuels.

The most familiar form of this fuel is “LPG bottles” used in commercial kitchens and home BBQs. For simplicity, and to minimise risk of confusion, in this report we term conventional LPG as cLPG.

Figure 7 – Chemical structure of key LPG components[7]

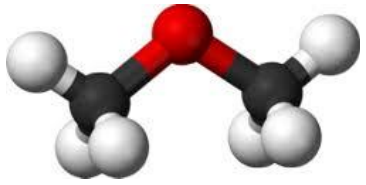


In New Zealand the ratio of C3/C4 varies depending on source and production ratios, although variation year to year can be >15%, the average higher heating value remains ~49 MJ/kg and emissions density is 62 $ktCO_{2eq}$/PJ.

Although renewable LPG (termed rLPG in this report) is not a conventional / internationally recognised naming convention, we have chosen to use this term to cover a broad range of low carbon LPG production pathways where naming conventions have not yet firmed. Some examples of the products that are potentially covered under this term include:

- BioLPG – LPG component that have been sourced from ‘biological’ material;
- SynLPG - LPG components that have been sourced from a gasification pathway (which generally has biomass as feedstock);
- eLPG – LPG components that have been sourced from combination of green hydrogen and carbon neutral carbon dioxide (e.g. direct air capture);
- Dimethyl-ether (DME) – A product of methanol dehydration which has chemical properties that allow blending up to 30% v/v in LPG without significant change in LPG blend properties – see Figure 8.

Figure 8 - Chemical structure of DME (CH_3OCH_3)



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[7] Source: Thompson, Robertson and Johnson, 2011

When we consider the nature of the energy service (or "duty") that cLPG provides, there are a number of energy carriers / fuel categories that provide the highly valued cLPG service. We consider three classes of energy carriers / fuels, namely:

1. "Drop-in" fuels – As the name implies these fuels can be added to existing LPG infrastructure at any concentration or physical condition, for example bioLPG and synLPG.
2. "Blend-in" components - These fuels can be added to existing LPG infrastructure within confined blend concentrations or physical conditions, for example rDME and butylene.
3. Indirect substitutes - These fuels can replace existing LPG services but will require new delivery infrastructure / end-use appliances in order to provide an equivalent service. Electrification and use of wood pellets are examples of indirect substitutes.

The technical, commercial and GHG abatement potential for rLPG as a drop in fuel and blend-in components are considered in the following chapters.

2.1 LPG market niche

LPG is primarily used where the high burn temperature or mobility value is prized and where providing this service with electricity is very expensive. The most familiar form of this fuel is "LPG bottles", which are used in commercial kitchens, homes for cooking and heating, and BBQs.

The reticulation of LPG via a pipeline network in Christchurch, Dunedin, Queenstown and Wanaka represents the value of LPG in communities where high-grade, clean heat is desired and natural gas is not readily available. This infrastructure provides highly reliable (and diversified) energy services to these communities.

In this Section we describe some of the most common uses of LPG and provide some context to illustrate why indirect substitution of this fuel is challenging.

2.1.1 Commercial and home kitchens

The high flame temperature and quick heating associated with LPG burners make it a preferred fuel for high stress commercial kitchen environments and domestic households nationwide.

Electric induction cooking can work as quickly as LPG / gas burners, but the electrical infrastructure required to support large electric induction unit is considerably more expensive than an LPG / natural gas based commercial kitchen. Further certain styles of cooking are not feasible with electricity based cooking e.g. wok-based cooking. Electric cooking is not resilient in the same way that LPG is, if the power goes off for any reason then food cannot be cooked. As LPG is stored in bottles / or a network, it has higher availability during adverse weather conditions.

Figure 9 - Commercial kitchen

Biogas is an acceptable substitute for most cooking applications. However, this substitution approach is only viable where a natural gas reticulation network exists – this covers a majority of population centres in the North Island, but none in the South Island.

Biomass pellets are a potential substitute; however, this substitution approach is not without significant conversion costs. The burners would be much less responsive then the LPG service and the poorer combustion characteristics of biomass pellets with low air recirculation raises GHG and indoor air quality concerns due to particulates released.

2.1.2 Space heating

Figure 10 - Cosy gas fire

Buildings with poor thermal efficiency rapidly lose the low-grade heat provided by electrical heat pump systems. Also, heat pumps don't provide the instant heating that a point source of heating like a fireplace does. Finally, heat pumps are not as resilient as LPG burners since any loss of electricity results in a loss of heating.

Biomass pellets are the most suitable substitute. They require a specific biomass pellet installation so are not without cost, however they produce heat in a similar manner to LPG / gas fires. Biomass is similarly resilient to LPG, as it is storable at the home, and is independent of external utilities. Recent air quality concerns in Christchurch has seen an increase in LPG fires to replace wood burners.

Biogas is a suitable substitute for LPG, but only in areas where natural gas reticulation systems exist.

2.1.3 Hot water heating

Up to 50% of the energy requirements of domestic homes relate to the heating of hot water. LPG and natural gas both provide instantaneous water heating services. These systems tend to be very efficient and cost effective because there are no losses associated with standing water cylinders.

Solar thermal and heat pump driven hot water systems can provide water heating services with comparable cost and lower greenhouse gas emissions. If time of use management tools are applied to the heat pump based systems, these can also provide grid balancing services.

Biomass fired water heating systems are viable, but are limited by sourcing limitations, higher labour / intervention and burn quality concerns.

2.1.4 Barbeques / portable cooking

Figure 11 - Classic NZ BBQ

Everyone loves a BBQ / portable cooking – be it in the backyard, on a camping trip, in a caravan / motor home, or on a boat. For all of these situations, the most practical fuel is LPG.

The implication of the CCC proposal is that by reducing demand for LPG, the costs associated with these BBQs / portable cooking appliances will likely rise.

Electrification is not a realistic replacement for LPG BBQs or portable cooking appliances. It is not practical to transport batteries of size such that they can replace the energy from an LPG bottle.

Biomass pellets are a potential substitute, do often have lower energy density and burner devices are less compact, hence are inherently less portable.

2.1.5 Industrial heating

Some industrial heating demands require high temperature heating that cannot be easily substituted via electrification or biomass based solutions.

A preliminary review of industrial LPG uses in New Zealand did not identify any services where the LPG service could not be indirectly substituted – subject to the challenges identified by other LPG end-uses above.

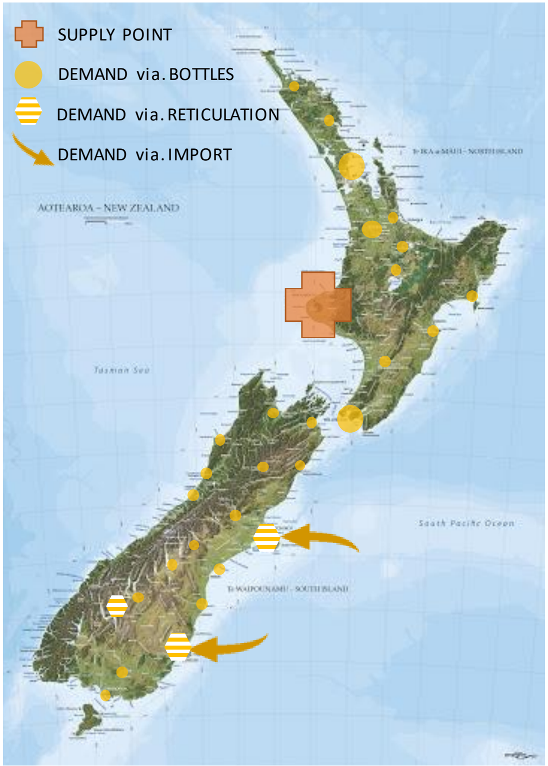
2.1.6 Autogas

Autogas currently makes up a very small portion of New Zealand LPG demand, however it has historically made up a significant portion of vehicles in the national fleet. The resilience provided by locally produced LPG and CNG during the 1970s oil crisis helped New Zealand continue to survive economically. At its peak gaseous fuels contributed as much as 11% of New Zealand's petrol demand, predominantly for light vehicles. We assume that autogas will be phased out entirely in the next few years.

2.2 LPG market size trend

The New Zealand LPG market size has progressively grown in step with the growth on the domestic natural gas and light condensate industry. The source of domestic LPG is the Taranaki region, with South Island demand being meet by shipping from the North Island or imports – see Figure 12.

Figure 12 – Illustrative demand-supply profile



The current market is characterised by:

Table 3 – Current LPG market parameters (based on 2020)

Parameter	Demand	GHG emissions
Annual domestic production	165 ktpa	
Domestic demand	95 ktpa North Island; 90 ktpa South Island (35 ktpa is reticulated) 185 ktpa total (20 ktpa is imported) 9.4 PJ/a	560 ktCO$_2$e/y
Indicative number of customer installations	178,000 excluding BBQs, camping and mobile	
Indicative industrial volume	56 ktpa	170 ktCO$_2$e/y
Indicative commercial volume	38 ktpa;	115 ktCO$_2$e/y
Indicative residential volume	70 ktpa	210 ktCO$_2$e/y
Indicative portable volume	21 ktpa	65 ktCO$_2$e/y

The drive to decarbonise is likely to substitute some LPG services to electricity, biogas or biomass pellets. LPG demand shrinkage is forecast to be as much as 50%[8] in Europe but is expected to be less significant in New Zealand due to more limited natural gas substitution potential, forecast population growth (Europe assumes flat population growth), and a much smaller portion of LPG demand from the autogas market to be offset by electrification.

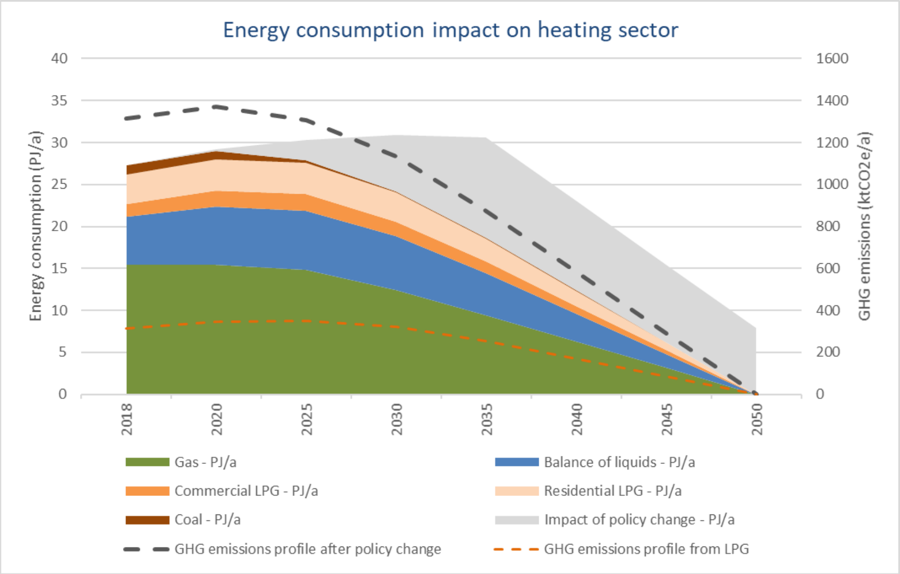
For this study we assume a 15% market shrinkage to 2035, with a further reduction to 20% by 2050, giving a demand forecast of 157 ktpa in 2035 and 148 ktpa by 2050.

We note that the CCC plan for natural gas energy end-use demand in 2035 is 52 PJ/a, which is 38.5% of the current end-use demand of 135 PJ/a (i.e. 180 PJ/a production – 45 PJ/a non-energy uses). If it was assumed that the future LPG yield from natural gas production is comparable to current yields, the domestic production of cLPG in 2035 is expected to be 63.5 ktpa (i.e. 38.5% of 165 ktpa) in 2035 and 40 ktpa in 2050. In reality, very little LPG is sourced from Pohokura, which is the dominant gas source and most like facility to reduce production, hence domestic cLPG production is likely to remain proportionately higher than this. We forecast domestic cLPG production of 90 ktpa in 2035 and 55 ktpa in 2050.

2.3 GHG emission reduction target

In Section 3.8.2 of the CCC Advice to Government (31 Jan 2021 Draft), it is recommended that "no further … bottled LPG connections occur after 2025". Based on the supporting energy demand profiles associated with the Commission's "our policy" setting, we have interpreted the break-out of commercial LPG and residential LPG end-use energy and greenhouse footprint trends implied by the "our policy" framework – see Figure 13, which is derived from CCC and MBIE data[9]. The Climate Change Commission seeks to fully decarbonise the ~320 tCO_{2eq} attributed to current LPG use in the heating sector.

Figure 13 - Forecast impact of CCC policy change on heating sector



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[8] "BIOLPG A renewable pathway towards 2050"- Liquid Gas Europe

[9] https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-statistics/oil-statistics/

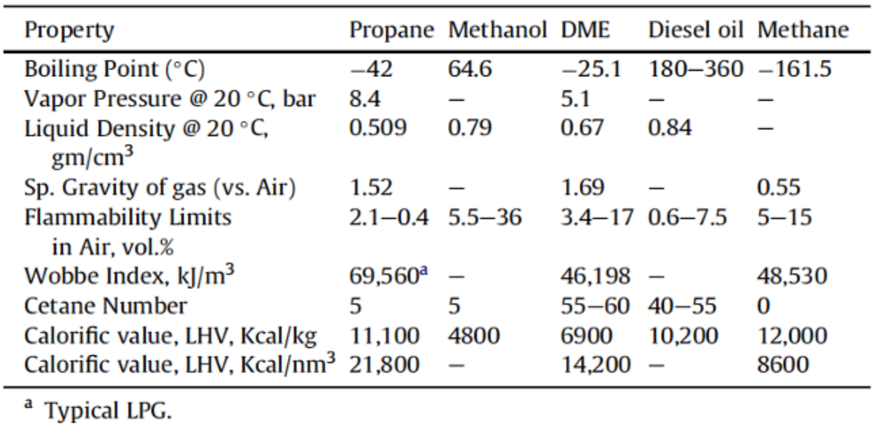
2.4 Potential role of rDME

An important use of rDME is as a blend stock for LPG. At blending levels below 20 vol %, the existing LPG blending facilities, local distribution infrastructure and end-use equipment can be used with minimal (if any) modifications.

DME / rDME is a flammable, thermally stable liquid like LPG and can be handled like LPG with similar safety guidelines and codes as LPG. Tables 4 & 5 below set out key physical properties of DME compared with specific conventional fuels. DME / rDME has a higher mass density than LPG but lower energy density, hence it takes ~1.6 kg of DME / rDME to provide the equivalent heating service (LHV) as a kilogram of LPG. The classic 9 kg bottle would weigh 1.4 kg more and carry 97% of the energy that a 100% cLPG bottle would.

In Section 6.1.2 we suggest that the GHG emissions intensity of rDME would likely be around 10 - 12 $ktCO_{2eq}$/PJ, hence a 20% DME/ 80% cLPG blend, has a ~3% lower heating capacity but has ~17% lower GHG intensity.

Table 4 - Key physical properties of DME and specific hydrocarbon fuels



Property	Propane	Methanol	DME	Diesel oil	Methane
Boiling Point (°C)	−42	64.6	−25.1	180–360	−161.5
Vapor Pressure @ 20 °C, bar	8.4	–	5.1	–	–
Liquid Density @ 20 °C, gm/cm^3	0.509	0.79	0.67	0.84	–
Sp. Gravity of gas (vs. Air)	1.52	–	1.69	–	0.55
Flammability Limits in Air, vol.%	2.1–0.4	5.5–36	3.4–17	0.6–7.5	5–15
Wobbe Index, kJ/m^3	69,560[a]	–	46,198	–	48,530
Cetane Number	5	5	55–60	40–55	0
Calorific value, LHV, Kcal/kg	11,100	4800	6900	10,200	12,000
Calorific value, LHV, Kcal/nm^3	21,800	–	14,200	–	8600

[a] Typical LPG.

Table 5 - DME / LPG blend properties

Parameter	Unit	DME	LPG	20 vol% DME / 80 vol% LPG
Mass density	kg/m^3	667	540	565.4
Heating value (LHV)	MJ/kg	28.8	46	42.6
Mass per bottle unit vol.	kg/m^3	567	432	459
Energy per bottle unit vol.	GJ/m^3	16.3	19.9	19.2

3. First generation “drop in” rLPG

Renewable LPG produced as a by-product of first generation biofuel production is considered to be a “drop in” replacement for conventional LPG. The fuel could be integrated directly into the current supply and distribution pathways and would not require any change of end-use appliances.

The two (2) production pathways considered in this chapter are:

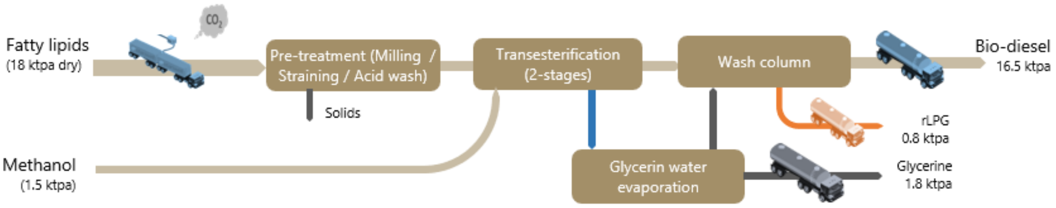
1. Transesterification of fatty lipids (FAME) pathway;
2. Hydrotreated vegetable oil pathway.

3.1 Transesterification of fatty lipids (FAME) pathway

The conversion of fatty lipids to biodiesel (FAME) pathway involves a comparatively simple transesterification process. The cost effectiveness of this 1st generation biofuel technology is constrained primarily by the cost and access to feedstock. The biodiesel yielded by this route is generally of high quality but requires care with management due to potential fuel instability and cold-temperature performance.

The primary feed for the pathway is fatty lipids, with glycerol being a key co-product. The typical minimum commercial scale is 50 tpd (~18 ktpa on a dry mass basis) with overview flow scheme summarised below. Fatty lipids are comprised of animal fats and vegetable oils

Figure 14 - Transesterification of fatty lipids summary flow schematic (50 tpd plant)



LPG production from FAME facilities will vary depending on both process conditions and the feedstock mix, but 5 -10% of the product slate is regularly identified.

ZBIOD plant

Z Energy built a fatty lipid to bio-diesel plant in Wiri, Auckland in 2016 for a nominal $26 million investment. The facility has a bio-diesel capacity of 20 million L/y (16 ktpa or 0.76 PJ/y) using tallow as feedstock. This is 0.5% of New Zealand’s current diesel demand.

The plant feed rate is ~50 ton/day.

Based on an expected 5% side yield, the potential renewable LPG yield is 0.8 ktpa.

Z state that double production is easily achievable for the plant given feedstock availability.

3.1.1 Potential scale

The biomass feedstock associated with this pathway is fatty lipids. The volume of fatty lipid feedstock in New Zealand is very limited, as summarised below:

- Non-edible tallow - Tallow is a triglyceride fat produced as an abattoir by-product at plants throughout New Zealand. The NZ Bioenergy Association estimates that there is some 150 ktpa of tallow produced in New Zealand, with some 120 to 130 ktpa exported - principally for use in animal foods and chemicals manufacture[10].
- Recovered waste cooking oil - The Bioenergy association estimates that 5 -7 ktpa cooking oil is available.

These two resources together can be used for the manufacture of around of approximately 120 ktpa of fatty acid methyl esters (biodiesel) and some 12 ktpa of glycerol.

3.1.2 Timing and decarbonisation value

New Zealand experience with FAME biodiesel manufacture is quite variable; due in part to a lack of consistency over the years in government policy regarding industry support. Whilst there has been a number of small-scale facilities producing biodiesel from waste cooking oil, the industry in NZ remains at a nascent state. Z Energy has built a 20 million L/y plant in Wiri Auckland utilising tallow as feedstock, but that plant is currently mothballed. Subject to ongoing tallow supply and plant performance challenges, but there is potential for that plant to be re-established and expanded to ~40 million L/y, subject to confirmation of feedstock supply[11].

By 2025 it would be expected that the Wiri plant would have been restarted and by 2030 another plant of similar scale would have been built.

The FAME pathway is in principle commercial now, and benefits from first mover advantage. Consequently, consistent with international trends, it is expected that this technology will advance in the near term (i.e. next decade), rather than later term.

The carbon footprint reduction associated with the FAME process is expected to be at least 60% less than conventional LPG. The majority of this footprint is associated with feedstock production and transport.

3.2 Hydrotreated vegetable oil pathway

The conversion of vegetable oils to biodiesel (HVO) pathway involves a comparatively simple but capital intensive hydrotreating. This 1st generation biofuels technology is the preferred commercial pathway worldwide. This technology yields high-quality bio-based diesel fuels without compromising fuel logistics, engines, exhaust aftertreatment devices, or exhaust emissions[4]. In particular it avoids the instability and cold-temperature performance concerns that can be associated with FAME-derived products.

The primary feed for the pathway is vegetable oil with a secondary feed of hydrogen. The typical minimum commercial scale is 50 tpd (~18 ktpa on a dry mass basis) with the overview flow scheme as summarised below.

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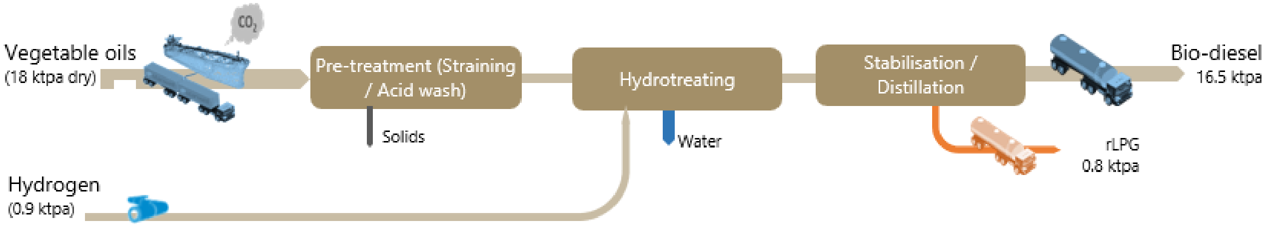
[10] https://www.liquidbiofuels.org.nz/documents/resource/WLB01_LiquidBiofuels-biodiesel-bioethanol-sources-details.pdf

[11] https://z.co.nz/assets/Biodiesel/Z-biodiesel-plant.pdf

Figure 15 - Vegetable oil hydrotreating summary flow schematic (50 tpd plant)



Chemically hydrotreated vegetable oils (HVOs) are mixtures of paraffinic hydrocarbons. The cold properties of HVO can be adjusted to meet the local requirements by adjusting the severity of the process or by additional catalytic processing. LPG production from HVO facilities will vary depending on both process conditions and the feedstock mix, but 5 -10% of the product slate is regularly identified.

Regionally the largest operation of this type is at the Neste's Singapore refinery – 3 million ton per year. The operation started operation in 2010 and produces exclusively renewable products based on its NEXTBL process[12]. At the end of 2018, Neste made an investment decision of €1.4 billion to expand[13] capacity to 4.5 million ton per year in 2023.

3.2.1 Potential scale

The biomass feedstock associated with this pathway are vegetable oils. The volume of vegetable oil feedstock in New Zealand is very limited, as summarised below:

- Waste oil – The Bioenergy association estimates that nearly 5 - 7 ktpa waste cooking oil is available out of an approximated national total of 30 ktpa.[14] [15] Much of what exists is already allocated to existing industries such as cement and asphalt manufacture, greenhouse heating, dust suppression. Distribution and availability broadly follows population centres, a government scheme to recover and reuse waste oil (i.e. ROSE) has been in place since 2011[16].
- Rapeseed industry – New Zealand currently produces around 15 ktpa of rapeseed in the South Island, the majority of which is sold as edible oil[17]. Diverting this oil from export to biofuel production will require a long-term diesel pump price close to $2 per litre to be a financially sustainable.
- Additional oil seed cropping to support biofuel industry growth is highly unlikely.

Hydrogen is a secondary feed to this process. It is assumed that green hydrogen production can be achieved relatively easily anywhere in New Zealand. Costs are still uncertain, but it is likely that cost will be high in the near term unless capital and energy input costs are supported by Government.

As noted, the hydrogenation process is capital intensive and benefits from scale. It is unlikely that New Zealand can domestically source enough vegetable oil feedstocks to justify a development of this nature.

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[12] https://www.neste.com/about-neste/innovation/nexbtl-technology

[13] https://www.neste.com/releases-and-news/neste-hosts-foundation-stone-ceremony-singapore-expansion

[14] https://www.wasteminz.org.nz/wp-content/uploads/Greg-Slaughter.pdf

[15] https://www.liquidbiofuels.org.nz/documents/resource/WLB01_LiquidBiofuels-biodiesel-bioethanol-sources-details.pdf

[16] https://www.beehive.govt.nz/release/used-oil-recycling-programme-extended

[17] https://www.stuff.co.nz/business/farming/99097913/former-biodiesel-plant-now-makes-culinary-oil

If Refining NZ were to undertake a reconfiguration in operation structure, it is possible that HVO bio-diesel production was possible using imported feedstock or bio-oil.

3.2.2 Timing and decarbonisation value

The movement towards decarbonisation, rise of electric vehicles and commercial pressures are impacting smaller refineries worldwide. It is therefore consistent with international trends to assume that a refinery reconfiguration would occur in the near term (i.e. next decade if economics allow), rather than in the later term. Should RefiningNZ decide to move to a simple import terminal operation as has been suggested, then it is unlikely that any refining capacity will remain in this country over the longer term.

Johnson in a paper published in 2017[18] shows that HVO biopropane's footprint varies considerably, by feedstock and production scenario but essentially the product qualifies for government support under the biofuel mandates enacted by EU member states. He reports an HVO footprint from imported feedstock of around 40 $ktCO_2$/PJ (i.e. 35% reduction in emissions intensity).

The majority of this footprint is in the harvest and transport of the feedstock, which will likely be in a different jurisdiction, hence the NZ GHG footprint could be an order or magnitude lower than cLPG.

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[18] E Johnson, A carbon footprint of HVO biopropane, Biofuels, Bioprod. Bioref. Wiley Online Library (wileyonlinelibrary.com); DOI: 10.1002/bbb.1796; 11:887–896 (2017)

4. 2nd generation “drop in” rLPG pathways

The second generation of biofuel production is expected to use a variety of conversion pathways to capture smaller volumes of “mixed” feedstocks to yield “drop in” replacements for conventional LPG. The fuel could be integrated directly into the current supply and distribution pathways and would not require any change of end-use appliances.

The production pathways that we considered in this chapter are:

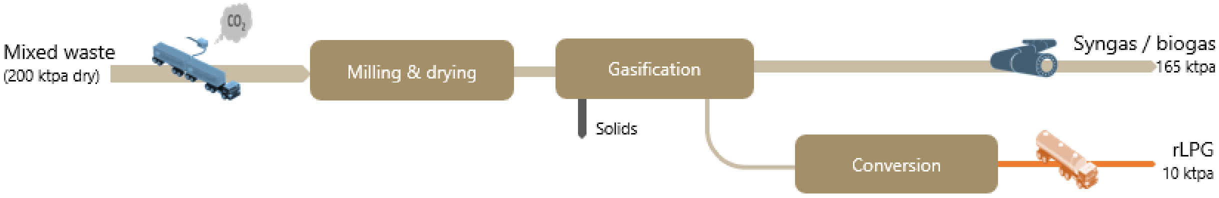
1. Small scale gasification and conversion;
2. Lignocellulosic fermentation;
3. Syngas fermentation;
4. Sugar fermentation.

4.1 Small scale gasification and conversion

The technology and processes for converting municipal solid waste (MSW) into low-carbon transportation fuels via thermochemical process routes is well understood with a number of developments world-wide aimed at commercial demonstration. These plants provide another pathway that might have application in the more population dense areas[19]. The common route of all small scale thermochemical pathways is gasification (or ionisation) to syngas, which is then further converted to yield either: methane, methanol, liquids via. MTG process, or liquids via Fischer-Tropsch process.

The typical minimum commercial scale for MSW gasification plants is ~200 ktpa (dry), but the minimum commercial scale for the subsequent syngas upgrading system is trending towards 10 ktpa (dry). An overview flow scheme is summarised below.

Figure 16 – Small scale gasification and conversion pathway flow schematic (200 ktpa feed / 10 ktpa rLPG plant)



Below are brief descriptions of three projects that represent potential viable routes, once fully proven.

4.1.1 Fulcrum Bioenergy

Fulcrum Bioenergy Sierra BioFuels Plant located in Storey County, Nevada, approximately 20 miles east of Reno. Once completed, Sierra is expected to process approximately 175 ktpa of MSW feedstock annually, creating 11 million gallons per year of renewable synthetic crude oil, or “syncrude,” that will be processed by Marathon Petroleum into transportation fuel[20].

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[19] Eric Johnson, *Process Technologies and Projects for BioLPG,* Energies 2019, 12, 250; doi:10.3390/en12020250

[20] https://fulcrum-bioenergy.com/technology/our-feedstock/

4.1.2 Advanced Biofuel Solutions

Advanced Biofuel Solutions has secured funding of £10 million to restart construction of a waste-to-gas facility in Swindon. The facility uses a multi-stage conversion process to convert MSW into bio-substitute natural gas (Bio-SNG). The facility is intended to convert 8 ktpa of waste into 22 GWh of pipeline gas each year[21,22]. The Advanced Biofuel Solutions process involves: Gasification; syngas clean-up; water shift to methane; CO_2 recovery; and natural gas grid injection.

4.1.3 Red Rock biofuel

The Red Rock biofuel technology platform converts waste woody biomass into low-carbon, renewable jet (SAF – sustainable aviation fuel) and diesel fuels[23]. The Red Rock process involves: Gasification; syngas clean-up; Fischer-Tropsch refining and hydro-processing. The Lake view project proposed to convert approximately 166,000 dry tons of waste woody biomass into 16.1 million gallons/year of low-carbon, ASTM-approved renewable jet and diesel fuels. rLPG production is estimated at approximately 8% of the final product slate[24].

4.1.4 Potential scale

The primary feedstock associated with this pathway is municipal solid waste stream. The volume of this feedstock in New Zealand is moderate:

- Municipal solid waste (MSW) – In the order of 3,300 ktpa across the country, which follows population density. This accounts for Class 1 landfills which are those which accept all waste from all sources including food waste. It is estimated that these landfills account for approximately 30% of total NZ net waste landfilled[25]. This MSW will produce around 5 PJ of landfill gas, or it can be processed to produce biogas providing in the order of 7 PJ of biogas.
    - Refuse derived fuel (RDF) is a product recovered from separation of high energy materials from recycled waste streams. After mild processing, this stream often has a consistent energy / moisture profile and is easily transported as a solid fuel.
- Food scraps – A portion of MSW is food waste. Across NZ this food waste is estimated in the order of 330 ktpa. The yield of biogas from food scraps can be up to 5× that of blended MSW.

Other feedstocks that can feed this pathway are crop residues, wastewater, and manure:

- Straw / stover – are the crop remnants left in the field after harvesting. It is treated as a residue of the arable crop from which it was grown and is often burned prior to replanting. It is estimated that around 950 ktpa of straw / stover is present across New Zealand[26].

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[21] https://www.letsrecycle.com/news/latest-news/waste-to-gas-plant-revived-after-administration/

[22] Advanced Biofuels, : https://absl.tech/about-us

[23] https://www.redrockbio.com/technology/

[24] Arno de Klerk , Fischer-Tropsch Refining, Thesis, Department of Chemical Engineering, University of Pretoria, February 2008

[25] "Waste Levy Extension Estimates of extending and raising levy" NZIER report to Ministry for the Environment November 2019

[26] 130614 Cover page + blank.pdf (far.org.nz)

- Crop waste – the crops which are simply not recovered after harvesting and wasted. They are estimated at around 500 ktpa[27].
- Municipal wastewater estimated at 470 million m^3/year – with 18 larger wastewater treatments plants (supplied by over 35,000 people) making up 80% of this volume[28].
- Dairy wastewater estimated at 60 million m^3/year.[29]
- Abattoir wastewater estimated at 20 million m^3/year. [30]
- Easily accessible and recoverable agriculture manure is estimated at 600 ktpa. [31]

If 1 PJ/y of biogas was converted to rLPG (refer to Section 6.4), then rLPG yields from this pathway would be ~18.5 ktpa.

4.1.5 Timing and decarbonisation value

Biofuel production trends associated with small scale gasification and conversion witnessed in Europe and North American provide promise that New Zealand will have several commercial pathways licensed and deployed prior to 2035. Population growth and continued technology evolution will likely yield continued upscaling of biogas to rLPG towards 2050.

The GHG footprint of biogas derived from MSW and RDF depend on the current disposal path and waste collection efficiency (i.e. fuel consumed by waste management trucks). If the waste is currently managed to yield landfill gas, then the GHG footprint of resulting rLPG from biogas will reflect the impact of ~10 - 20% conversion efficiency and will likely be 30 - 40 $ktCO_{2eq}$/PJ.

If the waste is currently not being managed (i.e. biodegrades to methane), then the GHG footprint of resulting rLPG from biogas will reflect the recovery and diversion of methane and will yield a negative GHG intensity between -100 and -80 $ktCO_{2eq}$/PJ.

4.2 Lignocellulosic fermentation

Lignocellulosic fermentation is a multi-step process where lignocellulosic biomass is pre-treated and then hydrolysed in order to convert the carbohydrate polymers, cellulose and hemicellulose, to monomeric sugars, which are fermented to produce ethanol. Scion and others have undertaken considerable work in this area to interpret New Zealand's potential for using this pathway. [32,33]

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[27] NZ Biomass Resource Atlas, Vol. 1 | Use Wood Fuel - a Bioenergy Association site

[28] https://www.lei.co.nz/images/custom/ltc-2016-cass_lowe-160205-.pdf

[29] B.Cox 'TNGB14 – sources of biogas feedstock'

[30] B.Cox 'TNGB14 – sources of biogas feedstock'

[31] B.Cox 'TNGB14 – sources of biogas feedstock'

[32] Scott-Kerr C et al, Bioethanol – status report on bioethanol production from wood and other lignocellulosic feedstocks" on line from: https://www.osti.gov/etdeweb/servlets/purl/21390241

[33] Scott-Kerr C et al, Bioethanol – status report on bioethanol production from wood and other lignocellulosic feedstocks" on line from: https://www.osti.gov/etdeweb/servlets/purl/21390241

It has been predicted that lignocellulosic fermentation will eventually replace first generation fermentation technologies for bioethanol production[34], however the unmanageable nature of lignin (which typically makes up 10% – 25% of volume and 25 – 35% of energy) fermentation remains.

To allow fermentation of the carbohydrate fraction of this resource, lignin must be separated from cellulose and hemicellulose polymers via a complex and costly pre-treatment process so that these polymers may be broken down into fermentable sugars by enzymatic hydrolysis. Methods used for pre-treatment include physical treatments such as milling and irradiation as well as chemical treatments such as the use of oxidising agents and strong acids.

4.2.1 Potential scale

The biomass feedstock associated with this pathway are easily accessible cellulosics, such as straw or crop wastes. Softwoods are unlikely to be a commercial option in any future supply scenario, except for speciality chemicals or bioplastics.

- Straw / stover – are the crop remnants left in the field after harvesting. It is treated as a residue of the arable crop from which it was grown and is often burned prior to replanting. It is estimated that around 950 ktpa of straw / stover is present across New Zealand[35].
- Crop waste – the crops which are simply not recovered after harvesting and wasted. They are estimated at around 500 ktpa[36].

These two resources together could be used for the manufacture of around of approximately 100 ktpa of rLPG.

4.2.2 Timing and decarbonisation value

Whilst New Zealand has relevant experience in fermentation, it is deemed an unlikely route for rLPG production because of the lack of feedstock and the more easily deployed and commercial alternative route to biogas via dry digestion of crop waste. However, there are commercial plants already in operation globally whose design can easily be licensed, should an economic opportunity arise.

4.3 Syngas fermentation

Syngas fermentation also offers an alternative route to methanol from biomass, but it is largely at a developmental stage.[37] A potential advantage over traditional thermochemical conversion routes is that the derived biofuels include; hydrogen, ethanol, butanol, acetic acid and butyric acid. Worldwide there is significant ongoing research and development with the literature suggesting some five demonstration or semi-commercial plants either operating or planned.

Known commercial syngas fermentation plants include Indian River (INEO) and Lighthouse in Pennsylvania (Coskata). LanzaTech (formerly Range Fuels) has operated a waste gas fermentation demonstration plant at

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[34] Gnansounou, E.; Dauriat, A. Techno-economic analysis of lignocellulosic ethanol: A review. Bioresour. Technol. 2010, 101, 4980–4991.

[35] 130614 Cover page + blank.pdf (far.org.nz)

[36] NZ Biomass Resource Atlas, Vol. 1 | Use Wood Fuel - a Bioenergy Association site

[37] Daniell J., *et al* Commercial Biomass Syngas Fermentation, Energies 2012, 5, 5372-5417 ; doi :10.3390/en5125372

Bluescope Steel in New Zealand and is reported to have developed two additional demonstration plants in partnership with Baosteel and Capital Steel in China. The current status of these plants is unknown. In recent news the US biofuels company, Aemetis, was reported as proposing a woody biomass gasification plant in India to produce ethanol via Lanzatech's microbial fermentation technology. To date, no investment decision has been made.

Meanwhile Lanzatech continues moving forward on scale-up of sustainable aviation fuels in US and Japan[38]. Commercialization of this process has been years in the making, but essentially remains unproven.

4.4 Sugar fermentation

Fermentation of sugars to ethanol is a first generation biotechnology, but sustained enterprise in the waste to alcohol pathway has led to the development of 2nd generation biotechnology that yields liquids such as isobutene and butanols. Many of the resulting products can be blended with conventional LPG and potentially contribute to the decarbonisation of the heating sector.

An interesting recent development by the French company, Global Bioenergies, converts sucrose into isobutene using genetically engineered microorganisms[39]. The process has been operating at demonstration plant level, capable of producing 0.15 ktpa of final product, with a commercial-scale facility in France expected to be commissioned in 2022. This project is currently at the planning stage and is reported to produce up to 50 ktpa of isobutene. We understand that consideration is also been given to entering the LPG market, by demonstrating the feasibility of blending isobutene into domestic bottled gas (LPG) as well as its compatibility with the logistics chain and domestic appliances[40].

4.4.1 Potential scale

The volume of "easy access sugars" that are available for this pathway are very low in New Zealand:

- Sugar beet – nominal amounts produced for stock feed. Assume nil available
- Sugar cane & sorghum – nominal amounts produced for niche edible products. Assume nil available.

We consider that the commercial development of sugar crops for fuel is highly unlikely for New Zealand

4.4.2 Timing and decarbonisation value

The GHG footprint of biofuels derived from sugar fermentation are generally low and likely between 10 – 15 $ktCO_{2eq}/PJ$.

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[38] https://www.greencarcongress.com/2019/11/201091121-lanzatech.html

[39] https://www.global-bioenergies.com/group/isobutene-process/?lang=en

[40] LPG Association NZ, personal communication.

5. 3rd generation “drop in” rLPG pathways

New Zealand’s most abundant biomass resource is softwood and woody residues. These resources are readily with available with secure and reliable supply chains, which would enable biofuel facilities to benefit from economies of scale. The majority of softwood resources are destined for export markets and hence command a premium price. Woody residue and comparatively stranded softwood supplies are available and may contribute to biofuel production and decarbonisation.

The selection of preferred processing pathways for this feedstock is generally not feedstock dependent, rather about conversion process efficiency and the technology risk management.

The production pathways that we considered in this chapter are:

1. Softwood to biofuels via conventional synthesis;
2. Softwood to biofuels via advanced synthesis;
3. Softwood to biofuels via pyrolysis.

5.1 Softwood to biofuels via conventional synthesis

Two pathways involving gasification (to syngas) followed by conversion to partially oxygenated liquid hydrocarbon products are well proven and established, namely:

a. Fischer-Tropsch (FT) production of syn-biofuels and mixed alcohols;
b. Methanol to gasoline (MTG) pathway.

Both technologies entail high capital costs for gasification and conversion units, and benefit from economies of scale, hence commercial units are expected to have a minimum of 500 ktpa (dry basis) capacity. The capital cost estimates for a first-of-its-kind commercial plant of this scale are forecast to be in the region of USD $600-900 million[41].

In previous work undertaken by Worley for Arena in Australia[42] a conceptual process configuration for a commercial softwood to biofuel plant based of the MTG pathway with feed capacity of 700 ktpa (2,000 tpd dry basis; 50% moisture content) was developed. The methanol (intermediate product) yield was 320 ktpa (913.4 tpd) at approximately 96% purity[43]. If the downstream plant targeted gasoline via the MTG route[44], the yield per metric tonne of dry biomass was 230 L of gasoline and 39 L of LPG, hence, the LPG (i.e. co-product) yield is ~15 ktpa. At a feed price of NZD 75.94/dry metric tonne, the gate prices for gasoline and LPG were NZD 0.71/L and NZD 0.54/L respectively. Alternatively, if the downstream plant targeted conversion to DME, then rDME yield is ~218 ktpa.

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[41] 2000 Summary of Task 39 report: “The potential and challenges of drop-in biofuels” ISBN: 978-1-910154-09-0 (electronic version) July 2014

[42] WorleyParsons, Australian Liquid Fuels Technology Assessment, BREE (Bureau of Resources and Energy Economics), Canberra, September 2014

[43] A grade suitable for subsequent use; either directly as transport fuel blend or indirectly as feed stock to a downstream MTG or DME conversion plant.

[44] Steven D. Phillips, et al Gasoline from Woody Biomass via Thermochemical Gasification, Methanol Synthesis, and Methanol-to-Gasoline Technologies: A Technoeconomic Analysis. ACS dx.doi.org/10.1021/ie2010675 | Ind. Eng. Chem. Res. 2011, 50, 11734–11745

The gasification technology presumed for the above study was based on the Battelle Columbus laboratory low pressure indirectly-heated circulating fluidised bed technology. However, we acknowledge that recent advances in gasification technology may offer improved yields and thermal efficiency over those utilised in this study. We note in particular that at small scale a variety of other gasifier types are being promoted.

5.2 Softwood to biofuels via advanced synthesis

In Section 4.1 of this report we highlight a sample of technologies that are able to cost effectively convert municipal solid wastes and softwoods to target liquid fuels. The improving efficiency and selectivity of these pathways brings forward the prospect of being able to realise large scale biofuel synthesis using readily available biomass.

The advances in gasification and conversion technology are likely to bring the minimum scale for commercial units towards 200 ktpa (dry basis) capacity.

New Zealand is well placed to be an early adopter of advanced synthesis options due to access to secure and reliable woody biomass supply chains, which may be augmented with MSW (or refuse-derived-fuel) supplies.

5.2.1 Potential scale

Feedstocks associated with this pathway are derived from New Zealand's existing forestry industry. The volume available is significant, and dense within certain regions[45]. The central North Island accounts for approximately 35% of the total NZ forestry area.

- Forest residue – roots, trimmings, waste not associated with saw or pulp logs, termed hog and chip quality, is estimated in the order of 1,680 ktpa (dry weight).
- Pulp logs – logs for use in the pulp and paper industry, currently allocated or exported, but if were repurposed provide approximately 3,360 ktpa (dry weight).
- Saw logs – used for timber both locally and internationally. Total cut for saw logs is approximately 13,000 ktpa (dry weight).

The advances in gasification and conversion technology are likely to bring the minimum scale for commercial units towards 200 ktpa (dry basis) capacity. Adopting a Fischer-Tropsch (FT) style conversion process will likely yield 1-3% rLPG of feed basis, hence 2 ktpa rLPG as a side product per plant of this size is entirely realisable. It is equally possible to target rLPG production and yield >20 ktpa rLPG per plant of this size.

5.2.2 Timing and decarbonisation value

Considering the technology and scale risks of this production pathway, it is unlikely to be an early mover, rather it is forecast that the first plants of this type will emerge near 2040.

The majority of the GHG footprint associated with this pathway is associated with the harvest and transport of the feedstock and intensified by conversion efficiency. The GHG footprint is anticipated to be between 15 – 25 $ktCO_{2eq}$/PJ.

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[45] https://www.mpi.govt.nz/dmsdocument/14221-Wood-Availability-Forecasts-New-Zealand-2014-2050

5.3 Softwood to biofuels pathway via pyrolysis

Thermochemical processing conditions for lignocellulosic feedstocks can be optimised to influence the ratio of the three main products, namely: bio-oil, synthesis gas and char, depending on the end-use application envisaged.

Bio Pacific Partners in their recent report to MPI and other government agencies[46] on the use of commercial forest biomass to move New Zealand towards a carbon-zero future, suggest that the manufacture of biocrude is an option for New Zealand's oil and gas industry to utilise its existing assets and distribution networks in ways which lower the carbon intensity of the fuel industry. Whilst the report is correct in observing that the processing of biocrude may well allow companies that operate refineries to generate carbon credits under a low carbon fuel standard, the reality is that at the scale required to maintain refinery operations via biomass pyrolysis in New Zealand will require feedstock quantities that are simply not possible.

Pyrolysis technology is limited by scale and also the need to find markets for the char by-product. There are commercially mature routes to substitute diesel from the pyrolysis of waste tyres and recovered waste plastics, but these routes typically use batch distillation (similar to waste oil recovery) of the produced pyrolysis oil under reduced pressure and do not entail any form of hydrotreating - this is not the case for a biomass feed, due to the material having low hydrogen and high oxygen contents. The process breaks the pyrolysis oil into usable fractions with minimal additional cracking or production of undesirable deposits or aromatics.

We note also that a major study was undertaken in 2008 by Norske Skog (Stump-to-Pump) and their technology partners Licella (Catalytic Hydrothermal Reaction (CAT-HTR)) to examine the feasibility of converting up to 1,600 ktpa (oven dried) wood residues to biocrude. They estimated the potential to produce up to 4 million barrels/year, or 10% of NZ crude requirements. This process centres on using supercritical water to break down carbon-oxygen linkages of the biomass structure to liquefy it into a form of bio-oil (also termed biocrude).

The severe process conditions required by this process have led to sustained challenges such as corrosion (or use of expensive alloys), and high wear on process components. The resultant high investment cost and also the high oxygen content of the derived bio-oil becomes a considerable hurdle to commercial deployment. Nevertheless, a few pilot / demonstration processes do exist, and this route may well evolve based on lower-oxygen, carbonaceous materials. The proposed demonstration project in New Zealand did not proceed.

5.3.1 Potential scale

The pyrolysis of woody biomass for biocrude is not envisaged to contribute strongly to biofuel or rLPG production in New Zealand.

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[46] BioPacific partners Wood Fibre Futures, report to NZ Forestry Advisory Group, 2020

6. “Blend in” component production

6.1 DME pathway

DME is a methanol derivative, with rapidly growing global production rates. DME is being produced for use as a fuel (in both the transportation and heating sectors), small-scale electric power generation, and specialty chemicals market. A number of DME plants are in different stages of development around the world with the majority of world supply either natural gas or coal based. However, DME from biomass, based on syngas production from biomass (including MSW and black liquor) [47], is both technically feasible and an emergent commercial play.

We assess rDME as being near-commercial in its capacity to meet renewable fuel standards as well as having an available mature distribution and fuels infrastructure. Whilst the conventional routes via methanol as an intermediary are technically mature, there are limitations associated with scale and cost. Several companies, including Haldor Topsoe, Japan JFE Holdings Company, and Korea Gas Corporation, have developed direct DME synthesis technologies which are at early-stage commercialisation[48]. The direct DME synthesis process, offers a significantly improved conversion per pass of syngas to DME and thus potentially improved economics.

6.1.1 Potential scale

The scale is potentially only limited by the availability of biogas.

6.1.2 Timing and decarbonisation value

A study by the European Commission Directorate Joint Research Centre, showed that Well-to-Wheels CO_2 emissions from the use of rDME in the diesel vehicle fleet to be less than 5% of petroleum diesel and about 20% lower than synthetic diesel via BTL Fischer-Tropsch.

A wheel-to wheel comparison for the production of rDME by Tomatisa, showed that the recycling of waste CO_2 as a gasifying agent significantly reduced total GHG emissions when compared to diesel (0.46 and 1.62 kg CO2-eq/km for rDME and diesel respectively) whilst also offering a lower impact on human health, and ecosystem (55 and 68% lower compared to pure diesel respectively). These numbers compare with studies in Thailand based on the conversion of rice straw to rDME[49].

On the basis that biogas is derived from a managed waste stream (i.e. carbon neutral source) we estimate that the GHG emissions intensity of rDME would likely be between 20 - 30 ktCO_{2eq}/PJ. However, in applications where the bioga / rDME is derived from an unmanaged waste stream (e.g. animal waste), the resultant product will have a largely negative carbon emissions value, this is true for rLPG also - see Section 4.1.5 [50]. We interpret that the resultant mixture of rDME and cLPG will have a significantly reduced carbon

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[47] T.H. Fleisch et al. / Journal of Natural Gas Science and Engineering 9 (2012) 94e107

[48] Marco Tomatisa, A life cycle analysis (LCA)-based case study in China, Fuel 254 (2019) 115627

[49] T. Silalertruksa et al., Life cycle GHG analysis of rice straw bio-DME production and application in Thailand, Applied Energy 112 (2013) 560–567

[50] https://www.sciencedirect.com/science/article/pii/S0959652620350137

emissions profile than cLPG on its own, at the requisite 80/20 blend of cLPG/rDME the net emissions trend towards zero.

There are significant advantages for rDME from a clean air perspective. Due to the high oxygen content of DME and the lack of direct carbon–carbon bonds, soot-free combustion is possible using DME allowing increased exhaust gas recirculation to help reduce NOx emissions. In engine tests, emissions from DME combustion have been shown to be lower than those from diesel combustion under almost all engines operating condition. CO emissions however are slightly greater[51].

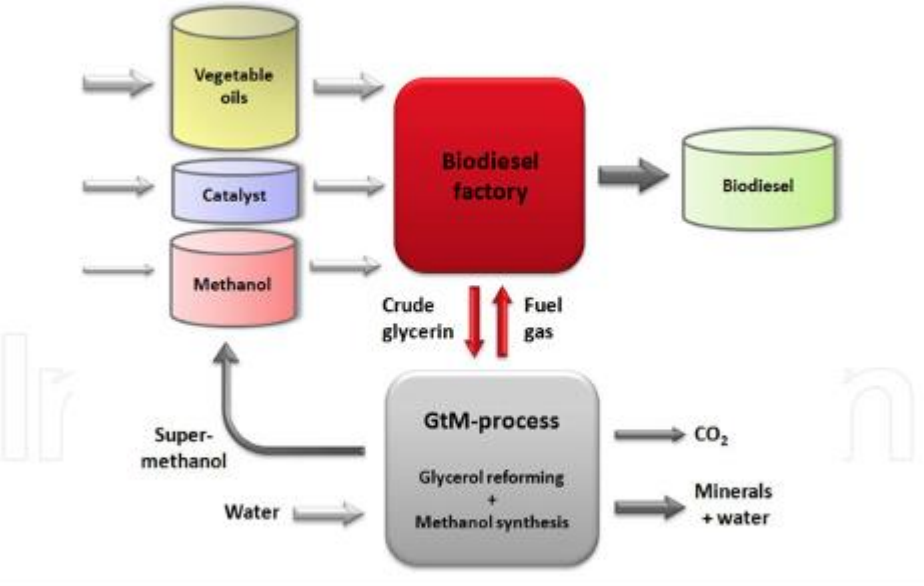
Given the lack of regulatory oversight specifically on DME handling and use within New Zealand, it would be prudent that this should be addressed to improve regulatory certainty and is something the Commission may wish to consider in its final recommendations.

6.2 Glycerol to DME / rLPG

Surplus glycerol from FAME biodiesel processing can be used to produce methanol via the (GtM) process[52]. This methanol can then be upgraded to DME or potentially rLPG.

This process is an integration of two separate processes, the reforming in supercritical water (RSCW) of glycerol to syngas, followed by the conversion of this syngas into methanol.

Figure 17 - Gas to Methanol BFD



In Europe this technology is at an early-stage of commercialisation with Bio-MCN being operated in the Netherlands. The company also produces bio-methanol from biogas sourced from waste digestion plants[53].

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[51] Su Han Park a, Chang Sik Lee, Applicability of dimethyl ether (DME) in a compression ignition engine as an alternative fuel, Energy Conversion and Management 86 (2014) 848–863

[52] Joost G. van Bennekom; http://dx.doi.org/10.5772/53691

[53] https://www.oci.nl/operations/biomcn/

6.2.1 Potential scale

Roughly 100 kg of glycerol is produced for every ton of biodiesel produced via the FAME biofuel pathway. As identified in Section 3.1.1, the potential 120 ktpa FAME biofuel capacity of New Zealand could yield ~12 ktpa of glycerol. After being converted to methanol, then DME and then rLPG the yield would be 0.2 ktpa.

6.2.2 Timing and decarbonisation value

In Section 3.1.2, it is forecast that FAME biodiesel will likely be advanced in the near term (i.e. next decade), and there is no reason why glycerol to DME / rLPG development would not occur in this same timeframe.

6.3 Biogas feedstock

Global biogas / biomethane production is estimated at 1,500 PJ[54]. The vast majority of production lies in European and North American markets, with some countries such as Denmark and Sweden boasting more than 10% shares of biogas / biomethane in total gas sales.

The primary source of this biogas is anaerobic digestion. Digestion technology has becoming increasingly popular in the last 25 years as it reduces environmental issues (e.g. wastewater loading and odours) facing primary producers.

The primary feedstocks for the anaerobic digestion pathway are: Agriculture wastewater (e.g. Dairy and piggery effluent); Crop residues; Municipal wastewater; Landfill gas and organic (e.g. food waste) municipal waste.

The rising interest in biomethane means that the number of operating plants worldwide is increasing rapidly. Around 60% of plants currently online and in development inject biomethane into the gas distribution network, with a further 20% providing vehicle fuel[55].

Fair Oaks Farms in northwest Indiana, has developed a biogas system for their 11,000 head cow herd to produce compressed natural gas (CNG). They convert dairy effluent to biogas for use directly as CNG fuel or conversion to DME via methanol. The CNG is used to operate 42 milk trucks taking carrying some 300,000 gallons per day of milk from the farms to the processing facility. Anaerobic digestion at Fair Oaks Farms generates about 865 MMBtu of renewable natural gas per day, displacing more than 1.5 million gallons of diesel fuel per year. Interestingly, in this case study the upgraded biogas is transported via pipeline to the fuelling station in Fair Oaks, where it is further compressed and dispensed as rCNG[56].

In Section 6.4 we describe how this biogas / biomethane can be converted to DME and rLPG.

6.3.1 Dry digestion

Dry digestion is seen as a highly desirable pathway for New Zealand's use of municipal waste and dry matter derived from energy cropping. Dry digestion involves anaerobic digestion at temperatures of between 50 - 58°C in either batch or continuous flow systems. The system is capable of processing a range

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[54] http://www.worldbioenergy.org/uploads/181017%20WBA%20GBS%202018_Summary_hq.pdf

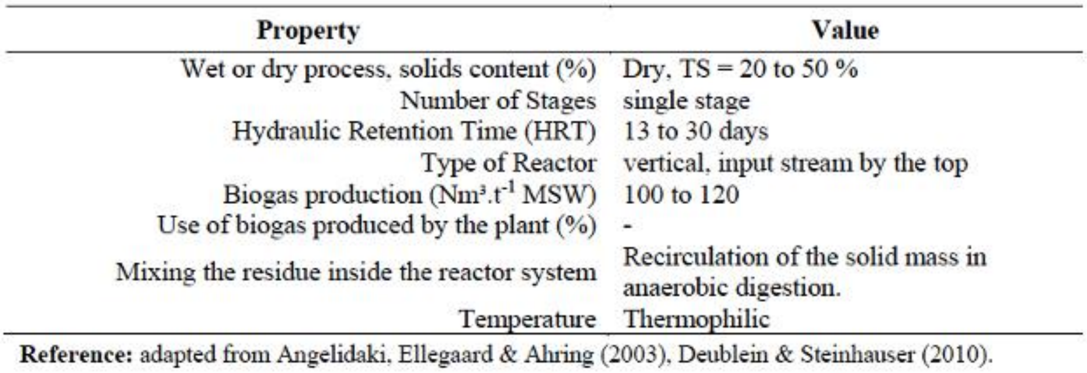
[55] IEA *Outlook for biogas and Prospects for organic growth*, World Energy Outlook Special Report, Biomethane, IEA 2020

[56] Tomich *et al*, Cow Power: A Case Study of Renewable Compressed Natural Gas as a Transportation Fuel, Argonne

of mixed waste streams with solids contents of up to 50%. It is also ideally suited for the digestion of energy crops such as maize, lucerne and other crops without further processing (apart from size reduction) or water addition.

Typical process properties for a dry digestion plant are given in the table below[57].

Table 6 – Dry digestion (Dranco process) key features



Property	Value
Wet or dry process, solids content (%)	Dry, TS = 20 to 50 %
Number of Stages	single stage
Hydraulic Retention Time (HRT)	13 to 30 days
Type of Reactor	vertical, input stream by the top
Biogas production ($Nm^3.t^{-1}$ MSW)	100 to 120
Use of biogas produced by the plant (%)	-
Mixing the residue inside the reactor system	Recirculation of the solid mass in anaerobic digestion.
Temperature	Thermophilic

Reference: adapted from Angelidaki, Ellegaard & Ahring (2003), Deublein & Steinhauser (2010).

6.3.2 Potential scale

Anaerobic digestion has progressed quietly in New Zealand but has never received significant focus. New Zealand has a few dozen examples of anaerobic digestion of agriculture wastewater and a few examples of anaerobic digestion of municipal wastewater (e.g. Mangere Wastewater treatment plant, Auckland).

Wastewater resources within New Zealand are scattered between North and South Islands, with municipal wastewater centred about population centres. Agricultural wastewater and manure follow areas of high agricultural intensity, Waikato and central North Island, and Canterbury basin.

- Municipal wastewater estimated at 470 million m^3/year – with 18 larger wastewater treatments plants (supplied by over 35,000 people) making up 80% of this volume[58].
- Dairy wastewater estimated at 60 million m^3/year[59].
- Abattoir wastewater estimated at 20 million m^3/year[60].
- Easily accessible and recoverable agriculture manure is estimated at 600 ktpa[61].

6.3.3 Timing and decarbonisation value

Anaerobic digestion is already technically and commercially mature, with rates of development dependent on the demand and pricing of biogas.

Of more importance, however, is the recent announcement from Ecogas Limited, who have announced a food waste & organics to biogas and biofertilizer facility at Reporoa, Central North Island which will be

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[57] de Lima H Q, *Anaerobic digestion AD of municipal solid waste in Santo Andre-SP – Review,* conference paper https://www.researchgate.net/publication/291334691,

[58] https://www.lei.co.nz/images/custom/ltc-2016-cass_lowe-160205-.pdf

[59] B.Cox 'TNGB14 – sources of biogas feedstock'

[60] B.Cox 'TNGB14 – sources of biogas feedstock'

[61] B.Cox 'TNGB14 – sources of biogas feedstock'

capable of processing up to 75ktpa of feedstock. This $30m+ facility will be the largest private biogas facility in the country[62].

If the waste is currently not being managed (i.e. biodegrades to methane), then the GHG footprint of resulting rLPG from biogas will reflect recovery of methane and will yield a negative GHG intensity between -160 and -100 $ktCO_{2eq}/PJ$.

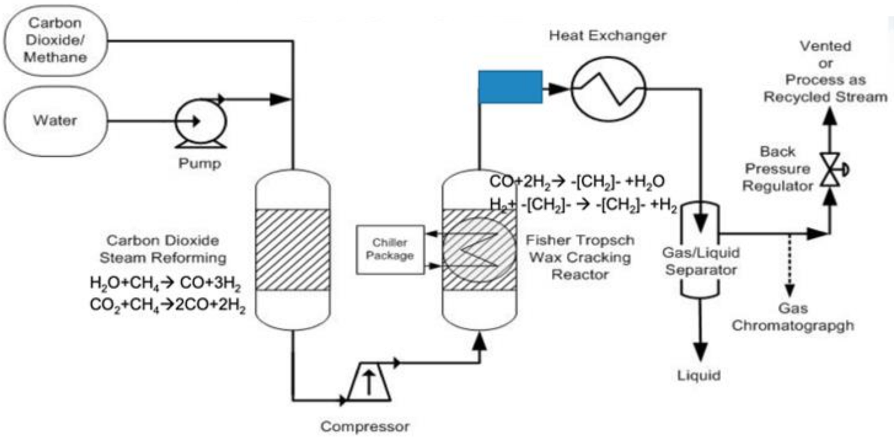
6.4 Biogas to rLPG pathway

There are a number of emerging technologies that take biogas through to useful fuels, including DME and rLPG. Two examples are provided below.

6.4.1 Cool GTL approach

The US-based Gas Technology Institute (GTI) has developed a process called Cool GTL17 that can convert digestor biogas to higher hydrocarbons, including propane and butane[63,64]. The process reforms the carbon dioxide and methane in the biogas into a syngas mixture that is fed to a Fischer-Tropsch reactor. FT reactors typically produce waxes that must be hydrotreated into liquid fuels, but the GTI technology integrates a wax cracking / isomerisation into the FT reaction step. Discussion with the Institute[65] indicates that Cool GTL is currently aimed at jet fuel but say that the process could just as readily make propane or butane.

Figure 18 - Cool GTL schematic



The Institute is also testing variants of their biogas technology to allow direct biomass conversion via their licensed IH^2 (Integrated Hydro-pyrolysis and Hydro-conversion) pyrolysis technology[66] or their in-house U-Gas fluidized bed gasifier. They report that the addition of the $IH^{2®}$ technology for conversion of biomass increases biogenic liquid yields by 40%. Liquid yields of 89 US gallons per dry tonne are claimed. LPG would be a by-product commodity.

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[62] Ecogas, personal communication, 2020. Also see https://www.ecogas.co.nz

[63] https://www.gti.energy/wp-content/uploads/2019/10/04-tcbiomass2019-Presentation-Terry-Marker.pdf

[64] https://www.gti.energy/cool-gtl-a-low-cost-system-for-converting-co2-rich-natural-gas-to-fungible-liquids/

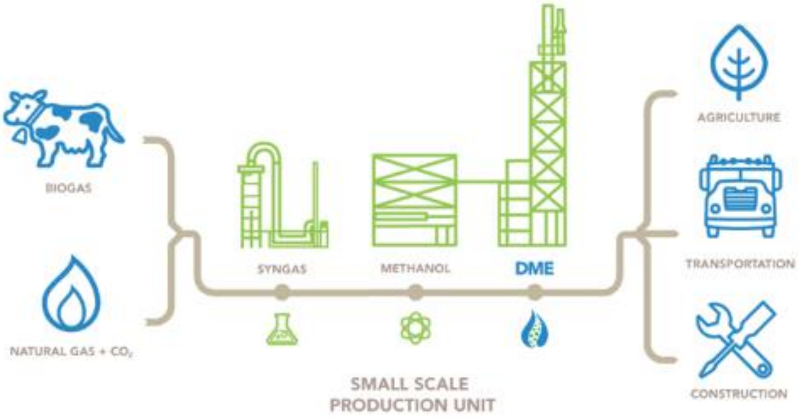
[65] E Johnson, personal communication

[66] https://www.shell.com/business-customers/catalysts-technologies/licensed-technologies/benefits-of-biofuels/ih2-technology/hydropyrolysis.html

6.4.2 Oberon – Modular conversion system

Oberon Fuels in California[67] utilise various feedstocks - such as biogas (animal and food waste, wastewater treatment, landfills), natural gas, and stranded gas to convert methane to DME.

Figure 19 - Oberon Fuels - Biogas to DME schematic



The company's modular designed plants are intended to be deployed to remote to industrial operations in order to monetize waste CO_2 streams or alternatively biogas (up to 50% CO_2). Example waste streams include pulp mill wastes and dairy farm effluent. The company has a deal with Suburban Propane (one of the largest US LPG companies) to supply DME for blending with propane for autogas. Suburban have taken up a 39% shareholding in Oberon. Standard plants are sized to produce 2.7 – 9 ktpa of DME (from 15,000 to 25,000 cows), which is 1.7 - 5.6 ktpa rLPG equivalent.

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[67] https://oberonfuels.com/technology/oberon-process/

7. Decarbonisation scenario assessment

In this section we assess two scenarios for decarbonisation of New Zealand's LPG industry, namely:

1. 70% rLPG substitution - to decarbonise the LPG portion of the heating sector;
2. 100% rLPG substitution - to decarbonise the entire LPG industry.

7.1 70% renewable LPG substitution scenario

For the 70% rLPG substitution scenario, it is anticipated that New Zealand's natural gas industry will continue to evolve and deliver conventional LPG up to and beyond 2050. To balance the decline in cLPG production, a healthy rLPG production industry will progressively evolve.

Based on our interpretation of the status of biofuel technology paths and current availability of feedstocks (refer to Sections 3 through 6) we characterised what we believe to be a conservative and realistic string of biofuel developments with rLPG yields. It was clear that the build-up of rLPG production capacity would not be able to match the decline in cLPG production, hence we assume that a proportion of the demand will be met through import of LPG / rLPG. Prior to 2035 it is assumed that majority of imports will be cLPG, but after 2035 rLPG will be imported.

We observed that this scenario resulted in 70% substitution of the 2050 demand and achieved an emission reduction trend comparable to that outlined in the Climate Change Commissions "our policy" approach for the heating sector. We note that our emissions intensity analysis / outcome is not rigorous and is highly dependent upon which feedstocks are recovered for biofuel production and point of ownership transition for these feedstocks – refer to Section 1.5.

The rLPG market build-up is summarised in Table 7 and visualised in Figure 20. Further detail is available in Table 9 / Appendix A.

Table 7 - 70% rLPG scenario plant scale

Plant by 2035	Plant by 2050
2 @ 100 tpd FAME biodiesel plants ≈ 3.2 ktpa rLPG	
2 @ Mixed waste gasification to rLPG plants ≈ 6 ktpa rLPG	3 @ Mixed waste gasification to rLPG ≈ 9 ktpa rLPG
2 @ Wastewater / manure to rDME facility ≈ 25 ktpa rLPG equivalent (40 ktpa rDME)[68]	3 @ Wastewater / manure to rDME facility ≈ 30 ktpa rLPG equivalent (48 ktpa rDME)
	Biogas to rLPG capability ≈ 40 ktpa rLPG
	1 @ Softwood to biofuels plant ≈ 20 ktpa rLPG

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[68] Capacity limited to avoid exceeding DMR / LPG blend limit.

Figure 20 – Target rLPG build-up – 70% rLPG substitution scenario

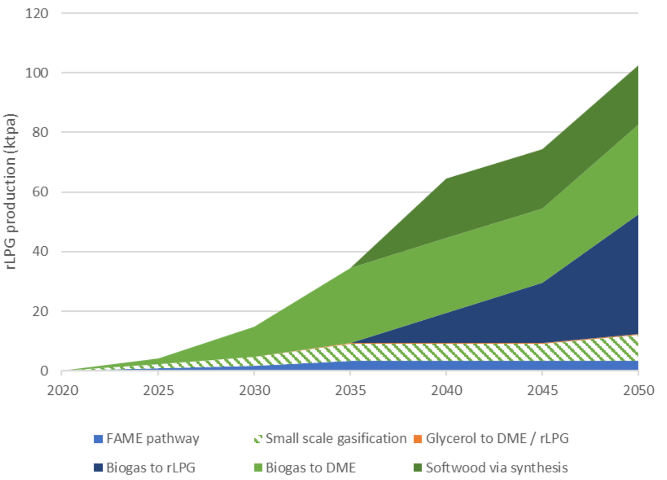
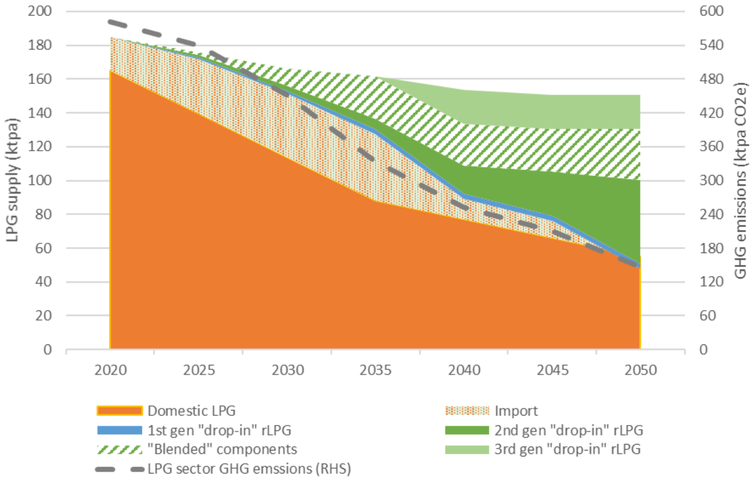


Figure 21 - NZ LPG market plan – 70% rLPG substitution scenario



The ~3 ktpa rLPG target from 1st generation biofuels represents around 40% of the domestically available feedstock – we believe that this is achievable and could be complemented by imported feedstock.

The ~70 ktpa rLPG equivalent target from 2nd generation biofuel technology represents less than 10% of available feedstock. There are likely to be two contributors to this target, namely:

Three mixed wastes (i.e. Cellulosics, forestry residues or MSW) to rLPG plants (2 in North Island and 1 in South Island), or a single rLPG targeted plant. This pathway targets less than 10% of available feedstock and is likely to yield zero or negative GHG emission profile due to the value of offsets attributed to diversion of waste streams.

Multiple small wastewater or manure to rDME plants, yielding up to 30 ktpa of rLPG equivalent. This pathway targets nearly 40% of available feedstock and is likely to yield zero or negative GHG emission profile due to the value of offsets attributed to diversion of waste streams. Our confidence in adoption of this pathway is based on:

i) Value add to stranded resources;

ii) Globally proven technology and cost effectiveness;

iii) GHG abatement value.

On the basis that biogas production from waste will be used to complement natural gas production, the direct conversion of biogas to rLPG provides a capacity flexible (i.e. opportunity based) mechanism for upgrading biogas to the much more readily transported / higher density rLPG fuel. We forecast that a development of this nature will occur post 2035, but earlier than 2050 and will on average produce ~40 ktpa by 2050.

The target of ~20 ktpa rLPG from 3rd generation biofuels is based on the development of a single large softwood to biofuels plant, from which rLPG would be a side stream rather than the main product. New Zealand's dense softwood reserves and demonstrated supply chains has generated interest in this pathway for several decades. We believe that facilities of this nature will be possible by 2050.

The resulting LPG market plan for the 70% rLPG substitution scenario is summarised in *Figure 21*.

7.2 100% renewable LPG substitution scenario

The more ambitious 100% rLPG substitution scenario is premised on a rapid decline / collapse of the natural gas industry prior to 2050 with commensurate demise of cLPG production. We characterised a hypothetical LPG sector response to this outcome based the same phased approach that was used for the 70% substitution scenario, but with acceleration of key production elements. The two areas of accelleration are:

1. 20 ktpa rLPG additional production from biogas conversion;
2. An additional softwood to biofuels plant (with 20 ktpa rLPG yield).

The proposed market build-up to meet the 100% rLPG target is shown in Table 8 and visualised in Figure 22. Further detail can be found in Table 8 / Appendix B. The resulting LPG market plan is summarised in *Figure 23*.

Table 8 - 100% rLPG scenario plant scale

Plant by 2035	Plant by 2050
FAME biodiesel plants ≈ 3.2 ktpa rLPG	
Mixed waste gasification to rLPG plants ≈ 6 ktpa rLPG	Mixed waste gasification to rLPG ≈ 9 ktpa rLPG
Biogas to rDME facility ≈ 25 ktpa rLPG equivalent	Biogas to rDME facility to 30 ktpa rLPG equivalent
Biogas to rLPG ≈ 20 ktpa rLPG	Biogas to rLPG ≈ 60 ktpa rLPG
	2 @ Softwood to biofuels plant ≈ 40 ktpa rLPG

Figure 22 – Target rLPG build-up – 100% rLPG substitution scenario

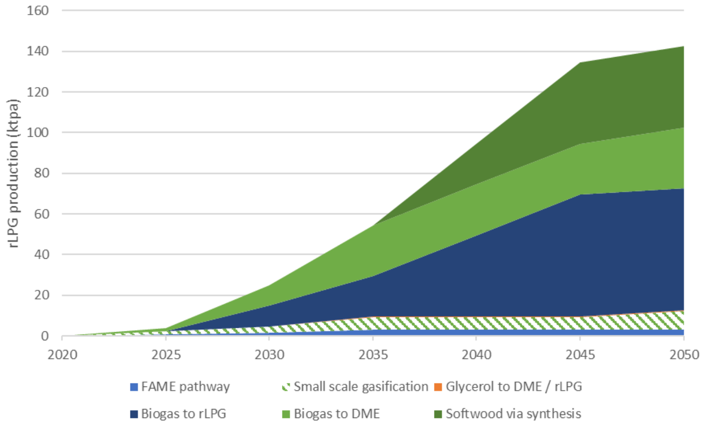
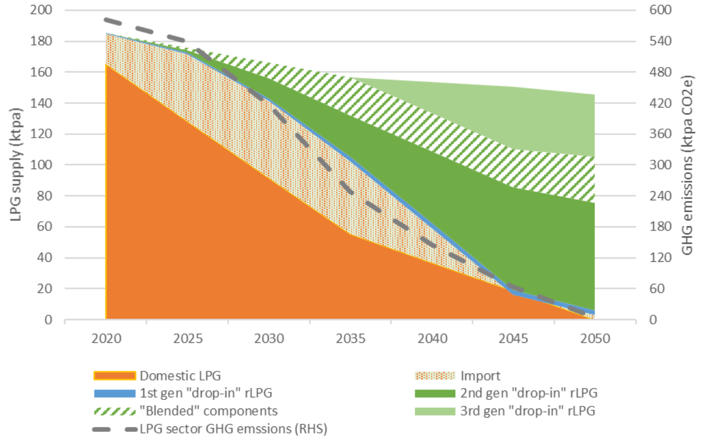


Figure 23 - NZ LPG market plan – 100% rLPG substitution scenario



The primary uncertainties related to this scenario are:

- A rapid decline / collapse of the natural gas network could substantially increase the demand for LPG / rLPG, hence targeted demand is highly uncertain;

- If the rLPG industry is given strong demand signals, but finds itself competing with cLPG production there will be heavy negative economic impacts that will supress rLPG industry growth;
- If the natural gas network volume declines significantly, then support of natural gas reticulation infrastructure and demand for biogas could be challenged. This would directly impact on the biogas to rLPG pathway that is slated to deliver ~60 ktpa;
- Competition for softwoods from pellets and biofuel industries;
- The successful commercialisation of softwood to biofuels technology has been aspirational for at least two decades. Delivering 40 ktpa from this pathway is certainly possible but will likely have rLPG cost impacts that are beyond what the current industry can sustain, and likely to be beyond the value provided by cost on carbon.

7.3 Interpretation of scenario analysis

Globally the LPG industry is actively pursuing opportunities to increase renewable LPG production so as to meet growing demand for this product[69]. New Zealand has a comparatively dense biomass production base and hence is an ideal location for advancing rLPG technologies. Overseas developments demonstrate that biogas and DME production (i.e. 2nd generation) pathways are already commercial in many sectors and promise to be so in New Zealand shortly.

This report has identified a number of immediate opportunities that will allow a significant measure of substitution of conventional LPG supplies by rLPG and also blended rDME. These opportunities have been classified into four groups based on feedstock source and technology maturity.

In our 70% rLPG substitution scenario we adopted a conservative interpretation of technology development and feedstock utilisation to yield a realistic and achievable decarbonisation pathway that matched the decline in cLPG production. We believe that this scenario would yield greater resilience and economic value than a ban on new connections, and result in a similar GHG emissions reduction.

The more ambitious 100% rLPG substitution scenario is premised on a rapid decline / collapse of the natural gas industry prior to 2050 with commensurate demise of cLPG production. We characterised a hypothetical LPG sector response to this outcome based the same phased approach that was used for the 70% substitution scenario, but with acceleration of the biogas to rLPG and softwood to rLPG pathways.

The primary uncertainties associated with the 100% rLPG substitution scenario are tabled in Section 7.2, and mostly relate to:

- Inconsistency between demise of the natural gas sector, and benefits of biogas as a biomass energy delivery vector;
- rLPG market signals and prospective LPG price that is required to accelerate development.

In view of the above comments, we consider that achieving 70% rLPG substitution is realistic and achievable, whereas achieving 100% rLPG substitution will require considered messaging regarding the sustained operation of the natural gas / biogas industry. The 100% rLPG pathway is technically plausible but faces numerous commercial challenges.

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[69] WLPGA, LPG Industry Narrative - LPG and Renewable LPG, 23rd November 2020

Appendix A. **70% rLPG Scenario**

Table 9 - 70% renewable LPG production build-up

Pathway	Feedstock	Potential feedstock volume	Potential energy	Potential rLPG or equivalent yield	Proposed plants by 2035	Proposed plants by 2050	GHG Emissions intensity (ktCO2eq/PJ) (Note 1)
Domestic cLPG	NG co-product	160 ktpa					61.8
Imported LPG / rLPG							61.8 to 6.2
1st gen "drop-in" rLPG	Fatty acids	150 ktpa tallow	~6 PJ	~7 ktpa rLPG	2 @ 36 ktpa tallow feed 3.2 ktpa rLPG yield	2 @ 36 ktpa tallow feed 3.2 ktpa rLPG yield	25
2nd gen "drop-in" rLPG	Cellulosics	500 ktpa crop waste 950 ktpa straw & stover	~6 PJ of biogas	106 ktpa rLPG	2 @ 60 ktpa mixed feed 6 ktpa rLPG yield	3 @ 60 ktpa mixed feed 9 ktpa rLPG yield	6
	MSW / food waste	3,300 ktpa of MSW 330 ktpa food waste	~11 PJ of biogas	~207 ktpa rLPG		2 @ 200 ktpa MSW 40 ktpa rLPG	0 (Note 2)
	Wastewater / manure	550 million m^3pa of wastewater 600 ktpa manure.					
3rd gen "drop-in" rLPG	Softwood Cellulosics	1,700 ktpa Residue & roots 3,400 ktpa Pulp logs 12,600 ktpa Total	~320 PJ	~260 ktpa rLPG (as a by-product yield)	Nil	1 @ 1,250 ktpa dry feed 20 ktpa rLPG yield (7.5% of total)	20
"Blended" components	Biogas from 2nd gen				Manure from 200,000 cows (~340 ktpa dry manure) 25 ktpa rLPG equivalent – with a high % rDME	Expansion to 30 ktpa rLPG equivalent – with a high % rDME	-30 (Note 3)

Note 1 – Emissions intensity analysis is not rigorous, see Section 1.5 for further detail.

Note 2 – Intensity for rLPG from MSW based which can be diverted away from atmospheric degradation, assume overall GHG emissions intensity is neutral. See Section 4.1.5 for detail.

Note 3 – Intensity for rDME based on manure from which a portion would otherwise degrade to methane, a modest negative GHG emissions intensity assumed. See Section 6.3.3 for detail.

Appendix B. **100% rLPG Scenario**

Table 10 - 100% renewable LPG production build-up

Pathway	Feedstock	Potential feedstock volume	Potential energy	Potential rLPG or equivalent yield	Proposed plant by 2035	Proposed plant by 2050	GHG Emissions intensity (ktCO2eq/PJ) (Note 1)
Domestic cLPG	NG co-product	160 ktpa					61.8
Imported LPG / rLPG							61.8 to 6.2
1st gen "drop-in" rLPG	Fatty acids	150 ktpa tallow	~6 PJ	~7 ktpa rLPG	2 @ 36 ktpa tallow feed 3.2 ktpa rLPG yield	2 @ 36 ktpa tallow feed 3.2 ktpa rLPG yield	25
2nd gen "drop-in" rLPG	Cellulosics	500 ktpa crop waste 950 ktpa straw & stover	~6 PJ of biogas	~106 ktpa rLPG	2 @ 140 ktpa mixed feed 6 ktpa rLPG	6 @ 140 ktpa mixed feed 9 ktpa rLPG (60% of potential)	6
	MSW / food waste	3,300 ktpa of MSW 330 ktpa food waste	~11 PJ of biogas	~207 ktpa rLPG		2 @ 200 ktpa MSW 60 ktpa rLPG	0 (Note 2)
	Wastewater / manure	550 million m^3pa of wastewater 600 ktpa manure.					
3rd gen "drop-in" rLPG	Softwood Cellulosics	1,700 ktpa Residue & roots 3,400 ktpa Pulp logs 12,600 ktpa Annual tree total	~320 PJ	~260 ktpa rLPG (as a by-product yield)	Nil	2 @ 1,250 ktpa dry feed 40 ktpa rLPG yield (15% of total)	20
"Blended" components	Biogas from 2nd gen				Manure from 200,000 cows (~340 ktpa dry manure) 25 ktpa rLPG equivalent – with a high % rDME	Expansion to 30 ktpa rLPG equivalent – with a high % rDME	-30 (Note 3)

Note 1 – Emissions intensity analysis is not rigorous, see Section 1.5 for further detail.

Note 2 – Intensity for rLPG from MSW based which can be diverted away from atmospheric degradation, assume overall GHG emissions intensity is neutral. See Section 4.1.5 for detail.

Note 3 – Intensity for rDME based on manure from which a portion would otherwise degrade to methane, a modest negative GHG emissions intensity assumed. See Section 6.3.3 for detail.

Appendix C. Sankey diagram of 70% rLPG scenario in 2050