Biofuel Insights

An independent report prepared for EECA

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29th March 2021

Contents

Appendices

Tables

Figures

Abbreviations

ASTM	Formerly American Society for Testing and Materials
ATJ	Alcohol-to-jet
BEV	Battery electric vehicle
BTL	Biomass to liquid
CARB	California Air Resource Board
FAME	Fatty acid methyl ester
FCHV	Fuel cell heavy vehicle
FT	Fischer – Tropsch process
GHG	Greenhouse gas
GVM	Gross vehicle mass
HEFA	Hydro- processed and fatty acids
HVO	Hydrotreated vegetable oil
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ICE	Internal combustion engine
IEA	International Energy Agency
ILUC	Indirect land-use change
IMO	International Maritime Organisation
IRENA	International Renewable Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
JRC	EU Joint Research Centre
LCA	Lifecycle analysis
LUC	Land-use change
MIA	Motor Industry Association
OEM	Original equipment manufacturer
RED	Renewable Energy Directive
SAF	Sustainable aviation fuel
SOC	Soil organic carbon
UCO	Used cooking oil

Executive summary

This paper aims to inform discussions about potential pathways of biofuel uptake and the associated emissions reductions in New Zealand's light and heavy road transport, and domestic aviation and shipping.

The paper is not a feasibility study of biofuel uptake in New Zealand. The purpose is to explore potential pathways of emissions reductions given available information on feedstock supply, technology maturity and fuel blending walls.

Emissions reductions are estimated on a lifecycle basis for both conventional and advanced biofuels. A lifecycle approach covers emissions produced during both the production and combustion of fuels, which allows capturing the total emissions impact from an atmospheric perspective.

For conventional biofuels the full lifecycle must be considered, as unsustainably sourced biofuels can result in significant emissions impact, either as a result of expansion of oilseed crops into natural vegetation, or indirect increase in palm oil consumption. This can be alleviated through the use of sustainably sourced feed stocks, therefore it is important to consider the whole lifecycle of the biofuel supply chain.

Lifecycle emissions from biodiesel produced from waste oils and animal fat are generally less than those from fossil fuels, but biodiesel needs to be blended with fossil fuels, and the blending is limited by technical considerations (typically 5%-7%). Similarly, a 10% blending limit is typically applied to bioethanol. The emissions reduction potential for conventional biofuels (for the energy equivalent of final fuel) is therefore low: 3%-6% for a B7 fuel, and 1%- 6% for an E10 fuel.

These blending walls, together with limited imports of bioethanol and limited domestic production of biodiesel, mean that the emissions reduction potential from biofuels in New Zealand through to 2024 is minimal (around 0.4% p.a.).

Compared to these conventional biofuels, advanced biofuels from biomass have much lower emissions related to land-use change. Furthermore, they can generate greater emissions savings because they can be blended at higher limits, or even used neat (undiluted). Emissions reductions are in the range of 21% to 50% for a final fuel containing 50% drop-in fuel, depending on the feedstock and conversion pathway.

Our analysis assumes that from 2025, technology developments would enable some domestic production of advanced biofuels to commence. Biomass feedstock would be increasingly used to produce drop-in diesel, drop-in aviation fuel and drop-in petrol, and tallow would be used to produce renewable aviation fuel. We find that there is enough local output of inedible tallow to meet around 20% of biofuel demand from aviation (assuming some tallow is also used for biodiesel production). For biomass feedstock, we assume supply would be available up to the estimates in Scion's Biofuel Roadmap for different scenarios.

To determine biofuel uptake beyond 2025, we assume two scenarios of technology pathways for the production of biomass-based advanced biofuels, largely determined by developments over the 2030-2035 period. In the progressive scenario, biomass-based drop-in fuel output ramps-up gradually; in the accelerated scenario, output grows exponentially.

We find that biofuel uptake would increase from 0.88 PJ (28.38 million litres) in 2022, to 8-11 PJ (257-335 million litres) by 2030, with a maximum output beyond 2040 of 43 PJ per annum (approx. 1,280 million litres per annum). By 2030, annual drop-in fuel output would reach 167-246 million litres, of which 120 -198 million litres would be from biomass feedstock.

By 2030, these biofuel pathways would lead to total lifecycle emissions savings per annum of 3.8%-5.4%, increasing to 9%-21% by 2035, and 38% by 2050. These emissions reductions are relative to a baseline of projected emissions from petrol-fuelled light-vehicles, diesel-fuelled heavy vehicles, fossil-fuelled aviation and shipping viewed together, having accounted for increased vehicle electrification, air travel and freight volumes in the future.

To achieve these emissions reductions, significant capital investments would be required. Through to 2025, the average annual investment cost would be between $39 and $93 million, primarily to scale-up production of biodiesel and renewable aviation fuel (HEFA). Over the 2026-2030 and 2031-2035 periods in the progressive scenario, additional investment costs of $51-$116 and $115-$254 million per annum would be required respectively to scale-up production of drop-in fuels from biomass feedstock. In the accelerated scenario, the additional investments required would be double and four-times higher than the estimates in the progressive scenario over the two periods respectively. Overall through to 2050, the total investment costs would be between $3.4 and $8.2 billion.

Introduction

Sapere has been commissioned by EECA to answer some of the key questions centred on the application and use of various types of biofuels in the transport sector as an alternative to fossil fuels.

In particular, this paper seeks to address the following questions. The paper's structure follows the order of these questions.

- What conversion technologies are used to produce biodiesel and drop-in diesel fuels (henceforth referred to as 'biofuels'), and what are the suitable applications in transport?
- What are the key issues regarding the compatibility of biofuels with existing engines and fuel infrastructure?
- What standards and blending limits are being applied to ensure compatibility / miscibility of fuels?
- How should biofuels be assessed in terms of their environmental impacts?
- What is the potential demand and supply of biofuels in New Zealand?
- What are the key aspects that need to be considered for a biofuel uptake in New Zealand's transport?

Setting the scene

The transport sector is New Zealand's second biggest source of GHG emissions, contributing 21.1 per cent to total emissions over the 1990-2018 period.[1] The sector is also by far the biggest contributor to the increase in New Zealand's gross emissions since 1990. De-carbonising the transport sector is therefore an important requirement for New Zealand to meet its international target of 30 percent reduction below 2005 over the next decade, and its domestic target of net-zero GHG emissions (except methane) by 2050.

To de-carbonise New Zealand's transport, a suite of options will have to be explored. As well as fuel switching, these include improved heavy freight fuel efficiencies, behavioural changes that will affect demand for fuel for light vehicles[2], and an optimised freight system that can move less-time-constrained freight to lower-carbon modes.[3] However, given the size of the task, transitioning to alternative fuels for transport will be key.

Some alternative fuels lend themselves better than others to different applications in transport. Early signs from global development suggest that passenger cars, delivery vans and two- and three-wheelers will be the first to be electrified (BNEF, 2020). From a technical perspective, electrification suits household transport in NZ because 95% of daily travel is less than 120 km, which is generally within the range of today's battery electric vehicles, noting that the range is likely to increase in the future (MoT, 2017). However, light passenger BEVs are currently more expensive to own, with their total cost of ownership projected to reach parity with conventional vehicles in the mid-2020s (MoT, 2017).[4] Until a significant uptake of BEVs due to improved battery economics, biofuels could be an alternative for light vehicles at least in the short-term. Early gains in emissions reductions from light vehicles is important given the 2030 target and the significant contribution of these vehicles to overall transport emissions (Figure 1).

By contrast to light vehicles, in high duty cycle transport, electric batteries have limitations particularly for heavy loads. In these applications, lithium-ion batteries would need to store enough energy to allow trucks to travel over long distances, with the resultant vehicle weight reducing payloads. Furthermore, for very heavy trucks there are productivity penalties associated with refuelling and charging times during the day,[5] although these penalties are likely to be addressed in the future.[6] Because hydrogen is much more energy dense, fuel cell technologies are well placed to address the battery size and weight issue. However, fuel cell heavy vehicles (FCHVs) are much more expensive, and local hydrogen infrastructure is in its early stages of development. These issues shift the focus on the

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[1] MfE's 1990-2018 GHG inventory https://www.mfe.govt.nz/sites/default/files/media/Climate%20Change/infographic%E2%80%93new-zealand%E2%80%99s-gross-greenhouse-gas-emissions-1990-2018.pdf

[2] e.g. remote work reducing commuting needs, increased use of public transport, ride sharing.

[3] e.g. from road transport to rail or shipping.

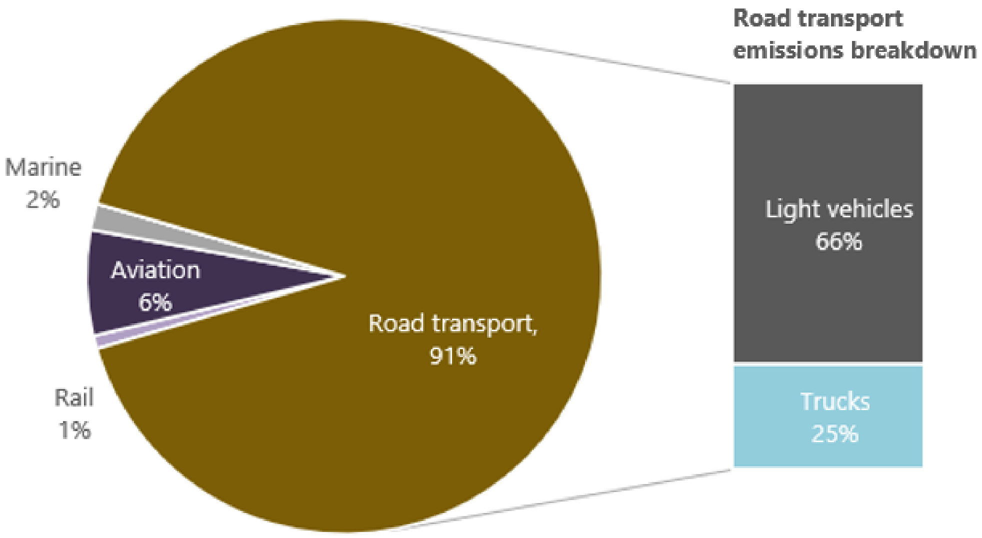
[4] This will be the main driver for BEV uptake from them on.

[5] EV productivity penalties refer to the fact that the heavier a vehicle weight is, and the longer away-from-base refuelling times are, the greater number of EV vehicles would be required to perform the same transport service as an ICE vehicle (MfE, 2020).

[6] (Concept, 2019) estimate that the current productivity penalty for very heavy vehicles is 18% improving to 6% in the future.

role that biofuels can play in de-carbonising heavy freight, which currently accounts for a quarter of road transport emissions (Figure 1).

Figure 1 – Domestic transport GHG emissions by mode (2017)



Source: based on (MoT, 2020)

Similarly, sustainable aviation fuel (SAF) is likely to be the primary tool utilised by the aviation industry to reduce its carbon footprint over the next decade. Battery electric technologies have been proven for small planes, but these are yet to be developed and commercialised for larger aircrafts travelling longer distances. Electric flight and hydrogen-powered propulsion are years away from application at scale (WEC, 2020).

In shipping, the International Maritime Organisation has introduced strict regulation on fuel sulphur levels, which means that 70 per cent of the fuels currently used by the sector worldwide need to be modified and changed. Biofuels have very low sulphur levels and are a technically viable solution to low-sulphur fuels meeting either the very low or ultralow sulphur fuel oil requirements (IEA Bioenergy, 2017). They are one of the few options for decarbonising shipping without installing new engines, particularly for large vessels such as container ships that transport New Zealand goods.

How are biofuels produced?

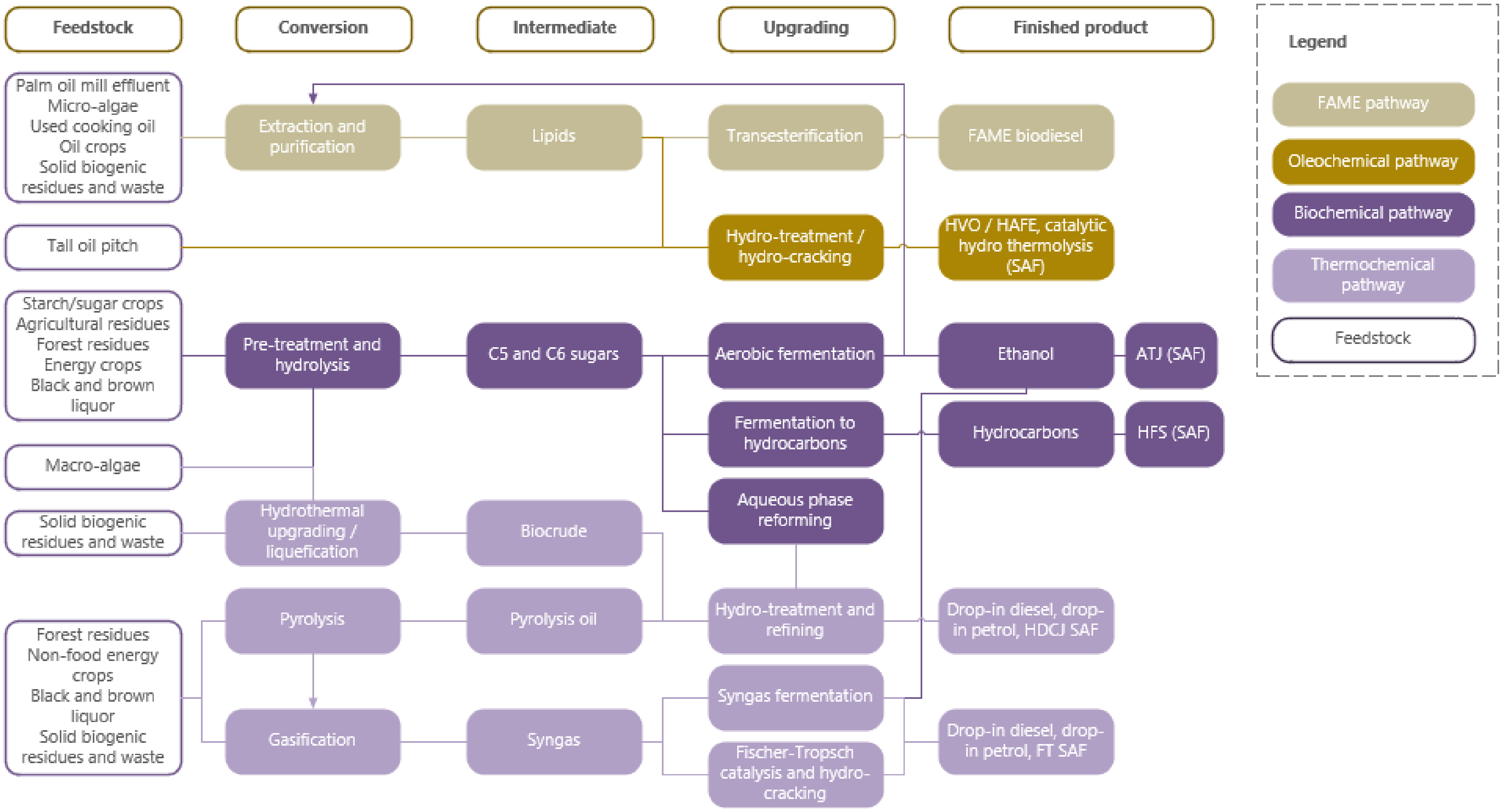
Summary

- Currently, most biofuels production is from conventional feedstocks and conversion technologies. Most biodiesel is produced from vegetables oil, although there is increasing production from waste oils (used cooking oil, animal fat). Most bioethanol is produced from agricultural crops.
- There are three key pathways for advanced biofuels production: (i) the hydro-treatment of lipids producing renewable diesel/aviation fuels (HVO/HEFA fuels), (ii) biochemical processes that have been particularly explored for the production of aviation fuels, and (iii) the thermal conversion of biomass to fluid intermediates that can be upgraded to hydrocarbon fuels.
- These pathways differ by the feedstocks used, conversion technologies and technology maturity, HVO/HEFA fuels are already commercially available. Thermochemical pathways are better positioned than biochemical ones due to their relatively higher yields.
- Thermochemical technologies are in demonstration or pre-commercialisation stages. Biomass gasification is a well-proven technology but has not yet been commercialised at lower scales needed for biomass feedstocks. Pyrolysis for biofuel production has been gaining a lot of attention in recent years, however major issues remain due to the high oxygen and water content of pyrolysis oil, which is problematic for biocrude upgrading at a refinery.

Biofuels refer to specific type of fuels that are derived from natural sources such as plants, animal wastes, forest residues, and other organic material. There are various production pathways for biofuels, resulting in different finished liquid products depending on the intended end use (Figure 2). An important question is the extent to which the finished product can replace existing petroleum fuels, as this can be constrained by engine compatibility issues. It is important to understand this limiting factor because it affects the degree to which different biofuels can contribute to overall transport emission reductions. From the engine-compatibility point of view, biofuels that have different properties than petroleum fuels, thereby creating the need for a blend wall, are called blending substitutes, whereas biofuels that are functionally equivalent to petroleum fuels are referred to as ‘drop-in’ fuels, referring to the fact that they can be ‘dropped-into’ the existing infrastructure (petroleum distribution and refining, fuel specifications etc.) (Karatzos, et al., 2014). Note that the ‘drop-in’ property does not necessarily mean these fuels can currently fully replace conventional petroleum fuels. Final fuels must meet a number of quality specifications, and blend walls may still be applied to drop-in fuels depending on how they are produced and how they are used. This is particularly relevant for aviation fuel.

This chapter provides and overview of production pathways for blending substitutes and drop-in fuels, leading into the chapter discussing blending limits.

Figure 2 – Biofuels production pathways



Source: Sapere based (IRENA, 2016), (Wood Mackenzie, 2010), (ICAO, 2018).

Production pathways for blending substitutes

The most common blending substitutes are bioethanol, which can be used as a blend for petroleum engines, and biodiesel (or FAME - fatty acid methyl esters) which is used with diesel engines (also referred to as 'biodiesel'). Ethanol can also be converted to jet fuel range of hydrocarbons (alcohol-to-jet, or ATJ) via chemical catalysis.

Currently, most bioethanol is produced by the fermentation of corn, wheat, sugar beet or sugar cane. Bioethanol produced in this way is referred to as first-generation because it competes with land that could otherwise be used for food or feed crops. More advanced technologies involve hydrolysis and fermentation of lignocellulosic biomass to produce second-generation (or advanced) bioethanol. This advanced pathway has shown great progress with the deployment of early commercial plants (Figure 3), is currently the cheapest and most developed advanced biofuels route, with several proprietary technologies available (IRENA, 2016).

Biodiesel can be produced from different oils (e.g. rapeseed, soy, cooking oils, and animal fats) by reacting these oils with an alcohol to form ester compounds (a process called trans-esterification). This reaction is necessary because unprocessed vegetable oils and animal fats are not acceptable as transportation fuel due to their very low cetane, inappropriate cold flow properties, high injector fouling tendency and high kinematics viscosity level (WWFC, 2019). FAME biodiesel is considered a first-generation (or conventional) biofuel on the basis that the technology is mature and commercially available at large scale (Karatzos, et al., 2014).[7]

Production pathways for drop-in fuels

Drop-in biofuels are functionally equivalent to current petrol, diesel, jet and related fossil derived transportation fuels. Within this category, a distinction is sometimes made between drop-in diesel made from biomass and that produced by reacting fats and waste oils with hydrogen (e.g. in (Suckling, et al., 2018). The latter category is also referred to as 'renewable diesel.'

Drop-in fuels can be produced via the following processes: (i) oleochemical; (ii) biochemical; (iii) thermochemical, and (iv) hybrid (Figure 2).

Oleochemical processes

To date, drop-in biodiesel has been primarily produced through oleochemical processes, which require a hydroprocessing step to catalytically remove oxygen from the fatty acid chains present in lipids.[8] The products are known as hydrotreated vegetable oil (HVO) or hydro-processed esters and

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[7] Note that there is no one single definition for what constitutes conventional or advanced biofuels. This categorization depends on several factors, e.g. technology maturity, type of feedstock, GHG emissions reduction, and product type and quality (see Appendix A).

[8] Lipids are fatty acids (or derivatives thereof) that are insoluble in wate but soluble in organic solvents. They include man natural oils.

fatty acids (HEFA).[9] Currently HVO is increasingly produced from waste and residue fat fractions sourced from the food industry, as well as from non-food grade vegetable oils (Neste, 2020).

This technology is well developed (Figure 3), and entails relatively low technological risk and low capital expenditure compared to other emerging drop-in biofuel production routes. HEFA-SPK is the only in five technology for aviation biofuel production that is currently technical mature and commercialised (IEA, 2019). Because of their relative commercial maturity, HEFA/HVO fuels are considered conventional biofuels in some literature.

Biochemical processes

Biochemical processes involve the conversion of biomass to longer chain alcohols and hydrocarbons. Biochemical conversion is particularly used to produce sustainable aviation fuel (alcohol-to-jet) from alcohol molecules made from sugar/starch bearing plants, lignocellulosic materials or innovative processes (e.g. LanzaTech).[10]

Another process uses genetically modified microorganisms to convert sugar into hydrocarbons or lipids. In some cases, these microorganisms produce synthetic iso-paraffin substances that can be converted into a product with characteristics similar to that of aviation fuel. This process is called HFS-SIP (Synthetic Iso-Paraffins produced from hydroprocessed) process.

Thermochemical technologies are well positioned to account for a considerable share of drop-in fuel capacity growth over the near term. This is primarily because biochemical processes typically provide lower yields of higher oxygenated intermediates that can command higher value in the growing bio-based chemical market (Karatzos, et al., 2014).

Thermochemical processes

Thermochemical processes involve the thermal conversion of biomass to fluid intermediates (gas or oil) which are then catalytically upgraded / hydroprocessed to hydrocarbon fuels. Three main types of processes are known:

Pyrolysis is the controlled thermal decomposition of biomass to produce oil, syngas and biochar. Pyrolysis oil can be produced via fast or slow pyrolysis. Generally, fast pyrolysis produces a higher percentage of oil, while slow pyrolysis more char. Although the technology requires a dry feedstock, the final product contains both oxygen (40%-50% of weight) and water (15%-30% of weight), which are problematic for a refinery. Furthermore, because pyrolysis oil is acidic, it requires purposefully selected metals in the processing equipment (BioPacific Partners, 2020).

There has been widespread research[11] and commercial activities on pyrolysis, however current production is limited. A full-scale plant producing bio-crudes is yet to be completed (BioPacific Partners, 2020).

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[9] Note that the reference to vegetable oils in the HVO term is a legacy from before 2010 when only vegetables oils were used as feedstock.

[10] The waste gas from steel mills is fermented to ethanol by bioengineered microbes, which is destined to the ATJ process to obtain jet fuel

[11] It has been studied in detail since early 1980s (Karatzos, et al., 2014).

Hydrothermal liquefication uses high pressure, high-temperature water with catalyst to convert the biomass to a bio-crude. Compared to pyrolysis oil, this process better deals with wet biomass, has lower oxygen content, and does not create the same acidity problems. For these reasons, the technology has been gaining attention in the last five years (BioPacific Partners, 2020).[12]

Technology providers are at different stages of development, including in terms of using different feedstock and improving on the conversion technology. As it stands, the base technology has gone through several scale-ups from the pilot stage through to the demonstration stage (Figure 3). .

Gasification of biomass or bio-oil produces synthesis gas, comprised of mostly H2 and CO. Syngas can also be upgraded to drop-in liquid biofuels via the Fischer-Tropsch process (FT). The FT process has its origins in the 1920s in Germany when access to oil was problematic (Karatzos, et al., 2014), but today represents a variety of similar processes. When biomass feedstock is used, it is also referred to as 'biomass-to-liquid' (BTL).[13] It can be made from a range of raw materials containing lignocellulosic matter, such as, agricultural waste, forestry waste or used paper. The FT process produces molecules with better cold flow properties which can then be blended directly into diesel (Wood Mackenzie, 2010). Depending on the hydrocarbon chain length, Fischer-Tropsch products may be blended with gasoline, diesel or jet fuels for use in road, rail, shipping or aviation (IRENA, 2016).

The Fischer-Tropsch technology is well-proven, however it benefits from scale. Although it is a standard technology used by the petrochemical industry, it is too large for biomass facilities. Developers' focus is therefore on improving the FT scalability (BioPacific Partners, 2020).[14]. However, both the biomass gasification and the conversion of resulting syngas to FT fuels are very capital intensive, with a current capex of $6.71-$10 per litre p.a. final fuel (see Figure 16 and Appendix J). This is higher than the capex for the pyrolysis pathway ($3.51–$8.8 per litre p.a.),[15] and significantly higher than for biodiesel ($1.41 -$1.47 per litre p.a.).

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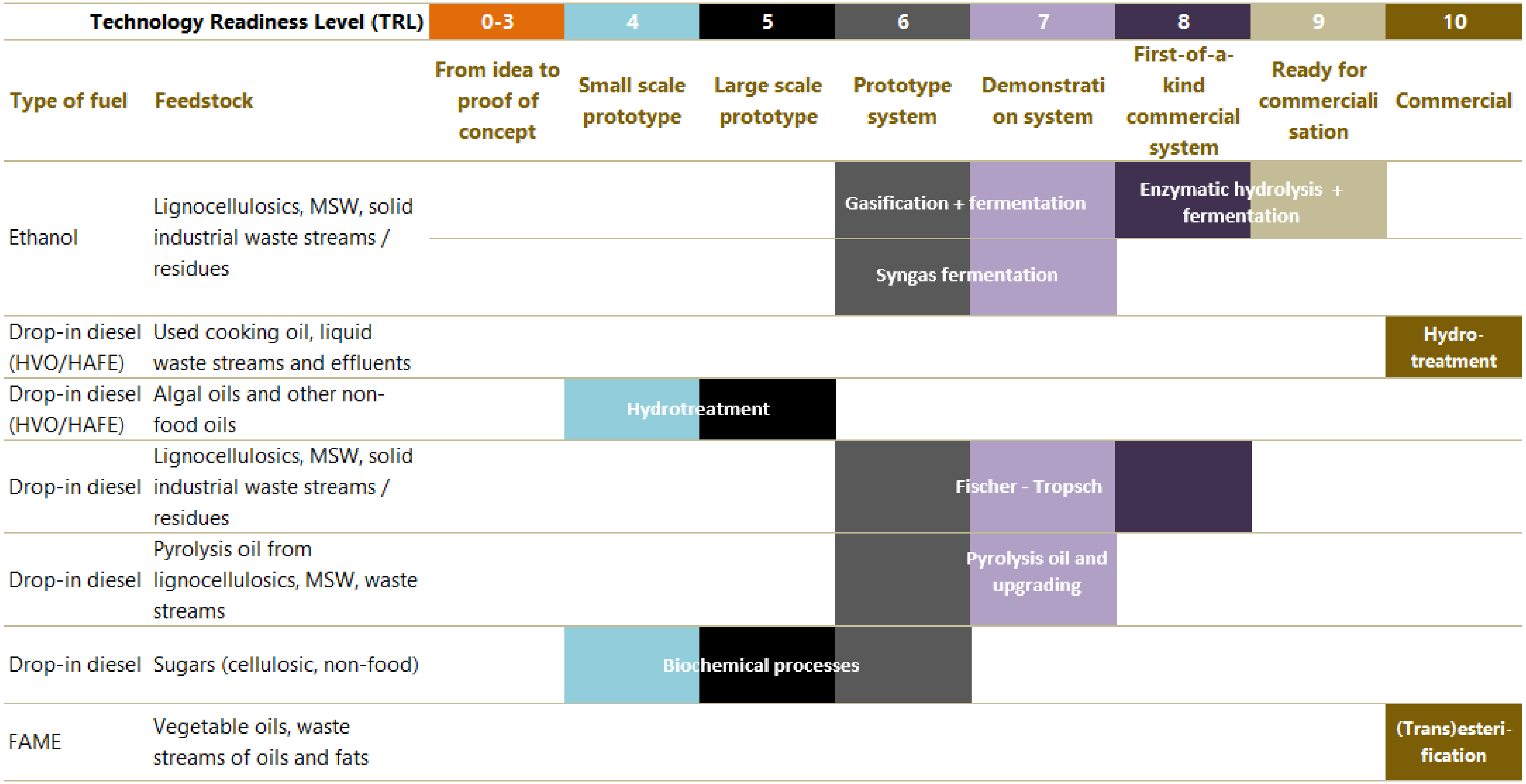
[12] It is worth noting that despite the lower oxygen content, it is still higher than conventional crudes, and water treatment is still necessary.

[13] FT process also applies to methane-based fuels (such as natural gas), power (multiple renewable sources exist) or coal into paraffinic diesel fuels, commonly referred to a GTL ('gas-to-liquid'), PTL ('power to- liquid') or CTL ('coal-to-liquid'). Together, these processes are known as XTL.

[14] Another focus is addressing the gas quality issue by optimising catalysts.

[15] The higher estimate reflects own H2 production.

Figure 3 - Commercialisation status of advanced biofuels conversion technologies



Technology Readiness Level (TRL)		0-3	4	5	6	7	8	9	10
Type of fuel	**Feedstock**	**From idea to proof of concept**	**Small scale prototype**	**Large scale prototype**	**Prototype system**	**Demonstration system**	**First-of-a-kind commercial system**	**Ready for commercialisation**	**Commercial**
Ethanol	Lignocellulosics, MSW, solid industrial waste streams / residues				Gasification + fermentation	■	Enzymatic hydrolysis + fermentation	■	
					Syngas fermentation	■			
Drop-in diesel (HVO/HAFE)	Used cooking oil, liquid waste streams and effluents								Hydro-treatment
Drop-in diesel (HVO/HAFE)	Algal oils and other non-food oils		Hydrotreatment	■					
Drop-in diesel	Lignocellulosics, MSW, solid industrial waste streams / residues				Fischer - Tropsch	■	■		
Drop-in diesel	Pyrolysis oil from lignocellulosics, MSW, waste streams				Pyrolysis oil and upgrading	■			
Drop-in diesel	Sugars (cellulosic, non-food)		Biochemical processes	■	■				
FAME	Vegetable oils, waste streams of oils and fats								(Trans)esteri-fication

Source: (IRENA, 2016), (Maniatis, et al., 2017), (BioPacific Partners, 2020)

Why are blending limits applied?

Summary

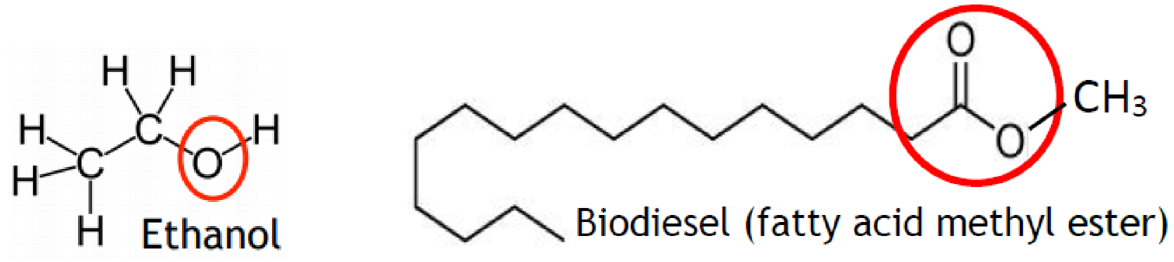
- Conventional biofuels have different chemical properties than fossil fuels, and blend limits are applied to ensure fuel compatibility. Globally, the mandated limits for road transport are typically low – 10% for bioethanol, and 5-7% for biodiesel, with some exceptions. For example, Brazil is expected to increase the biodiesel blend ration from 11% to 12% over the next decade, whereas the current blend requirement for bioethanol is 27% (OECD-FAO, 2020). Equipment manufacturers can allow higher biodiesel blends for specific fleets.
- In marine transport, due to poor performance in cold waters, blending limits of up to 7% of biodiesel are applied.
- Advanced biofuels are miscible with fossil fuels, which allows them to be blended in higher proportions with fossil fuels, or even be used neat. They are considered 'drop-in' fuels because they can be used with existing petroleum infrastructure, and can be blended in much higher concentrations. By contrasts, conventional biofuels require separate distribution channels (e.g. trucks) and storage tanks.
- Concentration limits can also be applied to drop-in fuels to ensure that the final fuels comply with the fuel standard specifications in a particular jurisdiction. In aviation, limits of up to 10% or up to 50% of drop-in fuels are applied depending on the conversion pathway.

Bioethanol and biodiesel are subject to blending limits due to their oxygen content

Both bioethanol and biodiesel are functionally different from the petroleum fuels they can substitute. Petroleum-derived fuels are oxygen-free, whereas bioethanol and biodiesel are only partially de-oxygenated (Figure 4). The presence of oxygen is highly problematic, as it can oxidise fuel components, reactors and pipeline metallurgy to cause corrosion. The oxygen content imparts polar and hydrophilic properties that have been of concern for original equipment manufacturers (OEM), especially at higher blends (see more details in Appendix B).

Due to these properties, blend walls have been applied limiting the concentration of bioethanol and biodiesel in the final transport fuels. These limits are stipulated and regulated by governments after consultations with automobile manufactures and oil companies (Karatzos, et al., 2014)

Figure 4 – Chemical composition of bioethanol and biodiesel



Source: (Karatzos, et al., 2014)

Bioethanol. For bioethanol, a blend wall of 10% has long been considered the maximum blend rate for conventional engines, although the majority of new cars currently have automaker approval for E15 (a blend of 15% ethanol) (BNEF, 2020b). For older cars, burning blends higher than E10 requires changes to the combustion cycle and also may require replacement or alterations to certain fuel lines or engine components (Rusco, 2012). Flex-fuel vehicles, can deal with this to some extent, allowing much higher blends, e.g. 85% in EU and US and even 100% in Brazil (IRENA, 2013).[16] The 85% limit is set to reduce ethanol emissions at low temperatures and to avoid cold starting problems in cold weather. In New Zealand, up to 10% of ethanol blended with petrol can be legally sold at petrol stations (MIA, 2021).

Biodiesel (FAME). For biodiesel, blend walls of up to 5% (B5) and 7% (B7) have been used in the US and Europe respectively. For higher blends (e.g. B20 or B30), the viscosity of fuels is an issue; they can only be used in dedicated fleets depending on specific OEM requirements. In New Zealand, the blend walls as indicated by engine manufactures are 5%-7% for light vehicles (MIA, 2020a), and 5%-30% for heavy vehicles depending on vehicle make and engine specifications (MIA, 2020b).

Neither bioethanol nor biodiesel are suitable for aviation because they do not fulfil the key jet fuel requirements such as stringent cold flow viscosity and high energy density specifications (Karatzos, et al., 2014). The latter issue is also caused by the oxygen presence in fuels which reduces their energy density (Appendix E). For marine uses, blends above B7 have not been preferred as they as perform poorly in cool waters, although there has been some effort going into developing biodiesel blends of up to 20% with marine diesel/gas oil (IEA Bioenergy, 2017). We are not aware of biodiesel being used in NZ coastal shipping currently.

Drop-in fuels can also be subject to blending limits to comply with standards

The functional equivalence between petroleum and drop-in fuels means that drop-in fuels must meet certain bulk properties such as miscibility with petroleum fuels, compatibility with fuel performance specifications, good storability, transportability within existing infrastructure, and usability within existing engines. From a chemical perspective, drop-in fuels are biomass-derived hydrocarbons that have low oxygen content, low water solubility and a high degree of carbon bond and saturation. The

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[16] E85 used in EU and USA is anhydrous ethanol, whereas E100 used in Brazil is hydrous ethanol.

exact specifications of such fuels are determined by several physiochemical properties such as viscosity, carbon number, boiling point range, freezing point etc. (Karatzos, et al., 2014).

Using the generalised term of ‘drop-in’ fuels can be confusing because it implies that these products can fully substitute conventional fuels in all circumstances. In fact, the nature of this substitution directly depends on engine specifications and fuel quality standards in a jurisdiction. Because different engines are made to work with different fuel specifications which are determined by standards, the same drop-in fuel may require a lower or higher (or even no) blend limit in the final fuel depending on the engine it is used with. For example, Neste’s Renewable Diesel (an HVO fuel) can be used neat with engines accepting EN 15940 fuels (the EU standard for paraffinic diesel – see Appendix O), but cannot be used neat under the EN 590 standard (the EU standard for B7) because its density is lower than what is allowed under that standard (Neste, 2020). However, in the US the ASTM D 975 standards does not have density requirements, so the allowed concentrations could be higher under this standard.

Given the above, ‘drop-in fuels’ can be classified as ‘neat drop-in fuels’ or ‘drop-in fuel blends.’ The distinction is particularly relevant in aviation, where maximum blend limits are applied to all drop-in fuels to ensure strict quality control conditions (see Table 10 in Appendix O). ICAO refers to the ‘drop-in’ fuel concept as a ‘drop-in jet fuel blend’ defined as

> A substitute for conventional jet fuel, that is completely interchangeable and compatible with conventional jet fuel when blended with conventional jet fuel. A drop-in fuel does not require adaptation of the aircraft/engine fuel system or the fuel distribution work, and can be used ‘as is’ on currently flying turbine-powered aircraft (p. 9 in (ICAO, 2018)).

On this basis, the concept of ‘drop-in’ fuels particularly refers to the fact that it can be used with the existing infrastructure, neat or in relatively higher concentrations. By contrast, bioethanol and biodiesel cannot be used directly with the existing petroleum infrastructure due to their hydrophilic nature that creates risk of fuel contamination from the segmenting slugs used in pipeline transfers.[17] These fuels must be blended through separate distribution channels, and instead of using existing pipelines, biodiesel must be transported via trucks, rail or coastal shipping, increasing the carbon footprint of the supply chain (see more details in Appendix C).

Different standards are used to control fuel compatibility

Standards define properties that are important for the operability, durability and tailpipe emissions of vehicles. Standards are important because they allow engine manufacturers to test their engines, determine engine compatibility with different fuels, and provide warranties linked to engines operating on specific fuels. Standards are evolving to keep up with developments in biofuel production.

Several organisations have adopted and continue to revise biodiesel specifications and guidelines. For FAME biodiesel, ASTM International sets standards for B6-B20 and B100, which are used in the US. The EU has its own Committee for Standardization (CEN) which sets standards for fuels and blends used in

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[17] In practice, there are operational solution to this issue.

road transport. Sustainable aviation fuels used in aviation must pass certification by ASTM. European and ASTM standards are discussed further below. Appendix N provides a summary.

In New Zealand, the Engine Fuel Specifications Regulations (EFSR) 2011 establish the requirements and test methods for neat and blended biodiesel and bioethanol. Currently, the blend limit for biodiesel is 7%, and the EFSR does not include fuel specifications for higher blends. Similarly, it does not include specifications for paraffinic diesel fuel from synthesis or hydrotreatment, under which HVO fuels would fall. With the forthcoming update to the EFSR, there is an opportunity to include the specifications guided by the EU standards for these fuels (see Appendix O for more details on international standards).

What is the lifecycle emissions reduction potential of biofuels?

Summary

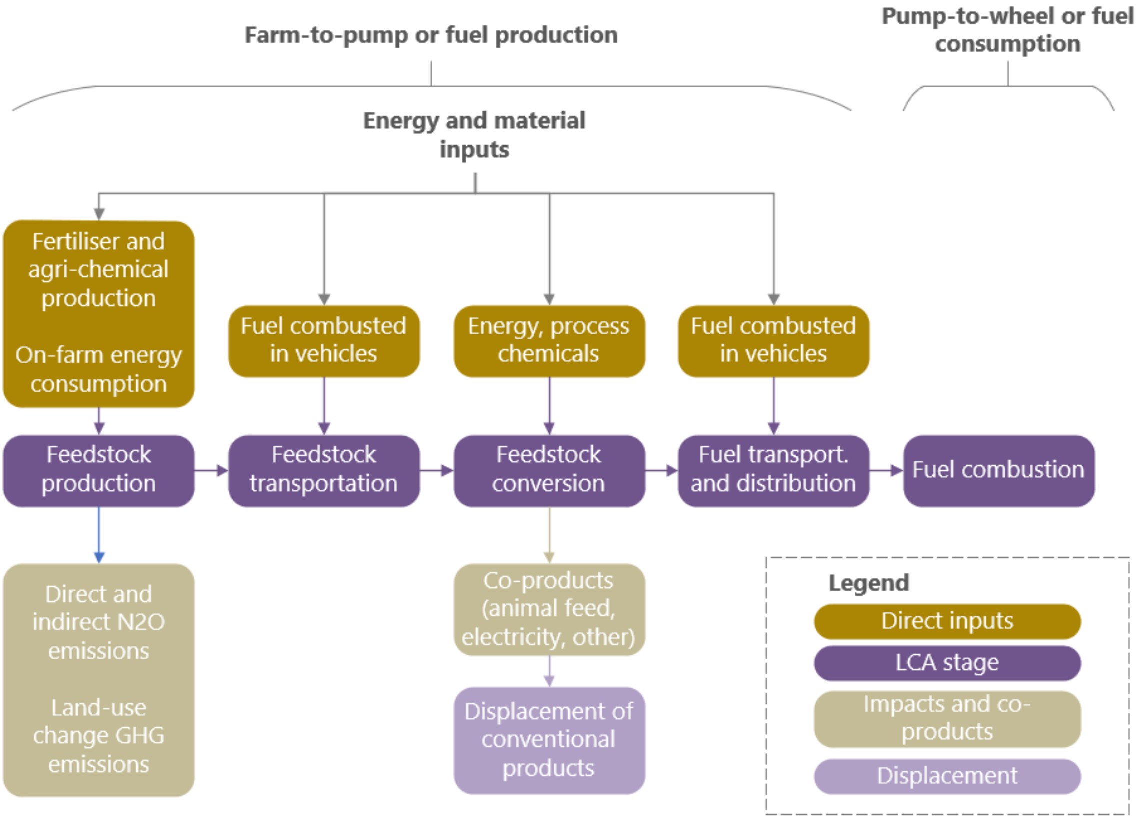
- Biofuel life-cycle emissions analysis allows estimating GHG emissions that are emitted both during the production and combustion of biofuels. Emissions from biofuel production can be significant , particularly as a result of land-use changes associated with the growth of biofuel feedstocks.
- For FAME and HVO products, vegetables oils can result in significant emissions from land-use change. Biofuels produced from these feedstocks can in fact result in higher emissions than from fossil fuels.
- Emissions from biodiesel production from waste oils are generally less than from fossil fuels but the savings potential (for the same MJ of final fuel) – of 3% to 6% for a B7 blend – is low due to the blending wall.
- Similarly, emissions from bioethanol production are also low due to the blending wall - 1% to 6% for an E10 blend.
- Advanced biofuels from forestry residues and energy crops have the highest emissions reduction potential due to their low land-use change impact and higher blend concentrations. On an energy basis, emissions savings are in the range of 21% to 50% for final fuels containing 50% drop-in fuels, depending on feedstock and conversion pathway.
- The concept of biofuel sustainability is wider than GHG emissions reductions. It includes impacts on biodiversity, water resources, competition for food, and regional development. EU's sustainability criteria for biofuels are a useful guide.

Emissions life-cycle analysis (LCA) is a methodological approach that aims to quantify GHG emissions across all of the stages of a product's lifecycle. For biofuels, this lifecycle covers both farm-to-pump (or well-to-tank) and pump-to-wheel (or tank-to-wheel) emissions, i.e. all stages from extracting, capturing and growing the primary energy carrier to vehicle re-fuelling and fuel combustion. This is illustrated in Figure 5.

One key benefit of LCA is that it identifies where an environmental impact is transferred from one stage to another (burden shifting), allowing mitigation or avoidance to be targeted. Furthermore, a life-cycle analysis can also help identify impacts that would have otherwise been omitted if only pump-to-wheel estimates were made. In the context of biofuels for example, feedstocks that require a significant amount of nitrogen fertiliser can result in significant N_2O emissions. Another example relates to land-use changes from feedstock growth.

There are a number of models used to determine emissions at different stages of the biofuel lifecycle, with different jurisdictions having a preferred model. For example, California Air Resource Board uses a modified version of GREET for its regulatory purposes, Canada Federal Government uses GHGenius, whereas in the EU the Joint Research centre (JRC) is in charge of updating the input data for calculating default emissions factors (see Appendix F). A key point is that, except GHGenius, these models do not include land-changes (LUC) emissions in their default estimates, although they allow users to model LUC as needed. GHGenius includes default land management emissions in most biomass production systems (e.g. soybean and palm) (Bonomo, et al., 2018).

Figure 5 – Generalised LCA stages for biofuels



Source: based on (Dunn, et al., 2017)

In the literature, there is also a lack of consensus on how to estimate indirect emissions from the use of wastes and residues as feedstock for biofuels when these products already have other productive uses. In some cases, environmental gains from biofuels combustion can be negated if these feedstocks are taken away from other uses where they are replaced with higher emitting sources of energy. For example, animal fats can be used for process fuel at the rendering facility, or used for energy in heat and power more generally. Displacing animal fats from these uses, could lead to other, more emissions-intensive fuels for energy (Mallins, 2017).

Nevertheless, for the feedstocks analysed here, available data suggests that emissions from land-use change in particular is the key parameter that determines the relative emissions performance amongst different groups of biofuel feedstocks. This is discussed in more detail below.

Advanced biofuels have low land-use change emissions. Fuels from vegetable oils have the highest emissions

Most biofuels today use feedstocks grown on land that can otherwise be used for food, feed or material production. An increase in biofuel consumption can lead to cropland expansion through direct or indirect land-use changes.

Direct land-use changes occur when land that would otherwise been in agriculture, producing food or feed crops, is converted to produce feedstock for biofuel production. In this process, the soil organic carbon (SOC) content can either be emitted or sequestered depending on the type of crop used.

Indirect land-use changes occur when land is converted to food, feed or biomass production from other states (e.g. forest or natural grasslands) to compensate for the loss of commodity production displaced by biofuel production. It can result in more intensive farming to raise yields or bring new land into food supply chains. It can also result in the displacement of high carbon stock land such as forests, wetlands and peat lands, leading to biodiversity loss and carbon emissions.

Estimating impacts from ILUC changes is complex and controversial in the scientific community (Prussi, et al., 2020c) . This is because ILUC cannot be observed or measured, so modelling is required. Techniques to estimate ILUC typically involve models that attempt to capture economic linkages that drive land-use change on an international scale. These are generally of two types: (i) computable general equilibrium models that consider all markets to be in equilibrium at each time step; and (ii) partial equilibrium models that consider the agricultural sector in detail, with the other sectors treated at a much higher level ((Dunn, et al., 2017).

Given the different modelling approaches used, it is also difficult to accurately separate direct land-use change effects from those that are indirect. For this reason, in this paper these effects are grouped together as 'land-use change effects.' Furthermore, the net impact from land-use change also depends on the treatment of waste and residues, and co-products that result from biofuel production. For example, the production of diesel from soybeans can co-generate 4.2 tonne of dry soy meal per tonne of diesel (Hoefnagels, et al., 2010), which could then displace soy meal that would otherwise be imported. How emissions from co-products generation are treated can significantly affect LCA emissions estimates – this explains some of the variation in biofuels emissions observed in the literature (see Appendix D for an overview of methods).

Figure 6 and Figure 7 below show that emissions from land-use change (LUC) can be substantial depending on the feedstock used.[18] Focusing on the LUC impacts alone, the following key points emerge from the figure:

- For the given feedstocks, emissions from land-use change can be significantly higher than emissions from biofuel processing, particularly for vegetable oils (Figure 6).
- The LUC impact is significant for vegetables oils. In Europe, although most cropland expansion (e.g. for rapeseed oil) is on abandoned land, expansion into other natural vegetation is still significant. Overall however, most of the LUC emissions for vegetable oil

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[18] The figure presents the maximum LUC emissions estimates reported in the literature reviewed.

is due to drainage of peatlands in Indonesia and Malaysia, particularly for palm oil (Ecofys et al., 2015). It has been estimated that 45% of palm oil expansion between 2008 and 2016 was onto land that was forest in 1989 (European Commission, 2019).[19]

- For the other vegetable oils, LUC emissions occur due to substitution effects as result of changing market conditions for co-products. Biofuel production often results in large volumes of co-products that can be used for power generation or animal feed. The use of co-products can therefore lead to net cost reductions from the cultivation of a specific crop, which in turn determines the most economic use of land. If these co-products are replaced with other feeds, the cultivation of a specific crop can become uneconomic.[20] In this case, the outstanding demand for oilseeds that are no longer available locally can be indirectly offset through the additional production of palm oil elsewhere in the world, causing net LUC emissions. Although this substitution effect is relatively limited, it still transfers some of the peatland emissions from palm oil to other vegetable oils (Ecofys et al., 2015). In a decreasing order, the largest LUC emissions are from palm oil, soybean oil, sunflower oil, and rapeseed oil.
- Conventional feedstocks for ethanol, such as sugar and starch, have much lower LUC emissions impacts. The LUC value for corn is lower than that for wheat and barley because corn has higher yield and because wheat co-products are more easily substituted with other protein sources, resulting in small oil palm expansion (due to the substitution effect above) (Ecofys et al., 2015).
- There is a wide range of estimates for animal fat feedstock, including or excluding non-land indirect changes. The latter is mainly related to displacement effects in oleochemical applications, and in heat and power generation. For example, if animal fats are diverted from use in soap, they may be substituted with cheap palm oil or soybean oil which can increase deforestation through land conversion (Baldino, 2019).
- Advanced biofuels result in low, and even negative, LUC emissions. This is because of the offsetting sequestration effect of new land covers (e.g. short-rotation plantations) or carbon sequestration in soil due to no-till practices. For perennial grasses (e.g. miscanthus, switchgrass) and short rotation woody crops, land-use change can negate other GHG emissions primarily because these crops tend to build soil carbon where they are grown (Valin, et al., 2015). By contrast, forestry residues can result in carbon soil loss through increased erosion and reduction of carbon inputs, although these effects can mitigated with only partial residue removal and sustainable management practices (Searle, et al., 2017).

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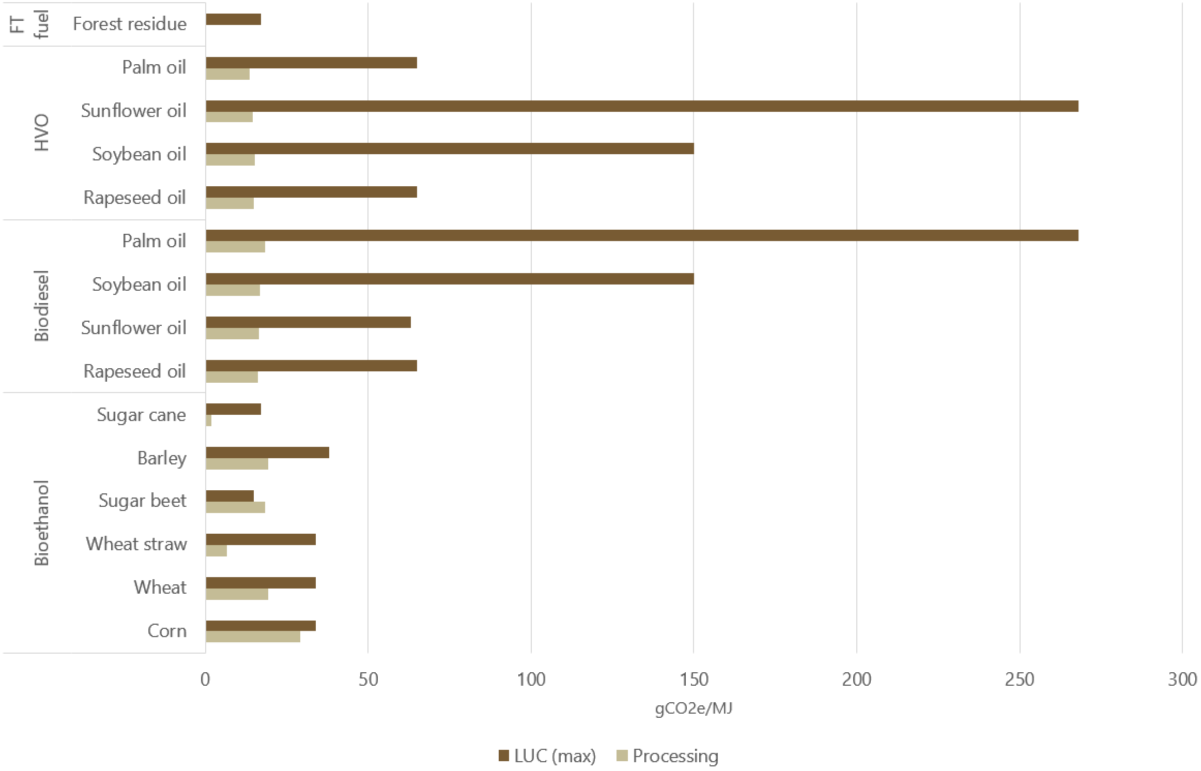
[19] The carbon stored in trees and soil is released when forests are cut down or peat lands drained.

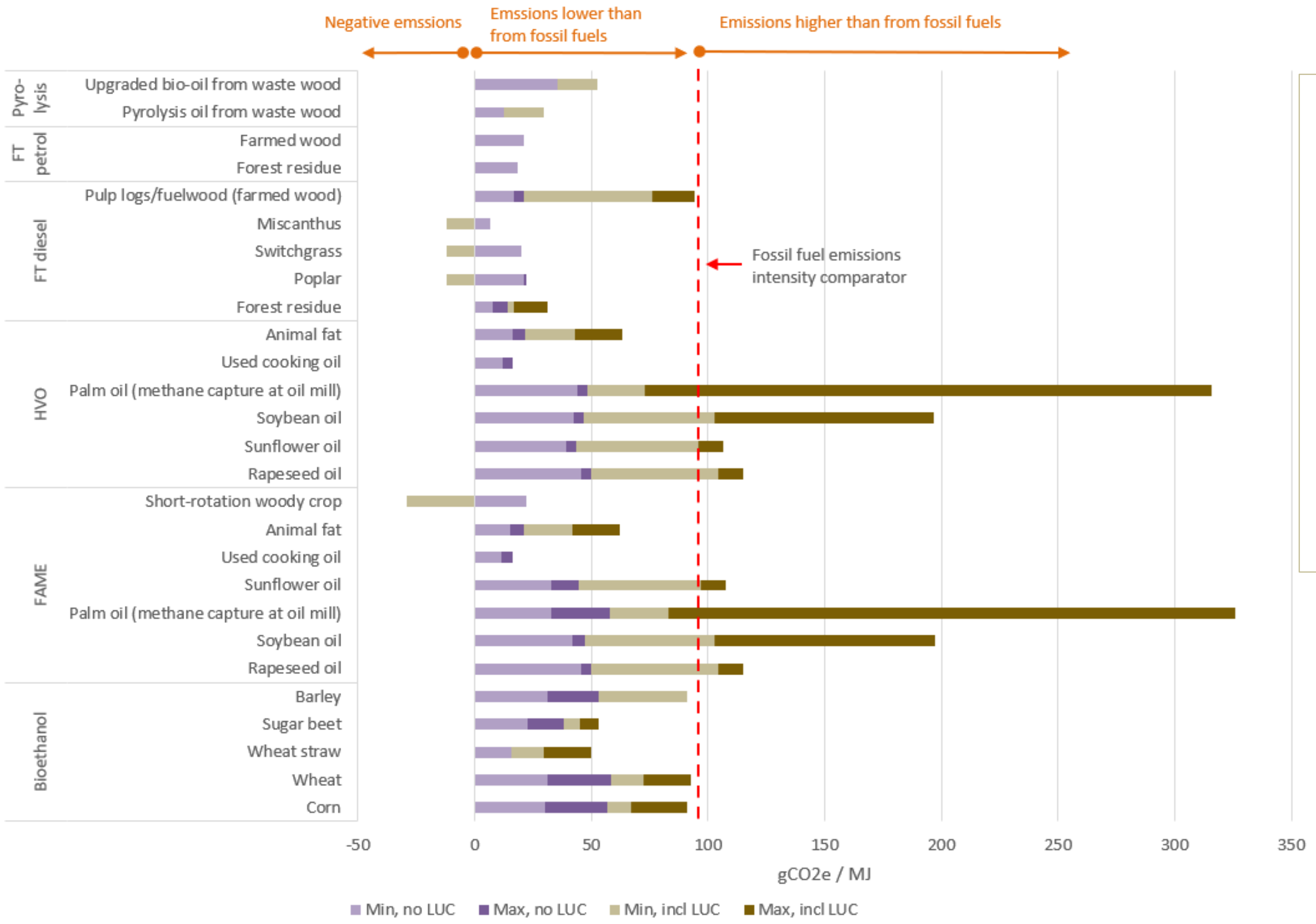
[20] For example, ethanol production from corn results in DDGS (distiller's dried grain with solubles), which can also be used for animal feed.

Figure 6 – Comparison of LUC emissions and emissions from biofuel processing



Source: Processing emissions - EU RED II; LUC emissions - (Ecofys et al., 2015), (Hoefnagels, et al., 2010)

Figure 7 – LCA emissions from biofuels, including land-use change



Note: The light and dark purple bars show estimates without LUC impacts, whereas the light and dark gold bars add incremental LUC impacts. The darker purple and gold colours add an upper bound for estimates without and with LUC impacts respectively. The shading of colours simply aims to show the variability of estimates from different sources.

The estimates are for biofuels consumed in Europe, except for liquid fuels from pyrolysis which are based on US numbers.

The vertical red line shows the fossil diesel comparator on an LCA basis as used in the EU RED (94 gCO2e/MJ).

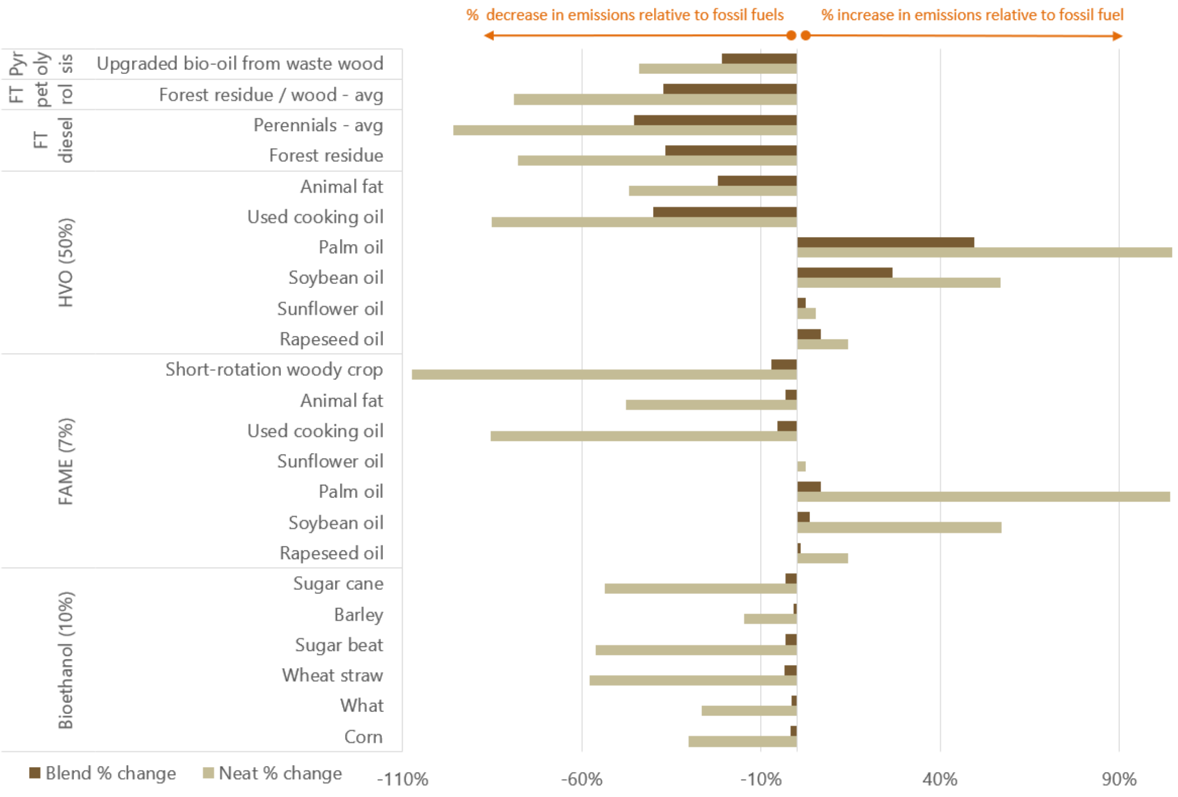
Source: Sapere based on (Camia, et al., 2018), (Flach, et al., 2019), (O'Connor, 2013), (Hoefnagels, et al., 2010), (Searle, et al., 2017), EU RED II, (Transport & Environment, 2016), (Ecofys et al., 2015)

Advanced biofuels have a higher emissions savings potential when accounting for blending limits

The previous section discussed biofuel lifecycle emissions on an energy basis, measured as gCO2e/MJ. In reality, the blend walls discussed previously will limit the amount of biofuel energy that can be consumed, which will affect the real emissions reduction potential depending on feedstocks and conversion technologies.

Figure 8 shows the overall emissions impact depending on the blend wall used (10% for bio-ethanol, 7% for biodiesel, and 50% for drop-in fuels). The comparison is with lifecycle emissions from fossil fuels (94 gCO2e/MJ), which include supply and combustion emissions. Appendix E includes the assumption on energy content for neat and blended fuels. Appendix G provides the detailed emissions reduction estimates by biofuel pathway.

Figure 8 – Comparison of emissions savings for neat vs blended biofuels, including LUC impact



Source: Sapere analysis. Fuels from pyrolysis and FT processes are assumed to be blended at a 50% concentration.

The figure suggests the following key points for the real-world application of biofuels:

- Liquid biofuels from vegetable oils can have higher lifecycle emissions than fossil fuels, although there can be exceptions on a case-by-case basis where net LUC impacts are shown to be minimal.
- Bioethanol have lower emissions, but the blend walls significantly reduce the potential for emissions reductions. These range between -1% and -6% for a 10% blend wall.

- Similarly, a 7% limit for biodiesel from waste oils results in emissions reductions of between -3% and -6%. A 50% limit on HVOs from waste oils results in emissions reductions of -23% (animal fats) or -43% (used cooking oil).
- Advanced biofuels from waste oils and biomass residues have the highest emissions-reduction potential, both due to the higher blend wall and lower LUC emissions. The emissions reduction potential for final fuels containing 50% drop-in fuels is between -21% and -50% on energy basis
- Of advanced fuels, those produced from upgraded pyrolysis oil have the least emissions savings mostly due to the hydrogen produced from natural gas that is required in the conversion process. However, if hydrogen were produced from bio-oil instead, emissions savings via the pyrolysis route could improve by 37%. However, this would considerably increase per-unit capital costs as 30% of the bio-oil would be used for hydrogen production rather than final fuel (O'Connor, 2013).[21]

The concept of biofuel sustainability is wider than GHG emissions

Although the analysis above has focused on GHG emissions specifically, it is worth noting that biofuel production can result in wider environmental and societal impacts. These include biodiversity loss due to deforestation, water resource depletion, competition with food, and regional development impacts as a result of land-use changes.

New Zealand does not currently have rules establishing criteria by which biofuel sustainability can be assessed, and the EU provides an example. In particular, the Article 29 of the EU RED II Directive specifies the following sustainability criteria (not exclusive):

- Biofuels produced from waste and residues derived from agricultural land are allowed (for the purpose of RED II) so long as where operators or national authorities have monitoring or management plans in place in order to address the impacts on soil quality and soil carbon.
- Biofuels made from raw material from land with a high biodiversity value or high-carbon stock are not allowed.
- Biofuels made from forest biomass must come with proof that the country where the feedstock originated has monitoring and enforcement systems in place to ensure the legality of harvesting operations, forest regeneration of harvested areas, areas designated for nature protection purposes are protected etc.

To deal with the second issue of indirect impacts, which are much more difficult to measure, RED II sets limits on the share of individual biofuels produced from food and feed crop (maximum 7% of final consumption in the road and rail transport sectors of a Member State). Furthermore, the EU regulatory context allows distinguishing between high- and low ILUC-risk biofuels, supported by a

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[21] See table 7-7 in (O'Connor, 2013).

recent technical report that was commission for this specific purpose.[22] High-risk ILUC biofuels (produced from food and feed crops for which significant expansion of production area into land with high-carbon stock is observed) are capped at 2019 consumption levels in Member States, declining to zero by 2030.

An important point is that the sustainability of the same type of feedstock can differ from case to case, depending on land impacts. For example, under the EU setting above, palm oil can qualify as either high- or low ILUC- risk feedstock, depending on whether it is grown on existing land or abandoned / severely degraded land (European Commission, 2019).

The box below summarises the general criteria by which feedstocks are assessed for the purposes of being accepted into the list of sustainable raw materials in EU RED II (Annex IX). As well as the criteria related to land use discussed above, it is worth noting the reference to the waste hierarchy[23] in assessing biofuel feedstocks. This is important because some biofuel pathways could result in diverting raw material from a higher value use, e.g. animal fats that are used in the chemical industry to make soaps, or pulpwood used to make paper.[24] In other words, there is an opportunity cost associated with use a resource for biofuel production. A recent paper by (Transport & Environment, 2020) has highlighted several gaps in RED's current classification of some feedstocks, calling for an additional oversight of such opportunity costs.

Box 1 – Principles guiding assessment of feedstock sustainability in EU RED II

To be added to Annex IX of EU RED II, a raw material needs to be assessed with regard to the following principles listed in Article 28(6)

(a) the principles of the circular economy and of the waste hierarchy established in Directive 2008/98/EC;
(b) the Union sustainability criteria laid down in Article 29(2) to (7);
(c) the need to avoid significant distortive effects on markets for (by-)products, wastes or residues;
(d) the potential for delivering substantial greenhouse gas emissions savings compared to fossil fuels based on a life-cycle assessment of emissions;
(e) the need to avoid negative impacts on the environment and biodiversity;
(f) the need to avoid creating an additional demand for land.

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[22] See (European Commission, 2019).

[23] The hierarchy is: (a) prevention; (b) preparing for re-use; (c) recycling; (d) other recovery, e.g. energy recovery; € disposal.

[24] We note that RED II allows the use of 'recycled carbon fuels' produced from solid waste streams of non-renewable origin which are not suitable for material recovery in accordance with the waste hierarchy. However, these feedstocks have not yet been included in RED II Annex IX.

What is the potential demand for liquid biofuels in NZ transport?

Summary

Note: estimates provided in this section reflect potential demand purely from a fuel compatibility perspective, i.e. abstracting from possible supply.

- Due to blending walls for biodiesel and bioethanol, maximum potential demand for these fuels on an energy basis is relatively small: 6% of current demand for diesel fuels by heavy trucks and marine, and 6% of current demand for petrol fuels by light vehicles respectively. Biodiesel is not suitable for aviation.
- The potential incremental demand for drop-in diesel is much higher at around 44% of total energy required by diesel heavy trucks, marine and aviation (assuming a 50% blending limit for drop-in fuels).
- Similarly, the potential demand for drop-in petrol is 47% of total energy required by light petrol vehicle, assuming the same blending limit.

From a fuel compatibility perspective, potential demand for drop-in diesel is much higher than for conventional biodiesel due to higher blending limits

In this section, we present the maximum potential from a fuel compatibility perspective only. In reality, the demand for biofuels will also be significantly impacted by economic factors such as maintenance costs and final fuel price, which will affect the total cost of vehicle ownership. The economic factors are discussed further below.

For aviation and shipping, data on current fuel consumption is based on MBIE oil tables which include energy consumption by domestic aviation and navigation.[25] For heavy trucks (GVM[26] > 10 ton), consumption is estimated based on vehicle configuration as per the NZTA vehicle fleet data,[27] fuel economy estimates by (Haobo, et al., 2019), and vkt estimates by GVM band from the Motor Vehicle Register (see Appendix L). Current fuel consumption by petrol light vehicles assumes a fuel economy of 8.98 litres per 100 km, [28] which is applied to total distance travelled by light petrol vehicles based

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[25] We note that the data for domestic navigation is not just coastal shipping but is likely to include recreational activities too.

[26] Gross vehicle mass

[27] https://nzta.govt.nz/resources/new-zealand-motor-vehicle-register-statistics/new-zealand-vehicle-fleet-open-data-sets/

[28] Based on MoT's 2018 vehicle fleet statistics. This number applies to the 2,000-2,999cc vehicle category, which is representative of the light vehicle fleet.

on the NZTA vehicle fleet statistics for 2018. The 2021 distance is estimated from historical values assuming a 2% growth p.a. (the average for 2014-2018 period).

Projections of total fossil fuel fuel demand (the baseline) are estimated based on assumptions in the base case scenario of MoT's 2017 Transport Outlook[29] for:

- vkt travelled by light petrol vehicles[30]
- vkt travelled by heavy ICE diesel vehicles (including projections of freight growth),[31] and
- million km travelled by domestic air
- freight movements by coastal shipping.[32]

The following key assumptions are made (see Appendix L for more details):

- All light vehicles can switch from petrol to E10.
- For heavy trucks, most of which run on diesel, we are able to determine the proportion of fossil energy consumption that can be replaced with blended fuels using NZTA's vehicle fleet data and OEM requirements based on compilation of information from engine manufacturers by the NZ Motor Industry Association (MIA) (see Appendix M). We also assume that as heavy trucks are retired (assuming a lifetime a 20-year lifetime), they are replaced with engines that can accept higher FAME biodiesel blends, B30 in particular as follows: old trucks are replaced with trucks that can run on B30 in proportion to the share of heavy vehicles that have less than a year since registration. We estimate this to be 4% currently. The switch to B20 is in proportion to the current share of heavy vehicles with registration under 10 years (43%). The remainder (53%) are replaced with trucks running on B7. The link to the year of truck registration is used as a proxy for fleet composition in terms of age and therefore likelihood for engine to use newer configurations allowing higher blends.
- For heavy trucks that do not accept biodiesel, we assume a blend of 50% conventional fuel and 50% drop-in fuel. We assume a blending wall for drop-in fuels to reflect possible restrictions that may be needed to meet fuel quality standards. For example, although the EU standard for paraffinic fuels does not require limits for diesel-like hydrocarbons, in practice HVO is blended up to 30% (Neste, 2020). Drop-in fuels from lignocellulosic drop-in fuels are not commercially available yet so we cannot comment on the observed blending limit for these fuels. However, we recognise that the direction is for such limits to be increased or even removed as standards for new fuels are being developed. Therefore, the 50% limit is a conservative assumption when viewed over the long term.
- In shipping, we assume a blend wall of 5% for biodiesel.
- In aviation, 50% of aviation fuel consumption can be replaced with drop-in fuels. In the shorter to medium term this is mainly HEFA-SPK which is commercially available. Over the

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[29] https://www.transport.govt.nz/assets/Uploads/Report/TransportOutlookFutureOverview.pdf

[30] The decline in vkt travelled by petrol vehicles is due to the increasing electrification of the fleet through to 2050.

[31] In MoT's study, vkt travelled by heavy ICE diesel vehicles decline y/y due to increased electrification of the fleet.

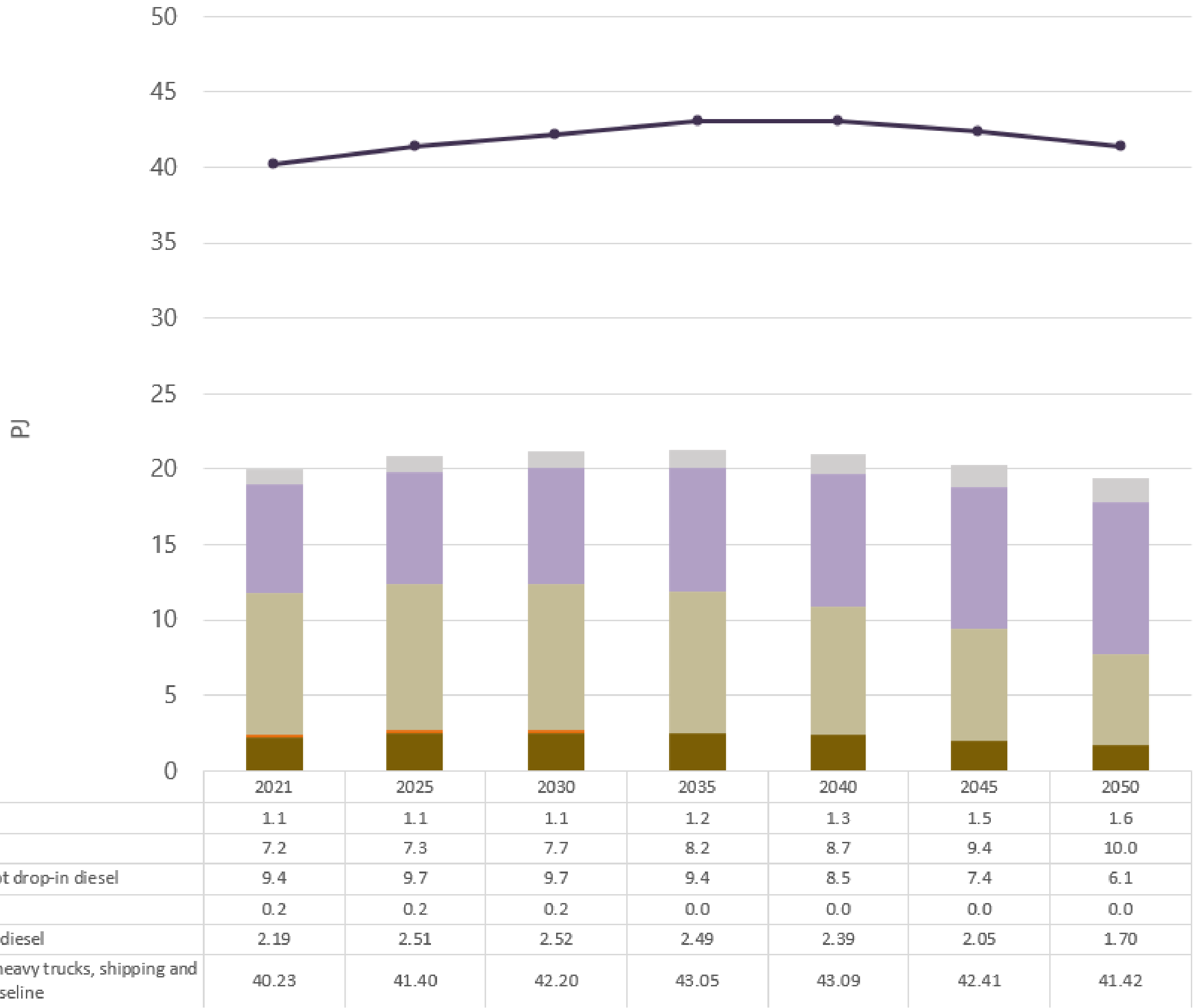
[32] These are assumed to be constant through to 2032, and increase by 1.84% p.a. from then onwards.

long term, other advanced biofuels could be used for which an ASTM standard has been approved, e.g. FT-SKA. We also assume a constant fuel economy through to 2050, although we recognise there are ongoing improvements made to increase fuel efficiency (NZ Government, 2016).

Key findings:

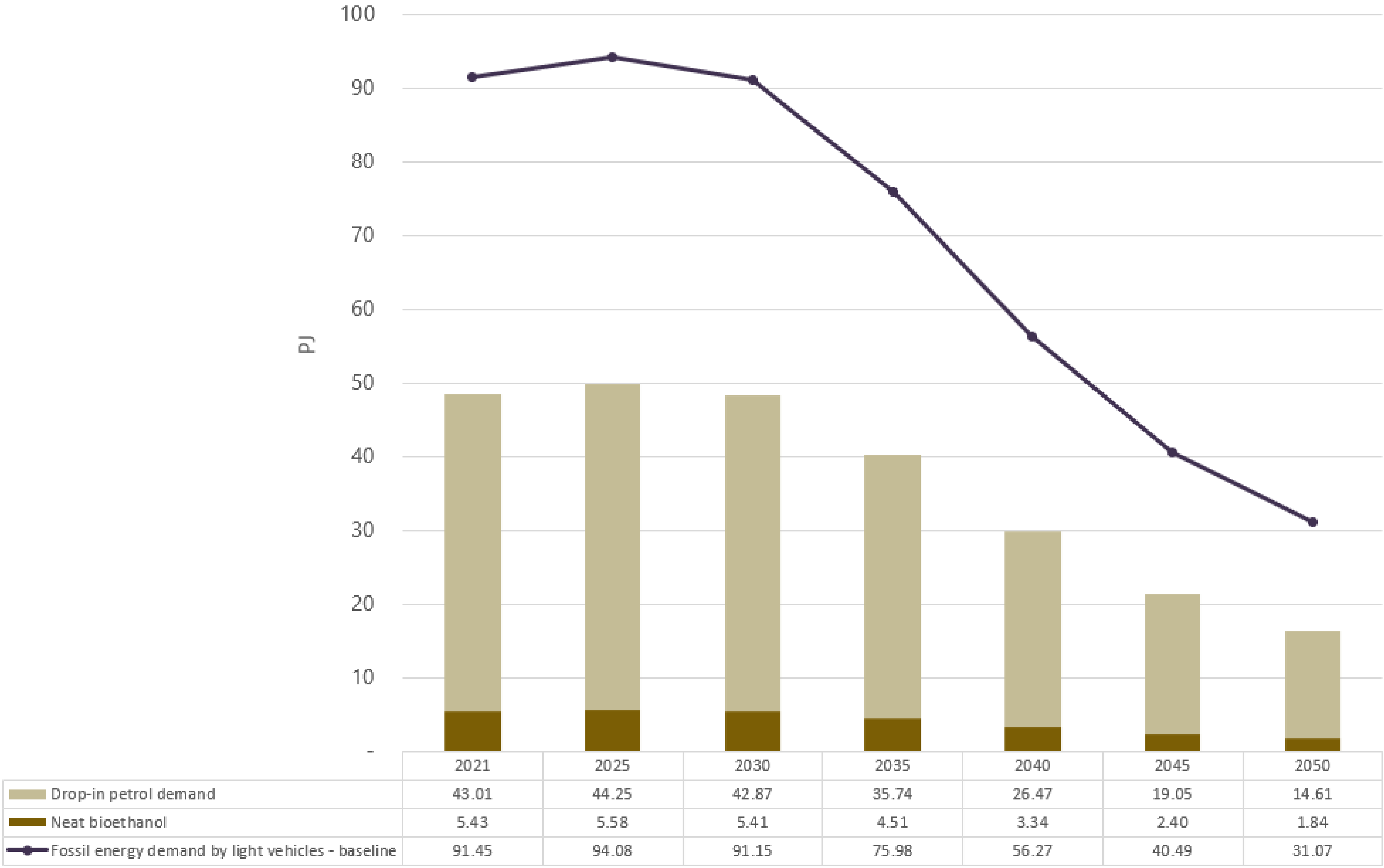
- Total potential demand for biodiesel out of total diesel energy consumed is 6% currently, dropping to 5% by 2050 (Figure 9). This low share reflects the blending walls applied across heavy trucks and shipping. On an energy basis, the proportion of heavy trucks that can use the higher blends (B20 or B30) is 4% today and 3% by 2050. In other words, the share of biodiesel out of total energy consumption is largely driven by the ability of heavy trucks to operate on these higher blends.
- Total potential demand for drop-in fuels blended at 50% is 44% today and 43% in 2050. This means that biodiesel and drop-in diesel can account for 50% of total diesel energy demand today, and 48% in 2050.
- Results are similar for light vehicles running on petrol. Total potential demand for bioethanol is estimated to be 6% of total energy consumption by petrol light vehicles (Figure 10). This stays constant though to 2050 because it is assumed that all petrol vehicles can use an E10 blend (which means that the proportion of bioethanol doesn't change). The potential demand for drop-in petrol (at 50% concentration) is 47% of total energy required.
- We note that the estimates for bioethanol and biodiesel demand reflect an upper limit. The availability of drop-in fuels over the long-term could increase demand for such fuels at the expense of conventional biofuels due to the former fuels having more beneficial technical and environmental characteristics.

Figure 9 – Potential demand for biofuels replacing fossil diesel/aviation fuel (incl. maximum demand for biodiesel)



	2021	2025	2030	2035	2040	2045	2050
Marine drop-in diesel	1.1	1.1	1.1	1.2	1.3	1.5	1.6
Aviation biofuel	7.2	7.3	7.7	8.2	8.7	9.4	10.0
Heavy trucks that can only accept drop-in diesel	9.4	9.7	9.7	9.4	8.5	7.4	6.1
Marine biodiesel	0.2	0.2	0.2	0.0	0.0	0.0	0.0
Heavy trucks that can run on biodiesel	2.19	2.51	2.52	2.49	2.39	2.05	1.70
Fossil energy demand by diesel heavy trucks, shipping and aviation - baseline	40.23	41.40	42.20	43.05	43.09	42.41	41.42

Figure 10 – Potential demand for biofuels replacing fossil petrol (incl. maximum demand for bioethanol)



	2021	2025	2030	2035	2040	2045	2050
Drop-in petrol demand	43.01	44.25	42.87	35.74	26.47	19.05	14.61
Neat bioethanol	5.43	5.58	5.41	4.51	3.34	2.40	1.84
Fossil energy demand by light vehicles - baseline	91.45	94.08	91.15	75.98	56.27	40.49	31.07

Source: Sapere analysis

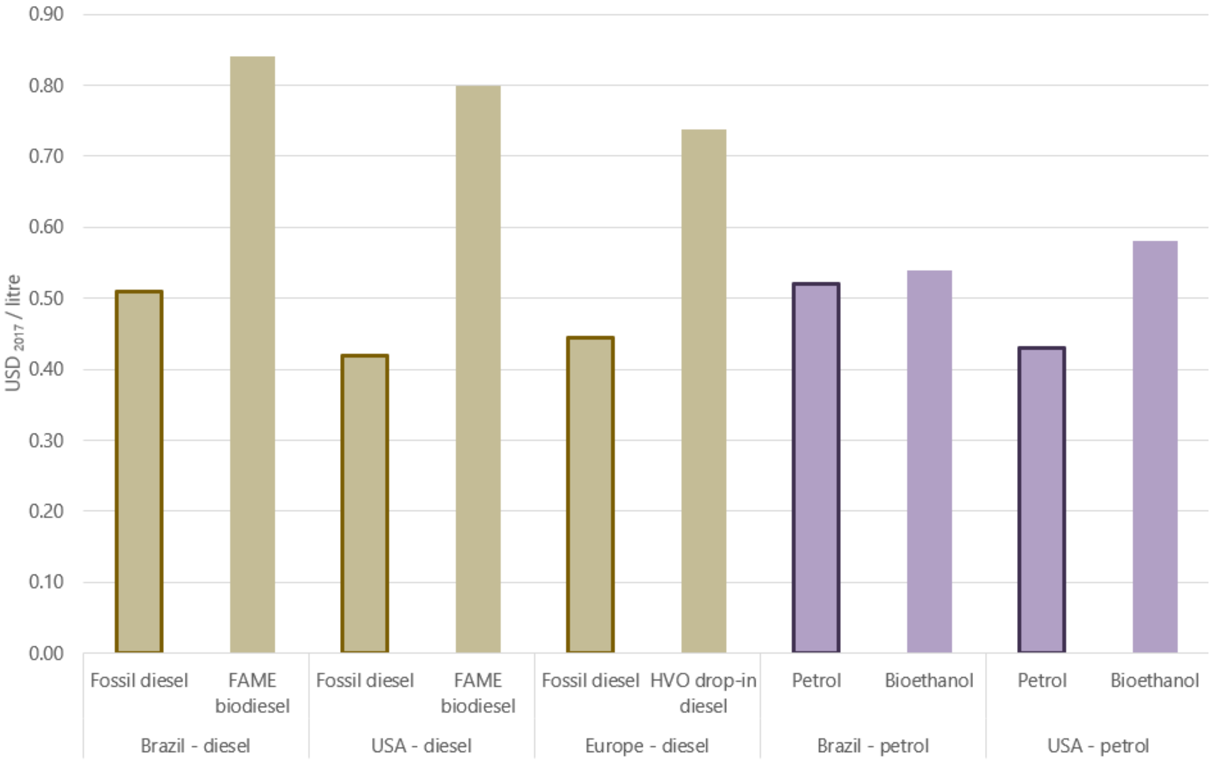
Actual demand for biofuels will be affected by higher vehicle ownership costs

The estimates of potential biofuel demand from the previous section assume full uptake of biofuels in accordance with the OEM's fuel requirements for different types of engines. In practice, this uptake will be significantly affected by the economics of switching from current to cleaner fuels.

First, production costs for commercially available biofuels (mainly conventional bioethanol, FAME biodiesel and HVO) is much higher than that for fossil diesel (Figure 11), contributing to a higher retail prices which can be double for a neat biodiesel compared to fossil diesel.[33]

We note, however, that a higher carbon price would reduce premia for a blend due to ETS savings in the cost of fuel at the pump. The current retail diesel price contains an ETS component (around 9 cents/litre at a carbon price of $32/tCO2e). The higher the blend and the carbon price, the lower the premia for biodiesel or drop-in fuel. This is shown in Figure 12. Here, blended fuel prices are shown as proportion of 2019 NZ fossil diesel prices, assuming B100 price is roughly twice that of fossil diesel, reflecting the US production cost ratios from Figure 11.[34]

Figure 11 – Biofuel production costs vs fossil fuel production costs



Source: Bioethanol and FAME costs from (IEA, 2017); HVO costs from (Maniatis, et al., 2017)

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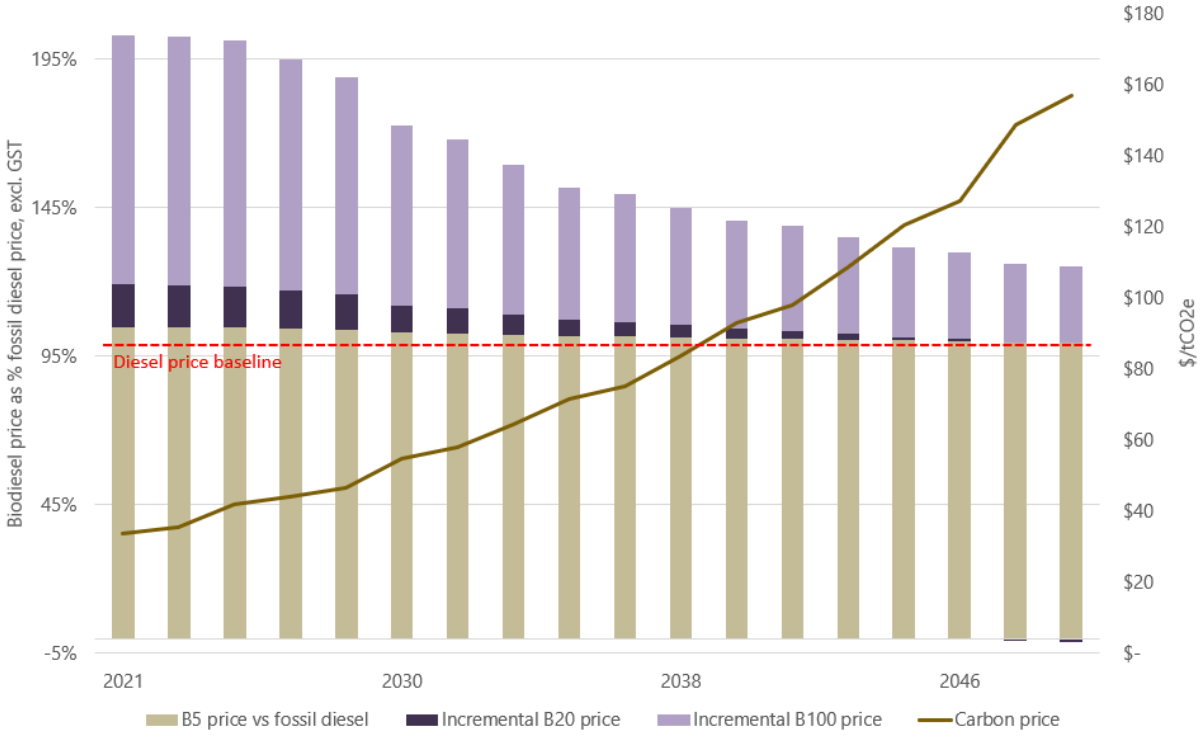
[33] Based on our current market analysis.

[34] We note that this double ratio was also observed during 2020 based on conversations with NZ fuel importers.

Figure 12 - Relationship between biodiesel blend premia and carbon price (excl GST)



Source: Sapere analysis

Second, the operating and maintenance costs associated with bioethanol and biodiesel could increase as a result of the fuel switch. This is because the unfavourable chemical properties of these fuels may require an increased frequency of vehicle servicing (e.g. oil change, fuel filtration elements) for higher blends. There could also be additional operating costs for paraffinic fuels. When a high concentration of paraffinic components is used, lubricity additive is needed in the final blend to protect fuel injection equipment against excess wear. However, we note that lubricity additive is also needed for conventional winter grade or sulphur-free diesel fuel (IEA-AMF, 2021b), so the additional cost for paraffinic fuels would not be as high in colder climate.

Furthermore, the low energy of biodiesel (33.5 MJ/litre neat), and particularly of bioethanol (21 MJ/litre neat), caused by the oxygen content means fuel consumption and refuelling frequency may be higher. We note that the use of closed-loop control systems of diesel consumption could help mitigate this issue for biodiesel (Wood Mackenzie, 2010).[35]

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[35] The increase in oxygen content of the fuel with open-loop control systems reduces peak power and torque, and increased volumetric fuel consumption, in line with the quantity of FAME blended into the diesel.

What is the outlook for biofuels supply?

Global market

- Over the next decade, it will be difficult to secure reliable international supply of biodiesel produced from non-vegetable oil feedstock (i.e. with low land-use change emissions). This is due to increased demand for such feedstock from the EU, which has been the main exporter of biodiesel. Australia's exports of biodiesel are expected to be insignificant.
- Although the global bioethanol export market has been dominated by USA and Brazil, New Zealand has not imported from those countries. Most of the bioethanol currently in the NZ market is imported from Australia, and we expect this trend to continue. Proximity brings the benefit of lower shipping costs and the ability to engage with local producers to ensure fuels are produced sustainably. However, exports of biodiesel from Australia over the next decade are projected to continue to be small at around 1.8 PJ p.a.
- A key trend in OECD countries is the shift towards advanced biofuels. This is driven by the need to overcome blending limits and sustainability concerns linked to conventional biofuels. Technology learning curves and the direction of EU and US policy support suggest that global uptake of advanced biofuels will start to grow from 2025.

Domestic production

- There is enough local supply of inedible tallow to meet 56% of biodiesel demand (on an energy basis) from heavy trucks and marine, and up to 28% of drop-in fuel demand from aviation. However, this supply is uncertain due to high competition for it from overseas. Tallow-based biodiesel currently sold in New Zealand is imported from Australia. Small volumes of biodiesel are produced from domestically sourced used cooking oil.
- Domestic bioethanol is primarily produced from whey, but output is extremely small (0.13 PJ), with feedstock supply susceptible to weather events (e.g. droughts). Most of bioethanol currently in the market is imported from Australia, but supplies have declined.
- New Zealand's biomass resources suggest significant potential for advanced biofuel production, however the rate at which this production can scale strongly depends on technology learning curves. Current technology projections suggest that a total production of 39 million litres of drop-in fuels is possible by 2025 gradually increasing to 2030 (at around 19% p.a.). From 2030, the rate at which production can be further scaled is uncertain. The optimistic scenario is that by 2035 the technology is mature enough to allow production of drop-in diesel and drop-in petrol to meet all diesel[36] and half of petrol demand[37] respectively. The less optimistic scenario is that this happens 5 years later - by 2040. Note also that these assessments do not consider other uses for biomass feedstock, which could affect the volumes available for biofuel production specifically.

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[36] All diesel demand from heavy trucks, marine and aviation.

[37] All petrol demand from light vehicles.

Available domestic supply of feedstock for conventional biofuels is small or uncertain

Biodiesel and HVO/HEFA

In New Zealand, there is enough inedible tallow to produce around 3.35 PJ of fuel energy (~100 million litres of FAME biodiesel)[38] per annum. However, there is significant competition for domestic tallow from international producers in jurisdictions with supportive biofuel policies. Currently, NZ tallow is exported to Singapore for manufacturing into biodiesel (Meat Industry Association, 2020). In 2018, Z Energy started producing FAME biodiesel from domestic tallow at its Te Kora Hao plant in Wiri South Auckland, which had initial capacity of 20 million litres p.a., with a potential scale-up of production to 40 million litres p.a. (Z Energy, 2016). However, in 2020 international competition for domestic tallow, which significantly increased the price for this feedstock, has led Z Energy to hibernate its biodiesel plant. Currently, the plant is used as a biodiesel import terminal, where mineral diesel and neat biodiesel are blended. This neat biodiesel is made from tallow feedstock, and is imported from Australia.

Another producer of biodiesel in New Zealand is Green Fuels. Their output is relatively small - around 500,000 litres biodiesel p.a. from used cooking oil (Rural Delivery, 2016). Potential FAME biodiesel production from canola oil as a break crop in grain farming was estimated to be another 20 million litres (PCE, 2010), [39] however this would require trade-offs with alternative uses of land. Only small quantities of used cooking oil are available.

In the figure below we compare the maximum potential demand for FAME biodiesel from the previous section with known capacities for domestic production. MBIE renewables statistics[40] indicate that around 0.02 PJ of biodiesel p.a. were domestically produced in 2015-2017. We assume this to be production by GreenFuels[41] that will continue for the foreseeable future.[42] We also assume a maximum output of 20 million litres of FAME biodiesel from Z Energy's Te Kora Hao plant in Wiri South Auckland.

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[38] As per (PCE, 2010).

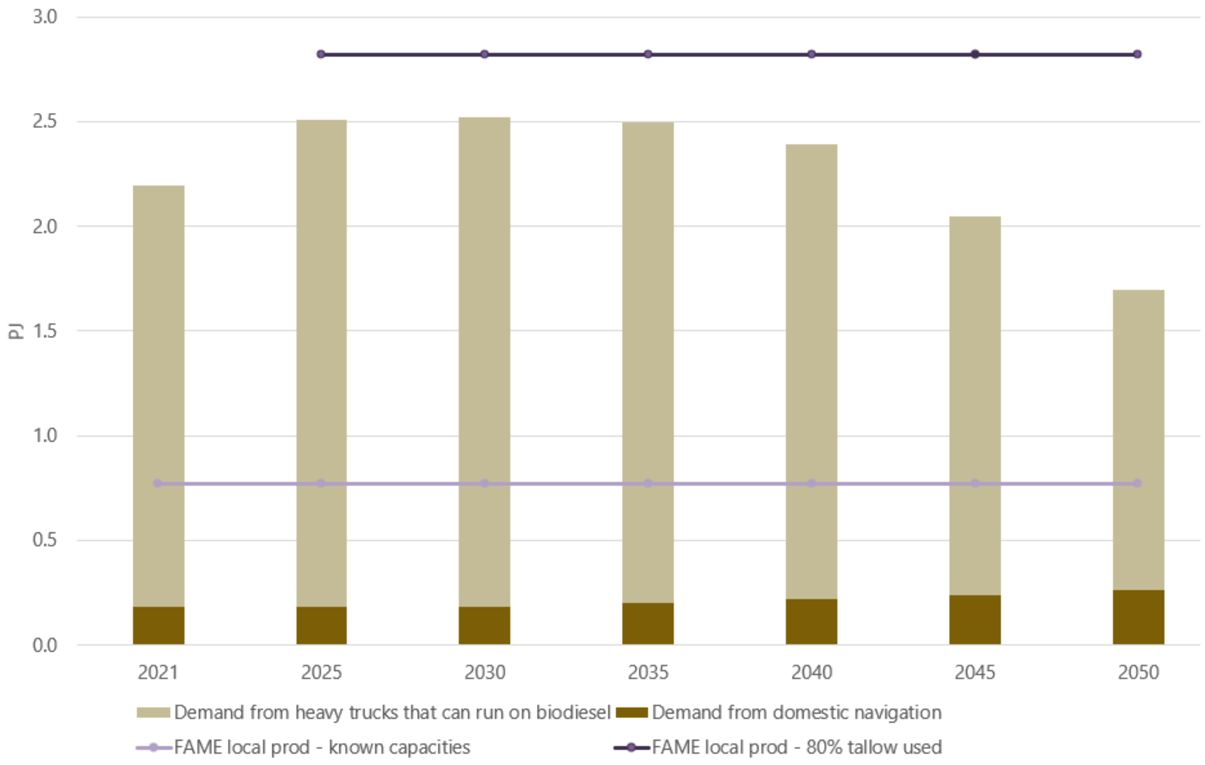
[39] New Zealand has almost 700 specialist grain farmers. If each of them planted a 20-hectare break crop of canola every year and obtained a yield of 4 tonnes of seed per hectare, that would be sufficient for at least 20 million litres of FAME.

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

[41] Z Energy made its first biodiesel sales in 2018-2019 based on their 2019 Annual Report.

[42] We discuss uncertainties on feedstock supply later on.

Figure 13 – FAME demand and domestic production



Source: Sapere analysis

The figure suggests that current capacity would meet biodiesel demand from the marine sector, but would only partially meet potential demand from heavy trucks. However, it also suggests that there is enough feedstock in New Zealand to meet all biodiesel demand from these two sectors. Existing plant capacity is at around 28% of maximum demand, but it could be easily scaled up to meet 50% by 2025.[43] The scale-up from the current built capacity of 25 million litres FAME p.a. [44] to 45 million p.a. would require up to $26 million in investment costs[45]. We should note that tallow could also be used for drop-in fuel production, e.g. HEFA-SPK for aviation. However, the residual supply[46] of tallow feedstock (producing up to 2 PJ or up to 59 million litres of fuel) would only cover up to 28% of aviation demand for drop-in fuels today, and 26% by 2030. The reported capital costs for such plants are $0.7-$2.5 per litre p.a. (ICCT, 2019). If additional production capacity were built to produce HEFA-SPK on the basis that tallow feedstock is available, then the investment costs would be $41-$148 million.

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[43] This refers to Z Energy's plant that can be scaled up to produce 40 million litres.

[44] Z Energy + Green Fuels

[45] Based on Z Energy plant's capital costs of $26m for 20m litres p.a. The scale-up of the plant may cost less than the initial greenfield investment.

[46] Total tallow supply less volumes required to produce 40 million biodiesel. If only 80% of total tallow output is used for biofuels, then HEFA production could meet around 20% of total aviation demand for biofuels.

Another option to meet demand would be to import biofuels and blend them locally. Z Energy is doing this currently, but the volumes are limited. As discussed in section 0, global trade in biofuels is small, and most of production is targeted at domestic consumption bolstered by policy support.

The uncertainty around global feedstock supplies is particularly evidenced by Gull's recent decision to discontinue its B5 Diesel Max fuel (as Z Energy's hibernation of its biodiesel plant discussed previously). Originally, Gull biodiesel was made primarily from used cooking oil and occasionally animal fats (tallow). Because consistent domestic supply was harder to find, over the last six years Gull has been importing biodiesel from a long-established Australian producer. However, in recent years, "even securing regular import supply has become difficult and with the lack of scale, viable options to automate the blending process have been limited" (Gull, 2020).

Bioethanol

In New Zealand, bioethanol has been primarily produced from whey (a dairy industry by-product) at Fonterra's Anchor Ethanol plants. This bioethanol has been blended with petrol, and sold at retail outlets primarily by Gull.

Domestic bioethanol use has been very small – 0.13 PJ in 2019 (MBIE, 2020), or 6 million litres of neat bioethanol. In 2020, Fonterra's output was affected by drought so local production is expected to have been much smaller. Gull has also been importing bioethanol, but has signalled issues with securing supply. As a consequence, although it continues to offer E10, it has discontinued E85 (Gull, 2020b).

Access to global supply of sustainable conventional biofuels is problematic

The main biofuels currently produced on the global scale are ethanol (produced mostly from corn, sugar cane and other crops) and biodiesel (produced from vegetable oils, and fats including used cooking oil). Global production has been increasing since 2010, including for HVO and HEFA production, to reach 4 exajoules in 2019. In 2019, ethanol accounted for 59% of global biofuel production (in energy terms), biodiesel 35%, and HVO/HEFA 6% (REN21, 2020).

United States remains the leading producer of biofuels, with 41% share, followed by Brazil (26%). In these countries, bioethanol production predominates.[47] Europe is the largest producer of biodiesel primarily from rapeseed oil and used cooking oil. Currently, EU accounts for 34% of global biodiesel production (OECD-FAO, 2020). Indonesia, China and Germany account for 4.5%, 2.9% and 2.8% of global biofuel production respectively (REN21, 2020).

An emerging trend over the next decade is declining biofuels production in both the EU and USA, due to a number of factors. In the US, domestic demand for ethanol declined in 2019 due to the approaching blend limits. In the EU, changes to the Renewable Energy Directive have limited the role of food-based biofuels. Over the longer term, domestic production is expected to decline in OECD countries due to improvements in vehicle fuel efficiency (US EIA, 2019), switch to alternative drivetrains (e.g. electric cars), and the growing role of shared mobility (BNEF, 2020). In Europe

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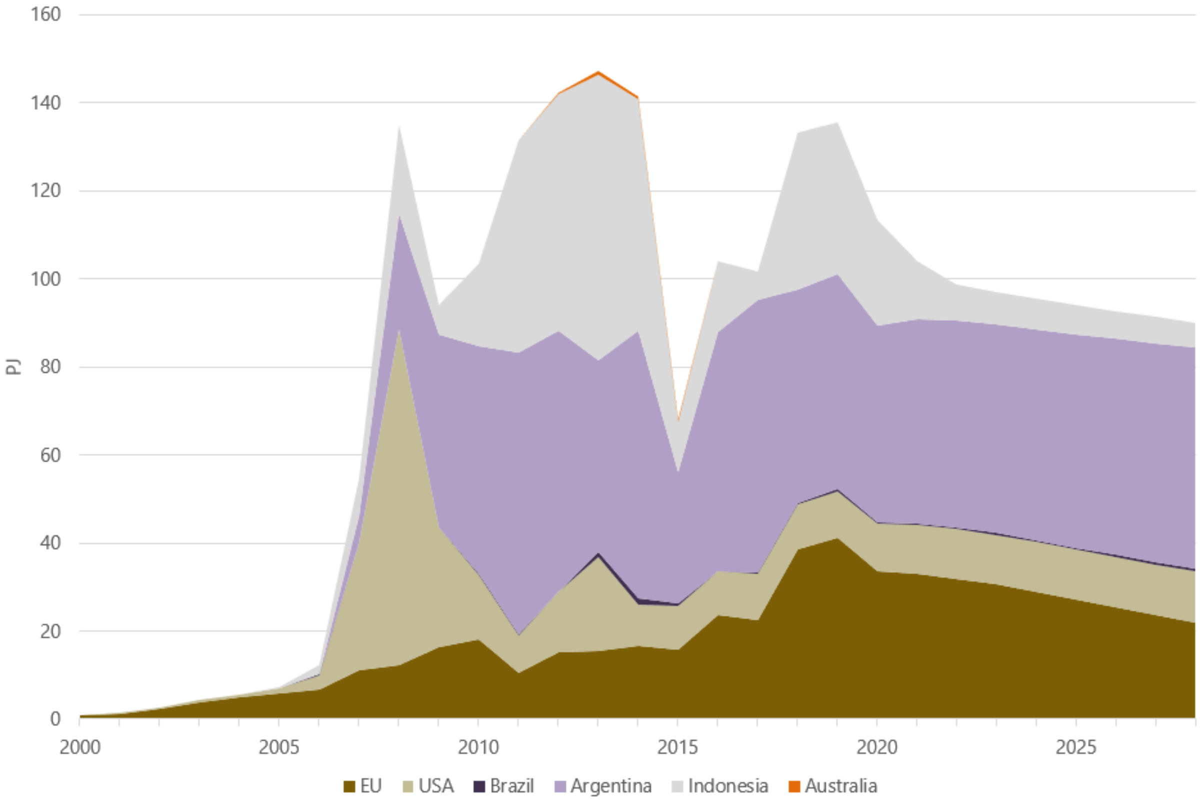
[47] USA and Brazil account for 50% and 33% of global ethanol production respectively.

particularly, consumption of diesel-type fuels is expected to decline as a result of increasing on-road efficiency standards (US EIA, 2019). Biodiesel consumption in the EU is expected to fall below current levels by 2029 (OECD-FAO, 2020).

Although this could in theory result in excess biodiesel capacity that could be used to meet demand signalled from outside EU, the issue of feedstock quality remains. As discussed previously, biofuels from vegetables oils can increase lifecycle emissions, so used cooking oil and animal fats feedstocks are preferred within the lipids pathways. However, the residual supply of this feedstock in EU is uncertain due to the policy boost they have received for domestic consumption. In particular, in an aim to promote the use of advanced biofuels in EU, these feedstocks are allowed to account for twice the energy content to meet Member States biofuel mandates (Flach, et al., 2019). Although over the next decade EU will remain the second largest exporter of biodiesel (Figure 14), its exports are likely to be dominated by biodiesel from rapeseed oil feedstock. To ensure that biodiesel produced from this feedstock does not result in higher lifecycle emissions than fossil fuels, engagement with local producers would be required to determine land-use change effects, such as potential expansion into natural vegetation from rapeseed oil cultivation. A similar engagement would also be required with Argentina (top largest exporter) and USA (third largest exporter), where biodiesel production is dominated by soybean oil. However, the large distances between NZ and these markets could make this engagement impossible. Australia has the advantage of geographical proximity, however OECD projects that biodiesel exports from Australia will be close to zero through to 2029.

Figure 14 – Projections of global exports in biodiesel through to 2029

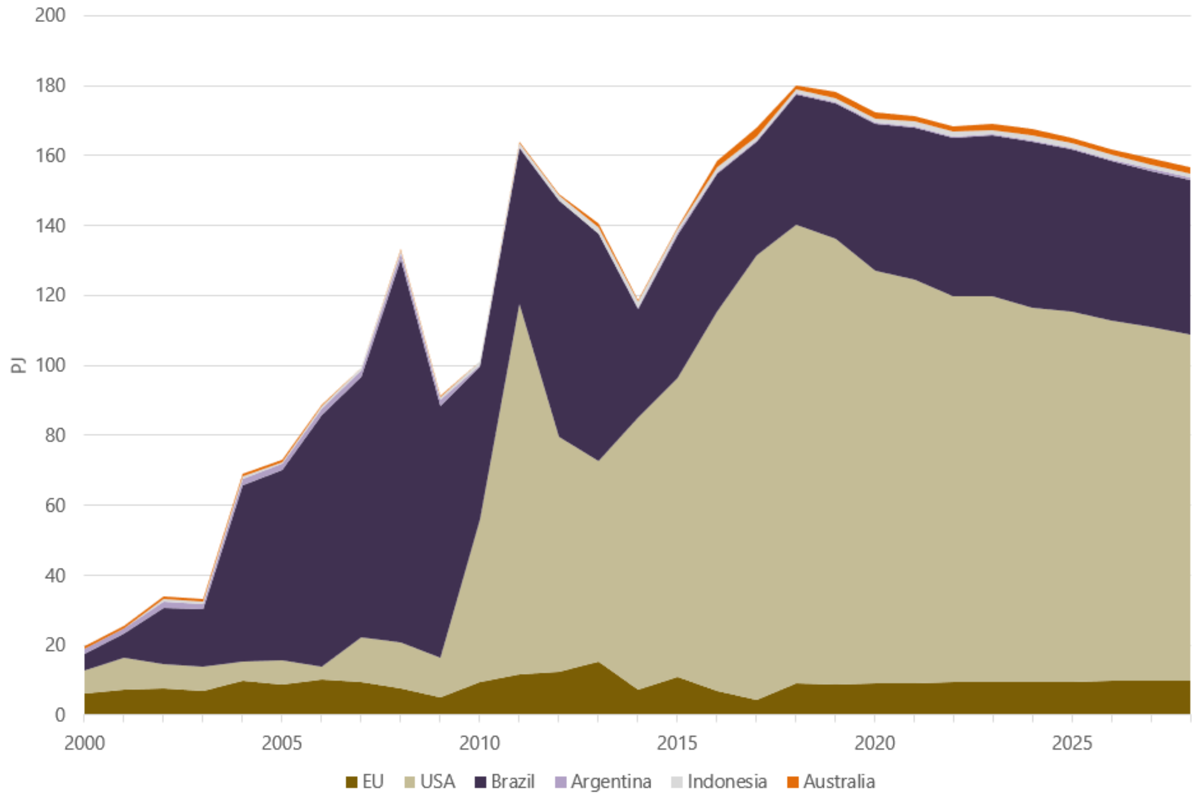


Source: OECD-FAO stats https://stats.oecd.org/

Figure 15 suggests that the top three exports of bioethanol over the next decade will be from USA where it is mainly produced from corn (an average of 107 PJ p.a.) from Brazil where is mainly produced from sugarcane (an average of 47 PJ p.a.) and Europe where it is mainly produced from sugar beat / corn / wheat (an average of 9.5 PJ p.a. The maximum estimated domestic demand for bioethanol for E10 blends is 6 PJ p.a. (in 2030), which is well under available export volumes globally. However, similar to biodiesel, these volumes would need to come from distant markets, from which New Zealand has not imported from before. Australia has been the main exporter of bioethanol for New Zealand use, although still in very small volumes. Proximity brings the benefit of lower shipping costs and the ability to engage with local producers to ensure fuels are produced sustainably. However, over the next decade, ethanol exports from Australia (where it is from starch-containing grains and agricultural residues) are expected to be small - around 1.8 PJ p.a.

Another important point is that projections are inherently uncertain. Once such uncertainty results from the competitive uses of feedstocks that can affect bioethanol production depending on the relative market prices of final products. For example, in 2020 the higher profitability of sweetener meant that the use of recoverable sugars for sugar rather than ethanol was expected to cause Brazilian ethanol output to fall (IEA, 2020). There is also the uncertainty of production yields due to climate change disruptions. In warmer climates, corn yields are expected to decline and become more variable. Because corn production is concentrated in only a few countries, simultaneous production shocks can significantly disrupt global markets (Tigchelaar, et al., 2018). Similarly, climate change can significantly disrupt sugarcane production, particularly in developing countries, due to low adaptive capacity and poor forecasting systems. Although climate change can improve sugarcane water use efficiency and cane yield, high temperatures over extended periods will reduce the amount of water available in soils, making planting increasingly difficult (Zhao & Li, 2015).

Figure 15 – Projections of global exports in bioethanol through to 2029



Source: OECD-FAO stats https://stats.oecd.org/

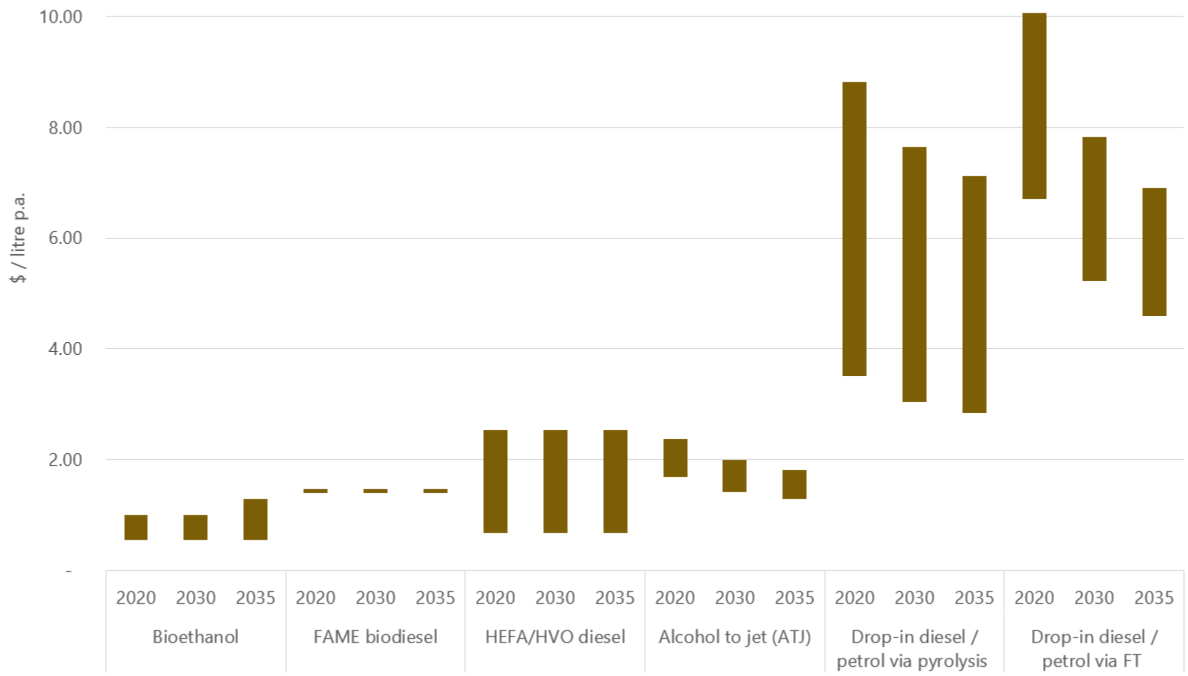
Global production of advanced biofuels is likely to expand from 2025, increasing competition for lignocellulosic feedstock

More advanced technologies based on cellulosic feedstock (e.g. crop residues, energy crops, forestry) do not currently account for a large share of global biofuel production. Over the next decade, most biofuels produced will be based on agricultural feedstock. However, global production of advanced biofuels could start to expand from 2025 (OECD-FAO, 2020), driven by technology improvements and policy incentives increasing demand for these fuels. This policy shift is particularly in response to sustainability concerns over conventional biofuels, as well as due to their limited emissions reduction potential resulting from the relatively low blending walls.

This will be driven by technology improvements and cost reductions

To a large extent, this trend will be due to the technology learning curve that will continue to reduce capital and total production costs. IRENA expects that capital cost reductions for FT synthesis will be around 3% p.a. between 2020 and 2030, and another 2% p.a. through to 2045 (see Figure 16). For pyrolysis oil upgrading, capital cost reductions are expected to be around 1% p.a. through to 2045 (IRENA, 2016). Detailed capex values are provided in Appendix J.

Figure 16 – Specific capital investment for biofuels[48]



Source: learning curves based on (IRENA, 2016). Estimates from the following sources have been adjusted to 2020 NZD - (Z Energy, 2016), (BioPacific Partners, 2020), (Wright, et al., 2010), (Zhao, et al., 2015), (CleanLeap, 2013), (Process Instrumentation, 2007).

Although the specific capital costs advanced biofuels are expected to remain significantly higher than for conventional biodiesel over the next 15 years, production costs between advanced and conventional fuels will continue to converge (Figure 18).[49] This will be due to

- improvements through learning and scaling up commercial rollout of various advanced pathways, and
- relatively cheaper feedstock for advanced biofuels from waste compared to conventional biofuels (see Figure 17).[50] This is important, because feedstock costs tend to be the greatest contributor to production costs, accounting for 40%-70% of total production costs (Appendix I).

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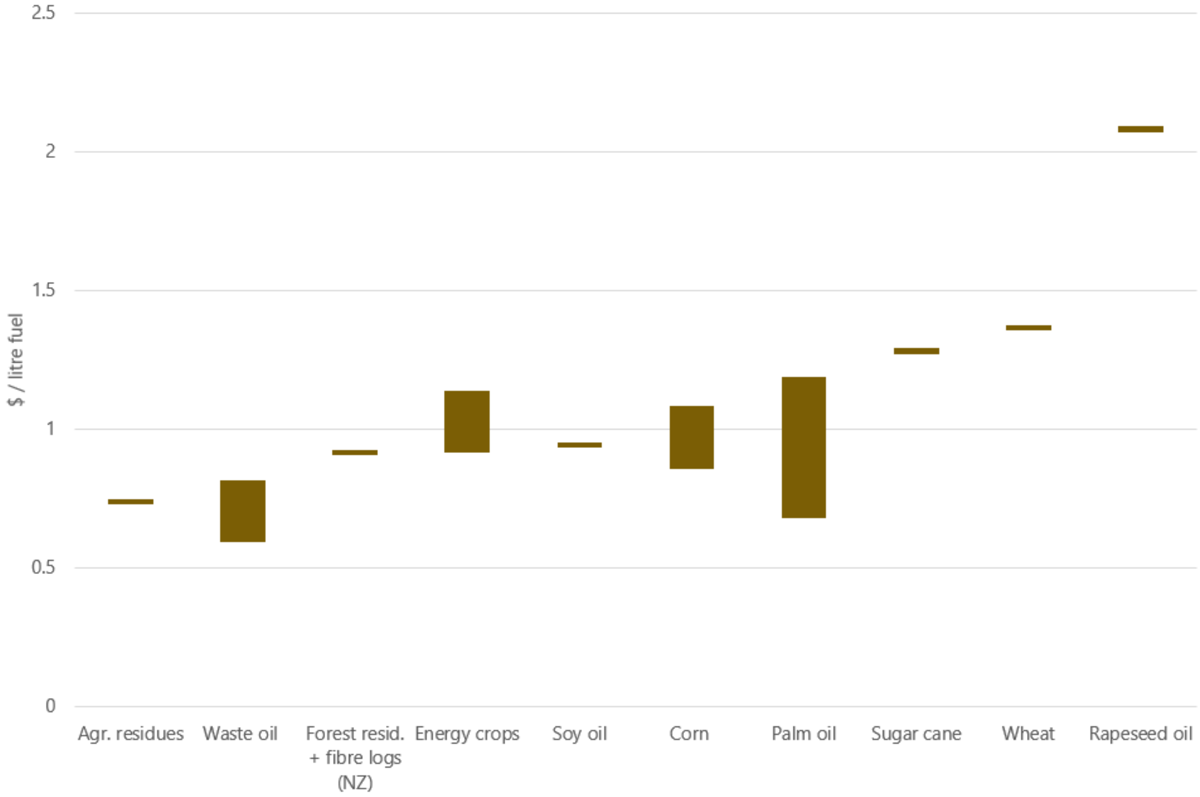
[48] Note these values are simply the ratio between investment cost and annul output. They are not the same as the capital cost component of total production cost determined over an asset's lifetime.

[49] (Festel, et al., 2013) find that some advanced biofuels can become competitive even at USD 50/bbl. IRENA however note that the competitiveness threshold is USD 100/bbl, and that under USD 80/bbl advanced biofuels are unlikely to compete with fossil fuels (IRENA, 2016).

[50] The figure shows old projection of costs – it is the relatively of different feedstock costs that is relevant here.

Figure 17 – Relative feedstock costs

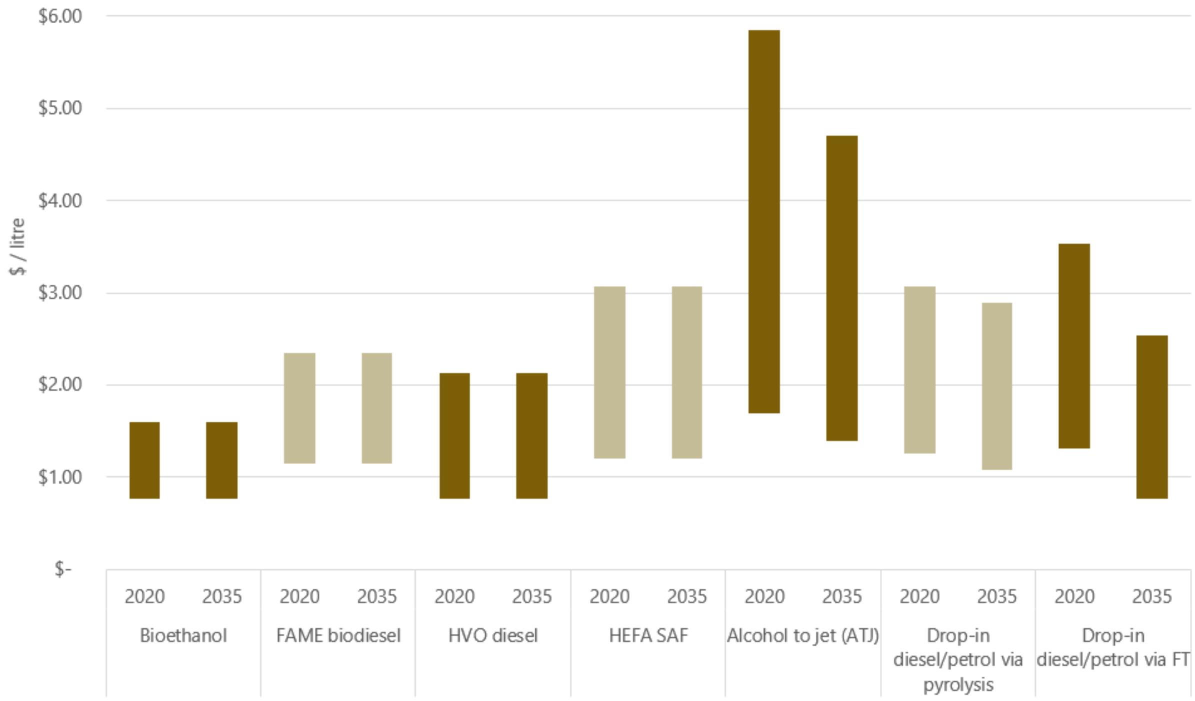


Source: (Festel, et al., 2013), (Pavlenko, et al., 2019), (Suckling, et al., 2018). For some feedstocks, a single datapoint was available.

It is also worth noting that historic price fluctuations have been higher for food feedstocks than for lignocellulosic feedstocks. For example, although soybean oil, sugar and wheat have fluctuated considerably since 2003, the same price for biomass such as hardwood log has been more stable (Appendix G). The supply of renderable animal material is not surprisingly a function of the status of the livestock industry. Consequently, it is subject to the corresponding short term seasonal-fluctuations that can also be observed from historical prices (Appendix G).

As a result of the two factors above, it is expected that the gap between total production costs of advanced and conventional biofuels will continue to narrow through to 2035 (Figure 18).

Figure 18 – Biofuel production costs



Source: (IRENA, 2016), (Pavlenko, et al., 2019), (IEA, 2017), (Maniatis, et al., 2017), (Suckling, et al., 2018)

The EU refining industry also expects a significant scale-up of advanced biofuel production, particularly from 2035, with lignocellulosic-based biofuels having a significant share of total biofuel production, increasing from 4 Mtoe in 2030 to about 75 Mtoe in 2050. The industry expects European HVO production to increase two-fold over the next decade (from 5 Mtoe to 10 Mtoe), but it will be dwarfed by lignocellulosic biofuels over the longer term.

It will also be driven by the imperative to accelerate emissions reductions from transport

IEA's Sustainable Development Scenario (SDS) outlines the major transformations that need to occur across the global energy system to achieve Sustainable Development Goals. The scenario is aligned with the Paris Agreement,[51] and provides a benchmark that can be used to assess current transformations are on track for achieving emissions reduction targets (amongst other sustainable development goals).

IEA's latest assessment is that the global biofuel production is not on track to meet its 2030 SDS target, with current levels need to almost triple over the next decade (IEA, 2020b). As mentioned previously, one of the factors explaining biofuel production shortfall in the EU and US is the blending

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[51] The SDS holds the temperature rise to below 1.8 ºC above pre-industrial levels, with a 66% probability without reliance on global net-negative CO2 emissions https://www.iea.org/reports/world-energy-model/sustainable-development-scenario

wall for conventional biofuels. Without higher biofuel blend rates or greater use of drop-in fuels, biofuel consumption is set to fall (IEA, 2020b).

Furthermore, current biofuel consumption is minimal in both aviation and international shipping. In 2018, aviation biofuel production of 15 million litres represented less than 0.01% of aviation fuel demand (IEA, 2020b). Under IEA's SDS however, biofuel consumption needs to increase to 7% and 9% of 2030 fuel demand in the aviation and shipping industry respectively.

Although the investment landscape for biofuels is challenging, policy interest remains strong particularly in

- Europe, where the Renewable Energy Directive set a 3.5% target (in terms of total energy consumed) for novel advanced biofuels by 2030. As mentioned previously, demand for advanced biofuels is supported by the double-counting rule where the energy content of these biofuels can count twice towards the member state mandates.
- The United States under the Renewable Fuel Standard and California Low-Carbon Fuel Standard, and
- India, which in 2018 pledged fiscal and investment support for advanced biofuels, with a target to develop 12 commercial-scale plants (IEA, 2020b).

Overall, there is no getting away from the fact that – due to their blend walls (even though they are increasing) – emissions reduction from conventional biofuels are (softly) capped. The EU and US are expected to lead the way in advanced biofuel production to overcome the blend limits that they have reached, which are now limiting the potential for further emissions reduction gains from biofuels.

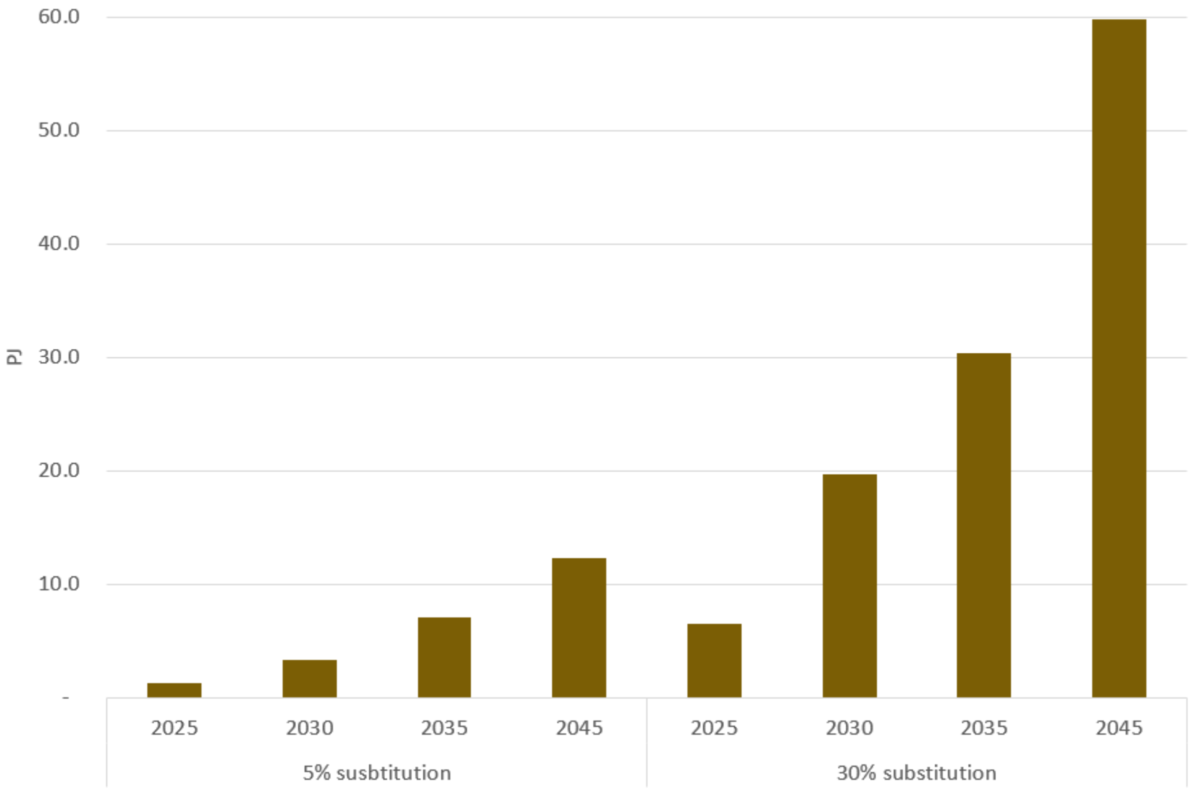
Although it is impossible to predict the rate at which the global advanced biofuel sector will expand in the second half of this decade, there are strong signals that the direction is upwards. This means that competition for advanced biofuel feedstocks will increase.

New Zealand could follow the trend of increased production of advanced biofuels from 2025, but will be exposed to global competition for biomass feedstock

Scion analysis suggests that New Zealand could have sufficient feedstock to substitute 30% of 2015 transport energy demand by 2050, with the predominant feedstocks being energy crops (if arable land is used), forest residues and fibre logs (Suckling, et al., 2018). We note that Scion's analysis abstracts from possible net trade impacts on domestically available biomass supply and final biofuel product. However it is possible that, as global competition for biomass feedstock and advanced biofuel increases, some of these could be redirected to export markets.

Figure 19 below shows the potential energy that could be produced from domestic feedstocks. These estimates are solely based on possible feedstock production rates on arable land only, i.e. fibre logs from existing, new and energy forests, as well as forest residues. Two estimates are provided: for 5% and 30% substitution by 2050 of fossil fuels consumed in 2015.

Figure 19 – Potential biofuel energy that could be produced from domestic biomass feedstocks (arable land only)



Source: Sapere analysis based on potential biofuel production volumes as per charts in (Suckling, et al., 2018), using energy conversion assumptions from Appendix E. Note that, given that biofuel volumes are extracted from charts, estimates here are approximate.

The 30% substitution scenario would require considerable output being available by 2025. However, given the technological challenges discussed previously, we think this ramp-up over the next five years is unlikely. A slow start from 2025 is more plausible. Scion's estimates of biomass resources in their 5% substation scenario suggest that there is enough feedstock available to produce around 22.1 million litres of drop-in diesel and 17.1 million of drop-in petrol in 2025.[52] From a technical perspective, this production capacity is plausible. (BioPacific Partners, 2020) note that a number of demonstration projects have already been completed for biocrude and liquid fuel production,[53] and suggest that a production capacity of 75 mlpa[54] and 57 mlpa for biocrude and liquid fuels respectively could be possible over the next 5-10 years. On this basis, we assume that Scion's estimated 2025 output in the 5% substitution scenario is possible.

Starting with 2025, we investigate two scenarios of advanced biofuel production from biomass as described below.

- The **progressive** production scenario assumes (i) an average 15% reduction in drop-in fuel production costs over this period, and (ii) a (low-end) learning curve of 5% for drop-in fuel

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[52] Note these values are approximate based on the charts in (Suckling, et al., 2018).
[53] This corresponds to TRL 8 in Figure 3
[54] mlpa = million litres per annum

conversion technologies based on (IEA Bioenergy, 2020), where this learning curve measures the production cost reduction at each doubling of cumulative production capacity. Based on the assumptions, between 2025 and 2035 output of advanced biofuels increases by a factor of 8. From 2035, output accelerates (see Figure 20). This is consistent with analysis by (FuelsEurope, 2020), which suggests that significant growth of lignocellulosic-based biofuels is expected beyond 2035 (Appendix K).

- The **accelerated** production scenario assumes that the 2035 volumes in Scion's 30% substitution scenario can be achieved from a technical perspective. These volumes imply that the output between 2025 and 2035 can increase by a factor of 23. Assuming a 5% learning curve as above, this scenario implies a production cost reduction of 21% and a doubling of capacity six times over this period. We think this is very ambitious, particularly given that a number of other factors will also affect the ramp-up, such as feedstock supply availability and lead-time required to add new infrastructure. We include this scenario to gain the following insights: (i) the upper boundary of output and (ii) the time lag between an ambitious and a more realistic scenario.

Figure 20 overlays previous estimates of potential demand for biodiesel and drop-in fuels (excl. drop-in petrol) with potential supply of these fuels in the progressive and accelerated supply scenarios. [55] The figure shows that between 2030 and 2040, assumptions on technology uptake significantly affect the extent to which local production of these drop-in fuels from biomass can satisfy demand, and as a result, the emissions reduction potential from these fuels. In the progressive scenario, it takes approximately five years longer to achieve the same cumulative emissions reductions that are achieved by 2035 in the accelerated scenario.

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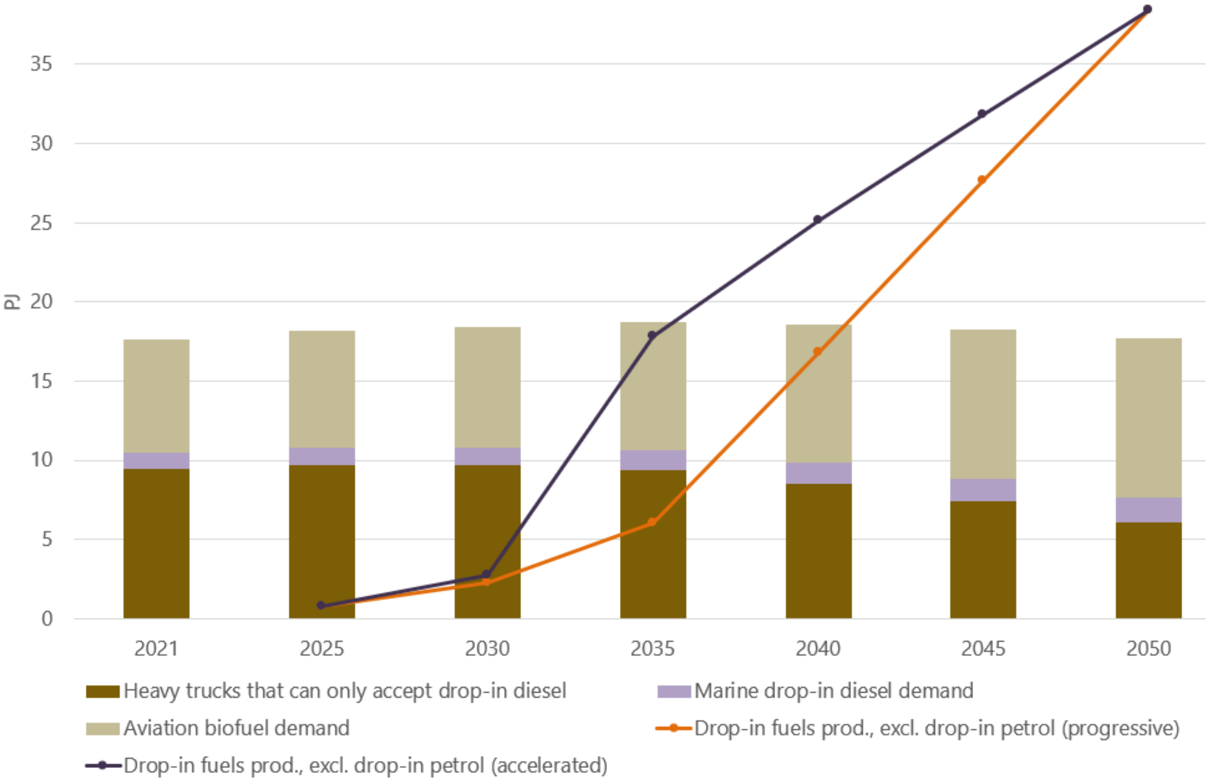
[55] It is worth noting that the supply on an energy basis was estimated based on Scion results presented in terms of million litres of drop-in petrol and drop-in diesel, and using the energy intensity conversions from Appendix E.

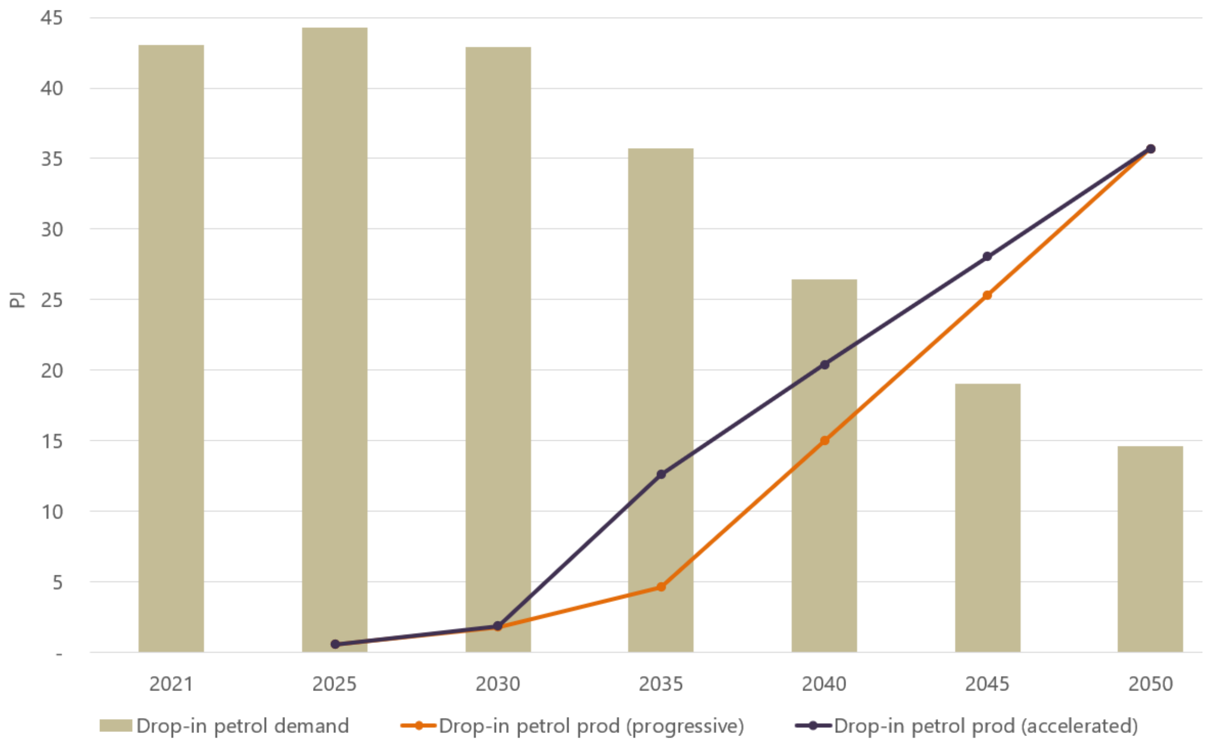
Figure 20 – Comparison of maximum drop-in fuel demand and supply volumes (excl. drop-in petrol), biomass feedstock from non-arable land



Source: Sapere analysis

The pyrolysis oil upgrade pathway produces a mix of drop-in diesel and drop-in petrol as final fuels (Suckling, et al., 2018)). The figure below overlays our estimates of potential demand for drop-in petrol with potential supply in the progressive and accelerated scenarios. The figure suggests that over the next decade, potential local production of drop-in petrol would only meet a small fraction of potential demand, with significant variation depending on assumptions on technology maturation.

Figure 21 – Comparison of maximum drop-in petrol demand and supply volumes, biomass feedstock from non-arable land



Source: Sapere analysis

What is a possible emissions reduction scenario for New Zealand?

Summary

This chapter investigates potential biofuel uptake under two scenarios: progressive and accelerated. The uptake estimates represent the intersection of demand and supply described in previous chapters, and reflect assumptions on feedstock availability, fuel compatibility and technology maturity. In reality, many other factors can affect actual uptake, the interaction of which can be complex and is not analysed here. These factors include: trade-offs among alternative fuels that could be used to de-carbonise transport, alternative uses of biofuel feedstock in other local industries, impacts from global competition on local feedstock supply, demand response to higher total ownership costs.

Scenario overview

- 2021-2025: conventional biofuels are primarily used in similar volumes in both scenarios. These comprise imported bioethanol and locally produced biodiesel from tallow. Bioethanol is only used to de-carbonise the light vehicle fleet, and is imported primarily from Australia, where it is produced from starch-containing grains and agricultural residues.
- 2025-2030: HEFA and biomass-based drop-in aviation fuels start to be used in the aviation industry in both scenarios. In the accelerated scenario, some drop-in diesel is also being used by heavy trucks. Drop-in petrol starts being used by light vehicles, but to a lesser extent in the progressive scenario.
- 2030-2035: Use of drop-in fuels gradually ramps up in the progressive scenario and scales exponentially in the accelerated scenario.
- Beyond 2035: drop-in diesel starts being used in shipping from 2035 and from 2040 in the accelerated and progressive uptake scenarios respectively. Drop-in fuel production in the progressive scenario catches up with that in the accelerated scenario beyond 2040.

Volume uptake

- Total biofuel uptake could increase from 0.88 PJ (28.38 million litres) in 2022, to 8-11 PJ (257-335 million litres) by 2030, with a maximum output beyond 2040 of 43 PJ p.a. (approx. 1280 million litres p. a.).
- The share of drop-in fuels (including renewable diesel/aviation fuel) out of total biofuels could increase from zero in 2024 to 65%-73% and 95% in 2030 and 2050 respectively.
- By 2030, drop-in fuel output could reach 167-246 million litres p.a., of which 120 -198 million litres p.a. would be from biomass feedstock.

Lifecycle emissions reductions

- Emissions reductions through to 2024 are small (-0.4% p.a. in either scenario) due to low blending limits and limited supply of conventional biofuels. By 2030, emissions reductions of 3.8%-5.4% p.a. can be achieved through increased drop-in fuel uptake (including renewable diesel/aviation fuel). Emissions savings can increase to 9%-21% p.a. by 2035, and 38% p.a. by 2050.

Capital costs

- To achieve these emissions reductions, significant capital investments would be required. Through to 2025, the average investment cost p.a. would be between $39 and $93 million in either scenario, primarily to scale-up production of biodiesel and renewable aviation fuel (HEFA). Over the 2026-2030 and 2031-2035 periods, additional investment costs of $51-$116 and $115-$254 million p.a. respectively would be required in the progressive scenario. In the accelerated scenario, the additional investments required would be double and four-times higher than the estimates in the progressive scenario over the two periods respectively. Beyond 2036, the relative trend in new capital costs is reversed between the two scenarios, such that more incremental investments are required on average per annum under the progressive scenario, as new production capacity is added.

In this section, we combine the previous analysis on potential demand and supply of biofuels, in order to develop two scenarios of biofuels uptake in NZ transport. In developing the scenario, we make the following assumptions:

- A maximum of 40 million litres (1.34 PPJ) of biodiesel can be produced from local tallow feedstock,[56] and another 500,000 litres of biodiesel is produced from used cooking oil. Biodiesel is used in marine (up to B5) and heavy trucks (B5, B7, B20 and B30).
- Residual tallow feedstock is used to produce HEFA for aviation (, so that a maximum of 80% of total tallow supply is used for biofuel production. It is blended at 50%.
- Most of bioethanol demand is met by imports from 2030 (only 0.13 PJ are produced locally). Imports are from Australia and represent 50% of Australia's exports of 1.8 PJ. Import volumes are gradually scaled up starting with 2022. Bioethanol feedstocks are dominated by corn and agricultural residues. Biofuels from these crops can deliver an average of 44% reduction in emissions for neat fuels on a lifecycle basis, or 4.4% for E10 fuels.
- Biomass drop-in fuels are blended at a 50% limit, and are used in all modes of transport to meet residual demand (i.e. net of demand for conventional biofuels and renewable diesel). On a lifecycle basis, the emissions reduction potential for neat drop-in fuels is 78%, or 39% for the final fuel with a 50% blend.
- As more drop-in diesel is being produced, biodiesel is phased-out as follows:
  - Progressive scenario: complete phase-out takes places in 2035 and 2040 for heavy trucks and shipping respectively.
  - Accelerated scenario: complete phase-out takes place in 2035 for both heavy trucks and shipping.

The resulting uptake volumes are shown in Figure 22 and Figure 23 for the progressive and accelerated scenarios (see Appendix P for data tables). Key findings:

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[56] This reflects the capacity at which Z Energy's biodiesel plant could be easily scaled up.

- In the progressive scenario, total biofuel uptake increases from 0.88 PJ (28.38 million litres) p.a. in 2022 to 8.06 (256.5 million litres) p.a. by 2030, reaching a maximum output of 43.14 PJ (1,287.2 million litres) p.a. by 2043. The share of drop-in fuels (including renewable diesel/aviation fuel) out of total biofuels increases from zero in 2024 to 65% and 95% in 2030 and 2050 respectively. In 2030, drop-in fuel output is 166.85 million litres, of which 120 million litres (72%) are from biomass feedstock.
- In the accelerated scenario, total biofuel uptake increases from 0.88 PJ (28.38 million litres) p.a. in 2022 to 10.74 PJ p.a. (335 million litres) p.a. by 2030, reaching a maximum output of 42.54 PJ (1,270 million litres) p.a. by 2040. The share of drop-in fuels (including renewable diesel/aviation fuel) out of total biofuels increases from zero in 2024 to 73% and 96% in 2030 and 2050 respectively, In 2030, drop-in fuel output (including renewable diesel/aviation fuel) is 245.52 million litres, of which 198 million litres (80%) are from biomass feedstock.
- Output reduction beyond 2040 reflects declining demand from road transport due to increased electrification, particular of light vehicles.

Figure 22 – Domestic uptake scenario for biofuels (progressive)

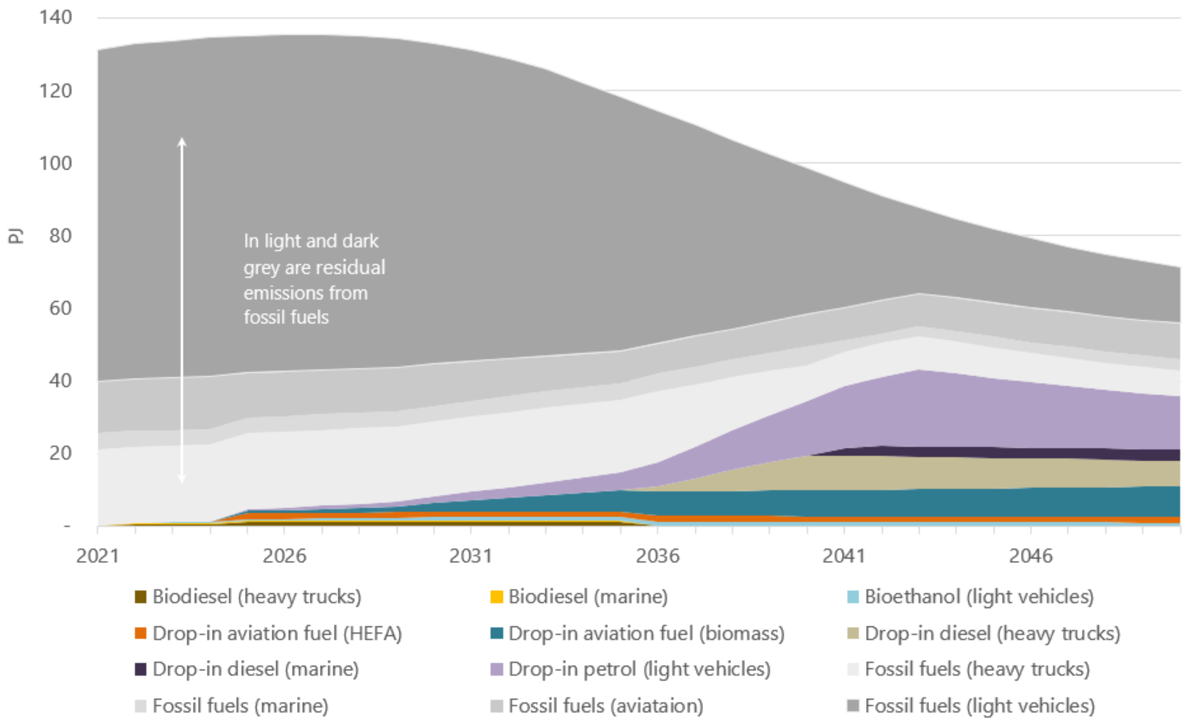
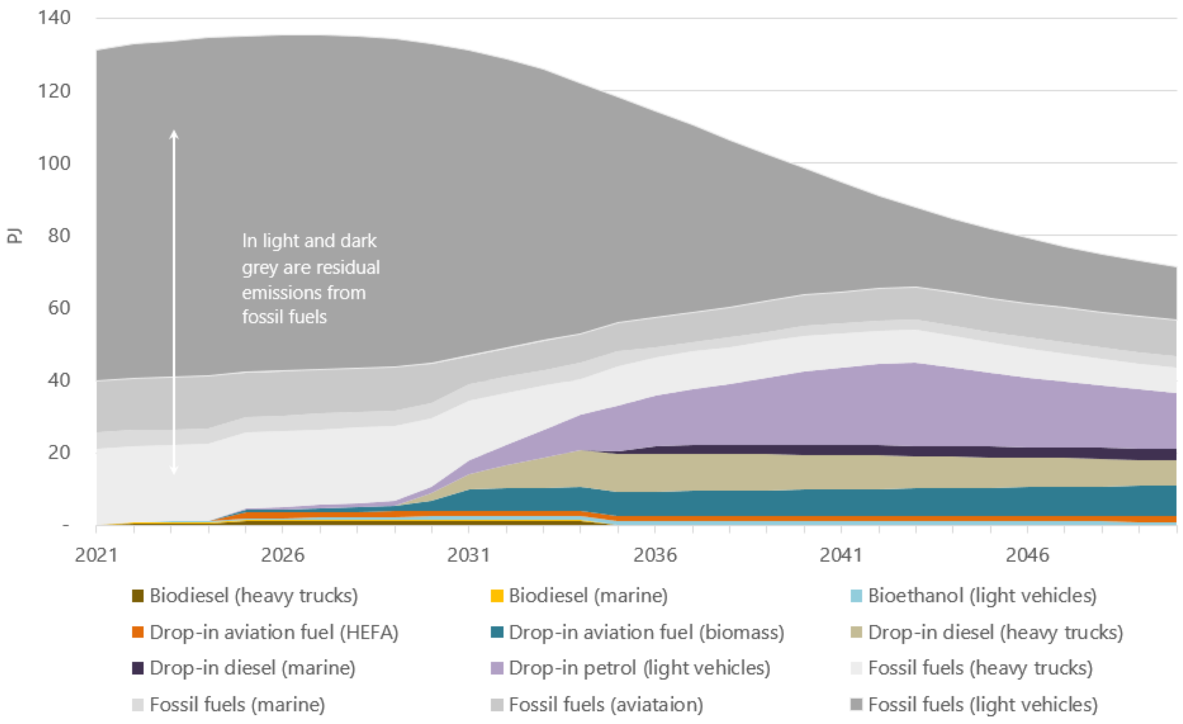


Figure 23 – Domestic uptake scenario for biofuels (accelerated)



Source: Sapere analysis

Figure 24 and Figure 25 illustrate the emissions reduction potential associated with the progressive and accelerated uptake scenarios respectively. Detailed emissions reduction value in ktCO2e are presented in Appendix Q. Figure 26 provides a summary.

We find that the emissions reduction potential over the next five year is small in either scenario: -2% p.a. in 2025 compared to fossil fuel consumption by light vehicles, heavy diesel trucks, domestic navigation and aviation taken all together. This is mainly due to the blending walls applied to conventional biofuels which dominate biofuels uptake through to 2040. By 2030, annual emissions reductions increase to -3.8% and -5.4% p.a. in the progressive and accelerated scenarios respectively. This is due to increased HEFA production for aviation and growing uptake of domestically produced drop-in fuels from biomass. As drop-in fuels uptake continues to grow, annual emissions savings reach 8.6% in 2035 and 26.6% in 2040 in the progressive scenario, and 21% in 2035 and 33% in 2040 in the accelerated scenario. By 2050, annual emissions savings in both scenarios converge to 38%. Most of the emissions reduction is from the use of drop-in petrol for light vehicles, followed by drop-in diesel used for heavy trucks and aviation.

Figure 26 shows that in terms of absolute emissions reductions (in ktCO2e), the progressive uptake scenario lags behind the accelerated uptake scenario by about 5 years. The scenarios start to converge after 2040 for two main reasons (i) convergence of technology maturity in both scenarios, and (ii) lower demand for drop-in petrol from light vehicles due to their increased electrification.

We note that the estimates for emissions reduction from drop-in fuels are based on a concentration limit of 50% for drop-in fuels. However, it is likely that as new engines and fuel standards are developed, this limit will be increased or lifted for more uses over the next decade. This means that the emissions reduction potential could even greater.

Figure 24 – Annual lifecycle emissions reduction potential in the progressive uptake scenario

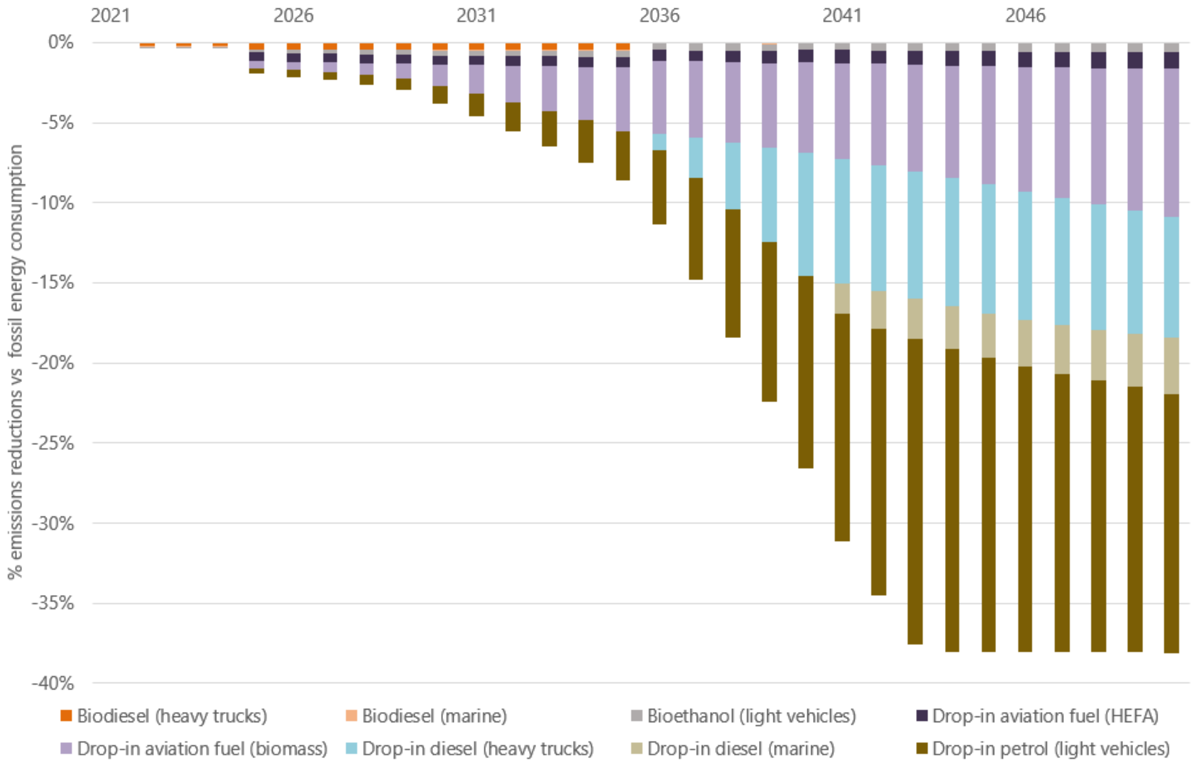
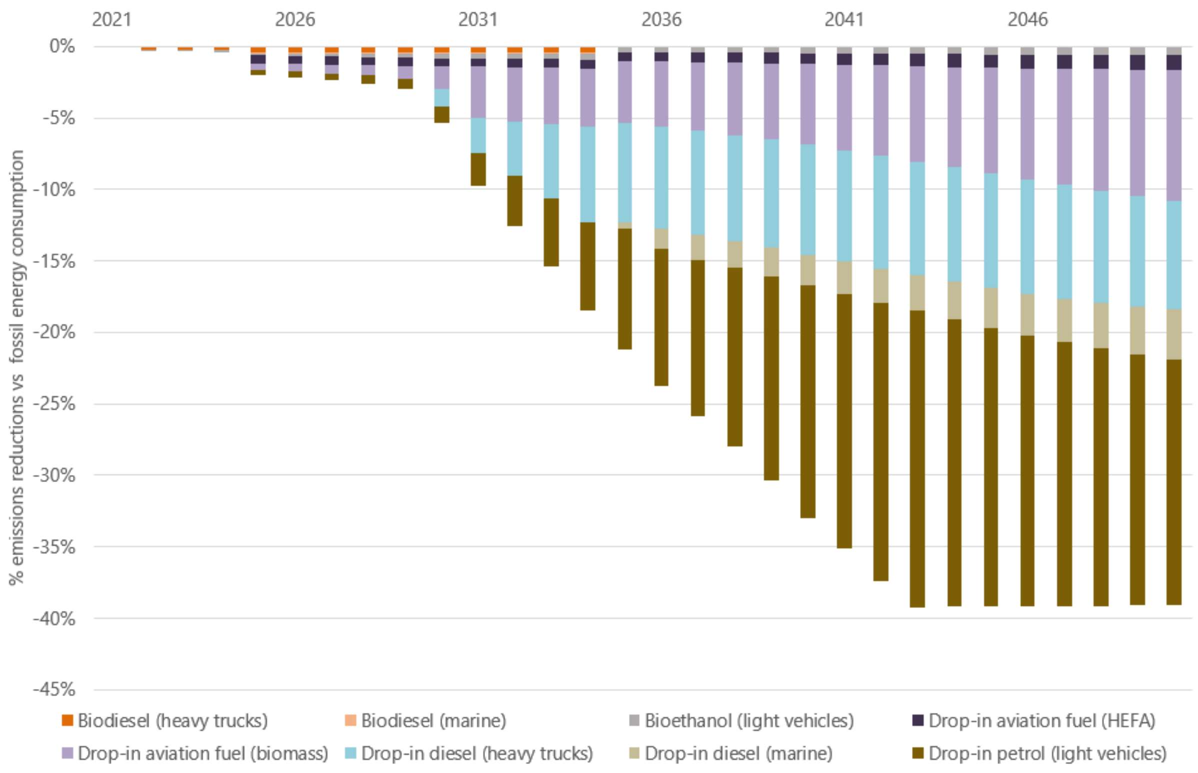
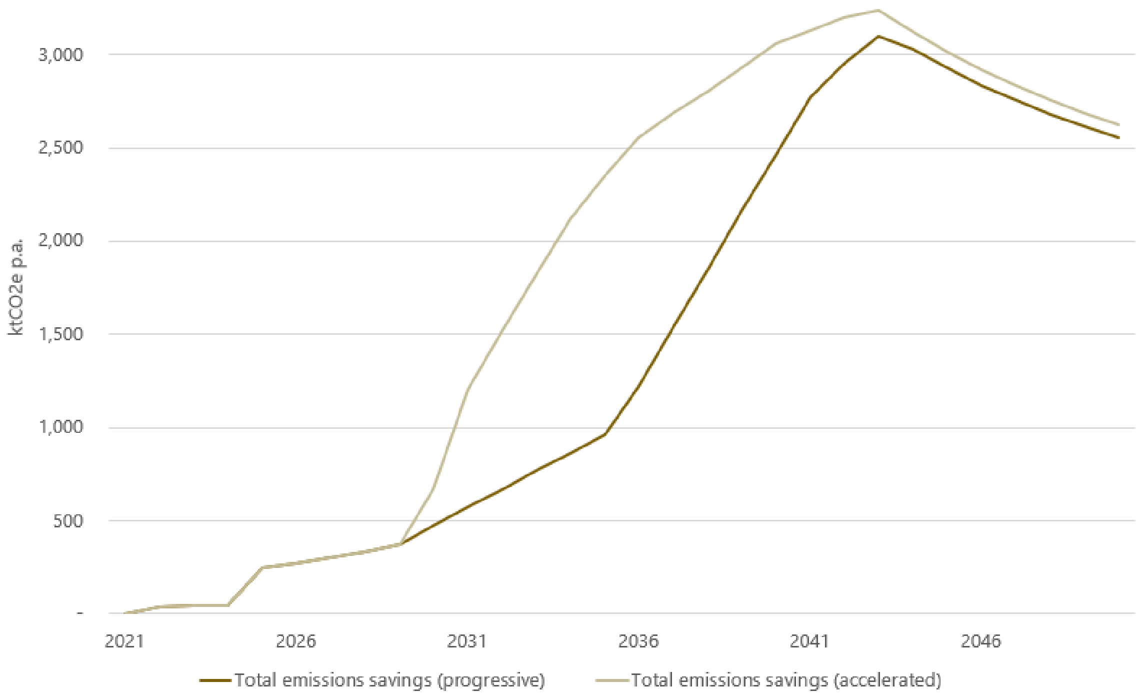


Figure 25 – Annual lifecycle emissions reduction potential in the accelerated uptake scenario



Source: Sapere analysis

Figure 26 – Comparison of annual lifecycle emissions reductions in progressive and accelerated scenarios

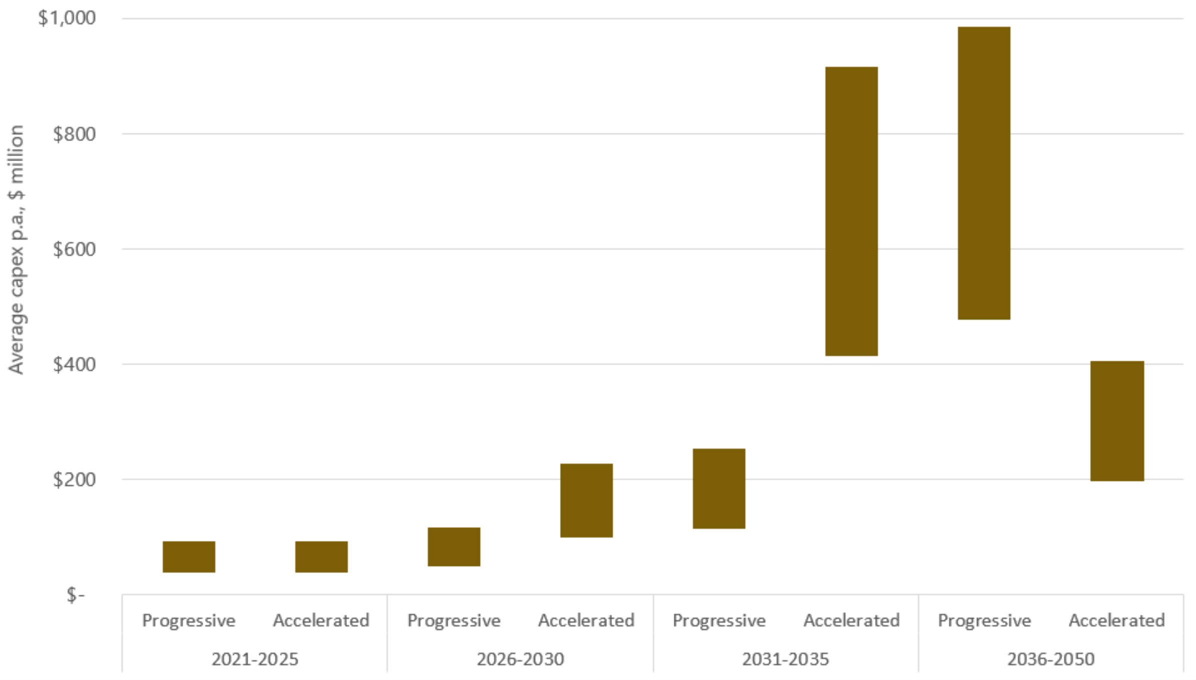


Source: Sapere analysis

To achieve these emissions reductions, significant capital investments would need to be made in either scenario. Table 1 and Table 2 provide the estimates based on minimum and maximum capital cost values observed in the literature, accounting for the technology learning curves for advanced biofuels through to 2035. The detailed capital costs are provided in Appendix J. The table shows that the average investment cost required over the next five years is similar between the two scenarios, between $39-$93 million p.a. primarily to scale-up production of biodiesel and renewable aviation fuel (HEFA).

Between 2026 and 2035, the capital investments that would be required under the accelerated scenario are much higher than those under the progressive uptake scenario, reflecting an accelerated production scale-up. Over the 2026-2030 and 2031-2035 periods, the average annual investments under the accelerated scenario are double and four-times larger than those under the progressive scenario over the respective periods. Beyond 2036, the relative trend in new capital investment reversed, with more incremental capital costs required on average per annum under the progressive scenario, as new production capacity is added.

Figure 27 – Average capex p.a. in the progressive and accelerated uptakes scenarios



Source: Sapere analysis

Table 1 – Capital costs required to achieve the domestic uptake scenario (undiscounted $ million), progressive uptake scenario

Fuel produced		**2021-2025**		**2026-2030**		**2031-2035**		**2036-2050**	
		Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**max**
Biodiesel	Total in period	$31	$34						

Fuel produced		**2021-2025**		**2026-2030**		**2031-2035**		**2036-2050**	
		Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**max**
	Avg. p.a.	$6	$7						
HEFA	Total in period	$32	$120						
	Avg. p.a.	$6	$24						
Drop-in fuels (biomass)	Total in period	$130	$313	$253	$582	$576	$1,269	$2,390	$4,924
	Avg. p.a.	$26	$63	$51	$116	$115	$254	$478	$985
Total fuels	**Total in period**	**$194**	**$467**	**$253**	**$582**	**$576**	**$1,269**	**$2,390**	**$4,924**
	Avg. p.a.	**$39**	**$93**	**$51**	**$116**	**$115**	**$254**	**$478**	**$985**

Table 2 – Capital costs required to achieve the domestic uptake scenario (undiscounted $ million), accelerated uptake scenario

Fuel produced		**2021-2025**		**2026-2030**		**2031-2035**		**2036-2050**	
		Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**max**
Biodiesel	Total in period	$31	$34						
	Avg. p.a.	$6	$7						
HEFA	Total in period	$32	$120						
	Avg. p.a.	$6	$24						
Drop-in fuels (biomass)	Total in period	$130	$313	$496	$1,135	$2,073	$4,577	$982	$2,033
	Avg. p.a.	$26	$63	$99	$227	$415	$915	$196	407
Total fuels	**Total in period**	**$194**	**$467**	**$496**	**$1,135**	**$2,073**	**$4,577**	**$982**	**$2,033**
	Avg. p.a.	**$39**	**$93**	**$99**	**$227**	**$415**	**$915**	**$196**	**$407**

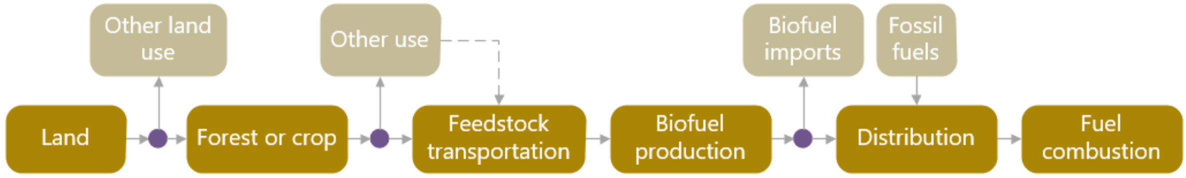
Source: Sapere analysis

What key issues emerge when the full biofuel chain value is considered?

- Biofuel supply chains are complex, and require integration across the agricultural/forestry, biofuel and conventional oil supply chain. The feedstock, conversion process, final fuel specifications, and the engines envisioned for transportation are highly interdependent and must be considered as a system. Furthermore, the different demands of the customers, engine manufacturers and energy companies must be aligned. All of these issues require clear policy direction.
- In New Zealand, there are also opportunities for biofuel production to replace existing uses of land, particularly where farming is economically challenging. However, demand for biomass for transport biofuel production is likely to compete with biomass demand from other sectors, e.g. process heat.
- For advanced biofuels, it could make sense to have a distributed network of processing plants located closer to where the feedstock is grown, with the high-density intermediate being subsequently transported to more centralised plants for conversion into final fuels (Suckling, et al., 2018).
- In terms of fuel distribution, biodiesel and bioethanol need separate infrastructure for blending and transport to retail points. Drop-in fuels could be used with the existing petroleum infrastructure.

Biofuel supply chains can be significantly more complex than those for conventional diesel as they require integration across the agricultural/forestry, biofuel and conventional oil supply chain.

Figure 28 – Biofuel value chain



Source: based on (Suckling, et al., 2018)

Figure 28 shows that other land and other feedstock uses are the first two checkpoints along the biofuel value chain. In New Zealand, opportunities exist for biofuel production to replace existing uses of land, particularly where farming is economically challenging. For example, dry-stock land owners in the relatively inexpensive and flat lands of the East Coast and Northland have been looking for more profitable alternativities to sheep and cattle (Suckling, et al., 2018). However, demand for biomass for transport biofuel production is likely to also compete with biomass demand from other sectors, particularly where such feedstock already has existing uses. For example, the pulp and paper and panel-board industries could be significantly affected in the near term if fibre logs are diverted away from these industries where it is used as primary energy.[57]

There will also be competition for agricultural and forest residues that could otherwise be used to de-carbonise process heat. Scion estimated that, overall for New Zealand, the energy potential of 18.8 PJ from biomass residues falls short of the total demand for coal used for process heat, which was 24 PJ in 2016 (Hall, 2017). However, the balance between biomass supply and coal demand varies widely across regions. For example, the East Coast has a substantial wood residue resource and almost no coal demand. By contrast, Waikato's coal demand is well in excess of its residual biomass supply. Although there is potential for regional movements to correct for these imbalances, there will be cases where biomass for process heat will be uneconomic due to long transport distances for biomass. Such cases could lend themselves to transport biofuel production.

For advanced biofuels, production plants can be on a much smaller scale, often nearer feedstock supply points. Scion's 2018 biofuels roadmap states that it may make economic sense to do the initial stages of biomass processing (such as drying, pelletising or pyrolysis) at smaller plants located close to where the feedstock is grown. The higher-density intermediate would then be transported to a larger centralised plant for conversion into the final fuel. Of course, the resulting transport cost savings would need to be balanced against the additional processing costs, and the extent to which economies of scale can reduce conversion costs by building larger plants (Suckling, et al., 2018).

Another issue is the production of hydrogen that is required for advanced biofuel pathways. Although hydrogen can be generated from the biomass feedstock itself, the process is inefficient compared to sourcing hydrogen from an external source. The hydrogen requirement represents a large proportion of both capital and operating expenses in a stand-alone facility. (Jones, et al., 2009) estimated that sourcing hydrogen from an oil refinery can reduce the capex and opex of a pyrolysis drop-in fuel by 40% and 15% respectively. Hydrogen is also required for gasification processes to enrich the syngas. Although hydrogen is typically produced from the syngas itself by a process known as the "water-gas shift" reaction, this reaction consumes feedstock carbon, reducing the biomass-to-fuel yields. An alternative option would be to obtain hydrogen from an external source.

As well as potential hydrogen supply, the refinery's role along the biofuel value chain could also include co-processing of biocrudes. However, this has significant technical challenges particularly for high proportions of biocrudes, including due to the high acidity and water content of these products. Another issue is that co-processing would require adapting the catalyst design, which is yet to be commercially proven (Karatzos, et al., 2014). Nevertheless, globally refineries has shown increasing interest in oil upgrading pathways, and the co-processing of biocrude along with fossil-based crude is being actively considered (BioPacific Partners, 2020).

The discussions above clearly indicate that introducing biofuels intro transportation supply chains requires decisions over where and how existing infrastructure and biofuel supply chains can join (e.g. at refinery, marine terminal, inland depot, retail points). The feedstock, conversion process, final fuel

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[57] Over the long-term, the nature of primary energy inputs in the industry will reflect the way in which the industry responds to changes in consumer preference, e.g. switch to more bio-degradable options, increased paper recycling etc.

specifications, and the engines envisioned for transportation are highly interdependent and must be considered as a system if an optimal process is to be identified. Accurate feedstock characterization (including both composition and variability) is essential given that this is an upstream boundary condition for the entire subsequent fuel-conversion process (Sandia National Laboratories, 2009).[58]

For bioethanol and biodiesel in particular, integration into existing distribution infrastructure is problematic due to the unfavourable chemical properties of these fuels as discussed previously. They need to be blended through separate distribution channels, and transported via trucks or ships instead of existing pipelines. Before introducing or scaling-up the use of these fuels, existing systems must be checked in terms of construction materials, their interfaces (for corrosion), and glands seals and valves.[59]

Existing fossil fuel distributors already have a substantial distribution infrastructure, so it would make sense to use this for drop-in biodiesel distribution. A potentially attractive way to transport these fuels would be to use existing coastal shipping network and fuel distribution terminals, as well as rail transport in some cases.

A final important checkpoint along the value chain is the intersection of demands by the customer, original equipment manufacturers and fuel suppliers (Table 3).

Table 3 – Requirements and concerns of customers, original equipment manufacturers and fuel suppliers

Customer demands	**OEM demands**	**Fuel supplier demands**
Performance	Competitive, yet profitable	Fungibility
Fuel economy	Emissions criteria	Feedstock availability
Fuel and vehicle cost	Fuel economy standards	End-product stability
Reliability	Customer satisfaction	Transportation and pipeline issues
Fuel availability	Service intervals	
Fuel odour	Warrantee issues	
Convenience		

Source: (Sandia National Laboratories, 2009)

Current vehicles are highly optimised systems, and they need to meet simultaneous requirements. Customers demand performance, fuel economy and affordability. Engine manufacturers must provide for long-service intervals and warranties. Fuel suppliers must deliver fungible fuels that comply with existing standards. Aligning these demands does not happen overnight. They require clear policy direction and regulatory support to influence consumer choices, promote OEM innovation, attract state-of-the-art technology, and allow fuel suppliers to prepare for a shift in the market.

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[58] https://www.liquidbiofuels.org.nz/documents/resource/Report-BioFuels7-19V5.pdf

[59] Mild and stainless steel, aluminium, Teflon and fibreglass are all considered acceptable materials of construction for handling biofuels, whereas copper, bronze, tin and zinc may lead to corrosion and sedimentation.

References

Baldino, C., 2019. *Kein cap? There's more than meets the eye with the EU's waste fats and oils limits.* [Online]
Available at: https://theicct.org/blog/staff/eu-alternative-fuels-oils-limit-20191119
[Accessed 20 January 2021].

Bioenergy Association, 2019. *Greenhouse gas emissions reductions from transport biofuels,* s.l.: s.n.

BioPacific Partners, 2020. *Wood fibre futures. Investment in the use of commercial forest biomass to move New Zealand towards carbon zero. Stage one report,* s.l.: s.n.

BNEF, 2020b. *The outlook for the world's largest biofuels market.* [Online]
Available at: https://about.bnef.com/blog/the-outlook-for-the-worlds-largest-biofuels-market/#:~:text=The%20U.S.%20is%20the%20world's,in%20the%20U.S.%20is%20biofuel.&text=BloombergNEF's%20'2020%20Road%20Fuel%20Outlook,demand%20will%20peak%20in%202023

BNEF, 2020. *Oil demand from road transport: Covid-19 and beyond.* [Online]
Available at: https://about.bnef.com/blog/oil-demand-from-road-transport-covid-19-and-beyond/

Bonomo, A. K. B. C., Chagas, M. F. & Souza, N. R. D., 2018. *Comparison of biofuel life cycle analysis tools. Phase 2, Part 1: FAME and HVO/HEFA,* s.l.: s.n.

Bunting, B., Bunce, M., Barone, T. & Storey, J., 2010. *Fungible and compatible biofuels: Literature search, summary, and recommendations,* s.l.: s.n.

Camia, A. et al., 2018. *Biomass production, supply, uses and flows in the European Union. First results from an integrated assessment,* s.l.: s.n.

CleanLeap, 2013. *Conventional bioethanol production costs.* [Online]
Available at: https://cleanleap.com/4-bioethanol/42-conventional-bioethanol-production-costs
[Accessed 4 February 2021].

Concept, 2019. *Hydrogen in New Zealand. Report 2 - Analysis,* s.l.: s.n.

Curry, R. B. et al., 1995. *Response of soybean to predicted climate change in the USA,* s.l.: s.n.

DCL, 2014. *E20/25 Technical Development Study. Task 1: Review of E20/25 parameters and test methods,* s.l.: s.n.

de Pont, J., 2006. *Enabling biofuels. Risks to vehicles and other engines,* s.l.: s.n.

Dunn, J. B., Han, J., Seabra, J. & Wang, M., 2017. Biofuel life-cycle analysis. In: *Handbook of bioenergy economics and policy: Volume II.* s.l.:s.n.

Ecofys et al., 2015. *The land use change impact of biofuels consumed in the EU,* s.l.: s.n.

European Commission, 2019. *Report from the Commission to the European Parliament, the Council, the European Economic and Social Committe and the Committe of the Regions on the status of production expansion of relevant food and feed crops worldwide,* s.l.: s.n.

Feddern, V., n.d. *Animal fat wastes for biodiesel production.* [Online]
Available at: https://core.ac.uk/download/pdf/45498488.pdf

Festel, G., Wurmsher, C. R., Boles, E. & Bellof, M., 2013. *Modelling production cost scenarios for biofuels and fossil fuels in Europe,* s.l.: s.n.

Flach, B., Lieberz, S. & Bolla, S., 2019. *EU BIofuels Annual. GAIN Report Number NL9022,* s.l.: s.n.

FuelsEurope, 2020. *Clean fuels for all. EU refining industry proposes a potential pathway to climate neutrality by 2050,* s.l.: s.n.

Gull, 2020b. *Gull Force Pro no longer available.* [Online]
Available at: https://gull.nz/fuel/force-pro/
[Accessed 4 February 2021].

Gull, 2020. *Gull Diesel Max no longer available,* s.l.: s.n.

Hall, P., 2017. *Residual biomass fuel projections for New Zealand.,* s.l.: s.n.

Hanson, S. & Agarwal, N., 2018. *Biodiesels produced from certain feedstock have distinct properties from petroleum diesel.* [Online]
Available at: https://www.eia.gov/todayinenergy/detail.php?id=36052

Haobo, W., McGlinchy, I. & Samuelson, R., 2019. *Real-world fuel economy of heavy trucks,* s.l.: s.n.

Hoefnagels, R., Smeets, E. & Faaij, A., 2010. Greenhouse gas footprints of different biofuel production systems. *Renewable and Sustainable Energy Reviews,* Volume 14, pp. 1661-1694.

Horizon Magazine, 2020. *Why raising the alcohol content of Europe's fuels could reduce carbon emissions.* [Online]
Available at: https://horizon-magazine.eu/article/why-raising-alcohol-content-europe-s-fuels-could-reduce-carbon-emissions.html
[Accessed 2021 February 2021].

IATA, 2020. *Sustainable aviation fuel: Technical certification,* s.l.: s.n.

ICAO, 2018. *Sustainable aviaton fuels guide.* [Online].

ICAO, 2020. *Conversion processes.* [Online]
Available at: https://www.icao.int/environmental-protection/GFAAF/Pages/Conversion-processes.aspx
[Accessed 18 January 2021].

ICCT, 2019. *The cost of supporting alternative jet fuels in the European Union,* s.l.: s.n.

IEA Bioenergy, 2017. *Biofuels for the maring shipping sector,* s.l.: s.n.

IEA Bioenergy, 2020. *Advanced biofuels - potential for cost reduction. Task 41,* s.l.: s.n.

IEA, 2017. *Biofuel and fossil-based transport fuel production cost comparison.* [Online]
Available at: https://www.iea.org/data-and-statistics/charts/biofuel-and-fossil-based-transport-fuel-production-cost-comparison-2017

IEA, 2019. *Are aviation biofuels ready for take off?.* [Online]
Available at: https://www.iea.org/commentaries/are-aviation-biofuels-ready-for-take-off

IEA, 2020b. *Transport biofuels.* [Online]
Available at: https://www.iea.org/reports/transport-biofuels
[Accessed 2 February 2021].

IEA, 2020. *Renewables 2020. Transport biofuels,* s.l.: s.n.

IEA-AMF, 2020. *Fuel information: Fatty acid esters (biodiesel): Compatibility.* [Online]
Available at: https://www.iea-amf.org/content/fuel_information/fatty_acid_esters/compatibility

IEA-AMF, 2021a. *Fuel information: Bio/synthetic diesel (paraffins): Properties.* [Online]
Available at: https://www.iea-amf.org/content/fuel_information/paraffins/properties
[Accessed 1 February 2021].

IEA-AMF, 2021b. *Fuel information: Bio/synthetic diesel (paraffins): Compatibility.* [Online]
Available at: https://www.iea-amf.org/content/fuel_information/paraffins/compatibility
[Accessed 1 February 2021].

IPCC, 2006. *IPCC Guidelines for National Greenhouse Gas Inventories; IPCC National Greenhouse Inventories Programme; published by the Institute for Global Environmental Strategies (IGES),* s.l.: s.n.

IRENA, 2013. *Road transport: The cost of renewable solutions,* s.l.: s.n.

IRENA, 2016. *Innovation outlook: Advanced liquid biofuels,* s.l.: s.n.

Jones, S. B. et al., 2009. *Production of gasoline and diesel from biomass via fast pyrolysis, hydrotrerating and hydrocracking: A design case.* [Online].

Karatzos, S., McMillan, J. D. & Saddles, N., 2014. *The potential and challenges of drop-in biofuels,* s.l.: s.n.

Mallins, C., 2017. *Waste not want not. Understanding the greenhouse gas implications of diverting waste and residual materials to biofuel production,* s.l.: s.n.

Maniatis, K. et al., 2017. *Building up the future,* s.l.: s.n.

MBIE, 2020. *Renewables statistics,* s.l.: s.n.

Meat Industry Association, 2020. *Industry fact sheet - Co-products.* [Online]
Available at: https://www.mia.co.nz/assets/Uploads/Co-Products-Fact-Sheet.pdf

MfE, 2020. *Marginal abatement cost curves analysis for New Zealand,* s.l.: s.n.

MIA, 2020a. *Engine manufacturer indicated compatibility of light vehicles,* s.l.: s.n.

MIA, 2020b. *Engine manufacturer indicated compatibility of heavy vehicles - 30 June 2020,* s.l.: s.n.

MIA, 2020. *Engine manufacturer indicated compatibility of heavy vehicles - 30 June 2020,* s.l.: s.n.

MIA, 2021. *Ethanol blended fuels - suitability.* [Online]
Available at: https://www.mia.org.nz/Documents

MoT, 2017. *New Zealand transport outlook: Future state,* s.l.: s.n.

MoT, 2020. *Green freight. Strategic Working paper,* s.l.: s.n.

Neste, 2020. *Neste renewable diesel handbook,* s.l.: s.n.

NZ Biojet Consortium, 2019. *The sustainable aviation fuel opportunity for New Zealand,* s.l.: s.n.

NZ Government, 2016. *Managing New Zealand's international and domestic aviation emissions,* s.l.: s.n.

O'Connor, D., 2013. *Advanced biofuels - GHG emissions and energy balances,* s.l.: s.n.

OECD-FAO, 2020. *Agricultural Outlook 2020-2029,* s.l.: s.n.

Pavlenko, N., Searle, S. & Christensen, A., 2019. *The cost of supporting alternative jet fuels in the European Union,* s.l.: s.n.

PCE, 2010. *Some biofuels are better than others: Thinking strategically about biofuels,* s.l.: s.n.

Process Instrumentation, 2007. *Ethanol plant construction costs are on the rise.* [Online]
Available at: https://www.piprocessinstrumentation.com/home/article/15551961/ethanol-plant-construct-costs-are-on-the-rise#:~:text=The%20study%20says%20while%20just,meaning%20the%20same%20100%20million
[Accessed 4 February 2021].

Prussi, M. et al., 2020c. *JEC Well-to-Tank report v5: Annexes,* s.l.: s.n.

REN21, 2020. *Renewables 2020. Global Status Report,* s.l.: s.n.

Rural Delivery, 2016. *Green Fuels biodiesel.* [Online]
Available at: https://www.ruraldelivery.net.nz/stories/Green-Fuels-Biodiesel
[Accessed 2 February 2021].

Rusco, F., 2012. *Biofuels infrastructure in the United States: Current status and future challenges,* s.l.: s.n.

Sandia National Laboratories, 2009. *Next generation biofuels and advanced engines for tomorrow's transportation needs. A HITEC Workshop,* s.l.: s.n.

Scion, 2009. *Bioenergy options for New Zealand. Analysis of large-scale bioenergy from forestry. Productivity, land use and environmental and economic implications,* s.l.: s.n.

Searle, S., Pavlenko, N., El Takriti, S. & Bitnere, K., 2017. *Potential greenhouse gas savings from a 2030 greenhouse gas reduction target with indirect emissions accounting for the European Union,* s.l.: s.n.

Suckling, I. D. et al., 2018. *NZ Biofuels Roadmap Technical Report,* s.l.: s.n.

Tigchelaar, M., Battisti, D. S., Naylor, R. L. & Ray, D. K., 2018. *Future warming increases probabilty of globally synchronised maise production shocks,* s.l.: s.n.

Transport & Environment, 2016. *Globiom: the basis for biofuel policy post-2020,* s.l.: s.n.

Transport & Environment, 2020. *RED II and advanced biofuels,* s.l.: s.n.

Trench, C. J., 2001. *How pipelines make the oil market work - Their networks, operation and regulation,* s.l.: s.n.

US EIA, 2019. *International Energy Outlook* , s.l.: s.n.

Valin, H. et al., 2015. *The land use change impact of biofuel consumed in the EU. Quantification of area and greenhouse gas impacts.,* s.l.: s.n.

WEC, 2020. *Clean skies for tomorrow. Sustainable aviation fuels as a pathway to net-zero aviation,* s.l.: s.n.

Wood Mackenzie, 2010. *Impact of the use of biofuels on oil refining and fuels specifications,* s.l.: s.n.

Wright, M. M., Satrio, J. A. B. R. C., Daugaard, D. E. & Hsu, D. D., 2010. *Techno-economic analysis of biomass fast pyrolysis to transportation fuels,* s.l.: s.n.

WWFC, 2019. *Worldwide fuel charter. Gasoline and diesel fuel,* s.l.: s.n.

Z Energy, 2016. *The Z biodiesel plant,* s.l.: s.n.

Z Energy, 2020. *Annual Report,* s.l.: s.n.

Zhao, D. & Li, Y. R., 2015. Climate change and sugarcane production: Potential impact and mitigation strategies. *International Journal of Agronomy,* Volume 2015.

Zhao, L. et al., 2015. Techno-economic analysis of bioethanol production from lignocellulosic biomass in China: Dilute-acid pretreatment and enzymatic hydrolysis of corn stove. *Energies,* Volume 8, pp. 4096-2117.

Appendix A Defining conventional vs advanced biofuels

Transport biofuels typically refer to liquid and gaseous fuels produced from biomass, and are commonly classified as conventional or advanced biofuels. Although there are generally four factors by which biofuels are determined as conventional or advanced, there is no standard definition that covers all these aspects, leading to differences in definitions (IRENA, 2016). These factors are:

- Conversion technologies deployed at commercial scale are referred to as conventional, whereas advanced biofuels are associated with less **mature technologies** that are in the earlier development or deployment stages.
- The focus on the **type of feedstock** is to determine potential competition with food or feed production. Conventional biofuels are those produced from feedstock that could be used for food or feed, whereas advanced biofuels are produced from agricultural and forestry residues, and organic waste, non-food/feed energy crops.

  There is an area of ambiguity for energy crops, used cooking oil (UCO), animal fats, and tall oil feedstocks. Some energy crops can compete with food / feed crops for land and water. Furthermore, animal fats and UCO are widely used with well-established conversion technologies, which means they often don't qualify as feedstocks for advanced biofuels.
- Achieving higher **GHG emissions reduction** is usually associated with advanced biofuels.
- The **product type and quality** can also significantly differ. Advanced biofuels are seen as more similar to fossil diesel, bunker and jet fuels ("drop-in" fuels), and can either blended in high proportions or used neat. Conventional biofuels are chemically different from fossil variants, creating compatibility issues with engines and infrastructures. This restricts them to relatively low blends.

Appendix B Biodiesel engine compatibility issues

Biodiesel (FAME)

The physical and chemical properties of FAME depend on the type of feedstock used, production process, and quality control, which affect the fuel's cold flow, volatility, cetane number and resistance to oxidation. Generally, the advantages of FAME biodiesel are good cetane number,[60] no aromatics and low sulphur. It is also thought to enhance the lubricity of conventional diesel fuel and reduce exhaust gas particulate matter. However, FAME loses its lubricity over a long period of time due to oxidation of unsaturated molecules present in the fuel and increased water from moisture absorption (IEA-AMF, 2020).

Engine manufacturers have been concerned with introducing biodiesel into the markets, especially at high blending rates. This is due to the following FAME biodiesel properties, a lot of which are caused by the high oxygen content imparting polar and hydrophilic:[61]

- It is less stable than conventional diesel fuel, which requires greater precaution to avoid problems linked to the presence of oxidation products in the fuel. There is some evidence that the problem can be exacerbated when the fuel is blended with ultra-low sulphur diesel fuels.
- It requires special care at low temperatures to avoid excessive viscosity and loss of fluidity. To alleviate this problem, additives may be required.
- Deposit formation in the fuel injection system may be higher with biodiesel blends than with conventional diesel fuel, so deposit control additive treatments are advised.
- At low temperatures, FAME can produce precipitated solids above the cloud point, which can cause filterability issues.[62]
- It can negatively affect natural and nitrile rubber seals in fuel systems. Metals such as brass, bronze copper, lead and zinc may oxidise from contact with biodiesel, and create sediments. Switching from conventional diesel to biodiesel may significantly increase tank sediments due to biodiesel's higher polarity, and these sediments can plug fuel filters. Fuel-system parts must therefore be specially chosen for their compatibility with biodiesel.
- Biodiesel fuel that comes into contact with the vehicle's shell may be able to dissolve the paint coatings used to protect external surfaces.

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[60] It should be noted that high cetane number is not preferable in marine gasoil/diesel as for road transport (Wood Mackenzie, 2010)

[61] The summary of issues is based on (WWFC, 2019), (Karatzos, et al., 2014), (Wood Mackenzie, 2010), (IEA-AMF, 2020).

[62] Two main temperature measures are cloud point when the first crystals appear in the fuel and the Cold Filter Plugging Point (CFPP) where sufficient crystals have formed to plug a test filer. Different biodiesels have different cloud points and CFPPs with those made from tallow and animal fats generally being higher that those made from vegetable oils (de Pont, 2006).

- FAME's freeze point is well above that allowed for jet fuel and FAME could cause other problems in jet engines. Therefore, these are not suited for aviation.
- Biodiesel esters are high-boiling compounds, which may lead to fuel dilution of the engine oil especially in engines using post-injection for particulate filter regeneration. The high boiling range of FAME results in fuel condensation on the cylinder walls when fuel is injected late in the working cycle. High-boiling components of FAME that do not burn completely can cause engine deposits and increased exhaust emissions, especially at low temperatures.
- Some studies show FAME can increase NOx emissions.

Appendix C Compatibility of bioethanol and biodiesel with existing infrastructure

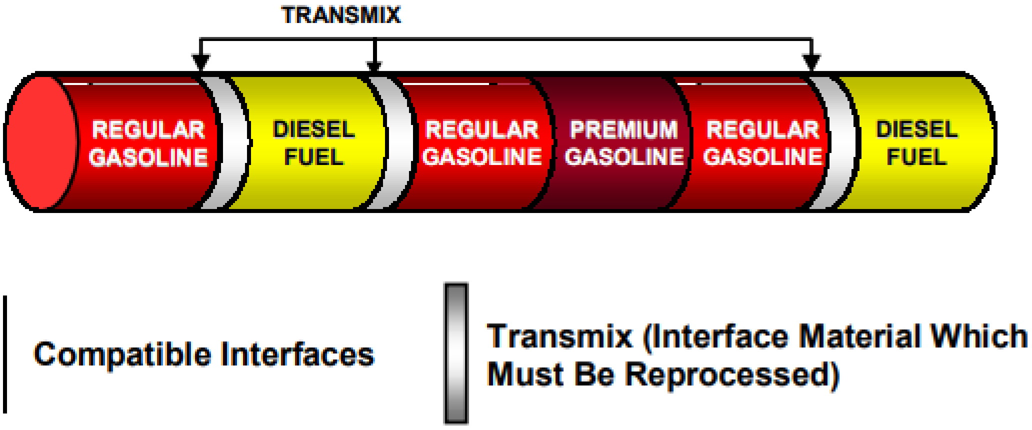
Contamination

Due to its chemical nature, FAME is incompatible with the existing infrastructure including pipelines and storage tanks, so it needs to be blended through separate distribution channels. Instead of using existing pipelines, biodiesel must be transported via trucks, rail or coastal shipping, increasing the carbon footprint of the supply chain.

Typically, pipelines run fossil fuel products in a specific sequence of batches to avoid cross contamination between fuels, as shown in Figure 29. Between batches, a small amount of co-mingled produced is generated. This is known as interface or transmix, and is normally segregated to refractionation to diesel and petrol, or returned to the refinery for processing (Bunting, et al., 2010).

Pipelines are therefore susceptible to contamination, which can carry over from batch to batch.

Figure 29 – Typical sequence of fossil fuel products through pipeline



Source: (Trench, 2001)

FAME is reactive with pipeline metallurgy, and can contaminate subsequent petroleum batches by adhering to the surfaces of pipeline walls. FAME transported through conventional fossil fuel pipelines can mix with the 'water plugs' that are inserted into the pipeline to separate the different fossil fuel liquids when they are transported through the pipeline. It can also stick to the pipeline wall and contaminate jet fuel plugs that follow. Jet fuels are particularly sensitive to biodiesel ester contaminants (Karatzos, et al., 2014).

Ethanol is hydrophilic, which means it picks up water from storage tanks and pipeline, thereby contaminating the fuel. It is also an effective solvent, which means it picks up residues of other materials that have passed through the pipelines, potentially damaging vehicle engines (Childs & Bradley, 2008). Ethanol can also segregate out of an ethanol gasoline mix into a water phase (Bunting, et al., 2010)

Because of its hydrophilic characteristic, ethanol at higher blends is suitable in any situation where you can keep it dry, this being particularly relevant for aviation. Modern cars have plastic sealed fuelled tank, which means they could work fine with high blend ethanol, provided that the ethanol has been kept dry and. The bigger issue is the storage and distribution infrastructure, which can introduce other impurities.

Ethanol cannot generally be transported via existing multi-fuel pipelines because it is a strong solver that can cause corrosion of pipelines and degradation of seals and other pump components. Because it can also dissolve residues left in the pipeline and absorbs water, it can arrive at the terminal outside the range of allowable specifications. This is particularly an issue where ethanol is blended with specifically formulated gasoline to met strict air emissions requirements. For this reason, in the US ethanol is primarily transport by rail, and biorefineries are built along existing rails lines (Rusco, 2012).

Given these characteristics, ethanol is usually transported by truck, train or barge. A greater scale-up of ethanol consumption could require dedicated pipelines to transport significant quantities, as well as storage tanks and distribution infrastructure at gas stations, including either new or extensively cleaned tanks, valves, filters, hoses and nozzles (Childs & Bradley, 2008).

The polarity of ethanol and FAME biodiesel can make the separation of dirt and water more difficult than for fossil fuels. Possible solutions include careful batch sequencing or the use of a separate pipeline to segregate jet fuel from FAME biodiesel (Bunting, et al., 2010).

As mentioned previously, FAME biodiesel also has poor oxidation stability. It contains carbon-to-carbon double bonds that are easily oxidised after production and during the storage and fuel use. Precautions must therefore be taken to deal with such oxidation reactions; these include the use of oxidation stability enhancing additives like butylated hydroxytoluene (BHT) when blending and distributing these fuels (WWFC, 2019).

FAME blends are solvents for a wider range of substances than fossil diesel, and therefore have a cleaning effect on systems using biodiesel, releasing organic residues which can cause blockage of filters. Generally, procedures for handling of biofuel blends require higher standards of cleanliness of systems as compared to fossil diesel. B100 permeates certain plastics such as polyethylene and polypropylene. Fluorinated plastics and nylon are more compatible (Wood Mackenzie, 2010).

Corrosion

Although microbial growth tends to occur anyway in the water phase of diesel storage, addition of FAME increases the availability of microbes. This can increase corrosion risk and may results in blockages in fuel dispenser filters and lines, especially at retail distribution (Wood Mackenzie, 2010). The problem typically occurs where fuels are stored for extended periods and thus is more common in storage tanks than in vehicle fuel tanks (de Pont, 2006).

Most of fossil fuel infrastructure, including pipelines, storage tanks and related equipment is made of low-carbon and low-allow steel, which means it is susceptible to rust and corrosion. Most pipeline networks have engineering features in place to remove contaminating water (Bunting, et al., 2010).

Dissolved water in biofuels can contribute to corrosion and stress corrosion cracking,[63] with the latter issues of particular concern with ethanol (Bunting, et al., 2010).

Ethanol is also extremely corrosive, which can affect the integrity of existing pipeline fittings and aluminium storage tanks. Because it is hydroscopic, it requires special handling to prevent high water content and the consequent risk of corrosion and microbial growth.

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[63] The latter is a particular issue for ethanol.

Appendix D Methods used to estimate emissions from co-products

Two main approaches are commonly used with respect to co-product treatment, as well as LUC estimates:

- **Attributional LCA** attributes energy and material inventories for each step in the lifecycle. Allocation can be done on the basis of weight, energy content or market value (economic) of products.
- **Consequential LCA** emphasises interactions among economic indicators, and allows accounting for avoided emissions due to co-products. This is sometimes also referred to as "displacement," "substitution," or "system boundary expansion" approach. This approach is also recommended by the guidelines for LCA issued by the International Organisation for Standardization ISO 14040-14049 guideline series, although is generally more complex (Hoefnagels, et al., 2010).

Both approaches are scientifically sound but are used for different decision-making purposes:[64]

- CO_2e inventories from attributional analyses are intended for LCA practitioners, industry users, and policy-makers interested in average GHG emissions data based on average operations, and are used in micro-economic decision settings.
- CO_2e inventories from consequential analyses are used by practitioners, industry users, and policy-makers interested in marginal impacts from new policies or market changes, and are used in macro-economic decision settings.

In the EU Renewable Energy Directive, the default emissions factors are generally based on the energy-content attributional approach, with the exception of co-product electricity produced from agricultural crop residues (including straw and bagasse), which is not accounted for. These agricultural crops residues also have zero life-cycle GHG emissions until the process of collection.

The LCA approach used for California's Low Carbon Fuel Standard is also generally attributional, with the exception of co-products and ILUC impacts which are estimated using a consequential approach. Emissions from direct and indirect land-use changes are estimated using the Global Trade Analysis Project that was developed for the California Air Resource Board (Dunn, et al., 2017).

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[64] Based on (EUCAR, 2020), (Prussi, et al., 2020a)

Appendix E Energy density assumptions for liquid fuels

Table 4 – Energy density assumptions for liquid fuels

	Blend	**MJ/litre neat**	**MJ/litre blend**
Bioethanol	10%	21	34.5
Biodiesel	7%	33.5	35.83
Drop-in fuel	50%	34	35
Fossil diesel		37.8	
Fossil petrol		35.4	
Fossil heavy fuel oil		40.9	
Aviation fossil fuel		35.4	

Source: For biofuels, these are average values based on Annex III in EU RED II. For fossil fuels, the values are based on MBIE's oil tables.

Appendix F LCA methodologies used worldwide

There are a number of models available to conduct biofuel LCA. Two prominent US-focused models are:

- GREET (Greenhouse Gases, Regulated Emissions, and Energy use in Transportation) developed by the Argonne National Laboratory. An adapted version of GREET is used by CARB to estimate direct emissions of producing and using transport fuels in the context of the Low Carbon Fuel Standard.
- GHGenius used by Canada Federal Government, Alberta, British Columbia.

In the EU, the BioGrace model was initially developed to provide a harmonised approach to LCA GHG emissions calculations in the EU, and to ensure compliance with the EU Renewable Energy Direct and Fuel Quality Directive. Currently, the EU Joint Research Centre (JRC) is in charge of updating the input data for calculating default emissions factors contained in the EU RED, and publishing a harmonised biomass database of LCA supply chains.[65]

Brazil uses the Virtual Sugarcane Biorefinery (VSB) model, which was initially developed to assess the sugarcane production chain. It has been subsequently expanded to include other feedstocks and conversion pathways for biorefining.

There are also commercial software packages that can be used to conduct biofuel LCA of emissions.

Table 5 summarises the key characteristics of the models above. They key points are:

- Most models have been developed for regulatory use
- Most models do not include LUC changes emissions in their default estimates, except GHGenius which includes default land management emissions in most biomass production systems (e.g. soybean and palm) (Bonomo, et al., 2018). Except VSB, other models allow the user to model LUC as needed.
- GREET and JRC models for CARB and EU RED respectively use the attribution approach, with some caveats and variations.

Table 5 – Key characteristics of international LCA models

	BioGrace	**GHGenius**	**GREET**	**JRC**	**VSB**
Model version	4d (2015)	5.0a (2018)	2017	2017	2018
Developed for	Yes	No (although used as one)	Yes	Yes	No

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[65] https://data.jrc.ec.europa.eu/dataset/jrc-alf-bio-biomass-db-lca-supply-chains-2018-protected

	BioGrace	**GHGenius**	**GREET**	**JRC**	**VSB**
regulatory use					
Default gases	CO2, CH4, N2O	CO2, CH4, N20, CO, VOC, NOx, fluorinated compounds	CO2, CH4, N2O	CO2, CH4, N2O	CO2, CH4, N2O
Lifecyle data	JRC[66] 2008	Internal	Internal	JRC 2017	Ecoinvent
Unit	MJ	km, MJ	Km, mile, BTU, MJ	MJ	km, MJ
Default allocation	Energy	Mostly substitution[67]	Variable[68]	Energy	Economic
Land use change	C stocks	Internal model	CCLUB/GTAP	C stocks	--
Boundaries	Well-to-wheel	Well-to-wheel	Well-to-wheel	Well-to-wheel	Well-to-wheel

Source: Based on (Bonomo, et al., 2018), (Dunn, et al., 2017)

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[66] The Joint Research Center of the European Commission is in charge of defining input values for the calculation of default GHG emissions for biofuels.

[67] For soybean meal, mass allocation is also used.

[68] For FAME and HVO, mainly energy/mass/economic allocations are used, even though the default allocation in GREET is displacement (substitution).

Appendix G Emissions reductions by biofuel pathway

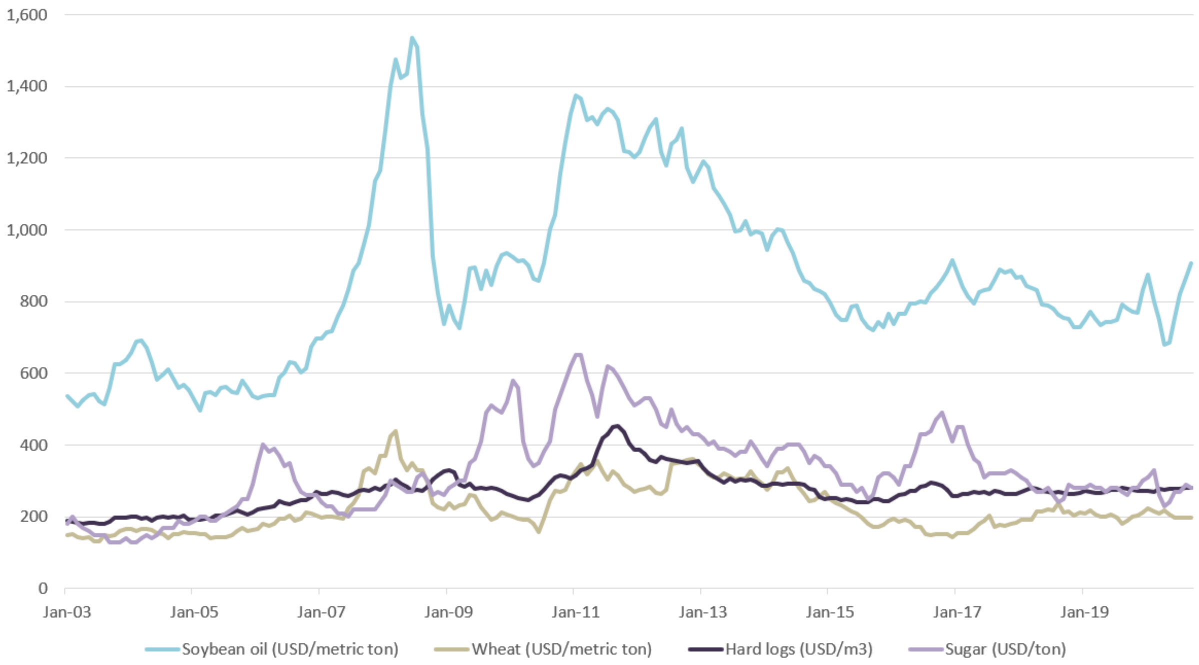
Table 6 – Lifecycle emissions by biofuel pathways

(blend wall in brackets)	**Feedstock**	**Neat % change**	**Blend % change**	**Min gCO2e / MJ**	**Max gCO2e / MJ**
Bioethanol (10%)	Corn	-30%	-3%	40	91
	Wheat	-27%	-3%	45	93
	Wheat straw	-58%	-6%	30	50
	Sugar beat	-56%	-6%	30	53
	Barley	-15%	-1%	69	129
	Sugar cane	-54%	-5%	42	46
FAME (7%)	Rapeseed oil	14%	1%	100	115
	Soybean oil	57%	4%	98	197
	Palm oil	104%	7%	58	326
	Sunflower oil	2%	0%	85	149
	Used cooking oil	-86%	-6%	11	16
	Animal fat	-48%	-3%	37	63
	Short-rotation woody crop	-107%	-8%	-7	-36
HVO (50%)	Rapeseed oil	14%	7%	100	115
	Sunflower oil	5%	3%	91	107
	Soybean oil	57%	28%	98	197
	Palm oil	105%	52%	69	316
	Palm oil mill effluent	-71%	-36%	27	27
	Used cooking oil	-85%	-43%	12	16
	Animal fat	-47%	-23%	37	63
FT diesel (50%)	Forest residue	-78%	-39%	11	20
	Poplar	-91%	-45%	9	-2
	Switchgrass	-91%	-46%	8	8
	Miscanthus	-106%	-53%	-6	-18
	Perennials - avg	-96%	-48%	4	-4
FT petrol (50%)	Forest residue	-80%	-40%	19	19
	Farmed wood	-78%	-39%	21	21
	Forest residue / wood - avg	-79%	-39%	30	30

(blend wall in brackets)	**Feedstock**	**Neat % change**	**Blend % change**	**Min gCO2e / MJ**	**Max gCO2e / MJ**
Pyrolysis (50%)	Pyrolysis oil from waste wood	-69%	-34%	53	53
	Upgraded bio-oil from waste wood	-44%	-22%	0	0

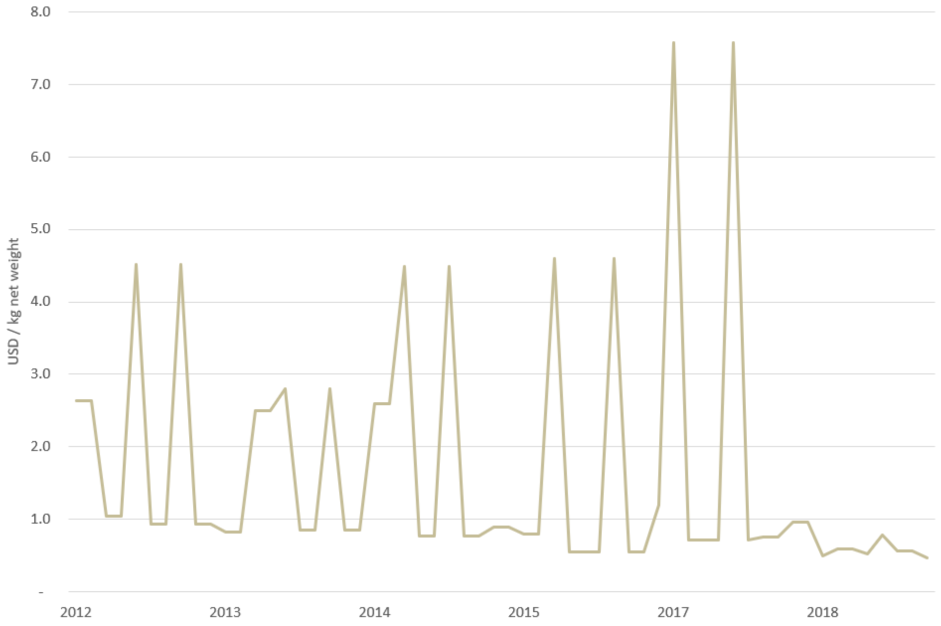
Appendix H Historical feedstock prices

Figure 30 – Commodity prices: soybean oil, wheat, hard logs, sugar



Source: Indexmundi 2021 https://www.indexmundi.com/commodities/

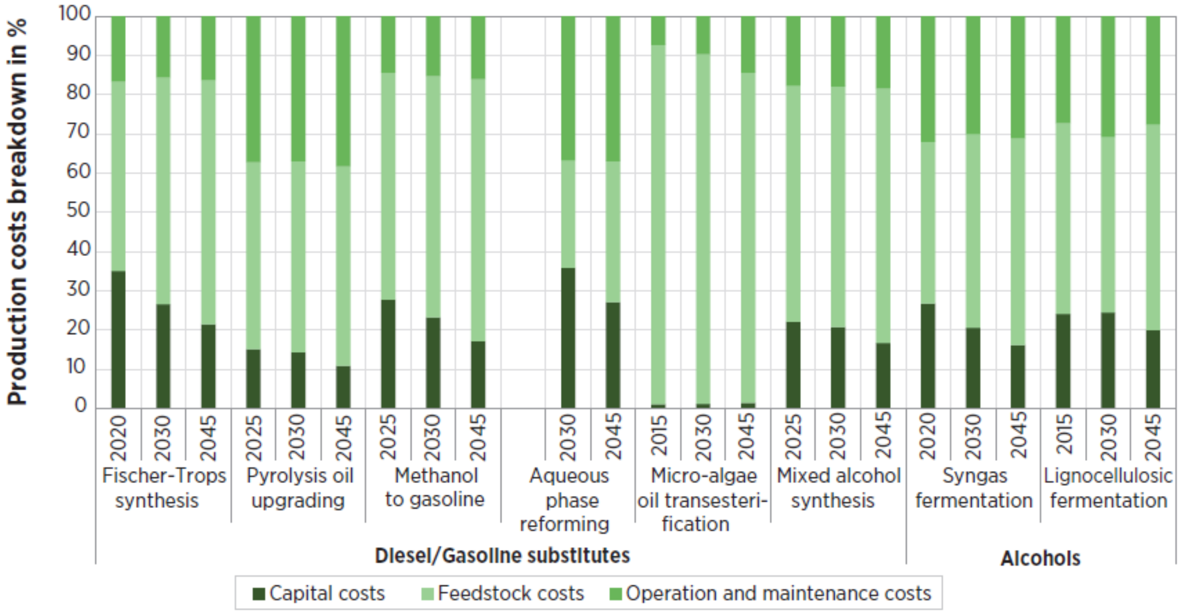
Figure 31 – Commodity prices: tallow



Source: Comtrade data on NZ tallow exports https://comtrade.un.org/data/

Appendix I Feedstock costs as % total production costs for advanced biofuels

Figure 32 – Production cost breakdown



Source: (IRENA, 2016)

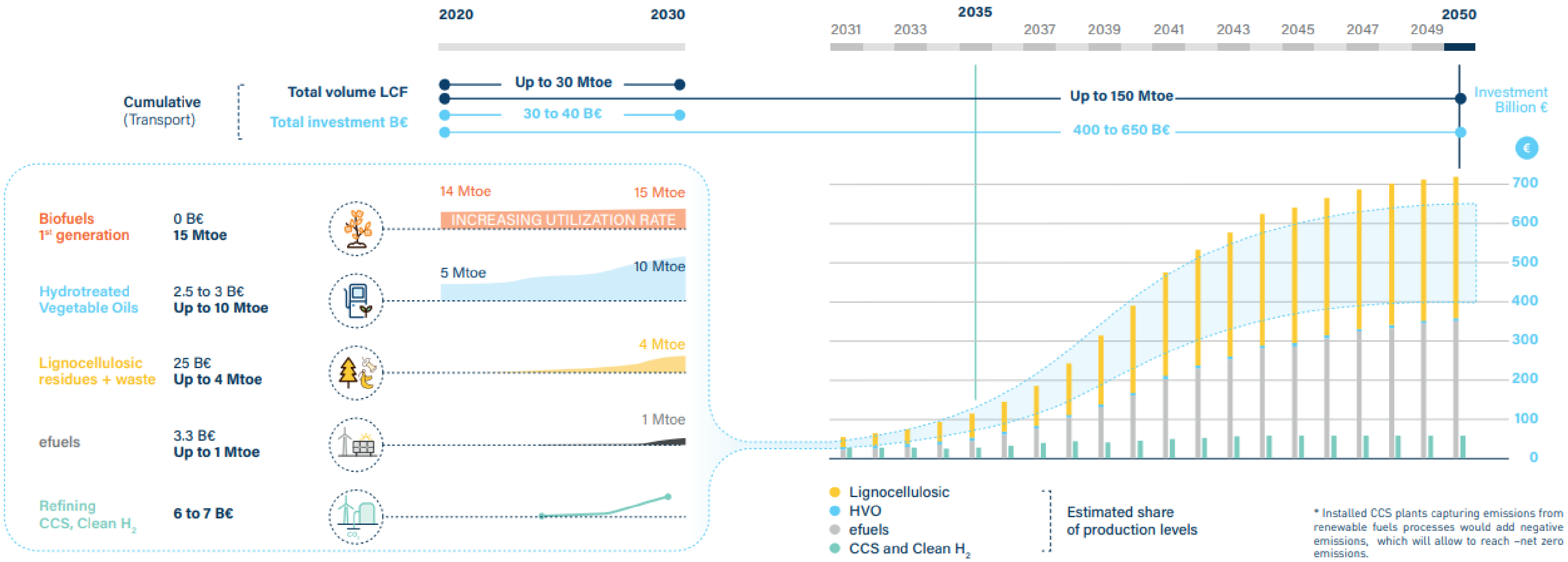
Appendix J Capital costs for biofuel pathways

Table 7 - Capital costs for biofuel pathways

Fuel type	Year	min ($/litre p.a.)	max ($/litre p.a.)
Bioethanol	2020	0.56	1.01
	2025	0.56	1.01
	2030	0.56	1.01
	2035	0.56	1.01
G2 bioethanol	2020	1.69	2.89
	2025	1.55	2.65
	2030	1.42	2.43
	2035	1.30	2.22
FAME biodiesel	2020	1.41	1.47
	2025	1.41	1.47
	2030	1.41	1.47
	2035	1.41	1.47
HEFA/HVO diesel	2020	0.68	2.54
	2025	0.68	2.54
	2030	0.68	2.54
	2035	0.68	2.54
Alcohol to jet (ATJ)	2020	1.69	2.37
	2025	1.55	2.17
	2030	1.42	1.99
	2035	1.30	1.82
Drop-in diesel / petrol via pyrolysis	2020	3.51	8.82
	2025	3.27	8.21
	2030	3.05	7.65
	2035	2.84	7.12
Drop-in diesel / petrol via FT	2020	6.71	10.07
	2025	5.92	8.88
	2030	5.22	7.83
	2035	4.60	6.90

Appendix K EU refining industry 2050 potential scenario

Figure 33 – EU refining industry 2050 potential scenario



Source: (FuelsEurope, 2020)

Appendix L Assumptions for estimating maximum potential demand for biofuels in NZ transport

Table 8 – Average vkt by GVM band

year	GVM band	vkt_billions	vkt millons	vehicles	mean gvm	Avg vkt/vehicle pa
2019	HGSV < 5000	.267	266.7	26599	4385	10,028
2019	HGSV < 7500	.363	363.2	35275	5825	10,296
2019	HGSV < 10000	.215	215.4	18993	8676	11,343
2019	HGSV < 12000	.129	128.7	8576	10669	15,010
2019	HGSV < 15000	.116	115.9	8132	13181	14,252
2019	HGSV < 20000	.150	150.2	8842	16286	16,990
2019	HGSV < 25000	.417	416.5	16928	23324	24,606
2019	HGSV < 30000	.590	589.8	15948	26875	36,983
2019	HGSV > 30000	.844	844.2	13956	32267	60,488

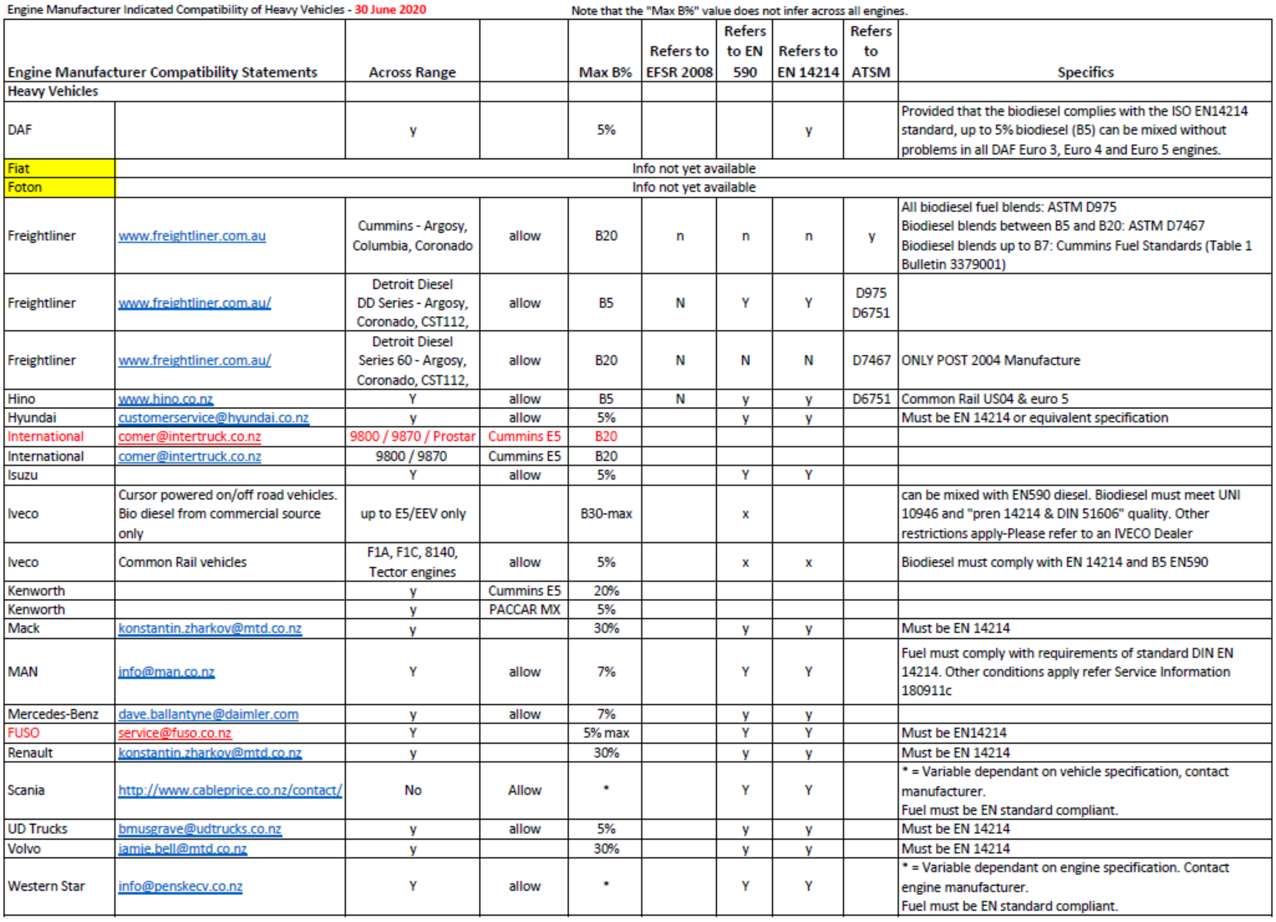
Source: based on Motor Vehicle Register

Table 9 – Fuel economy estimates by RUC type

RUC type	Million tkm	Avg load (t)	Lifetime (years)	Avg litres / 100km
2	1,949	1.8	20	29.5
6	8,302	10.8	20	47.0
14	15,012	14.3	20	57.0
19	67	14.5	20	61.3

Source: based on (Haobo, et al., 2019). Fuel economy is estimated based on the 0.0016*GVM+7.8857 function

Appendix M Engine manufacturer indicated compatibility with heavy vehicles



Engine Manufacturer Indicated Compatibility of Heavy Vehicles - 30 June 2020

Note that the "Max B%" value does not infer across all engines.

Engine Manufacturer Compatibility Statements		Across Range		Max B%	Refers to EFSR 2008	Refers to EN 590	Refers to EN 14214	Refers to ATSM	Specifics
Heavy Vehicles									
DAF		y		5%			y		Provided that the biodiesel complies with the ISO EN14214 standard, up to 5% biodiesel (B5) can be mixed without problems in all DAF Euro 3, Euro 4 and Euro 5 engines.
Fiat	Info not yet available								
Foton	Info not yet available								
Freightliner	www.freightliner.com.au	Cummins - Argosy, Columbia, Coronado	allow	B20	n	n	n	y	All biodiesel fuel blends: ASTM D975 Biodiesel blends between B5 and B20: ASTM D7467 Biodiesel blends up to B7: Cummins Fuel Standards (Table 1 Bulletin 3379001)
Freightliner	www.freightliner.com.au/	Detroit Diesel DD Series - Argosy, Coronado, CST112,	allow	B5	N	Y	Y	D975 D6751	
Freightliner	www.freightliner.com.au/	Detroit Diesel Series 60 - Argosy, Coronado, CST112,	allow	B20	N	N	N	D7467	ONLY POST 2004 Manufacture
Hino	www.hino.co.nz	Y	allow	B5	N	y	y	D6751	Common Rail US04 & euro 5
Hyundai	customerservice@hyundai.co.nz	y	allow	5%		y	y		Must be EN 14214 or equivalent specification
International	comer@intertruck.co.nz	9800 / 9870 / Prostar	Cummins E5	B20					
International	comer@intertruck.co.nz	9800 / 9870	Cummins E5	B20					
Isuzu		Y	allow	5%		Y	Y		
Iveco	Cursor powered on/off road vehicles. Bio diesel from commercial source only	up to E5/EEV only		B30-max		x			can be mixed with EN590 diesel. Biodiesel must meet UNI 10946 and "pren 14214 & DIN 51606" quality. Other restrictions apply-Please refer to an IVECO Dealer
Iveco	Common Rail vehicles	F1A, F1C, 8140, Tector engines	allow	5%		x	x		Biodiesel must comply with EN 14214 and B5 EN590
Kenworth		y	Cummins E5	20%					
Kenworth		y	PACCAR MX	5%					
Mack	konstantin.zharkov@mtd.co.nz	y		30%		y	y		Must be EN 14214
MAN	info@man.co.nz	Y	allow	7%		Y	Y		Fuel must comply with requirements of standard DIN EN 14214. Other conditions apply refer Service Information 180911c
Mercedes-Benz	dave.ballantyne@daimler.com	y	allow	7%		y	y		
FUSO	service@fuso.co.nz	Y		5% max		Y	Y		Must be EN14214
Renault	konstantin.zharkov@mtd.co.nz	y		30%		y	y		Must be EN 14214
Scania	http://www.cableprice.co.nz/contact/	No	Allow	*		Y	Y		* = Variable dependant on vehicle specification, contact manufacturer. Fuel must be EN standard compliant.
UD Trucks	bmusgrave@udtrucks.co.nz	y	allow	5%		y	y		Must be EN 14214
Volvo	jamie.bell@mtd.co.nz	y		30%		y	y		Must be EN 14214
Western Star	info@penskecv.co.nz	Y	allow	*		Y	Y		* = Variable dependant on engine specification. Contact engine manufacturer. Fuel must be EN standard compliant.

Source: (MIA, 2020)

Appendix N Summary of biofuel applications and limits

Fuel family	Conversion technology	Biofuel produced	Blend limits
Road diesel	Trans-esterification of lipds	FAME biodiesel	5% - 7%. Higher blends can be used depending on OEM specifications
	Hydro-treatment of lipids	Hydrogenated renewable diesel	There are no regulatory limits to blending HEFA in diesel. However, it is blended with conventional diesel fuel to meet fuel specifications.
	Gasification / Fischer-Tropsch	Drop-in diesel	EN 15940 does not apply regulatory limits to blending FT diesel
Aviation	Hydro-treatment of lipids	HAFE	Up to 50% HEFA in jet fuel
	Hydro-processing of bio-derived hydrocarbons	HH-SK / HC-HEFA	Up to 10%
	Fischer-Tropsch	Drop-in diesel	FT kerosene is certified for maximum 50% blends with jet fuel
	Cathalytic hydrothermolyosis	Drop-in diesel	Up to 50%
Marine	Trans-esterification of lipds	FAME biodiesel	Technically, up to 7% blends can be used. Standards being developed
	Bio-oil upgrading	Drop-in	Technically, can be used as a direct replacement for fossil marine fuel. Standards being developed
	Mild bio-oil upgrading	Drop-n	Can be used in a marine engine. Standards being developed

Source: (IRENA, 2016), (Maniatis, et al., 2017), (Suckling, et al., 2018)

Appendix O International biofuel standards

Bioethanol for road transport

In Europe, two standards are applicable to bioethanol:

- EN 15376 establishes specification for ethanol to be blended with petrol
- EN 228, the European gasoline fuel specification, is also applicable to ethanol blends up to 10% (DCL, 2014).

At present, most EU members states are using a low 5% blend, although many members states have started moving towards E10 (Horizon Magazine, 2020). In some countries, e.g. France, E10 has been widely used for some time now (DCL, 2014).

FAME biodiesel for road transport

Within the European Union, there are three two sets of standards that define the specifications of low FAME blend fuels. These specifications define a range of properties of the fuel, some of which are related to the intrinsic chemistry of the molecules, e.g. cetane number, viscosity and iodine number, and some of which are more related to the processing method, e.g. residual glycerides, water content, sterol glucosides, alkali metals and free acids (Wood Mackenzie, 2010).

- EN 590 (European Diesel Fuel Specification) sets a maximum limit of 7% for FAME blends in fossil diesel, regardless of the type of feedstock. This is higher than the 5% limit allowed under ASTM D975, which is used in the US.
- Similarly, EN 16734 set a limit of 10% for FAME blends at the EU level. However, Member State legislation can set additional requirements, or even prohibit the marketing and delivery of these fuels.
- EN 14214 (Fatty Acid Methyl Ester (FAME) Fuel Specification) sets the specifications for neat FAME (B100). It establishes specifications for biodiesel use as either (i) a final fuel in engines designed or adapted for biodiesel use, or (ii) a blendstock for conventional diesel fuel. Under ASTM, neat biodiesel is governed by the ASTM D6751 standard, however this contains specifications for neat biodiesel as a blending component, and not as a final fuel (WWFC, 2019).

For higher blends, the viscosity of fuels is an issue. The EU Fuel Quality Directive (Annex II) sets a maximum limit for the density at (15 °C) of fuels that are sold, at 845 kg/m3. This limits the potential for high FAME blends. Because B20 / B30 do not meet this requirement, they can only be used in dedicated fleets, so long as they meet the EN16709 standard for B20/B30 blends.

HVO and synthetic fuels for road transport

There are no regulatory limits to blending HVOs and synthetic fuels. However, they are blended with conventional diesel fuel to meet fuel specifications.

The fuel standard EN 15940 covers hydrotreated paraffinic renewable diesel fuel and synthetic Fischer-Tropsch products in the EU. It was approved in 2016, opening up the possibility for drop-in biodiesel in current and future diesel vehicles up to 100% (Maniatis, et al., 2017). The standard does not explicitly regulate the origin of the feedstock, as that part of the fuel supply chain is covered by the Fuel Quality Directive and Renewable Energy Directive.

When used in a blend, the neat paraffinic diesel fuel does not necessarily need to meet EN 15940, as long as the final fuel meets the diesel fuel blend requirements defined in other standards, such as EN 590 for B7 FAME, and EN 16734 for B10 FAME (Neste, 2020).

This standard can be used as guidance for the production of synthetic fuels and HVO when used as blending components. However, additional engine validation may be needed to ensure that the fuel works well with the existing vehicle and engine. Subject to validation and care using additives, these fuels can be used in any diesel engine either in pure form or blended with fossil diesel as long as the finished fuels meets the required standard (WWFC, 2019).

Sustainable aviation fuel

For aviation fuel, international standards have been adopted due to the fact that the same aircraft can be fuelled in different countries. The standard regulating the technical certification of SAF is ASTM D7566, which evaluates the technologies can be used for producing neat SAF. Once blended, the final fuel must meet ASTM D1655 standard, which determines if the fuel is fit-for-purpose based on various parameters, such as composition, volatility, corrosion, thermal stability, energy content, freeze point, combustion characteristics, lubricity, material compatibility etc.

The figure below shows the seven technology pathways that can currently produce drop-in SAFs, and the ASTM certification status.

Table 10 - Approval status for sustainable aviation fuels

Conversion technology	**Feedstocks**	**Maximum blend (%)**	**ASTM status**
Fischer-Tropsch (FT) and FT containing aromatics (FT-SKA)	Wastes (MWS, etc.), coal, gas, sawdust	50%	Included in ASTM D7566 in 2009 and 2015 respectively (Annex 1 and 4)
Hydro-processed esters and fatty acids (HEFA/HVO)	Vegetable oils: palm, camelina, jatropha, used cooking oil	50%	Included in ASTM D7566 in 2011 (Annex 2)
Direct sugars to hydrocarbons producing synthetic iso-paraffins (SIP)	Sugarcane, sugar beet	10%	Included in ASTM D7566 in 2014 (Annex 3)
Alcohol-to-jet (ATJ, isobutanol or ethanol)	Sugarcane, sugar beet, sawdust, lignocellulosic residues (straw)	50%	Included in ASTM D7566 in 2016

Conversion technology	Feedstocks	Maximum blend (%)	ASTM status
Hydroprocessed hydrocarbons (HH-SPK or HC-HEFA)	Oil produced from (botryococcus braunii) algae	10%	Included in ASTM D7566 in 2020 (Annex 7)
Cathalytic hydrothermolyosis (CHJ)	Triglycerides such as soybean oil, jatropha oil, camelina oil, carinata oil, and tung oil	50%	Included in ASTM D7566 in 2020 (Annex 6)

Source: based on (IATA, 2020), (ICAO, 2020)

Marine fuels

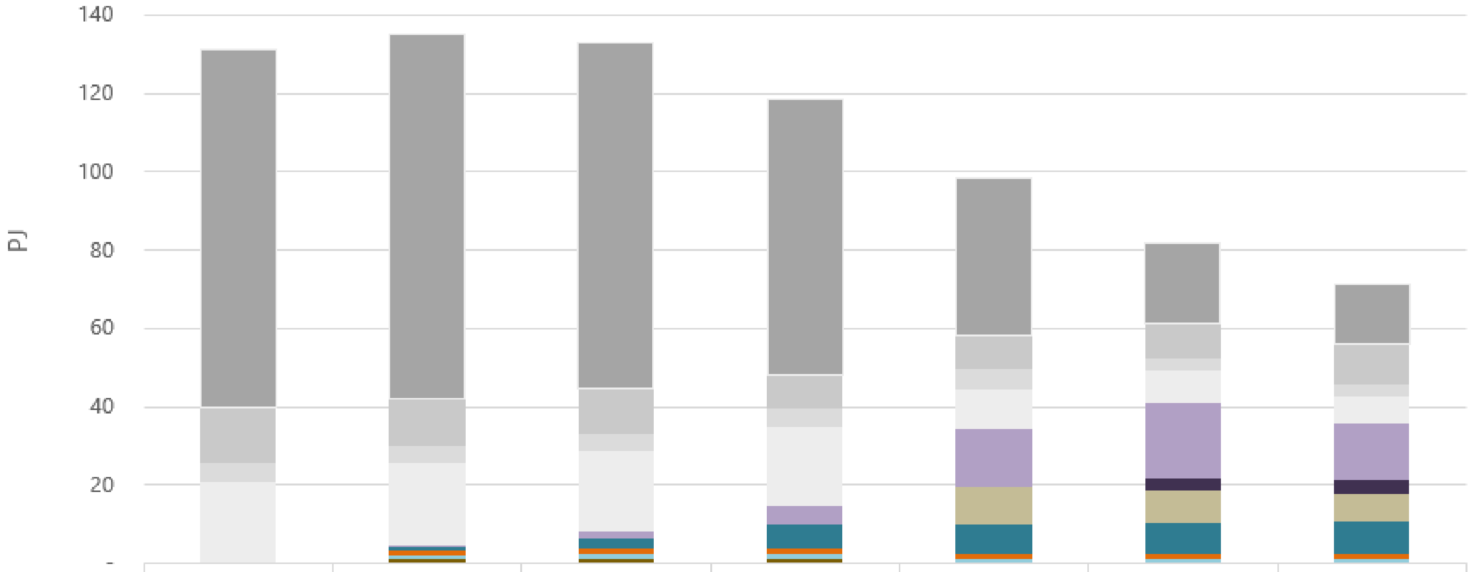
ISO standards on bio-derived fuels for the shipping sector are still work-in progress. Key issues that need addressing are fuel stability towards oxidation, minimal water content to inhibit microbial growth, and low-temperature flow properties of biofuels. Currently, regulations do not allow biodiesel blending with marine distillate or residual fuels, as they are seen as contaminants. FAME content in marine fuels cannot exceed 0.1% volume in distillate fuels, due to lack of data concerning storage, handling, and treatment in a marine environment (IEA Bioenergy, 2017).

Nevertheless, the International Marine Organisation's limits on sulphur emissions from 2020 is encouraging for biofuel use in shipping. Larger vessels that use marine heavy fuel, either diesel or diesel-electric, will be able to use biocrude-based blends from sustainable feedstocks with limited upgrading (Bioenergy Association, 2019). HVOs are also a technically good replacement of heavy fuel oils and is compatible with current engines and supply chain. Newer fuels like DME (dimethyl ether), bioLNG, bioethanol, and (bio)methanol are compatible with modern marine diesel engines, though their widespread acceptance in shipping is limited by availability (IEA Bioenergy, 2017).

The IEA Bioenergy Task 39 are working on development of a suitable marine standard for biofuels (Bioenergy Association, 2019).

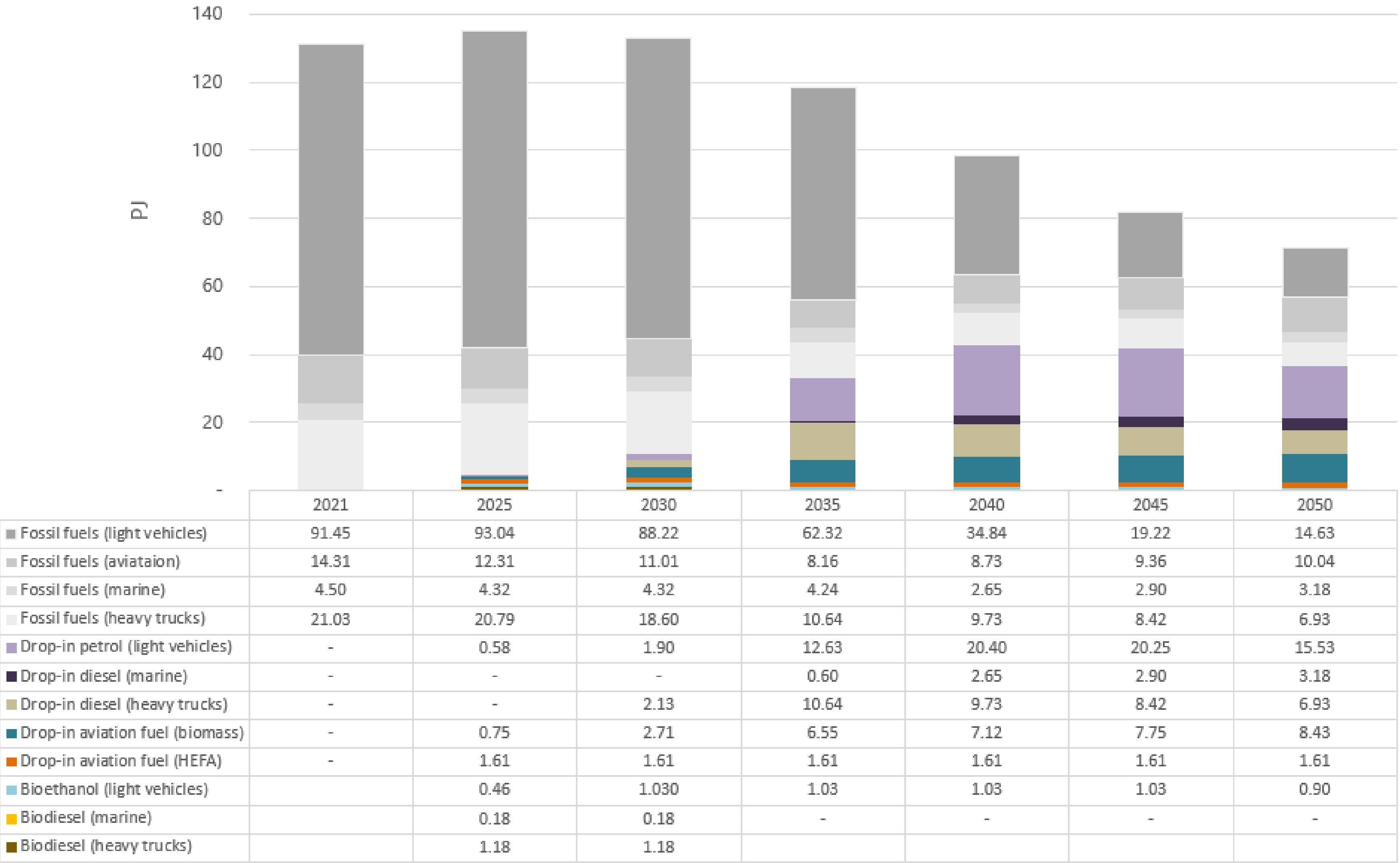
Appendix P Domestic uptake scenario for biofuels

Figure 34 – Biofuel uptake volumes in progressive uptake scenario



	2021	2025	2030	2035	2040	2045	2050
■ Fossil fuels (light vehicles)	91.45	93.04	88.31	70.29	40.23	20.42	15.50
■ Fossil fuels (aviataion)	14.31	12.31	11.47	8.69	8.73	9.36	10.04
■ Fossil fuels (marine)	4.50	4.32	4.32	4.65	5.30	2.90	3.18
■ Fossil fuels (heavy trucks)	21.03	20.79	20.73	20.11	9.76	8.42	6.93
■ Drop-in petrol (light vehicles)	-	0.58	1.81	4.66	15.01	19.05	14.61
■ Drop-in diesel (marine)	-	-	-	-	-	2.90	3.18
■ Drop-in diesel (heavy trucks)	-	-	-	-	9.70	8.42	6.93
■ Drop-in aviation fuel (biomass)	-	0.75	2.26	6.01	7.12	7.75	8.43
■ Drop-in aviation fuel (HEFA)	-	1.61	1.61	1.61	1.61	1.61	1.61
■ Bioethanol (light vehicles)		0.46	1.030	1.03	1.03	1.03	0.95
■ Biodiesel (marine)		0.18	0.18	0.19	-	-	-
■ Biodiesel (heavy trucks)		1.18	1.18	1.17			

Figure 35 – Biofuel uptake volumes in accelerated uptake scenario



	2021	2025	2030	2035	2040	2045	2050
■ Fossil fuels (light vehicles)	91.45	93.04	88.22	62.32	34.84	19.22	14.63
■ Fossil fuels (aviataion)	14.31	12.31	11.01	8.16	8.73	9.36	10.04
■ Fossil fuels (marine)	4.50	4.32	4.32	4.24	2.65	2.90	3.18
■ Fossil fuels (heavy trucks)	21.03	20.79	18.60	10.64	9.73	8.42	6.93
■ Drop-in petrol (light vehicles)	-	0.58	1.90	12.63	20.40	20.25	15.53
■ Drop-in diesel (marine)	-	-	-	0.60	2.65	2.90	3.18
■ Drop-in diesel (heavy trucks)	-	-	2.13	10.64	9.73	8.42	6.93
■ Drop-in aviation fuel (biomass)	-	0.75	2.71	6.55	7.12	7.75	8.43
■ Drop-in aviation fuel (HEFA)	-	1.61	1.61	1.61	1.61	1.61	1.61
■ Bioethanol (light vehicles)		0.46	1.030	1.03	1.03	1.03	0.90
■ Biodiesel (marine)		0.18	0.18	-	-	-	-
■ Biodiesel (heavy trucks)		1.18	1.18				

Appendix Q Absolute emissions reductions in the two scenarios

Table 11 - Possible LCA emissions reductions from biofuels in New Zealand transport (ktCO2e) – progressive uptake

	2021 - 2025	2026 - 2030	2031 - 2035	2036 - 2040	2041 - 2045	2046 - 2050
Biodiesel for heavy trucks	129	260	258	0	0	0
Biodiesel for marine	33	41	42	34	0	0
Bioethanol for light vehicles	47	166	213	213	213	205
HEFA	71	355	355	355	355	355
Drop-in aviation fuel (biomass)	55	513	1,654	2,524	2,748	2,989
Drop-in diesel for heavy trucks	0	0	0	2,058	3,287	2,764
Drop-in diesel for marine	0	0	0	0	994	1,125
Drop-in petrol for light vehicles	43	417	1,307	4,036	7,186	6,006
Total	**335**	**1,751**	**3,830**	**9,221**	**14,784**	**13,444**

Table 12 – Possible LCA emissions reductions from biofuels in New Zealand transport (ktCO2e) – accelerated uptake

	2021 - 2025	2026 - 2030	2031 - 2035	2036 - 2040	2041 - 2045	2046 - 2050
Biodiesel for heavy trucks	129	260	207	0	0	0
Biodiesel for marine	33	41	33	0	0	0
Bioethanol for light vehicles	47	166	213	213	213	209
HEFA	71	355	355	355	355	355
Drop-in aviation fuel (biomass)	55	546	2,313	2,524	2,748	2,989
Drop-in diesel for heavy trucks	0	156	2,942	3,717	3,287	2,764
Drop-in diesel for marine	0	0	44	907	1,027	1,125
Drop-in petrol for light vehicles	43	424	2,913	6,310	8,073	6,385
Total	**379**	**1,947**	**9,020**	**14,027**	**15,704**	**13,820**

Source: Sapere analysis

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