New Zealand Biofuels Roadmap Technical Report

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NZBiofuelsRoadmap

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Executive summary

New Zealand consumed 8.6 billion litres of liquid fuels in 2015, almost all from imported fossil fuels. Using these fossil fuels generates carbon dioxide (CO_2), a greenhouse gas (GHG) that contributes to climate change. Combustion of liquid fossil fuels was responsible for approximately 23% of New Zealand's domestic GHG emissions in 2015, so reducing fossil fuel use would have a big impact on lowering the country's carbon emissions and meeting our international GHG commitments.

Biofuels could be a significant part of the solution for reducing New Zealand's fossil oil use. Biofuels are produced from biological sources such as agricultural or forest crops. The carbon dioxide they generate during their use is reabsorbed by the next generation of crops, closing the CO_2 cycle and significantly reducing the overall contribution to climate change compared to fossil fuels. Additional benefits of the production and use of biofuels in New Zealand include greater security of energy supply, regional development, and maintaining access to international markets for our goods and services.

However, liquid biofuels currently make only a very minor contribution, less than 0.1%, to transportation fuels use in New Zealand. This is despite their extensive deployment in other parts of the world. Internationally, deployment has been largely driven by three key strategic drivers: climate change, energy security/independence and rural economic development. All drivers are very pertinent to New Zealand.

Study objective
This New Zealand Biofuels Roadmap study was carried out to inform and stimulate debate on the large-scale production and use of liquid biofuels in New Zealand – as a way of significantly reducing New Zealand's greenhouse gas emissions and improving energy security.

Specifically, this study sought to understand what a large-scale biofuels industry could look like here, for example

- What currently available crops could be grown and where should they be grown?
- What technologies should be used to convert these crops to liquid fuels?
- Which liquid fuels should be targeted as a priority?
- What are the key considerations and implications in developing such an industry?

How the study was carried out
Quantitative scenario modelling, coupled with qualitative analysis, was used to 'look at the future' and create scenarios of what large scale production and use of biofuels in New Zealand might look like out to 2050 and to identify the lowest cost value chain(s) under these different scenarios.

Quantitative modelling was conducted using the Energy Technologies Institute's Bioenergy Value Chain Model after modification to make it suitable for New Zealand use. This model has previously been successfully used to assess and understand the prominent role bioenergy could play in meeting the United Kingdom's greenhouse gas emission reduction targets, informing policy and legislation development.

This modelling did not set out to identify the single "best" pathway for biofuel implementation in New Zealand. Rather, it was used to understand the impacts, implications, and consequences of answering multiple "what-if" questions. The goal was to provide objective information to inform and stimulate debate covering a wide range of possible futures. In particular, we looked at scenarios spanning biofuel levels from 5% up to 100% substitution, different feedstock and land use assumptions, and scenarios targeting specific fuel types.

Stakeholders were extensively involved in the entire process. They included government departments and agencies, energy companies, forestry companies, pulp and paper companies, research organisations, Māori and others. This engagement gave an insight into stakeholders' diverse opinions on biofuels, as well as their views on the drivers and barriers to biofuels implementation in New Zealand.

This Technical Report presents:

- information on the current status of biofuels production and use in New Zealand and globally,
- the mathematical optimisation model that was used to generate quantitative results,

- the results of the multiple "what if" scenarios that were studied,
- additional considerations to define how biofuels might best be deployed in New Zealand, and
- concludes with the key findings of the study and the proposed next steps.

Key findings

- Large-scale biofuel production and use within New Zealand can happen.
- Biofuels can be a large, longer-term answer to reducing New Zealand's carbon emissions, particularly for difficult-to-decarbonise sectors such as aviation, shipping and long-haul road freight.
- Large-scale biofuels opportunities must consider the whole value chain.
- Biofuel production could provide strong regional economic development opportunities in regions such as Northland, East Coast and the central North Island.
- Drop-in biofuels from non-food feedstocks, particularly forestry grown on non-arable land, is the most attractive longer-term opportunity.
- Government policy support will be needed to kick-start large-scale biofuel production because market forces alone will not be sufficient.

Next steps

It is vitally important that New Zealand fully understands, and reaches a national consensus on the future role biofuel deployment should play in decarbonising New Zealand. This should include defining how to best achieve the desired outcomes while understanding the impacts on other parts of the whole New Zealand economy before committing to any large scale implementation. The information contained in this study provides a starting point for an open and fact-based discussion around the New Zealand biofuels opportunities.

To move to large-scale biofuel production key players need to:

- Agree on the future role and scale biofuels should play in decarbonising New Zealand. Key decisions are needed on:
    1. Which fuel families and which specific biofuels should be targeted.
    2. Acceptable land and feedstocks for biofuel production.
    3. The level of biofuel substitution required, and in what timeframe.
    4. The best uses of biomass.
- Develop and carry out an implementation plan that is nationally co-ordinated and aligned with stakeholders
- Continue exploring short-term niche biofuel opportunities to start building momentum
- Plant the large and sustainable supply of feedstock needed for future biofuels
- De-risk future options for biofuel implementation by developing knowledge on growing energy crops and conversion technologies suited to New Zealand

A more concise summary of this report, titled New Zealand Biofuels Roadmap: Growing a biofuelled New Zealand can be found online at: www.scionresearch.com/nzbiofuelsroadmap.

Glossary

Term	Description
Arable land	Land, typically flat, capable of being ploughed and used to grow crops or be mechanically harvested. In this study, class 1 and class 2 land.
Arable crops	Crops grown on arable land. In this study examples are canola, sugar beet, maize and corn.
BEC2050 study	BusinessNZ Energy Council study: New Zealand Energy Scenarios, Navigating energy futures to 2050.
Biodiesel	A biofuel produced from canola and tallow by reaction with methanol. The product is a fatty acid methyl ester.
Biofuel	A fuel produced from biomass.
Biomass	Any organic matter, *i.e.* biological material, available on a renewable basis. Includes feedstock derived from animals or plants, such as wood and agricultural crops, and organic waste from municipal and industrial sources.
Bio-oil	The liquid fuel resulting from thermal liquefaction of biomass. In this study, produced either by fast pyrolysis or hydrothermal liquefaction.
Cellulosic ethanol/butanol	Ethanol or butanol produced from lignocellulosic materials such as agricultural residues or wood.
Central North Island	Area of New Zealand including the Waikato, Bay of Plenty and Coromandel.
Char	Solid black carbonaceous material left after thermal processing of biomass.
CO_2-e	A unit to describe how much global warming a given type and amount of greenhouse gas may cause, using the functionally equivalent amount or concentration of carbon dioxide (CO_2) as the reference. For example, emissions of 1 tonne of methane is equivalent to 21 tonnes of carbon dioxide.
Conventional ethanol	Bioethanol produced by fermenting edible carbohydrates from starch and sugar crops.
Conventional forests	In this study, plantation-grown *Pinus radiata* forests grown on a 30-year rotation to maximise timber production, but producing a range of different logs and forest residues.
Conversion technology	Process for converting a feedstock plus other intermediates to produce products.
Co-product	Material or energy that is produced at the same time as the main product.
Discounted cost	A commonly-used way of determining the cost, taking into account the time value of money. It involves discounting the cost by using the cost of capital (7% in this study) to determine the present value of the cost.
Distributed processing	Distributed processing utilises small-scale facilities to pretreat the biomass close to the biomass collection points to increase its density before it is sent to a larger centralised plant for conversion into the final biofuel.

Drop-in biofuel	A hydrocarbon fuel produced from biomass that is chemically identical to its fossil fuel equivalent. It can be used in existing engines and fuel distribution infrastructure without significant modification.
Electric vehicle	Vehicles charged from an external electricity source, operating either only on batteries or, using a combination of batteries and a conventional engine – called plug-in hybrid electric vehicles.
Energy crops	Crops grown specifically for energy production. In this study, miscanthus and willow.
Energy forests	Short rotation forest plantations targeting maximum wood production. A 15-year rotation *Pinus radiata* forest is assumed in this study.
Food crops	Crops capable of being used to produce food. Examples from this study include canola, sugar beet and maize.
Forest residues	In this study, the mix of cutover residues and landing residues recovered from a conventional [plantation] forests (Box 7).
Fuel family	Here, the group of biofuels which could replace a type of fossil fuel, *e.g.* petrol, diesel, aviation or marine fuels.
GDP	Gross domestic product - the total value of everything produced by all the people and companies in a country.
Greenhouse gas	Gases in the atmosphere that absorb and re-emit radiation reflected from the earth, particularly in this study, carbon dioxide and methane.
Indirect land use change	Change in the use of land elsewhere occurring indirectly as a result of displaced demand previously destined for food, feed and/or fibre markets, owing to biofuel demand.
Land class	Productive land varies in quality, so 5 land classes are used in this study to indicate the suitability of land for growing feedstock crops.
Land use capability class	Land use capability classes indicate the potential productive use of an area of land. They do not necessarily reflect its current use.
Land use change	Change in the purpose for which land is used by humans, *e.g.* conversion of forestry to dairying.
Landed price	The cost of importing fossil fuel to New Zealand, which includes the cost of purchasing the fuel, shipping it to New Zealand, insurance and losses, and wharfage and handling.
L-e of fuel	Litre equivalent on an energy basis. Typically used to compare biofuels with different energy content. For example 1 litre of ethanol corresponds to 0.62 litres of petrol, as the energy content of ethanol is lower than that of petrol.
Levelised biofuel cost	An economic assessment of the average per litre cost of constructing and operating the whole value chain over the timeframe modelled, widely used in the energy sector to compare different methods of energy production.
Lignocellulose	The major structural component of woody and non-woody plants, consisting of carbohydrate polymers (cellulose and hemicelluloses) and lignin.
Municipal solid waste	In this study, the putrescible or green part of the waste collected by municipalities (mainly garden and kitchen waste).
Pyrolysis/upgrading	Combination of two processes in which the first one (fast pyrolysis) produces an intermediate bio-oil from lignocellulosic biomass and the second one (upgrading) produces a mixture of drop-in petrol and diesel by reacting the bio-oil with hydrogen.

Renewable diesel	A hydrocarbon fuel produced by reacting fats and waste oils with hydrogen, which can be used as a direct replacement for diesel.
Renewable jet	A hydrocarbon fuel produced by reacting fats and waste oils with hydrogen, which can be used as a replacement for jet fuel.
Scenario	A possible future outcome for modelling. In this study, this would be a required level of biofuel substitution, while meeting other constraints.
Sulfur oxides (SO_x)	Sulfur oxides are compounds of sulfur and oxygen, particularly sulfur dioxide and sulfur trioxide, which are precursors of acid rain and important in particulate pollution. Sulfur oxide emissions are mainly due to the presence and burning of sulfur compounds in the fuel.
Syngas	Synthesis gas. A mixture of hydrogen and carbon monoxide produced by gasification of biomass and/or fossil materials.
Technology readiness level	A scale used to assess the commercial readiness of technologies (Box 10).
Value chain	A set of activities that are performed to transform raw materials into a valuable product or service.
Waste wood	Wood sent to landfill, including construction and demolition waste.

Abbreviations

$	New Zealand dollar
bbl	Barrels - of oil (158.9 L)
BVCM	Bioenergy Value Chain Model
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
COP	Conference of Parties
ETI	Energy Technologies Institute
ETS	New Zealand Emissions Trading Scheme
EV	Electric vehicle
GDP	Gross domestic product
GHG	Greenhouse gas
GST	[NZ] Goods and Services tax
ha	Hectare
kg	Kilograms
km	Kilometres
L	Litre
L-e	Litre equivalent in energy basis
LPG	Liquefied petroleum gas
LUC	Land use capability
MPI	[NZ] Ministry of Primary Industries
M	million
m^3	cubic metres
NZ	New Zealand
NZU	New Zealand Units (in ETS)
odt	Oven dried tonnes
OECD	The Organisation for Economic Co-operation and Development
PJ	Petajoules
SO_x	Sulfur oxides
TRL	Technology readiness level
US	United States
yr	Year

New Zealand Biofuels Roadmap Technical Report

Table of contents

Executive summary 3
Glossary 5
Abbreviations 8
1 Introduction 11
1.1 Fossil fuels and their effect on the environment 11
1.2 Biofuels and how they can help reduce GHG emissions 11
1.3 Additional benefits of biofuels to New Zealand 12
1.4 Global biofuels growth 12
1.5 Need for this study 13
1.6 Study purpose 13
1.7 How the study was carried out 14
1.8 Outline of the report 15
2 Current situation 16
2.1 Fuel sources and distribution 16
2.2 Fuel uses 17
2.3 Greenhouse gas emissions from current fuels 19
2.4 New Zealand Greenhouse gas reduction targets 20
2.5 Future fuel demand 20
2.6 Biofuels 24
2.7 Biofuel value chain 27
2.8 Alternatives to liquid fossil fuels 28
2.9 Biofuel implementation barriers 30
3 Quantitative modelling 32
3.1 Description of Bioenergy Value Chain Model 32
3.2 Overview of how the BVCM was used in this study 33
3.3 Model inputs 35
3.4 Greenhouse Gas Emissions 42
4 Results from 30% substitution scenarios 44
4.1 Feedstocks and fuels 44
4.2 Where are feedstocks and fuels produced? 46
4.3 Regional development opportunities 52
4.4 Infrastructure and services 52

4.5 Fuel distribution 53
4.6 Opportunity scale 54
4.7 Greenhouse gas emission reduction 55
4.8 Cost of biofuels 56
5 Results of other scenarios 61
5.1 Different levels of biofuel substitution 61
5.2 Complete substitution by biofuels 64
5.3 Producing specific fuel types 64
5.4 Residuals and by-products 66
6 Additional considerations 67
6.1 Technical risk 67
6.2 Land use considerations 69
6.3 Timing 70
6.4 Competition for biomass 71
6.5 Environmental and social implications 72
6.6 Implications across the biofuel value chain 73
7 Future narratives 74
8 Study findings 77
9 Way forward 78
9.1 Next Steps 80
10 References 81
11 Appendices 85
11.1 Appendix 1 – Maps showing BVCM grid 85
11.2 Appendix 2 – Crops modelled 87
11.3 Appendix 3 - Feedstock descriptions 88
11.4 Appendix 4 - Technology descriptions 90
11.5 Appendix 5 - Biofuels 92

1 Introduction

Liquid fuels drive the New Zealand economy. New Zealand consumed 8.6 billion litres of liquid fuels in 2015 [1].[1] This volume is equivalent to 1,910 litres per year (or 5 litres per day) for every one of the country's 4.6 million inhabitants.

This amount of fuel is needed because New Zealand has a small population spread over a large area. Nearly 7.2 billion litres of liquid fuels were used domestically in 2015 to transport people and goods around the country [1] and in a range of off-road industries such as agriculture, forestry, fishing, construction, mining and tourism. On top of this, a further 1.4 billion litres of liquid fuels were sold in 2015 for getting our exports to market and flying inhabitants and tourists to other parts of the world.

Almost all liquid fuels currently used in New Zealand are derived from imported fossil fuels.

1.1 Fossil fuels and their effect on the environment

Fossil fuels come from the fossilised remains of decayed plants, algae and animals. These organisms absorbed carbon dioxide from the atmosphere and converted it into other carbon-containing compounds as they grew. After they died, their decayed remains were exposed to heat and pressure in the Earth's crust over hundreds of millions of years and formed underground deposits of oil and gas. These deposits were a massive carbon store but are being returned to the atmosphere in the form of carbon dioxide (CO_2) as the fossil fuels are burnt. Increased levels of CO_2 and some other gases in the atmosphere trap heat like the glass in a greenhouse so are commonly known as "greenhouse gases" (GHGs). Levels of these gases are increasing and are causing the overall temperature of the Earth's atmosphere to rise because they reduce the amount of heat loss. Human activities such as combustion of fossil fuels, agriculture and industrial processes are key sources of GHG emissions and have been correlated with the steep rise in global mean temperature since the beginning of the industrial revolution [2]. Increases in the Earth's temperature are also affecting weather patterns, causing more extreme droughts, storms and floods. This effect is often called "climate change".

Combustion of liquid fossil fuels was responsible for approximately 23% of New Zealand's domestic GHG emissions in 2015, so reducing these will have a big impact on lowering carbon emissions overall [3].

1.2 Biofuels and how they can help reduce GHG emissions

One way to reduce GHG emissions from liquid fuels is by producing them from renewable biological sources such as agricultural or forest crops. Such fuels are known as biofuels. Biomass[2] captures CO_2 from the atmosphere during its growth, so the GHGs released on combustion of biofuels produced from such crops have only been locked up temporarily in the biomass. When the same amount of carbon that was burnt is re-captured by the next generation of crops and forests then the overall process is considered to be low-carbon, reducing the contribution to global warming.

Government representatives from around the world attended an Earth Summit held in Rio de Janeiro in 1992 to develop a plan aimed at stabilising atmospheric concentrations of GHGs. A Conference of Parties (COP) is held annually to review the implementation of this plan. The COP held in Paris in 2015 led to a legally binding and universal agreement on climate. The Paris Agreement's central aim is to strengthen the global response to the threat of climate change by keeping the global temperature rise this century well below 2ºC above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5ºC [4]. New Zealand is one of the parties to this agreement and has committed to reducing its GHG emissions to 30% below 2005 levels by 2030 [5].[3]

[1] 2015 is used as the benchmark year throughout this study.
[2] Renewable organic materials, such as wood, agricultural crops or wastes, and municipal wastes, used for bioenergy and biofuel production.
[3] Discussed further in Section 2.4.

Replacing liquid fossil fuels with biofuels can play an important part in the overall strategy to reduce the GHG emissions caused by energy use in New Zealand [6]. Other complementary parts include: greater energy efficiency; greater use of public transport; moving goods by rail/ship instead of trucks;[4] and increased use of electric vehicles (EVs).

1.3 Additional benefits of biofuels to New Zealand

Biofuels offer a number of benefits in addition to GHG reduction such as increased gross domestic product (GDP), employment and an improved economic situation for New Zealand. For example, the industry-developed New Zealand Bioenergy Strategy [7] envisages biofuels providing 30% of the country's transport fuels and meeting 25% of its energy needs by 2040, enabling [8]:

- Greater security of fuel supply via reduced reliance on imports.
- Economic growth, leading to a gain of +1.2% in GDP[5] ($6.2 billion/yr) and a +1.2% improvement in balance of payments (~$2 billion/yr) over business as usual.
- Employment growth leading to an extra 27,000 regional jobs.[6]
- New business opportunities for existing land owners, including Māori who own more than 300,000 ha of land suitable for afforestation.
- An improved carbon footprint for New Zealand exports and the New Zealand tourism sector, which might become important if the country's export markets start to focus more on the embodied carbon in imported goods and perhaps even services (tourism) [9].
- Reduced erosion and nitrogen leaching if forests replace pasture.
- Development of associated industries, *e.g.* bio-based chemicals and new skills growth.

1.4 Global biofuels growth

Global liquid biofuel production has increased steadily over recent years (Fig. 1.1) and biofuels now account for an estimated 4% of all fuels used for road transport in 2016 [10]. Levels of transport biofuels vary widely, with Brazil now powering more than a quarter of its road transport by biofuels.

The main motivations for growth have been environmental benefits, rural economic development and security of fuel supply, with the relative importance varying in different parts of the world. Implementation to address these concerns has been driven largely by Government policy interventions.

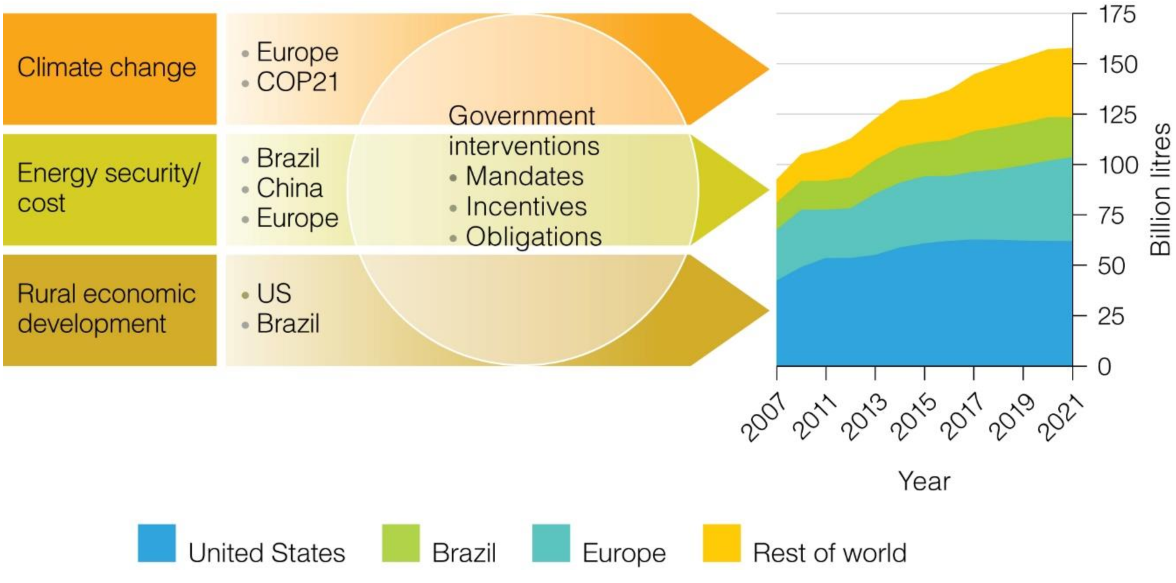

Figure 1.1: Growth in world biofuel production.[7]

[4] Transport of freight by rail on a per tonne kilometre basis produces about one third the GHG emissions, and coastal shipping about two thirds the GHG emissions of road transport [6] .
[5] New Zealand's GDP in the year to December 2015 was $245 billion.
[6] Approximately 1.1% of national employment.
[7] The biofuel production graph is from ref. [10].

All these drivers for biofuel growth, environmental benefits, rural economic development and security of fuel supply also exist in New Zealand.

Furthermore, it is increasingly likely that, as sustainability becomes more important in world trade, market pressure will dictate that New Zealand exporters of goods and services (*e.g.* tourism) show a greatly reduced GHG footprint and move to low-carbon transport fuels. Unless this country has clearly demonstrated low GHG transport fuel production it faces the risk of non-tariff barriers to entry in many markets.

1.5 Need for this study

Despite all their benefits, and the drivers for biofuel deployment existing in New Zealand, biofuels currently account for less than 0.1% of liquids fuels used in New Zealand and are not yet widely seen as an option for New Zealand. This situation reflects that:

- the scale and complexity of the opportunity is daunting, making it too difficult to know where to start,
- there is no existing large-scale biofuel value chain linking feedstock production, conversion and fuel distribution, and
- viable business cases for investing in biofuel production are currently difficult to prepare, as both biofuel production costs and the technical risk are too high.

All these challenges have already been overcome in different ways in other parts of the world, so there is a real opportunity for New Zealand to leverage this international investment, knowledge and experience to come up with a fit for purpose biofuel deployment.

A first step in defining how biofuels could be deployed in New Zealand is to identify which of the huge number of crop, feedstock, and conversion processes and biofuel options being used or developed overseas are best for this country. In answering this question, a large number of interrelated factors need to be considered, as do answers to four key questions (Fig. 1.2).

Biofuels will only be a part of New Zealand's future low-carbon economy, and will complement other options as the country transitions to a more sustainable society.

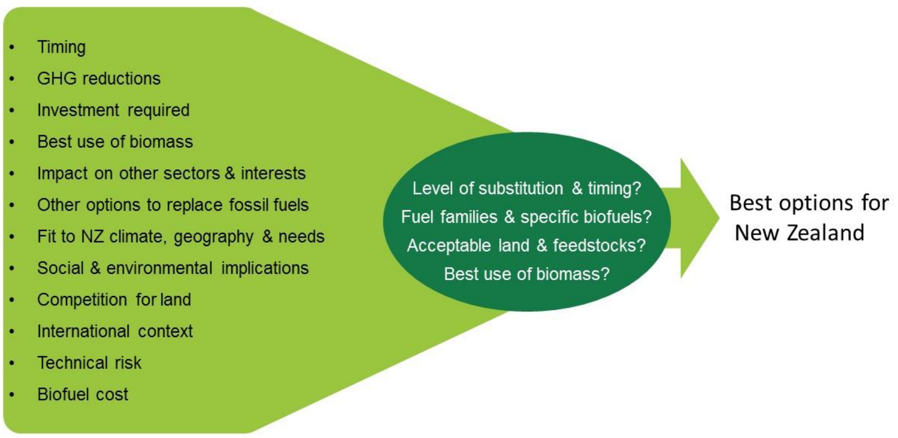

Figure 1.2: Factors and questions critical to defining the best option(s) for large scale production and use of liquid biofuels in New Zealand.

1.6 Study purpose

The overall aim of this study was to:

- provide robust objective information to inform and stimulate debate on large scale production and use of liquid biofuels in New Zealand, and
- start cutting through the complexity and narrowing down from amongst the large number of feedstock, conversion processes and biofuel options those best suited to New Zealand.

This study will enable businesses, government and communities to have an informed discussion about the future role for liquid biofuels in New Zealand and to begin to understand the implications, options and trade-offs required for growing, processing and using biomass to produce biofuels. It complements other studies showing what New Zealand needs to do to transition to a low-carbon economy [6, 11, 12].

1.7 How the study was carried out

This study was carried out in two closely inter-related parts.

Quantitative scenario modelling
Quantitative scenario modelling was used to 'look into the future' and create scenarios of what large scale production and use of biofuels in New Zealand might look like out to 2050 and to identify the lowest cost biofuel value chain(s) under the different scenarios.

Quantitative modelling, and in particular mathematical optimisation techniques, are able to explicitly address the trade-offs between the millions of alternative choices within a value chain. Optimisation models are widely applied in many industries, with applications including resource allocation, process selection, transportation, facility location, inventory management, production scheduling and infrastructure planning. The biofuels value chain in New Zealand includes elements of many of these applications, so is well suited to analysis using an optimisation approach.

There are a huge number of possible feedstock, technology and futures we could envision for New Zealand and include in our modelling. For this first-of-a-kind study for New Zealand we selected a limited number of exemplar feedstocks, conversion technologies and fuels. These spanned a broad range of potential feedstock and conversion technology options, and were all grown or operated under "typical" conditions.[8,9] We also assumed today's knowledge, costs, infrastructure and business environment were retained for the whole modelling period.[10] Crop choices were focussed on crops which are already or could realistically be grown at large scale in New Zealand and conversion technologies which are either commercially mature or are relatively well developed with reliable process and cost data.[11]

While these assumptions are clearly rather artificial, they can still lead to valuable information on the sorts of solutions which are favoured and the factors important in determining the lowest cost solutions, as well as identifying issues and possible solutions.

This modelling did not set out to identify the single "best" pathway for biofuel implementation in New Zealand. Rather, it was used to give the impacts, implications, and consequences of answering multiple "what-if" questions. The aim here was to provide objective information to inform and stimulate debate covering a wide range of possible futures.

Qualitative analysis
A parallel qualitative component of the study was undertaken to understand in detail the issues, implications and potential barriers facing biofuel implementation in New Zealand. In particular, there are many considerations such as the technical risks associated with new technologies, social and environmental implications and competing uses for biomass that are difficult to deal with by quantitative modelling.

Furthermore, many countries, including Brazil, Sweden and the United States, are further down the path to implementing biofuels, so their experience provides valuable lessons and perspectives for this country.

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[8] The aim was to remain feedstock, biofuel and technology neutral and avoid eliminating potentially attractive options by narrowing down the options at this stage.
[9] Each scenario took a long time to reach a solution, up to 2 weeks. Consequently the number of options included needed to be limited and the way in which we modelled different parts of the value chain simplified so that the model would solve in a reasonable timeframe.
[10] One exception here is that the modelling assumes immature conversion technologies mature, so costs drop and yields increase with time.
[11] Meaningful results from quantitative modelling needed reliable input data on crop growth and costs as well conversion process technology yields and costs.

A third early component of the study involved interviewing key stakeholders from across the potential future biofuel value chain[12] to gauge their thinking and understanding of biofuels in New Zealand. Although the results of this component of the project are reported elsewhere, this provided critical input into the other components of the project [13].

Stakeholders from each part of the future biofuels value chain were extensively involved in the entire process, including participating in interviews, workshops, and shaping the scenarios. This helped ensure that the issues, concerns and implications around all parts of the value chain were identified, so that future deployment of biofuels can become a reality.

We envision this initial broad study as a "conversation-starter", which could be followed up in future by more focussed studies to probe favoured options, consider what happen under different possible futures, include new technologies options, or to explore other "what ifs".

Scope

The study focuses on:

- large scale production and use of liquid biofuels in New Zealand out to 2050, and
- narrowing down a broad range of options to find the best solutions for New Zealand.

The following were not covered in detail in the study.

- Evaluation of niche applications which could provide one-off opportunities in specific locations or situations. Pursuing such opportunities is nevertheless very important to build the confidence, expertise and public buy-in needed for large-scale implementation.
- Predicting New Zealand's future fuel demand. Available public information was used.
- A detailed comparison of biofuels against other options to replace liquid fossil fuels, such as electric vehicles (EVs), or biofuel production against other potential biomass uses.

1.8 Outline of the report

The remainder of this report is structured as follows. Chapter 2 gives an overview of current fossil fuel use in New Zealand and introduces how liquid biofuels are currently produced and used globally and in this country. The quantitative scenario modelling is introduced in Chapter 3. We next describe the results of a number of possible future biofuel deployment scenarios in Chapters 4 and 5. Chapter 6 introduces a number of additional considerations which are not covered in the quantitative scenario modelling, but which will impact on final choices. Then, to illustrate these findings, Chapter 7 presents five hypothetical "future narratives", or possible futures for New Zealand, and discusses how biofuel deployment in New Zealand could play out in each case. The report concludes with a summary of the study findings in Chapter 8 and how to move forward in Chapter 9.

This report complements the companion Summary Report which outlines the key messages, conclusions and suggested next steps from the study in less technical detail. It can be found at www.scionresearch.com/nzbiofuelsroadmap, together with the report summarising the results of the stakeholder interviews [13].

[12] A value chain is a set of activities that are performed to transform raw materials into a valuable product or service.

2 Current situation

Liquid fuels, derived largely from fossil oil provide almost half (46%) of New Zealand's total consumer energy. This Chapter describes the use of the different fossil fuels in New Zealand and trends in future liquid fuel demand. We then provide an overview of the biofuels being used or developed globally, including their status in New Zealand, and finish by introducing the future biofuel value chain and key barriers to its implementation.

2.1 Fuel sources and distribution

Supply

New Zealand imports almost all (~98%) of its liquid fossil fuel from overseas as a mix of crude oil and refined fuels. These liquid fossil fuels, totalled 7.3 million tonnes in 2015 and were worth $6.1 billion, or nearly 10% of New Zealand's total imports [1, 14].

New Zealand also produced 1.9 million tonnes of crude oil in 2015 [1]. Almost all of this was exported, because our crude oil has a low sulfur content, while the country's sole refinery is geared to process lower-value high-sulfur crude.

Demand

New Zealand consumed 8.6 billion litres of fossil fuels in 2015. Domestic consumption of liquid fuels was at its highest level since 2007, with 7.2 billion litres used domestically to transport people and goods around the country by road, rail, sea and air, as well as off-road in industries such as agriculture, forestry, fishing, construction, mining and tourism [1]. A further 1.4 billion litres were used for transporting people and goods to other countries.

New Zealand per capita fuel consumption is amongst the highest in the world, reflecting one of the highest car ownership rates in the OECD, a sparse population, limited public transport, and a relatively old and inefficient vehicle fleet [15].

The vast majority of liquid fuel use is as petrol, diesel, marine fuel and aviation fuel (Fig. 2.1). Domestic and international transport is the largest oil-consuming sector, accounting for 85% of total liquid fuel demand.

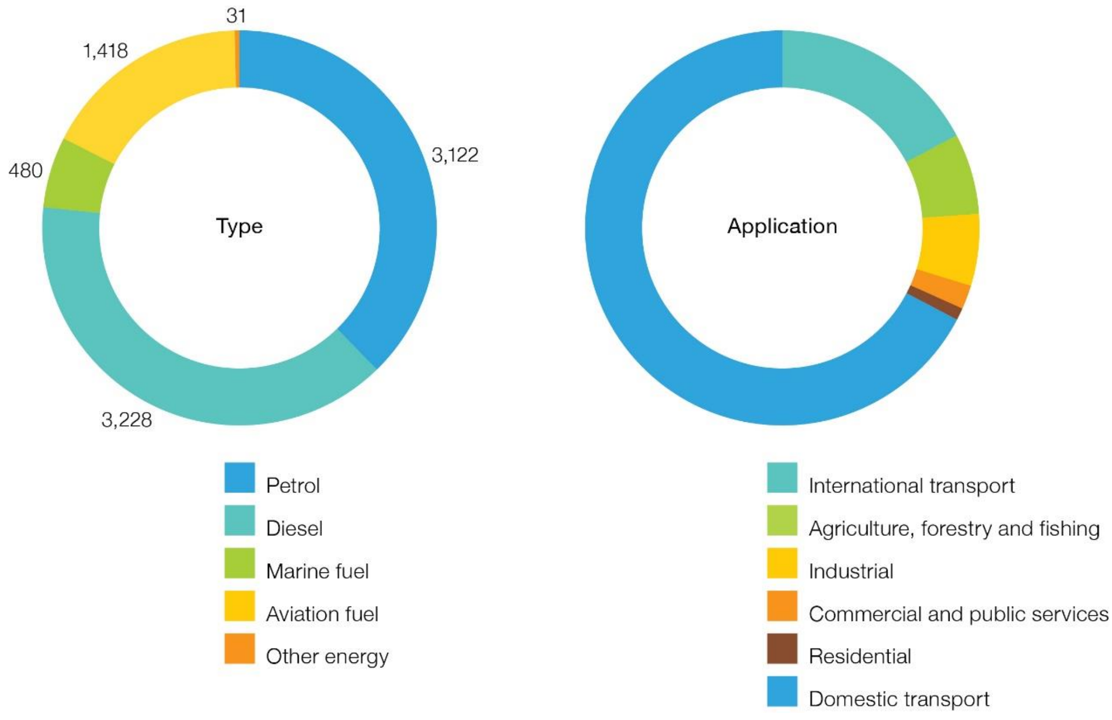


Figure 2.1: Liquid fuel use in New Zealand in 2015, by fuel type (million litres) and application [16].

Distribution

Most of our fuel (72%) is imported as crude oil for refining at Marsden Point. RefiningNZ charges a toll for doing this; in 2016 the three oil majors (BP, Mobil and Z Energy) owned 65% of the refinery, with the rest held by other investors. Each of these companies organise their own crude oil imports and distribution.

Additionally, all three oil majors import refined fuel, mostly petrol and diesel coming in to Mt Maunganui, Wellington and Lyttleton. A fourth company, Gull New Zealand, also imports some refined fuels for distribution through its own North Island network.[13]

Oil products distribution in New Zealand is problematic because of the country's shape (long narrow islands), its mountainous topography and low population density. A pipeline transports about 40% of Marsden Point's output to storage at Wiri in South Auckland. Most of the remaining refined fuel is distributed by ship to distribution terminals at or close to the country's ports. Road tankers, marine barges and pipelines then move fuel to retail service stations, truck stops and commercial customers.

The demand for fuel varies across the country, driven in the first instance by population. Demand for the various fuel types varies by region, with, for example, most of the jet fuel used in Auckland, Christchurch and Wellington [1].

2.2 Fuel uses

Petrol

Nearly 98% of petrol is used in the transport sector, mostly in light passenger vehicles (Box 1) [16].

Box 1: New Zealand's vehicle fleet

New Zealand had a total vehicle fleet of 4.0 million in 2016, with the majority being light passenger and commercial vehicles [18]. There is no car manufacturing industry in New Zealand, so all vehicles are imported, mainly from Asia. Many used vehicles are also imported (mostly from Japan) so that half of New Zealand's light passenger vehicle fleet has already been used overseas.

Type	Numbers (000s)	Average age	Proportion of used imports (%)	Fuel type [a,b]
Light passenger	3,094	14	50	Petrol (90%), Diesel (10%)
Light commercial	537	13	19	Diesel (79%), Petrol (21%)
Truck	139	18	35	Diesel (>97%)
Bus	10	17	36	Diesel (>97%)
Motorcycle	164	16	24	Petrol (>99%)

[a] By distance travelled.
[b] Excludes EVs (~2,500 in 2016 [19]), hybrids (~18,500) and small numbers powered by compressed natural gas or liquefied petroleum gas.

The country's light vehicle fleet is relatively old by international standards. This, coupled with the high proportion of used imports and no domestic vehicle manufacturing or assembly industries, means it will be difficult and slow to deploy a biofuel which could only be used in new vehicles.

[13] Gull has an approximate 5% market share [17].

Box 2: Fossil fuel types

Fossil fuels are mixes of hydrocarbons, which are chains of carbon atoms with attached hydrogens. In a petroleum refinery, crude oil is processed into fractions having different boiling points, properties, applications and carbon chain lengths [20, 21].

Fuel type	Typical boiling point range (ºC)
Petrol	38 - 204
Jet fuel	140 - 280
Diesel	180 - 360
Marine fuel	>350

Diesel

Diesel is the primary fuel used for commercial land transport (Box 1), so its use is strongly linked to the country's economic performance. Approximately 70% of the diesel is used for domestic transport, split between heavy commercial vehicles (45%), light commercial vehicles (32%), light private vehicles (18%) and buses and rail (3%).

The remaining 30% of diesel is used in off-road applications such as in agriculture, forestry and fishing, as well as in industry for applications such as mining and construction.

Aviation fuel

As a remote nation, air services are vital to New Zealand's economy; with almost all tourist arrivals, 14% of exports and 22% of imports by value being carried by air [22]. Domestic aviation is also extensively used to travel between regions.

Jet fuel powers most turbine and jet engine aircraft. In 2015, domestic flights consumed 0.3 billion litres of jet fuel, and international flights a further 1.1 billion litres [1].[14]

Marine fuel

Shipping is also critical to the New Zealand economy. Ships moved 99.5% of New Zealand's international trade by weight [23]. In 2015, international shipping consumed 0.3 billion litres of fossil fuels, while coastal shipping and fishing used a further 0.2 billion litres [1]. Shipping is an efficient mode for moving goods on an energy per tonne-kilometre basis, so coastal shipping is used for transport of bulk products such as fuel, fertilizer and cement.

A concerted international push away from high-sulfur heavy fuel oils (the dominant marine fuels, permitted to have up to 3.5% sulfur) is underway to decrease sulfur oxide (SO_x) emissions. It is estimated that shipping accounts for 4–9% of all global sulfur oxide emissions. As a result, international regulatory bodies such as the International Maritime Organisation have introduced regulations to limit SO_x emissions from shipping [24]. A global limit of 0.5% sulfur in fuels used outside emission control areas will come into force in 2020, whilst special emission control areas have been established where the sulfur content of fuels is even lower, < 0.1%.[15,16]

This move to low-sulfur fuels provides an opportunity for biofuel use in marine applications, as biomass has a low sulfur content, so the biofuels would readily meet new limits of 0.5% sulfur. Other alternatives to biofuels include using higher-priced distillate fuels, liquefied petroleum gas (LPG), or installing on-board scrubbers to remove sulfur oxides. All these options add cost [26-28].

[14] A small amount of aviation gasoline is also used to power aircraft with piston-engines (14 million litres in 2015).
[15] New Zealand has yet to sign up to Annex VI of the International Convention for the Prevention of Pollution from Ships (Marpol), but is considering doing so [25].
[16] These cover areas such as the Baltic Sea and within 200 nautical miles of the coasts of the United States and Canada.

2.3 Greenhouse gas emissions from current fuels

New Zealand's net GHG emissions (gross emissions less CO_2 taken out of the atmosphere by trees) increased by 64% between 1990 and 2015. They totalled 56.4 million tonnes CO_2-e in 2015 [3].

Energy was responsible for 41% of New Zealand's gross emissions in 2015, the second largest contributor after agriculture (Fig. 2.2) [29].

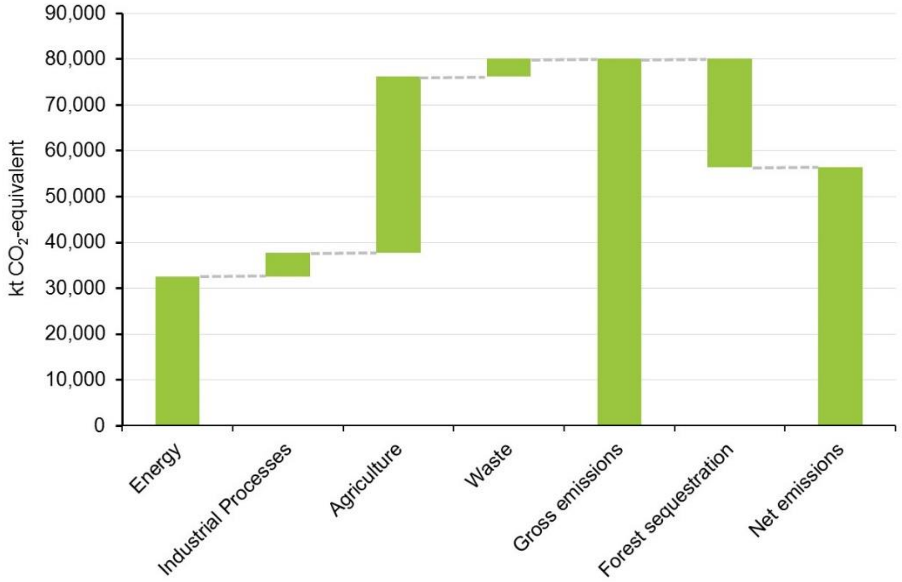


Figure 2.2: New Zealand GHG emissions by sector in 2015 [29].

Within the energy sector, liquid fuels account for 58% of emissions [30]. The rise in liquid fuel use is largely responsible for the rise in New Zealand's energy sector emissions since 1990 (Fig. 2.3).

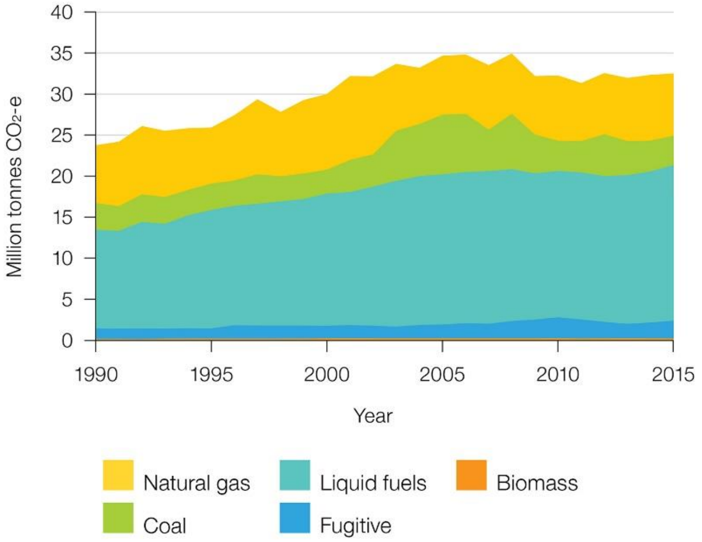


Figure 2.3: Energy sector GHG emissions by fuel type [30].

The amount of non-renewable CO_2 emitted from combustion of fossil fuels is related directly to the volume of fossil fuel consumed.[17] Consequently, reducing fossil fuel use will reduce GHG emissions.

[17] This also depends on the type of fossil fuel used. For example, the emission factor for petrol is 2.4 kg CO_2-e/L whereas diesel and heavy fuel oil have emission factors of 2.7 and 3.0 kg CO_2-e/L respectively [31].

2.4 New Zealand Greenhouse gas reduction targets

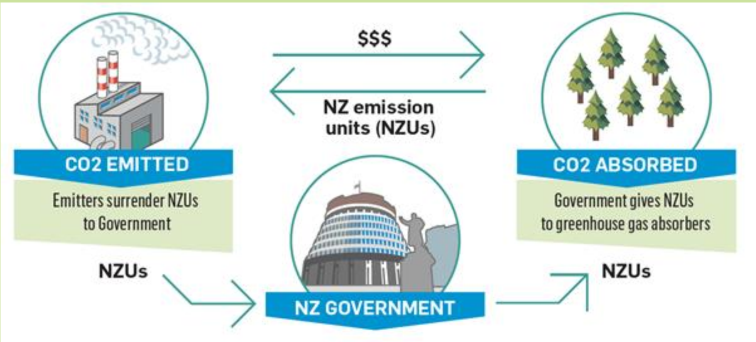
New Zealand currently (as of the end of 2016) has a series of GHG reduction targets as shown in Table 2.1 [32]. The new Government has signalled an intent to introduce a new 2050 target.

Table 2.1: New Zealand GHG reduction targets in December 2016 [32].

Year	Target	Emissions, million tonnes CO_2-e per year	
		Gross	**Net**[18]
Actual			
1990		64.6	34.5
2005		82.5	53.7
2015		82.3	56.4
Targets			
2020	Net 5% below 1990 gross emissions		61.3
2030	Net 30% below 2005 gross emissions		57.7
2050	Net 50% below 1990 gross emissions		32.3

Box 3: Emissions trading scheme

The New Zealand Emissions Trading Scheme (ETS) is a key tool for reducing carbon emissions from fossil-fuel use. By putting a price on emissions, a financial incentive exists for businesses and consumers to invest in emission-reducing technologies and practices. It also provides a financial benefit to forest growers for the carbon their trees remove from the atmosphere. The ETS works by allowing emitters and absorbers to trade emission units with the price set by the market. One emission unit (1 NZU) equals one tonne of carbon dioxide (CO_2) or its equivalent (CO_2-e) [33].



2.5 Future fuel demand

The types and quantities of liquid fuels required in the future is vital when considering options for large-scale biofuel production.

Drivers of future fuel demand

There is considerable uncertainty about what New Zealand's liquid fuel demand will be out to 2050. Long-term changes in New Zealand's fuel demand are likely to be driven by a number of factors, particularly [34]:

- population growth,

[18] Net emissions are total (gross) emissions minus the carbon dioxide taken out of the atmosphere by trees each year.

- economic growth, in and outside New Zealand,[19]
- on-going efficiency gains in vehicles and engines,
- long-term trends in future liquid fuels price and availability, and their alternatives,
- uptake of electric powertrain vehicles,
- disruptive developments such as hydrogen-fuelled vehicles, or breakthrough battery technologies,
- government policies and decision-making,
- changes to the modes of transport, *e.g.* greater use of public transport, shifting of freight from trucks to rail and ships, use of autonomous vehicles,
- future social/demographic changes such as urbanisation, digital connectivity and changing attitudes to climate change - which might alter society's attitudes towards travel, and
- global developments including supply chain disruptions due to wars, climate change and socio-political uncertainty.

The number of potential factors here and the interplay between them, coupled with the rate at which any changes might occur, make forecasting future demand complex and beyond this study's scope.

Fuel demand projections

The BusinessNZ Energy Council's BEC2050 study (see Box 4) provided credible future demand projections that were used in this study [35].

These demand projections for future liquid fuels under both their high and low use scenarios are given in Figure 2.4. As they were not included within the BEC2050 study, we also assume that the volumes of diesel used in off-road applications, such as construction and agriculture, and heavy fuel used in marine applications remain constant.[20,21]

These projections include fuel demands for international air travel and international shipping – the dominant use of both aviation and marine fuels in New Zealand.

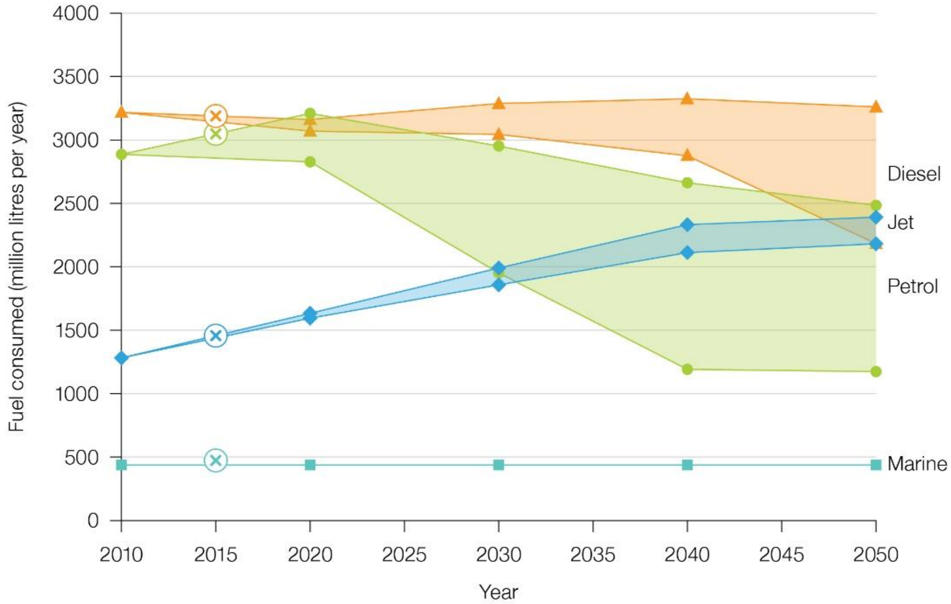


Figure 2.4: Future fuel demand projections for liquid fuels in the high and low use scenarios based on BEC2050 modelling. Actual 2015 fuel consumption volumes (crosses) are used as reference in later scenarios.

[19] Historically, population and economic growth have been the main drivers of the country's growing fuel demand.
[20] We assume off-road diesel use is 5.5 M bbl/yr (average of non-transport domestic diesel use from 2007-16), and marine fuel use is 2.4 M bbl/yr (average fuel oil used for domestic and international travel from 2010-2015) [16].
[21] While the BEC2050 scenarios provide projections on biofuel consumption, these are not considered here and biofuels are included with the respective fuel families in Figure 2.4.

Box 4: Business New Zealand Energy Council future energy demand scenarios

In their BEC2050 study, the Business New Zealand Energy Council has developed two scenarios for future energy consumption in New Zealand out to 2050, which included transport fuel demand projections [35]. They see these as boundary scenarios, with the future falling somewhere between the two scenarios. Of these two scenarios, the lower use scenario assumes a lower population and economic growth and a higher carbon price. It projects a much larger reduction in total energy sector emissions (-47 *vs* -13%) and transport fuel consumption (-20 *vs* +14%) by 2050.

Key features of the two BEC2050 energy demand scenarios.

	High use (Kayak)	**Low use (Waka)**
	Markets drive supply chain decisions and innovation, with businesses and consumers making informed decisions in their own interests based on price and quality.	Changing global circumstances and heightened environmental awareness drive business, consumers and government to make decisions in the national interest.
Population	+ 0.9%/yr	+ 0.6%/yr
Per capita GDP	+ 2.1%/yr	+ 1.6%/yr
Carbon price in 2050, $\$_{2011}$/t CO_2-e	60	115
Energy sector carbon emissions in 2050 *vs* 2010 actuals	-13%	-47%
Light vehicle fleet		
Total distance driven	+56%	+10%
Vehicle km travelled per capita by 2050		27% lower than for the high use scenario
EV penetration	31%	66%
Transport fuel consumption	+ 14%	- 20%

Total 2050 fuel demand is projected to remain almost the same as actual 2015 demand in the high liquid fuel use scenario, but to decrease by approximately 30% in the lower use scenario. However, in both cases the mix of fuels required changes significantly.

Jet demand is projected to rise under both scenarios,[22] while diesel demand remains either relatively constant or decreases.

Petrol demand decreases under both scenarios, but more so under the low use scenario, due to reduced private vehicle travel and greater penetration of EVs into the light vehicle fleet (66% of the light vehicle fleet is EVs in 2050).

Even in the low use scenario, almost 6 billion litres of liquid fuels will still be required in New Zealand in 2050.

[22] Other government studies support a continued growth in international air traffic activity (+3.4%/yr) out to 2050, with the consequent increase in jet fuel demand [22].

Fossil fuel costs

Currently, taxes and levies make up almost half the final retail cost of petrol, so the cost of the fossil fuels is only one part of the actual pump price (Fig. 2.5) [36, 37].[23,24]

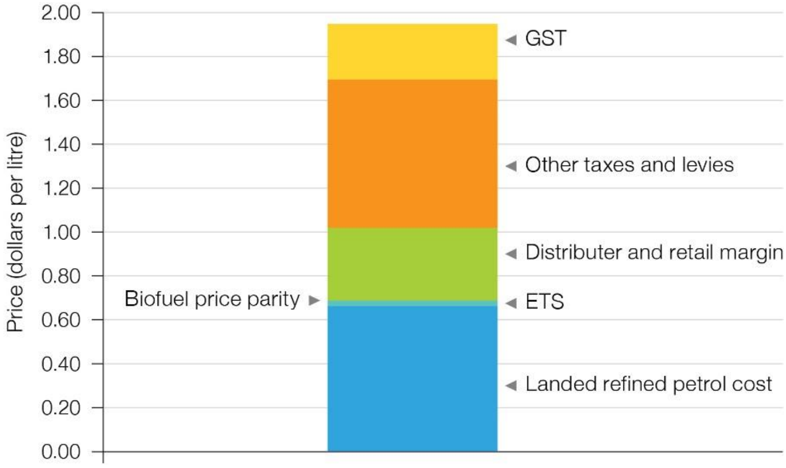


Figure 2.5: Retail petrol price breakdown for the week starting 17 February 2017 [36, 37].

Fossil fuels are a volatile commodity and consumers are very sensitive to the fuel cost, either directly at the pump, or indirectly via goods and services they purchase (Fig. 2.6).

While most of the fuels used in New Zealand are produced from imported crude oil processed at RefiningNZ, almost one quarter is imported as refined product. The cost of this landed refined fuel provides a good indication of the New Zealand cost of fossil fuel (Fig. 2.6). The landed refined fuel cost is heavily influence by both the cost of crude oil and the US/NZ dollar exchange rate.

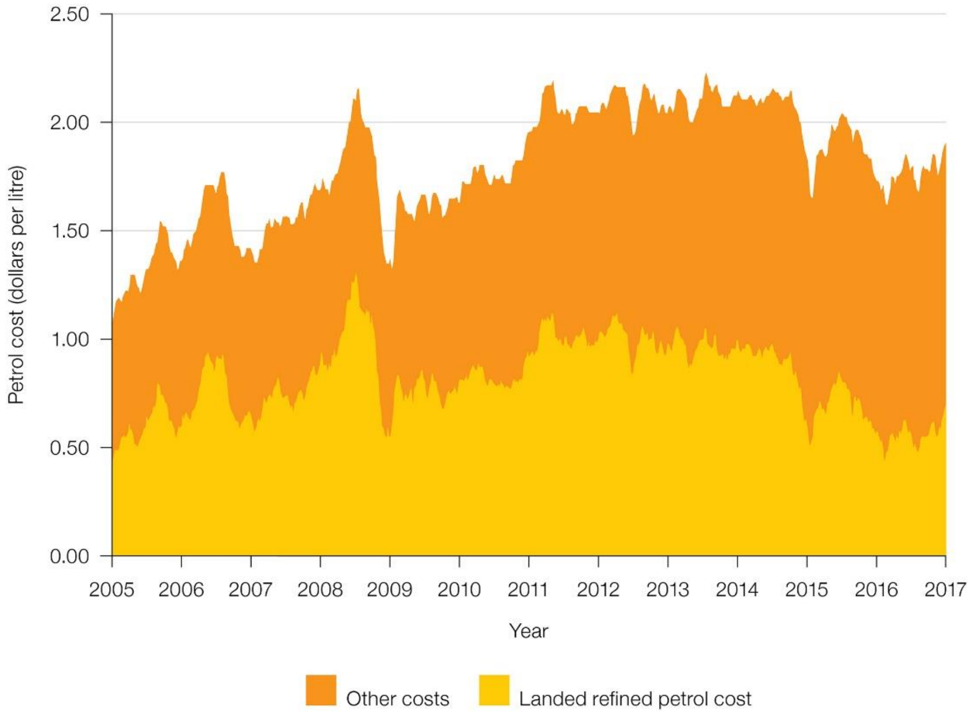


Figure 2.6: Variation in the retail price of petrol and landed refined petrol cost since 2005 [37].

[23] Diesel vehicles used on-road are subject to road user taxes rather than the excise tax, as a significant portion of the diesel is used off-road.

[24] As combustion of fossil fuels falls within the ETS, motorists are charged on a per-litre basis for the carbon emitted when using the fuel. This depends on the price of carbon under the ETS. Phasing out of the one-for-two transitional measure in the ETS over 3 years starting in 2017 will increase this tax.

2.6 Biofuels

Global liquid biofuel production for transport, predominantly on-road, has increased steadily over recent years (Fig. 2.7) and accounted for an estimated 4% of global road transport fuel use in 2015 [10]. In Brazil, biofuels now power more than a quarter of its road transport.

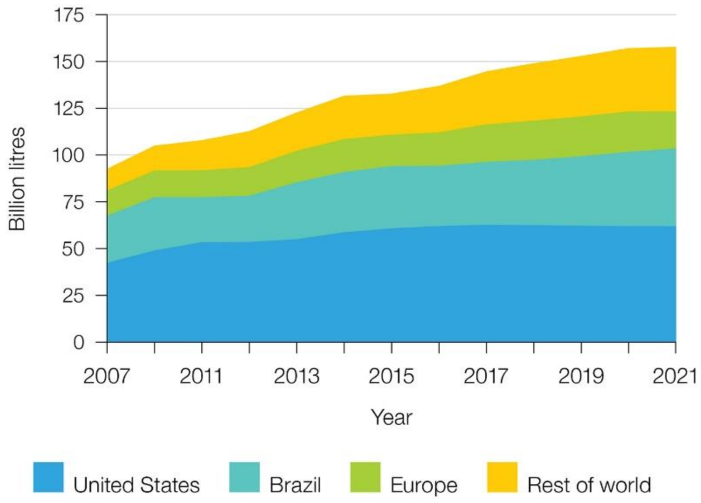


Figure 2.7: Global biofuel production [10].

There is a great potential for New Zealand to leverage this international experience in implementing biofuels based on our availability of land, temperate climate and strong agricultural and forestry sectors.

Current liquid biofuels

The main types of liquid biofuels currently being produced globally are: bioethanol (74% of global production); biodiesel (22%); and renewable diesel (4%) [38].

Bioethanol: Bioethanol is normally used as a blend in petrol, and is made by fermenting edible carbohydrates such as starch (from corn or wheat) or sugar (from sugarcane). Such bioethanol is generally referred to as conventional or first generation ethanol, and is the dominant biofuel used in countries such as Brazil and the United States. Blends of up to 10% bioethanol in petrol can be used in most existing petrol engines without modification, while blends up to 85% bioethanol can be used in "flex-fuel" vehicles.[25] Pure bioethanol[26] is also used in Brazil.

Biodiesel: Biodiesel is produced by reacting vegetable oils such as canola[27] or soybean, animal fats such as tallow (a by-product from the meat-processing industry) or waste cooking oils with methanol to produce a fatty acid methyl ester. Biodiesel can be blended with fossil diesel, typically up to 7%, for use in existing compression engines. It can also be used in its pure form, but may require engine modifications to avoid maintenance and performance problems.

Renewable diesel: This is a mix of hydrocarbons produced by reacting fats and waste oils with hydrogen, so is distinct from biodiesel [39]. Renewable diesel is the first fully drop-in fuel, because it is chemically very similar to diesel from fossil fuels. Major limitations around the greater use of renewable diesel are the high cost of the starting fats or oils (often worth more than the final fuel[28]), the limited volumes of such feedstocks and whether biofuels should be produced from potential food crops.

[25] Flexible fuel vehicles have an internal combustion engine and are capable of operating on petrol and any blend of petrol and ethanol up to 85%. The engines can adjust operating conditions depending on the fuel they are using.
[26] A mixture of 95% bioethanol and 5% water.
[27] A variety of rapeseed that that has been selectively bred to remove undesirable components.
[28] In January 2016, for example, the cost of palm oil was US$ 0.45/L, while the price of jet fuel was US$ 0.25/L [40].

Renewable jet: This drop-in biofuel is produced via the same route used to produce renewable diesel [40]. Almost all commercial bio-jet fuels are currently produced in this way. However, bio-jet production is still only a small fraction of total global aviation fuel production.

Biomethane: This is a gas which can be produced by anaerobic digestion of biomass, and is suitable for use as a transport fuel in modified vehicles.[29] It is especially applicable in countries that already have significant vehicle fleets powered with natural gas, together with the associated gas refuelling infrastructure [41].[30] Biogas made up 1.3% of the energy used in road transport in Sweden in 2015, where it is sold, often as a blend with natural gas, for use in passenger cars, heavy vehicles and busses.

Future biofuels

There is an enormous amount of work going on globally to develop new routes to biofuels from non-food feedstocks [38]. These focus particularly on utilising cellulose-based biomass such as agricultural and forestry residues, forests and non-food energy crops, as well as municipal solid wastes and algae.[31] Such feedstocks have the advantage of not competing with food and being able to be grown on lower quality land. This opens up opportunities for much larger-scale production of biofuels than possible with edible carbohydrates.

Cellulosic ethanol: One major thrust of technology development has been on the production of ethanol from non-food feedstocks, particularly cellulose-based biomass and wastes. The first commercial cellulosic ethanol plants, which convert lignocellulosic feedstocks such as corn stover and sugarcane bagasse into ethanol have recently started to produce ethanol, whilst Enerkem has started producing ethanol from municipal solid waste in Edmonton [42].

Drop-in biofuels: Drop-in biofuels, or hydrocarbon biofuels that can be blended with existing fossil petrol, diesel, jet and marine fuels in high proportions, or used neat while still meeting existing fuel standards, are a second major focus of biofuel technology development [39]. Their chemical makeup is such that they can be used in vehicles without engine modifications and can utilise existing fuel infrastructure and distribution systems. A wide variety of biological and thermochemical processes are being developed to produce drop-in fuels from biomass. However, the routes to manufacture these new fuels have yet to be commercially demonstrated.

Biobutanol: This alcohol offers a number of advantages over bioethanol, including a higher energy density and higher blend limits in petrol [43].[32] It can be produced from the same feedstocks as bioethanol, but fermentation to biobutanol is less well developed, and the conversion yields are often lower.

Biomethanol: Fossil methanol is currently used as blend in petrol in China. It was formerly used in the United States and is permitted as a 3% blend in petrol in New Zealand.[33] While producing biomethanol from biomass is relatively simple and well proven, it has received limited attention globally because of its toxicity and low energy density.

Dimethyl ether: Dimethyl ether is a gas that has been successfully used as an alternative to diesel in specially modified trucks. Dimethyl ether can be produced either from natural gas or biomass using relatively simple and well established processes, but must be kept in pressurised storage tanks.

[29] Biomethane can also be produced chemically from woody plants using a process called gasification.
[30] In the 1980s, New Zealand led the way globally in using compressed natural gas and liquefied petroleum gas to power motor vehicles, but very few vehicles still run on these fuels.
[31] These are frequently referred to as "Advanced" or "2nd Generation" biofuels, although there is no universal agreement on how these terms are defined, so they are not used here.
[32] US fuel standards allow up to 16% in petrol.
[33] Methanol is most commonly produced from natural gas, *e.g.* at the Methanex plant in Taranaki.

Biofuel use in New Zealand

Liquid biofuels make up less than 0.1% of total liquid fuel sales in New Zealand [1].

Bioethanol is produced by Fonterra's Anchor Ethanol plants from whey, a by-product of cheese production [44]. This bioethanol, 2.9 million litres in 2015 [45], is blended with petrol and sold at retail outlets, particularly by Gull.

Retail blends are limited to a maximum of 10% bioethanol in petrol.[34] Domestically-produced bioethanol is currently supplemented with imported bioethanol produced from sugarcane.

Biodiesel production was 0.6 million litres in 2015 [45]. The largest current domestic producer of biodiesel is Green Fuels, which produces biodiesel from recycled vegetable oil [46]. Z Energy will soon start producing 20 million litres a year of biodiesel from tallow [47].[35] New Zealand retailers (i.e. service stations) are currently permitted to sell biodiesel blends of up to 7%.[36]

A number of New Zealand companies are or have been exploring the potential to produce biofuels. Some examples follow.

- Z Energy and Norske Skog, with funding support from the Ministry for Primary Industries, completed the Stump to Pump project to evaluate the commercial feasibility of producing biofuels from forest residues [48].
- Air New Zealand ran a biofuel test flight in 2008 [49].
- Air New Zealand, partnering with Virgin Australia, put out a request for information for bio-jet fuel supply [50].
- KiwiRail issued a request for proposals for supply of bio-marine fuel for their Interislander ferries.

Biofuel costs

Biofuels are currently more costly to produce than fossil fuels; one of the major barriers to their greater deployment. In addition, a significant upfront capital investment is required to begin biofuel production. Consequently most overseas biofuel implementation programmes have involved government subsidies or mandated levels of biofuel incorporation - making the retail prices of biofuels equivalent to those of fossil fuels and allowing biofuel production to begin in earnest.

Here in New Zealand, bioethanol use is currently exempt from contributions to the National Land Transport fund, providing an incentive of $0.59/L for its use. While such incentives can be a good way to get new industries started, long-term policy and policy stability are critical for investment in biofuel production plants to occur, as investments are large and investment horizons are long (10–20 years). Such incentives could have a major implication on Government revenues.

Biofuels and the ETS

Under the ETS, biofuels are considered to emit no CO_2-e except for any fossil carbon used in the production of the delivered biofuel [51].[37]

Therefore, in the absence of any other incentives, the costs of producing biofuels in New Zealand over the long term will need to be at or below the sum of the cost of importing their fossil equivalents plus any benefit under the ETS (Fig. 2.5). The profitability of domestic biofuel production will consequently depend heavily on both the landed fossil fuel price and the price of carbon under the ETS, with profitability increasing as oil prices and/or carbon prices rise.

While the ETS should provide an incentive for replacing fossil fuels with biofuels, to date it has actually provided very little incentive for consumers to switch to biofuels. Currently the ETS only

[34] Blends with a higher level of bioethanol may be sold as long as there is a commercial contract or agreement in place with the customer.
[35] Most of New Zealand's tallow is currently exported.
[36] Again higher blends are permitted if there is a contract in place with the end user.
[37] The size of the emission reduction given by biofuels depends significantly on the type of biofuel, technology and feedstock used and on how the impact of any Indirect Land Use Change is taken into account.

adds $0.04 to the current retail price of petrol of around $2.00 per litre [37], well within the volatility consumers expect due to other factors.

Carbon emissions from international aviation and shipping lie outside national GHG emission obligations.[38] Historically this has led governments to concentrate incentives on reducing road transport emissions, particularly biofuel replacements for petrol and diesel. However voluntary industry commitments to reduce carbon emissions in the aviation sector and regulatory pressure to reduce maritime SO_x emissions are now putting much greater focus on aviation and marine biofuels. For example, last year the International Civil Aviation Organization approved a carbon-offsetting strategy to cap international aviation emissions after 2020. A total of 65 nations (representing 85% of international air traffic) have indicated they will participate in the first phase of this scheme [52].

Recalling that most aviation and marine fuel demand in New Zealand is actually for trips outside New Zealand, excluding carbon emissions from international aviation and shipping has some significant impacts:

- replacing aviation and marine biofuels can only make a limited contribution meeting the country's emission reduction targets,[39] and
- the ETS would only provide an incentive to producers of marine and aviation biofuels for biofuels used in domestic applications.

Nevertheless, there could be compelling reasons for New Zealand to still pursue aviation and marine biofuels. In addition to meeting growing demand by airlines and shipping lines, aviation and marine biofuels could be key tools to decreasing the GHG footprint of New Zealand's exports of goods and services.

2.7 Biofuel value chain

A future biofuel value chain requires a number of different interlocking components, as depicted very simplistically in Figure 2.8. These include:

- growing a crop to produce a biomass feedstock, either as the main product or as a waste product,
- harvesting and transport of the feedstock to a biofuel production site,
- conversion into a biofuel, and
- distribution of the biofuel to the point of demand and it's use to power the final vehicle, ship or plane.

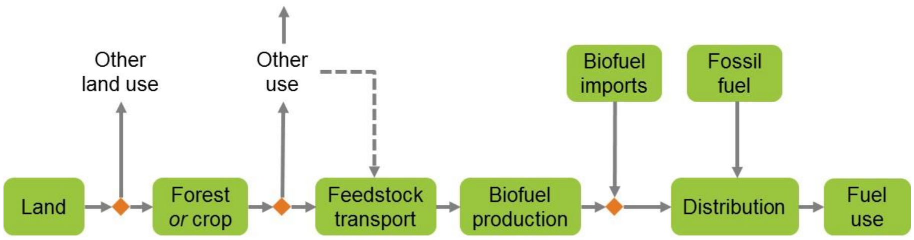


Figure 2.8: Simplistic representation of a future biofuel value chain.

This will require linking the existing agriculture and/or forestry sectors through to the energy sector; each of these sectors already having their own existing profitable value chains.

For biofuels to be adopted, every step in the value chain needs to be profitable - especially since participants at different stages have options. For example, there are different possible land use choices, growers can determine where best to sell their products, and a fuel distributor could use imported rather than domestically-produced biofuels.

[38] They are therefore not included within the New Zealand ETS and are not considered when meeting our international commitments.
[39] Domestic aviation and marine fuels make up 7-8% of total domestic liquid fossil fuel use, and are responsible for less than 2% of New Zealand's gross emissions.

No biofuel value chains of any significant scale currently exist in New Zealand.

Choosing from all the possible options to identify the best future biofuel value chains for New Zealand is extremely complex. The existence of dozens of potential feedstocks, numerous transport and conversion options, multiple fuel type (differing in demand, ease of manufacture, and price) and diverse options for obtaining or growing the feedstock, create a risk of implementing sub-optimal solutions that are not in the country's long-term best interest [38, 53-55].

There is not 'one biofuel story' for New Zealand, but many different scenarios - each with their own advantages, disadvantages, costs, market challenges and opportunities.

2.8 Alternatives to liquid fossil fuels

Biofuels are not the only option as renewable replacements for liquid fossil fuels. Others include electric vehicles, hydrogen for fuel cell-powered vehicles and gaseous biofuels. Each has its own advantages and barriers to implementation.

A mix of options will likely be the best way to decarbonise New Zealand's energy system – and include more efficient vehicles, greater use of public transport, and switching freight to more efficient models such as from trucks to rail or ship.

Alternatives to liquid fuels need to be considered not only in terms of producing the replacement energy carrier, but also in terms of how they are distributed to where they will be used, and the vehicles in which they are used. The major barriers to implementation vary depending on the option considered (Fig. 2.9).

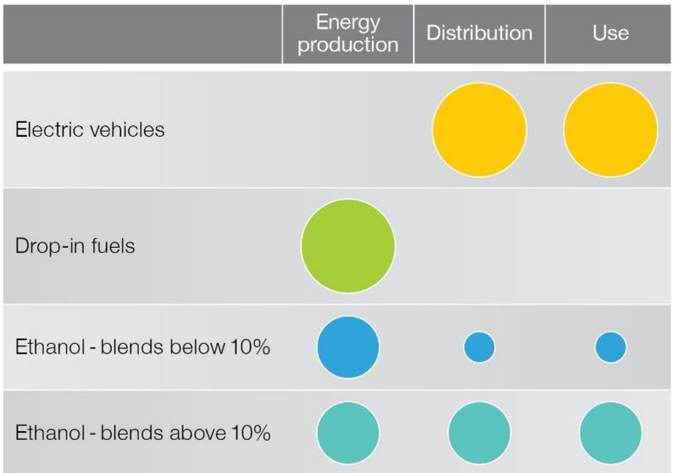


Figure 2.9: Significance of implementation barriers for different alternatives to fossil fuels. Larger dots represent bigger barriers. Modified from ref. [56].

Battery electric vehicles (EVs)

- The main barriers are the need for both completely new vehicles and a new charging infrastructure. This introduces significant financial and technical barriers.
- However, electricity is already produced and distributed at a large scale in New Zealand.

Drop-in biofuels

- The main challenge is to produce large volumes of drop-in biofuels at a competitive cost (i.e. the focus of this study).
- But once produced, drop-in biofuels can be blended with existing fossil fuels and used in existing vehicles and distribution infrastructure.

Ethanol

- While in use overseas, and able to be used in blends of up to 10% in most existing petrol engines,[40] the barriers to implementation are mostly in producing the fuel at scale.
- Blends above 10% require significant upgrades to distribution infrastructure, and modified vehicles. However these upgrades are much less radical than moving to EVs, as they are relatively minor modifications to current vehicles and infrastructure.

The best way to decarbonise the New Zealand transport sector will be application specific. EVs could replace a significant portion of New Zealand's light vehicle fleet (passenger vehicles and light commercial vehicles). But it is much more difficult to see electricity replacing liquid fossil fuels in international aviation and shipping, at least out to 2050.

This study focuses on the production of liquid biofuels.[41]

Box 5: What are sustainable feedstocks?

If large-scale production and consumption of biofuels is to take place in New Zealand, production in particular will need to be 'sustainable'. What constitutes 'sustainable biofuels' in a New Zealand context, and how this might evolve with time is still not clear [57].

But in all cases, the feedstock and land choices are critical.

Global first-generation biofuel deployment initially used existing agricultural commodity food crops such as sugarcane and corn; encouraged by government mandates in many countries. But international food shortages, tensions around best land use and food security issues have seen food crops for fuel production become an increasingly unacceptable option.

A further sustainability issue is the energy balance, or the ratio of the energy released on burning the final biofuel relative to the energy input that went into growing and processing the biomass. Some early studies reported that that more energy went into growing and processing the corn to produce ethanol than came out as fuel, but this is less of an issue with current biofuels.

Additionally, expansion of croplands due to increased global demand for biofuels also raised concerns about the land use change impacts of biofuels. For example, the conversion of rainforest to palm oil production, and consequent emissions of carbon and loss of biodiversity, has caused an outcry in parts of the world.

It is likely that New Zealand would follow overseas trends and be unwilling to allow arable land to be used for growing biofuel feedstocks.

[40] Not all petrol vehicles are warranted to run on this blend and some relatively minor fuel infrastructure upgrades would be required.

[41] Gaseous biofuels such as biomethane or bio-dimethyl ether are excluded as they would require a new distribution network and vehicle modifications. Likewise hydrogen, a promising longer term option, has been excluded from further consideration. Biomethanol is not considered because of its toxicity.

2.9 Biofuel implementation barriers

For large-scale biofuel production and deployment to occur a number of significant barriers will need to be overcome. These barriers are discussed more fully in other parts of this report, but include:

The challenge of implementation

- The scale, complexity and timeframes are daunting, and no broad societal/political consensus exists on biofuels' role within New Zealand.
- The best choices of biofuel(s) and feedstock(s) for implementation in New Zealand are not clear.

Financial

- Biofuels are currently more costly to produce than fossil fuels, and upfront investment costs are high.
- Competition for resources with existing industries/sectors is likely, as resources such as land, capital and feedstock already have existing uses.

Technical

- There is technical risk, particularly around biofuel conversion technologies that have yet to be commercially proven and new crops not grown at large scale in New Zealand.

Timing

- Biofuel introduction will require all parts of the value chain to act in a coordinated way, and at a large scale.
- Feedstocks, particularly trees, can take a long time to grow.
- There is a risk of a "chicken and egg" situation occurring. Feedstock producers are unlikely to commit to growing a crop without a guaranteed market, whilst an investor will not build a conversion plant without guaranteed access to a sustainable feedstock supply.

Social/environmental

- For biofuels to have a significant role in reducing the New Zealand energy sector's environmental footprint, the public must buy into the benefits of addressing climate change, the role of biofuels in addressing these, and the impacts/trade-offs that will be required.

These, and other challenges, have been overcome in different ways in other parts of the world, so New Zealand could leverage this international knowledge and experience with a fit-for-purpose biofuel deployment.

Necessary first steps are to identify:

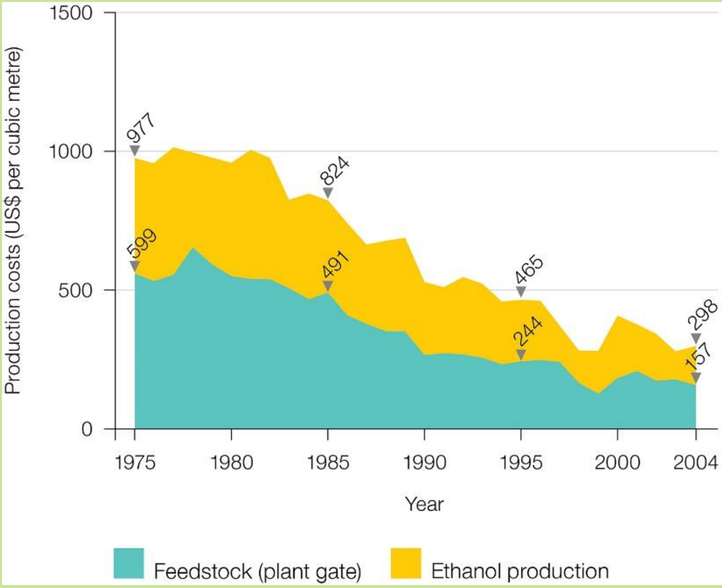
1. Which of the large number of feedstock, feedstock transport, conversion processes and biofuel options being used or considered for implementation overseas are best suited for New Zealand?
2. What are the actual issues, barriers and risks going to be for biofuel implementation in New Zealand under a range of possible futures - as a precursor to working out ways to address them?

The purpose of the study was to use qualitative analysis together with quantitative modelling of various biofuel deployment scenarios to address these questions.

Box 6: Biofuel costs and technical risk will reduce with time

A biofuel technology, when at commercial scale, will see both capital and operating costs drop substantially over time, as the technologies are optimised and commercial experience increases. Such 'technology learning' is normal for new technologies and new feedstocks and should improve biofuel competitiveness relative to fossil fuels over time.

As an example, the figure below shows that between 1975 and 2004, the conversion cost and delivered feedstock costs for producing bioethanol from sugarcane in Brazil fell by 66% and 74%, respectively.



Decrease in production costs of Brazilian ethanol as the technology matures.
Redrawn from ref. [58].

3 Quantitative modelling

For this project we adapted an existing comprehensive modelling framework – the Bioenergy Value Chain Model (BVCM) - to investigate feasible options over space and time for the development of a biofuel value chain in New Zealand.

The BVCM was developed by the Energy Technologies Institute (ETI) in the United Kingdom and successfully used to assess and understand the prominent role bioenergy could play in meeting the United Kingdom's GHG emission reduction targets [59, 60].

Scion licenced the BVCM and modified it to make it suitable for New Zealand requirements, and then populated it with New Zealand-specific data.

3.1 Description of Bioenergy Value Chain Model

The BVCM is an optimisation modelling system.[42] Input data, together with user defined constraints are used to generate a "what if?" case or "scenario" (Fig. 3.1). The model is then requested to produce an optimal solution to the problem presented in the scenario – in our case to meet a required level of fuel production at lowest cost while meeting any other user-defined constraints.[43] The model then provides single case outputs which are interpreted by spatial mapping and an Excel analysis tool.

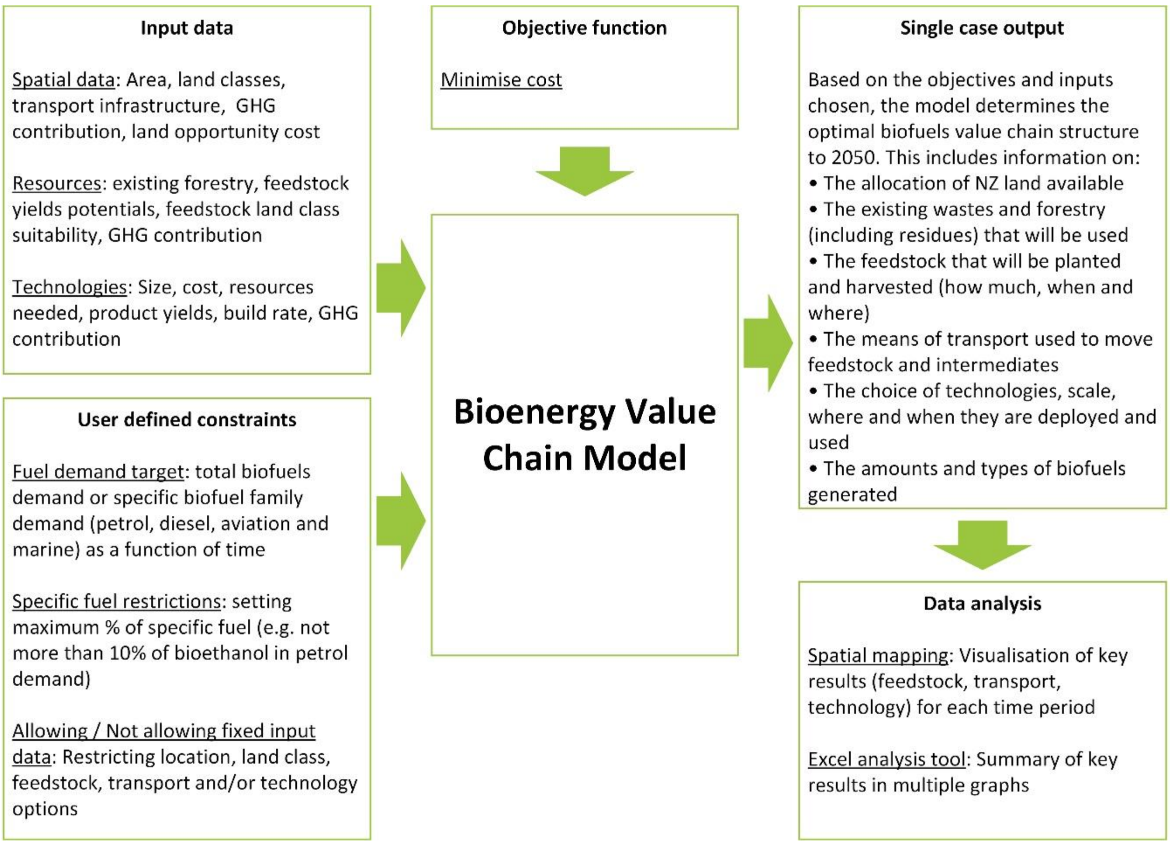


Figure 3.1: Bioenergy Value Chain Model overview. Modified from ref. [61].

[42] The BVCM is a mixed integer linear programming (MILP) problem built in AIMMS (https://aimms.com/) and uses Cplex (https://www-01.ibm.com/software/commerce/optimization/cplex-optimizer/) as a solver.
[43] While not used in this study, alternatives to the cost minimisation objective function are GHG minimisation and profit maximisation.

3.2 Overview of how the BVCM was used in this study

Figure 3.2 gives an overview of how the BVCM was used in this study.

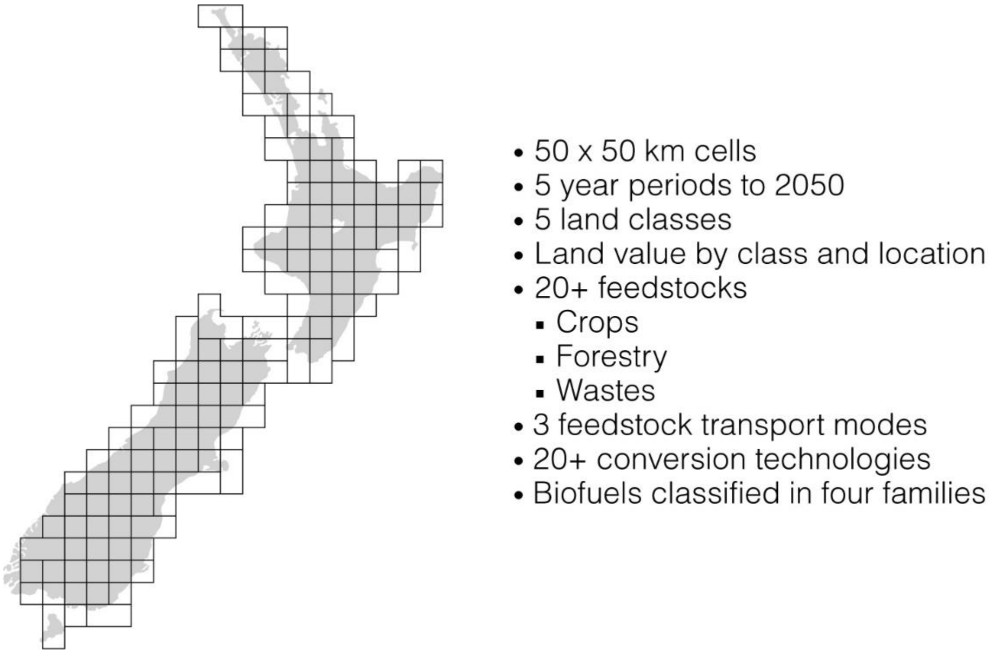


Figure 3.2: Overview of the BVCM as applied in this study.

Spatial information: New Zealand is divided into 132 cells of 50 km x 50 km size (Appendix 1). Each cell contains information on the area of land in each of the five land classes used, the value of the land per land class, growth rates for each crop, transport infrastructure such as roads, rail and ports, plus the availability of wastes and existing forest resources.

Fuel families: The biofuels being produced are assigned to one of four fuel families according to their ability to substitute for fossil petrol, diesel, aviation and marine, *e.g.* bioethanol as a replacement for petrol, or biodiesel as a replacement for fossil diesel (Appendix 5). This allowed us to track or model specific biofuel substitution for each of the main fuel types used in New Zealand.

Crops, feedstocks and transport: The model also contains data on a range of crops, feedstocks, transport modes, and conversion technologies (Appendices 2 - 4). It also includes options such as chipping or pelletisation, which produce intermediate products that can then be sent to another technology for further conversion to fuel. Realistic links[44] are then established between each of these crops, feedstocks, intermediates, transport modes, conversion technologies and final fuels to generate a huge number of potential value chains. As an example, the potential pathways available to just one feedstock, fibre logs from forest plantations, are shown in Figure 3.3.

[44] For example, canola oil can be used to produce biodiesel but not as feedstock for cellulosic ethanol.

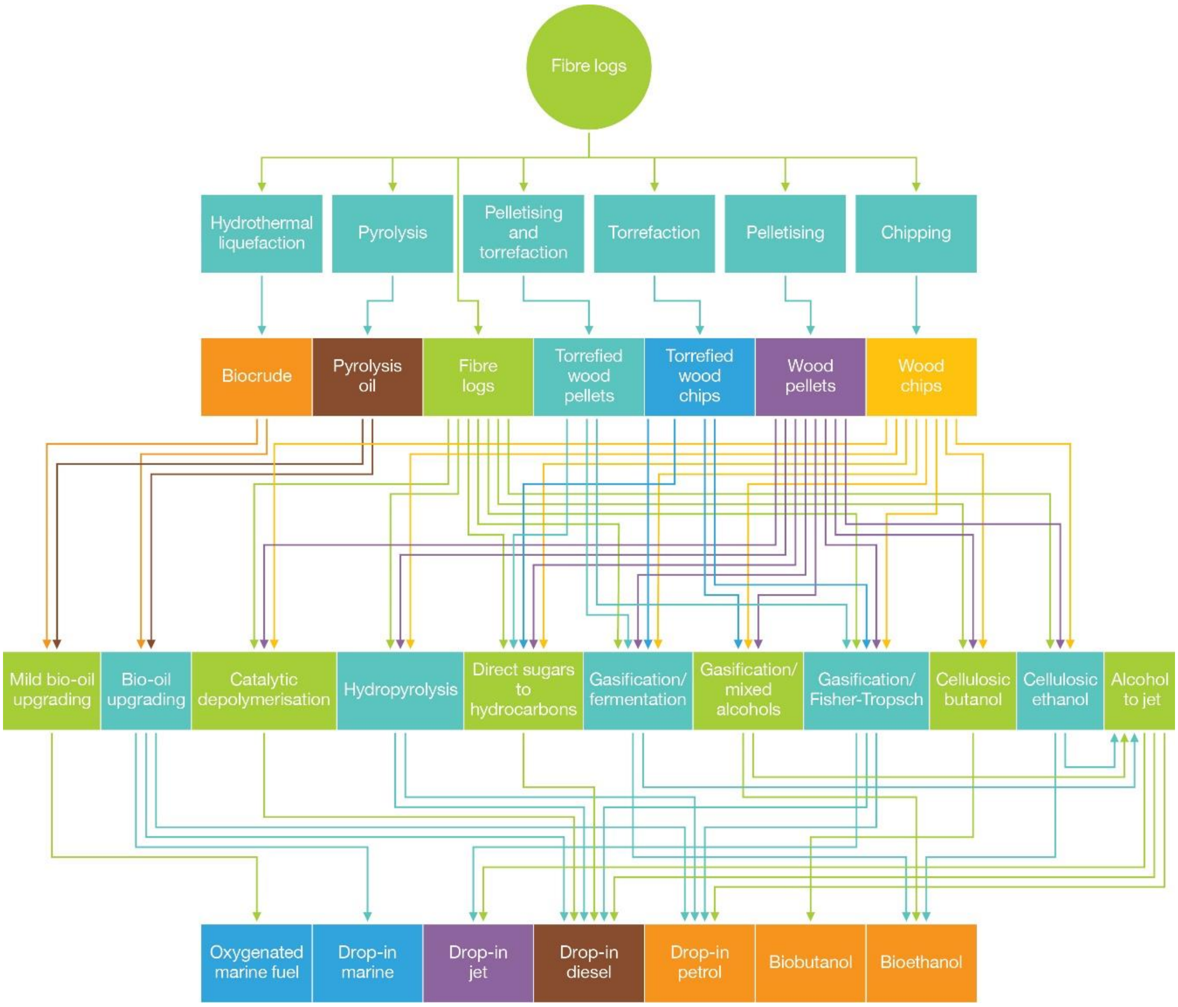


Figure 3.3: Potential pathways for fibre logs from forest plantations.

Optimisation: Constraints, such as the minimum of each fuel family to be substituted by biofuels as a function of time, are applied and the BVCM then optimises across the large number of potential biofuel system pathways to come up with the lowest cost option.

This lowest-cost option is determined as the discounted production cost to the whole biofuel value chain over the whole timeframe modelled. It is expressed per litre of biofuel produced ($/L-e).[45] Within this, the feedstock producer and transporter are assumed to make a profit,[46] so in practice this becomes the minimum selling price of the biofuel at the conversion plate gate.

Costs can be offset by including revenues from the sale of any co-products produced; in which case revenues are assigned to the whole value chain.[47]

Scenario result visualisation: For each scenario the BVCM shows how this level of substitution is achieved as a function of time and space, including where and when feedstocks are planted, where the conversion plants are located and how the feedstocks are transported. It also models the GHG emissions incurred at each step of the value chain.

[45] This compares the volumes of biofuels produced on an equivalent energy basis, e.g. 1 L of petrol has the equivalent energy content to 0.62 L of fossil petrol.
[46] Approximately 10% of costs.
[47] These include not only co-products produced during biomass conversion (electricity, char, etc), but also revenue from selling logs when it is more profitable to do this than to use them for biofuel feedstocks (particularly the sawlogs from conventional forests planted within these scenarios).

High-level modelling assumptions and limitations

Before discussing the modelling inputs in detail, it is useful to introduce some of the key modelling assumptions and limitations.

- Distribution of the final biofuels produced is not modelled. This assumption is made for computational efficiency and because the cost of transporting the final biofuel to where it will be used is much less than the cost of shipping an equivalent volume of the original biomass.
- The interaction between supply and demand and its impact on costs/prices is not considered, *i.e.* the impact of large-scale biofuel production on other parts of the economy is not considered.
- Constant input costs and co-product prices based on 2016 values.
- Non-feedstock inputs (*e.g.* natural gas or electricity) are available in unlimited quantities at the same cost throughout the country and there is no limit on the amounts of co-products that can be sold.
- The land opportunity cost assumes that the land is free to be used for the highest value application possible, except that existing forestry land is assumed to be re-planted.
- All conversion technologies will be commercially proven, with cost reduction over time.
- Discounted costs are used. A single discount rate of 7% was applied for all parts of the value chain. This value is suggested by The Treasury for the development of new technologies [62].
- Imports or exports of biofuels or imports of feedstocks are also not considered in the modelling.
- The level of detail (or aggregation) used in the BVCM is designed for national-level modelling. For specific biofuel investment analyses more detail will be required.[48]

3.3 Model inputs

Land and land use

Within each cell there is wide variation in land quality and therefore land suitability for crops, potential yields and production costs. Productive land within each cell is therefore divided into land classes to reflect these differences.

The productive land in New Zealand was divided into five classes based on aggregations of the Land Use Capability (LUC) classes [63] and three slope classes (Table 3.1). Non-productive land such as that managed by the Department of Conservation, urban areas, water bodies and very steep mountain land with high erosion potential (i.e. LUC 8) are excluded. Existing plantation forestry land was also excluded, as this is modelled separately.

It is important to note that these land classes indicate what a given piece of land is potentially capable of being used for, and not necessarily its current use.

A land opportunity cost was used to reflect the value of the land under a competing land use. The cost of land makes up a significant portion of the cost of growing crops, so this opportunity cost, akin to a land rental, provides a simple means to include the value of the land in the production cost of growing a crop. This opportunity cost was estimated using a land value dataset developed at Scion using real estate information.[49]

[48] At lower levels of aggregation it may be possible to identify feasible opportunities that are not apparent when using averages across broader areas.
[49] Information from trademe.co.nz and nzfarms.co.nz. This dataset was developed in 2015 and contains the land values ($/ha) of a sample of 101 traded land blocks in various regions with varying land qualities and slopes. This dataset was then extrapolated spatially using AsureQuality's AgriBase and the Land Cover Database V4.1.

Table 3.1: Land classes and their suitability for feedstock crops[50,51]

BVCM Land Class	LUC Classes	Slope (º)	Total area (M ha)	Description	Allowable crops in BVCM
1	1, 2, 3s & 3c	0-15	2.3	High productivity flat	Arable crops Energy crops Forestry
2	3e, 3w & 4	0-15	3.8	Medium productivity flat land	Arable crops Energy crops Forestry
3	3e, 3w & 4	> 15	0.24	Rolling	Forestry
4	5 & 6	> 0	7.7	Typically steep[a]	Forestry
5	7	> 0	5.4	Typically very steep	Forestry

[a] Also includes flat land unsuitable for arable cropping, *e.g.* because of boulders, stony soils, waterlogging, etc.

Feedstocks

The model also includes options to use feedstocks from purpose-grown crops, existing plus new forests, and a number of point-source feedstocks.

Crops
To meet the dual aims of including a wide range of crop options (*i.e.* being feedstock-neutral) and keeping the modelling solution time reasonable, we chose a small number of exemplar crops covering a range of arable crops, energy crops and forestry.

These exemplar crop options were chosen on the basis of commercial experience in New Zealand or overseas and previous research on their potential as biofuel feedstocks in New Zealand.

Each of these crops produces one or more feedstocks and some also produce co-products.

<u>Arable crops</u>
Four examples of arable crops were chosen. All require reasonably flat terrain to allow mechanical harvesting, and so are assumed to be grown only on class 1 or 2 land.

> *Canola* is an annual crop that is already being grown commercially in New Zealand. It is harvested to produce canola seed, which is transported to a plant for pressing to produce the canola oil. The oil can then be used for food or for biofuel production. Canola has been extensively grown for biodiesel production internationally and has been grown commercially at a modest scale in New Zealand for both food applications and for processing into biodiesel.
>
> *Sugar beet* received attention in New Zealand after the 1970s oil shock, and is related to fodder beet, an increasingly popular feed crop grown for the dairy industry. Sugar beet is suited for conversion to ethanol via well-established processes applied in other parts of the world.
>
> *Maize* (corn grain) is already widely grown in New Zealand for stock feed. It can be grown to produce maize (grain) in the North Island and sunnier parts of the South Island, and is the main feedstock for (conventional) bioethanol production in the United States.

[50] Includes all land technically capable of growing feedstock crops. However, there may be social and environmental reasons to restrict crop production in certain areas, *e.g.* from native tussock grasslands for biodiversity and amenity reasons, horticulture and high producing grassland and cropland, or highly erodible steep land best managed under permanent forest cover.
[51] These 5 land classes allow some of the variation within a cell to be represented while keeping the model size manageable.

Corn (whole plant) is also grown in New Zealand for stock feed as whole plant silage. It has a shorter growing season and is less dependent on the weather than maize. This is assumed to be a viable feedstock for all second generation processes.

Energy crops

Two potential energy crops, miscanthus and willow, were included in the modelling. As for the arable crops, both are mechanically harvested, so are assumed to be only grown on class 1 and 2 land. Both have been used overseas and promoted in recent years in New Zealand, although trial data is still limited.[52] In both cases they can be burnt directly for heat, or converted to liquid biofuels using 2nd generation processes.

Willow Willows and poplars are both highly productive when grown on coppice systems and are widely used for bioenergy overseas, particularly in Sweden, which has 20,000 ha of short rotation coppice willow. We assumed that willow would be harvested every third year for 18 years, and would not include any co-product production (e.g. extractives).

Miscanthus (a tall grass) has been promoted in New Zealand and both its productivity and conversion to energy have been investigated. Overseas miscanthus is generally more productive than alternative crops, with the added advantage that as a sterile hybrid it does not pose a biosecurity risk [67]. The initial establishment cost is high but it can then be harvested annually for 15 years before needing to be re-established.

In the BVCM, crop yields and GHG emissions during crop production are input by period, cell and land class. Typical productivities and production cost values are shown in Table 3.2. A simple approach to yield modelling was taken because a lack of experience with growing some of these crops in New Zealand meant that productivity and growing cost information is often lacking.[53] Yields, costs and greenhouse gas emissions are based on limited information so should be regarded as indicative.

Table 3.2: Typical productivities of crops used in this modelling.

Crop	**Yield range, odt/ha/yr**	**Production cost, $/ha/yr**	**Production cost range, $/odt**
Canola seed	2.0 - 4.2	1100	262 – 550
Corn (whole plant)	10 – 27	3,315	123 - 332
Maize (grain)	7.5 – 13.5[a]	3,315	246 - 474
Miscanthus	3 - 15	913	61 - 304
Sugar beet	10 - 23	3,125	136 - 313
Willow	5 - 11	461	42 - 92

[a] Zero in most of the South Island.

New Zealand crop yield estimates were used where possible, but in some cases estimates were made based on relativities between the same crops reported in overseas studies. Estimated typical yields were varied by cell based on temperature and rainfall classes.[54]

Planting of willow and miscanthus was limited to an average of 16,000 ha/yr in 2016-20, rising to, 160,000 ha/yr in 2021-25 and 200,000 ha/yr thereafter.

[52] Willow [64]. Miscanthus: Miscanthus New Zealand [65]; Fonterra [66]; Oji Fibre Solutions – confidential information.

[53] Past experience overseas suggests that commercial-scale productivity is generally much less than that modelled or measured in experimental trials.

[54] As canola and sugar beet cannot be grown on a site every year, they were assumed to be grown on a site for one year in four. The model represents this separation over time as a separation in space, so the allocation of land to these crops must be four times higher. Returns from the alternative crop area were assumed to be represented by the land opportunity cost for the allocated land. The impacts of climate change on crop suitability were not considered.

As a simplification, all crops were modelled assuming year-round rather than seasonal harvesting, so storage of feedstocks to spread availability over the year was not considered.[55]

Forestry

As indicated above, the model includes two options for new forest crops and the option to get feedstocks from New Zealand's existing 1.7 million hectare plantation forest estate. These were treated separately in our modelling.

<u>Existing forestry</u>

Existing plantation forests were modelled based on the Ministry of Primary Industries (MPI) wood availability forecasts, which provides scenarios of future wood supply by region [68]. These were allocated spatially to land classes within cells using Land Cover Database data. Yields by cell and land class were modelled in the Forest Investment Finder [69] assuming a radiata pine regime to give three sawlog grades and a fibre log grade. Yields were then scaled to give the same regional production each period as in the MPI forecast.

For existing forests the BVCM does not incur growing or harvest costs. Instead, if logs are required for biofuel production an opportunity cost must be paid, based on the return that the owner would otherwise get from an alternative market. For sawlogs this was taken as the price paid at the closest sawmill or port [70], less the transport cost. For fibre logs, the closest port was used unless the forest is within 100 km of one of the ten mills that accepts fibre logs.

Forest residues are assumed available at the cost of collection, *i.e.* that there is no alternative market for this material. The quantity available was set at 4% of total merchantable volume at the landing and 8% available on the cutover. Landing residue collection cost is the same for each land class, but collecting cutover residues is much more expensive on steep land. Three of the five and classes contain a mix of slope classes, so an area-weighted cost was estimated for each cell. It was assumed that only residues incur GHG emissions associated with their collection.

Existing forest is assumed to be replanted after harvest and managed on a 30-year rotation, so the area harvested in the first period is available to be harvested again in the last period.

<u>New forests</u>

Two options for new forestry were included. In both options the model incurs the full costs of growing and harvesting.

> *Conventional forests:* The first new forestry option was unpruned radiata pine grown on a 30-year rotation, designed to give high yields of structural log grades plus fibre logs. Collection of either landing and/or cutover residues was optional, and any logs not required for the biofuel value chain, particularly the higher-value sawlogs, are able to be sold to offset costs. Resource sales are modelled at a national level, so the price was set based on the delivered price at the port minus an average transport cost.
>
> *Energy forests:* The second new forestry option was a 15-year radiata pine rotation specifically grown to produce only fibre logs for bioenergy, with no recoverable residues.

Yields for both regimes were estimated using the Forest Investment Finder, with estimates of GHG emissions from ref. [71]. Harvesting costs were determined for the three slope classes and again area-weighted for each land class within a cell.

Planting of both new conventional forests and energy forests was limited to an average of 20,000 ha/yr of each type in 2016-20, rising to 160,000 ha/yr in 2021-25 and 200,000 ha/yr thereafter.[56]

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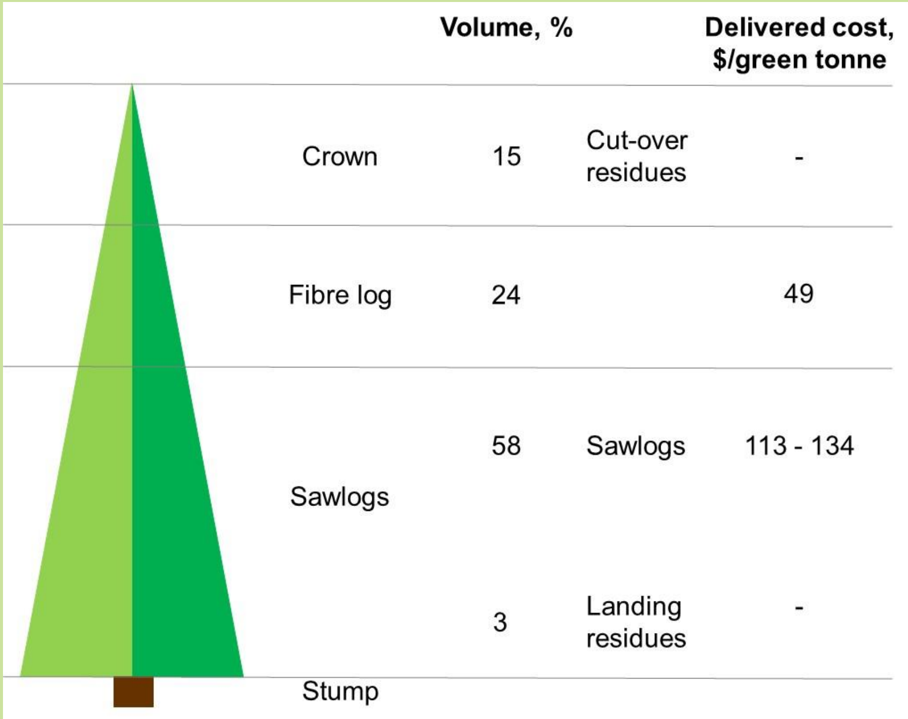
[55] In practice all arable and energy crops are harvested in specific seasons, so the resulting feedstocks would need to be stored to enable the processing plants to run year-round. Feedstock storage would add cost and may lead to yield losses.

[56] Afforestation was limited to 100,000 ha over the first five-year period to allow for a more reasonable rate of expansion from the recent low annual planting rates.

Box 7: New Zealand's current plantation forest industry

New Zealand's current forestry industry is based on plantation-grown forests. These are largely (>90%) radiata pine trees typically grown on a rotation of 25-30 years and optimised for sawlog production. Each tree produces a number of products: a number of higher-value sawlogs of varying quality; a lower-quality fibre log (pulp log) as well as forest residues which are currently largely left in the forest. The different log grades all have well-established uses and values.

There are two distinct types of forest residues: landing residues, produced where the harvested trees are cut into the various log grades and consist largely of stem sections and large branches; and those left behind on the forest floor when the trees are felled and consist of the crown of the tree and smaller branches. While these two residue types were modelled separately, they are reported collectively as forest residues in this report.



Indicative breakdown of current conventional plantation-grown *Pinus radiata* tree and delivered costs for grown under a structural regime. Source: refs [72, 73].

Point source feedstocks

Four point-source feedstocks were modelled – tallow, sawmill chip, waste wood and municipal solid waste. These are treated as point-source feedstocks, with the quantity available by period within a given cell specified, together with a purchase price. For all these feedstocks it was assumed that the annual supply would remain constant over the 35-year planning horizon.

Tallow is a well-proven feedstock for the production of both biodiesel and renewable diesel, and is produced in New Zealand as a by-product of the meat processing industry. It is mainly exported, although Z Energy is currently commissioning a plant to convert tallow to biodiesel. Tallow was modelled as being available at the seven ports from which it is exported and at Wiri (Z Energy's biodiesel plant), rather than at individual rendering plants at an assumed cost of $806/tonne [74].[57]

Sawmill chips are produced, together with sawn timber, at most existing sawmills. They are another possible feedstock, although they have existing well-established uses, particularly in

[57] 2015/16 average export price [74].

the pulp and paper and panelboard industries. They were modelled assuming any wood chips produced at a given site and not currently used at that site (Scion data) were available at that site at a cost of $65 per green tonne.

Waste wood, largely from construction and demolition, is a potentially attractive feedstock available in significant volumes from the country's 44 municipal solid waste sites (*e.g.* landfills). It was assumed that this material is available free of charge, with no cost for segregation.

Municipal solid waste, or the non-woody biological waste disposed of at the country's municipal land-fills is a further potentially attractive feedstock available in significant volumes. This material is composed mainly of kitchen wastes and non-woody green wastes such as grass clippings, and does not include plastics or inorganics. It was assumed that this material is available free of charge, with no cost for segregation.

Other biomass waste feedstocks such as horticultural waste, whey and used vegetable oil were not included as they were considered to lack sufficient scale at a national scale, are widely distributed or already have established uses [75].

Transport

Once a feedstock or intermediate (e.g. wood pellets from forest residues) is harvested or produced, it must be transported to the conversion plant. The model includes options for moving these materials by road, train or ship, assuming existing transport networks.

Transport costs are specified for each resource on a $/t/km basis for each of the three modes. These values take into account feedstock volumetric density as well as handling costs at the interface between transport modes.

- Transport distances are calculated between cell centres, then adjusted by a tortuosity factor that allows for the average ratio between actual road/rail length and straight line distance within the cell. In the case where feedstocks are grown and processed within the same cell, a within-cell transport distance was used.
- The model takes account of the existing roading and rail network by only allowing transport between cells when there is an existing road or rail link.
- For low volumetric density products such as miscanthus bales or wood chips, the truck (or railway wagon or ship) will hit a volume limit before it hits its full payload weight limit; which increases unit costs.[58]

For products where the density is sufficiently high for the payload to be limited by weight, transport costs are typically $0.19 to $0.21 per t/km for trucks. Costs for rail and shipping are more variable due to the differences in the cost of transferring different products from one mode of transport to another; liquids are cheaper to load than bulk products such as logs or chips.

Conversion technologies

In the BVCM, a conversion technology is a process that takes a feedstock plus other inputs and uses them to produce a product or mix of products. Conversion technologies are defined by a number of variables including:

- feedstock and other inputs (*e.g.* gas, electricity, chemicals) required,
- plant scale & utilisation rate,
- capital cost – annualised over the expected lifetime of the plant,
- fixed and variable operating costs,
- yield of fuel(s) produced – feedstock-specific,
- yields of co-products produced,
- plant operating life, and
- build rates, *i.e.* how many plants can be built in each period.

[58] For example, volume and weight limits for trucks of 100 m^3 and 29 tonnes are assumed.

There are a wide range of potential conversion technologies which could be included in the model. As will be discussed in more detail later, these are at different stages of commercial maturity, ranging from well-proven commercial processes for producing biodiesel or conventional bioethanol, to those which are still only at a laboratory scale.

This remains an area of rapid global technological development. While beyond the scope of this study to review the technologies under development in detail, interested readers are encouraged to consult the many recent reviews in the area, *e.g.* refs [20, 38, 39, 55, 76-79], and the Biofuels Digest website [80] which provides a broad coverage of the whole biofuels area.

The BVCM already includes many technologies of potential interest, and which have already been validated by ETI's industry partners.[59] In addition, a number of technologies were added to the model. These additions were made to ensure exemplars of a broad range of approaches were included and a good fit to likely New Zealand feedstocks, fuels and geographical requirements. They focussed on more developed technologies, and technology options where reliable process and cost information was available from reputable scientific or industry sources.[60]

The list of technologies, including a short description, is described given in Appendix 4. The conversion technologies fall into five broad classes.

- Commercially-proven process:
  - fermentation of sugars from sugar beet to produce either (i) bioethanol (2 variants) or (ii) biobutanol
  - biodiesel production from vegetable oil or tallow
  - hydrotreating of vegetable oil or tallow to produce either (i) renewable diesel or (ii) a mix of renewable diesel, renewable jet and drop-in petrol
  - conversion of sugar beet via aqueous phase reforming to drop-in diesel
- Routes from lignocellulosic feedstocks via sugars intermediates:
  - cellulosic ethanol via enzymatic hydrolysis to sugars and fermentation (2 variants)
  - cellulosic butanol via enzymatic hydrolysis to sugars and fermentation
  - drop-in diesel via enzymatic hydrolysis to sugars and fermentation
  - conversion of cellulosic [or conventional] ethanol to a drop-in jet fuel
- Routes from lignocellulosic feedstocks via bio-oil intermediates:
  - fast pyrolysis to produce pyrolysis oil, which is then upgraded (by catalytic hydrogenation) to a mix of drop-in diesel or petrol or (ii) to an oxygenated marine fuel
  - hydrothermal liquefaction to produce a biocrude, which is then upgraded (by catalytic hydrogenation) to a mix of drop-in diesel or petrol or (ii) to an oxygenated marine fuel
  - catalytic hydropyrolysis to produce a mix of drop-in petrol and diesel[61]
  - catalytic depolymerisation in an oil and condensation of gasses to produce a drop-in diesel[62]
- Routes from lignocellulosic and waste feedstocks via gasification to produce syngas:
  - plus gas phase fermentation to bioethanol
  - plus catalytic conversion to bioethanol
  - plus conversion to drop in fuels by Fischer-Tropsch synthesis (2 variants)
- Biomass pre-processing
  - chipping[63]
  - pelletising to densify bulky biomass into [dry] pellets
  - torrefaction to increase the energy density of biomass by heating
  - oil extraction to produce canola oil from canola seed

[59] The terms of our BVCM licence mean that input data on the conversion technologies cannot be disclosed.
[60] Good modelling outcomes rely on reliable process and cost data for each process. This is often not available for less developed processes, or is held by individual developers in the case the more mature options.
[61] For a description of this process see ref. [81].
[62] For a description of this process see ref. [82].
[63] Forest residues and waste wood are assumed chipped via small mobile chippers prior to transport to the processing plant. While this is an option for other woody material, *e.g.* logs, on-site chipping at the conversion plant is assumed possible.

Box 8: Distributed processing

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 and then transport the higher-density intermediate product to a larger centralised plant for conversion into the final fuel. The resulting reduced transport costs must be balanced against the costs of the additional processing and the extent to which economies of scale reduce conversion costs by building larger plants.

Distributed processing (see Box 8) may be particularly appropriate to New Zealand's geography, so options for this were included within the model. In particular, options are included to allow: densification of biomass wastes via torrefaction or conversion to pellets; oil extraction of canola oil from the seed; and intermediate production of bio-oils by pyrolysis or hydrothermal liquefaction and then transport of this bio-oil to an upgrading plant.

Most technologies producing drop-in hydrocarbon fuels make a mix of final fuels. For example, bio-oil upgrading produces a mix of drop-in petrol and drop-in diesel. All conversion technologies are assumed to produce various final products (and any co-products) in fixed proportions.

The model can choose the plant size at a given location within constraints specified for each technology. For many technologies up to three different size ranges are modelled to partially take into account the fact that both capital and operating costs drop as plant size increases (Fig. 3.4).

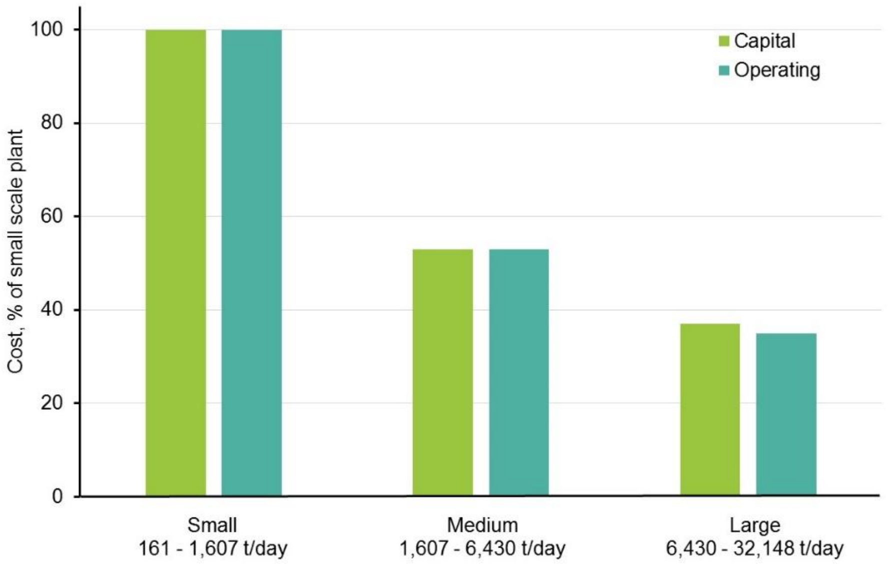


Figure 3.4: Relative capital and operating costs for pyrolysis plants in the BVCM.

As commercial experience with new conversion technologies is gained, both capital and operating costs are assumed to drop (*e.g.* Box 6). This may mean that while a new process may not be profitable currently, it may become so in the future. The model takes this into account by penalising the less mature technologies[64] in the early periods of the modelling by increasing their operating and capital costs. For well-proven technologies such as chipping, biodiesel production and conventional ethanol, most of this technology learning has already occurred, so costs are held constant.

3.4 Greenhouse Gas Emissions

For a given scenario, the model accounts for GHG emissions from fossil sources and GHG avoided by using the biofuels and any co-products. It estimates GHG emissions from transportation and conversion based on the energy used. For transport by truck and ship it is based on diesel and

[64] This is done based on the technology readiness level (Section 6.1).

marine fuel used on a per km basis. Conversion technologies produce emissions if fossil fuels are used as inputs. Emissions from electricity use are based on the current average New Zealand national electricity GHG emissions.

Feedstock production emissions are based on cradle-to-gate estimates. This includes emissions associated with the production of fertiliser and agri-chemicals, but not with the production of agricultural machinery. We have assigned all emissions to the feedstock, rather than making a mass or value-based allocation to co-products. Forestry production GHG emissions have been assigned to the log products – residues only incur the emissions associated with their collection and transport. The feedstock crops themselves are considered to be biogenic, taking up and releasing CO_2 in a sustainable cycle so emissions at harvest are not included. However waste feedstocks that are currently sent to landfill (municipal solid waste and municipal waste wood) have negative GHG emissions to reflect the methane that would otherwise be emitted.

Our modelling does not include emissions from land use change[65] or carbon sequestration in new forests established as biofuel feedstocks.[66]

Avoided emissions are calculated for the amount of fossil fuels that have been displaced by biofuel production, whilst avoided emissions from co-product production are based on the alternative product – for example, char is assumed to be used as a coal replacement.

[65] For example, changes in livestock emissions and soil carbon stocks following conversion of pasture to forests or crops is not modelled.
[66] Any long-term storage in wood products is ignored and it is instead assumed that the uptake of CO_2 will be balanced by the loss after harvesting.

4 Results from 30% substitution scenarios

In this Chapter we present the results of scenarios where the minimum level of biofuel production was set to climb linearly from 0% in 2020 to 30% of 2015 fuel demand in 2050 (Fig. 4.1). While this is not necessarily a realistic biofuel deployment scenario, it provides a good illustration of what the lowest cost options are for large-scale deployment and the issues revealed when biofuels are implemented at this relatively high level - with as few restrictions as possible.

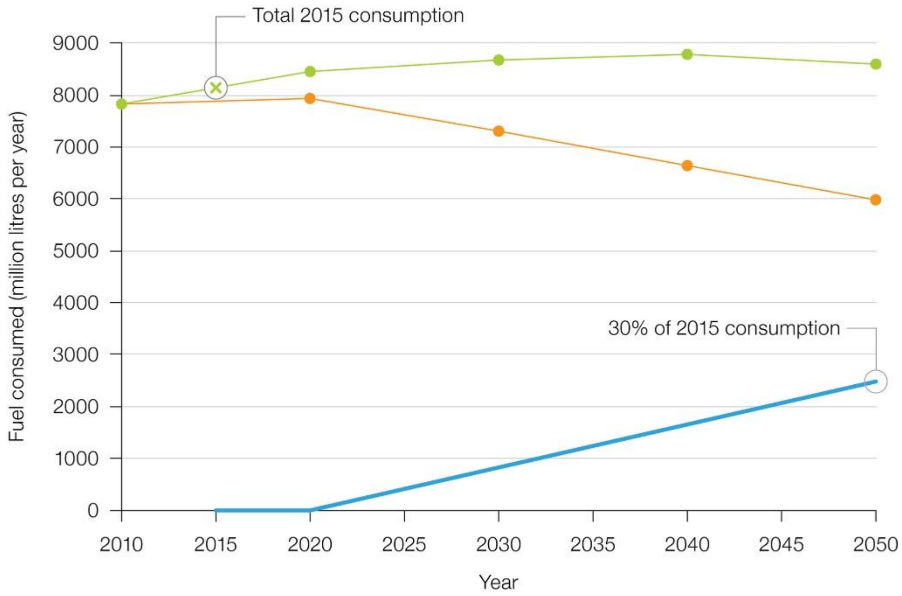


Figure 4.1: 30% biofuel substitution scenario (blue) relative to the total liquid fuel demand projections made under high use (green) and low use (orange) fuel demand projections.

These scenarios were run to determine the lowest-cost way to achieve this minimum level of substitution, leaving the model free to:

- choose which biofuels to produce, and
- allow all feedstocks and all conversion technologies to be used.

Two different land class use options were modelled.

- Scenario 1 (All land classes) – where feedstocks can be produced on all land classes, *i.e.* with as few restrictions as possible.
- Scenario 2 (No arable land) – where all other variables are held the same as in Scenario 1, except that feedstocks are only able to be grown on land unsuitable for arable crops. This restricts possible feedstocks to forestry feedstocks and wastes - as neither food crops nor energy crops such as miscanthus or willow can be grown.

The second scenario was used to understand what would happen under a situation where New Zealand decides that not only is using food crops for biofuel production ethically unacceptable; using land capable of growing food is also unacceptable.

4.1 Feedstocks and fuels

In Scenario 1, where all land classes are included, the main biofuels produced are biodiesel from canola and a mix of drop-in petrol and diesel through pyrolysis/upgrading of lignocellulosic feedstocks, mainly miscanthus, willow, fibre logs and forest residues (Figs 4.2 and 4.3).

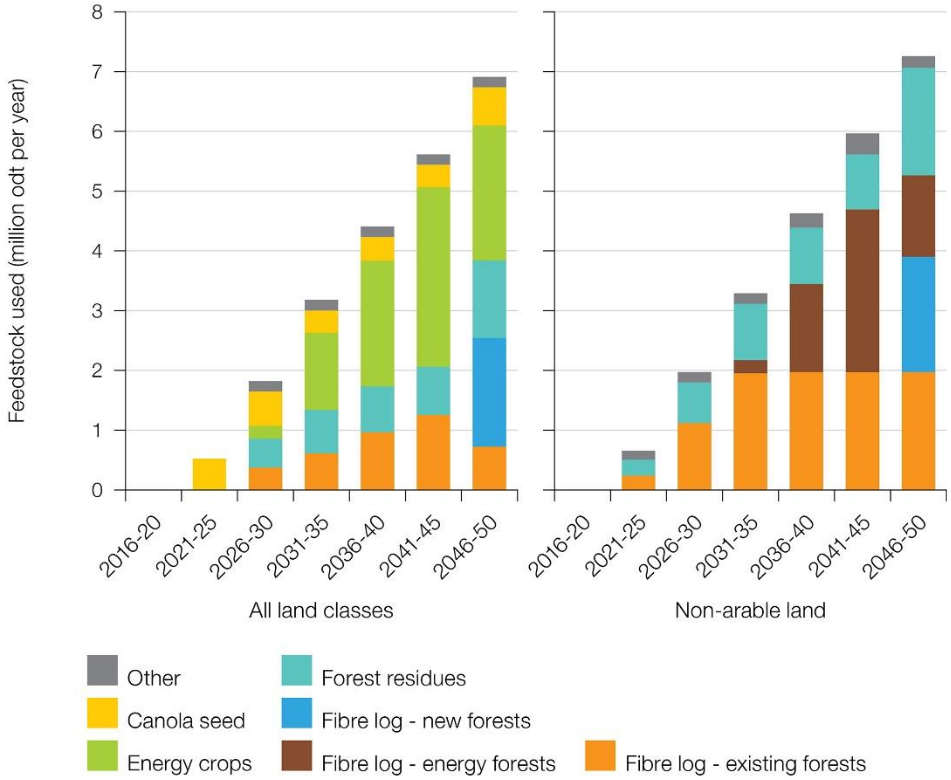


Figure 4.2: Feedstocks used as a function of time in the two 30% substitution scenarios, Scenarios 1 and 2.

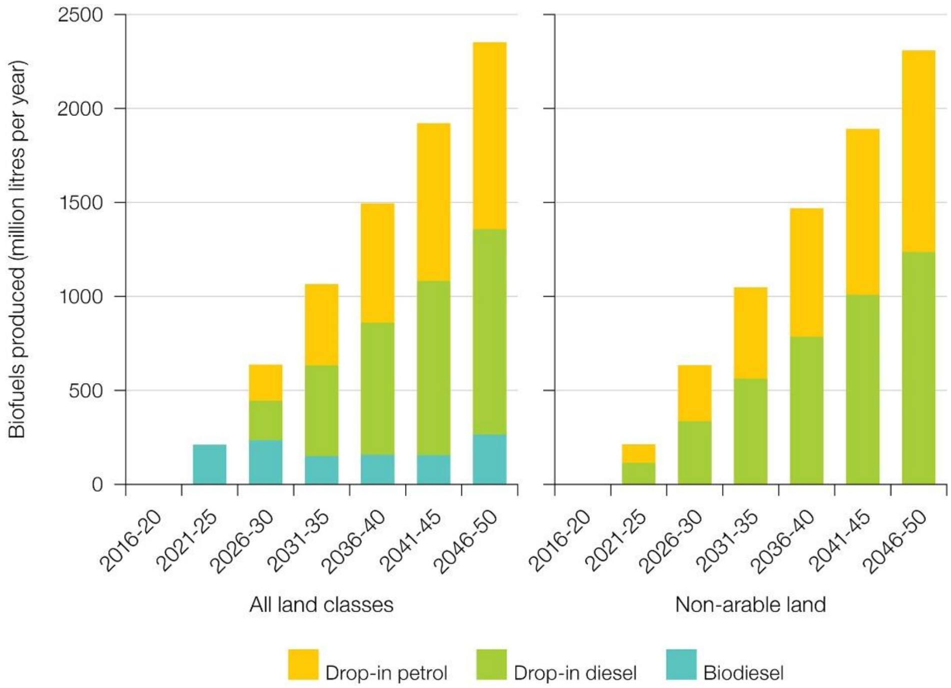


Figure 4.3: Biofuel production as a function of time in the two 30% substitution scenarios, Scenarios 1 and 2.

In Scenario 2, where arable land cannot be used, then neither canola nor mechanically-harvested energy crops can be used. In this case:

- biodiesel is replaced by larger volumes of drop-in petrol and diesel,
- energy crops are replaced by larger volumes of fibre logs and forest residues from existing forests, new conventional forests and energy forests, and

- fibre logs from new conventional forests are only available after 2045, as these forests take 30 years to mature, and fibre logs from energy forests are only available after 2030, 15 years after planting.

Conversion technology choice

While the BVCM model optimises across the whole value chain and timeframe modelled, the conversion technology is a major determinant of the final biofuel cost, as it makes up most of the cost of producing the final biofuel (see Section 4.8).

Table 4.1 lists the key factors the model uses to choose amongst the available conversion technologies. Thus, the lowest overall biofuel cost can be obtained in many different ways.

In Scenario 1, biodiesel is produced from a high-cost feedstock, canola oil, but the conversion process has a relatively low capital cost, high yield and significant co-product sales. On the other hand, lignocellulosic feedstocks are cheaper, but they are converted to a biofuel via a more costly process and in a lower yield.

Table 4.1: Key factors involved in determining the technology chosen.

Factor	Preferred state
Delivered cost of feedstock ($/tonne)	Low
Capital cost of the plant ($/L fuel/year)	Low
Operating cost, including energy, chemicals, labour, maintenance etc ($/L fuel)	Low
Co-product sales ($/L fuel)	High
Product yield (L fuel/tonne feedstock)	High
Plant scale[a]	Large

[a] Capital and fixed operating costs drop as plant scale is increased.

Obviously, if specific biofuels such as bio-jet are required, then the technology choices will necessarily be limited to those producing the targeted biofuel(s).

4.2 Where are feedstocks and fuels produced?

The maps in Figures 4.6 - 4.11 show where and when the feedstocks are produced and where the biofuel production plants are located as a function of time for Scenario 1.

In the 2021-25 period for Scenario 1 only biodiesel is produced. This biofuel is produced by a single biodiesel plant, established in the Auckland area, which continues to operate at varying rates through to 2050. It is fed by 26 smaller plants extracting canola oil from the canola seeds grown across the country, especially in Northland.[67] Canola oil is transported to the biodiesel plant by a mix of truck, rail and ship.

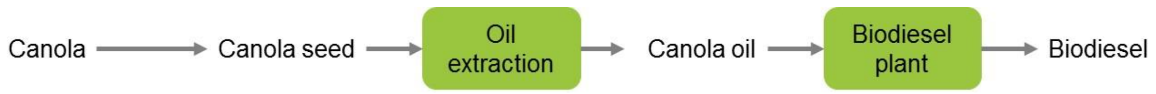


Figure 4.4: Biodiesel production from canola.

Then, in subsequent periods increasing volumes of fibre logs and forest residues from existing forests, particularly in the central North Island, are consumed. In addition, increasing volumes of willow and miscanthus are used. These energy crops are grown principally in Northland, East Coast and in the central North Island. In the last period, new conventional forests planted in the first

[67] The maps are designed to allow time-based comparison between the different feedstocks. Consequently they show only the main regions of canola production, with smaller volumes of canola (and all other feedstocks) falling below the threshold for inclusion in the maps.

period, primarily in the East Coast region, mature and become important feedstocks. All these feedstocks are used to produce drop-in petrol and diesel.

The drop-in petrol and diesel are produced in 15 upgrading plants fed by 29 pyrolysis plants. The intermediate pyrolysis oil is transported, if required, mainly by road and rail. The first pyrolysis and upgrading plants are built in 2026-30, and then additional plants are added as the biofuel demand is increased. The pyrolysis plants utilise a mixture of waste wood, forest residues, willow, miscanthus, and fibre logs (Fig. 4.5). The forest residues and fibre logs come largely from existing forests, except in the last period, where new conventional forests planted in the first period mature and can be harvested.

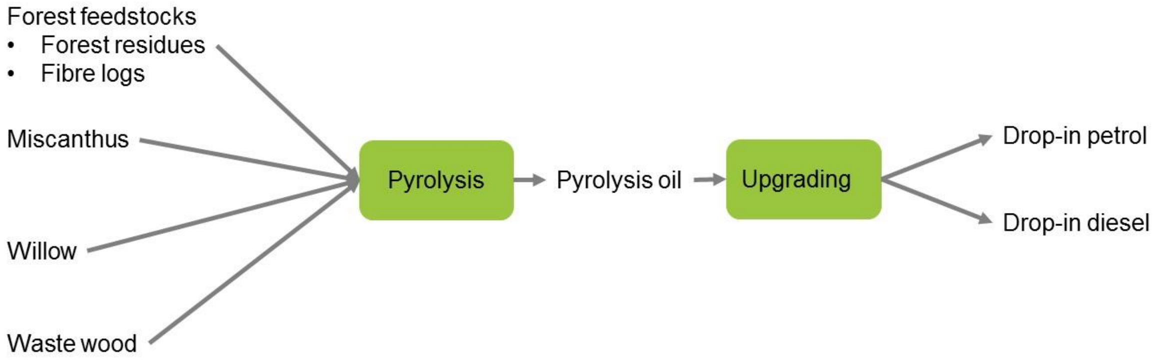


Figure 4.5: Drop-in diesel and petrol production.

In Scenario 2, where only non-arable land can be used, biodiesel is no longer produced and neither willow nor miscanthus are used as feedstocks. In this case drop-in petrol and diesel is produced by pyrolysis/upgrading, mainly of forestry feedstocks. The use of greater volumes of feedstocks from existing and new forests means the location where the biomass is consumed change relative to that seen in Scenario 1. This is discussed further in Section 4.3.

Figure 4.6: Maps showing feedstock consumed and biofuels produced for Scenario 1 (30% substitution, all land classes) in the 2021-25 period. The area of the dots in this and the following figures is proportional to the amount of feedstock consumed or final biofuel produced.

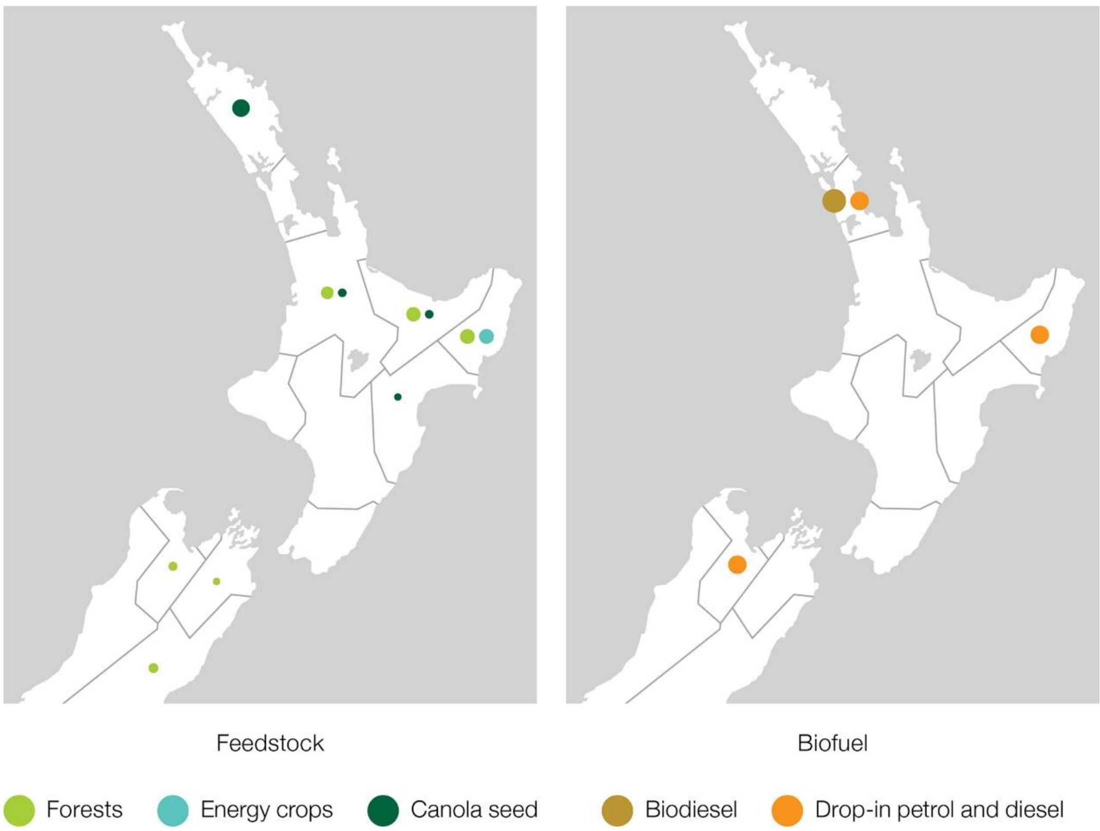


Figure 4.7: Maps showing feedstock consumed and biofuels produced for Scenario 1 (30% substitution, all land classes) in the 2026-30 period.

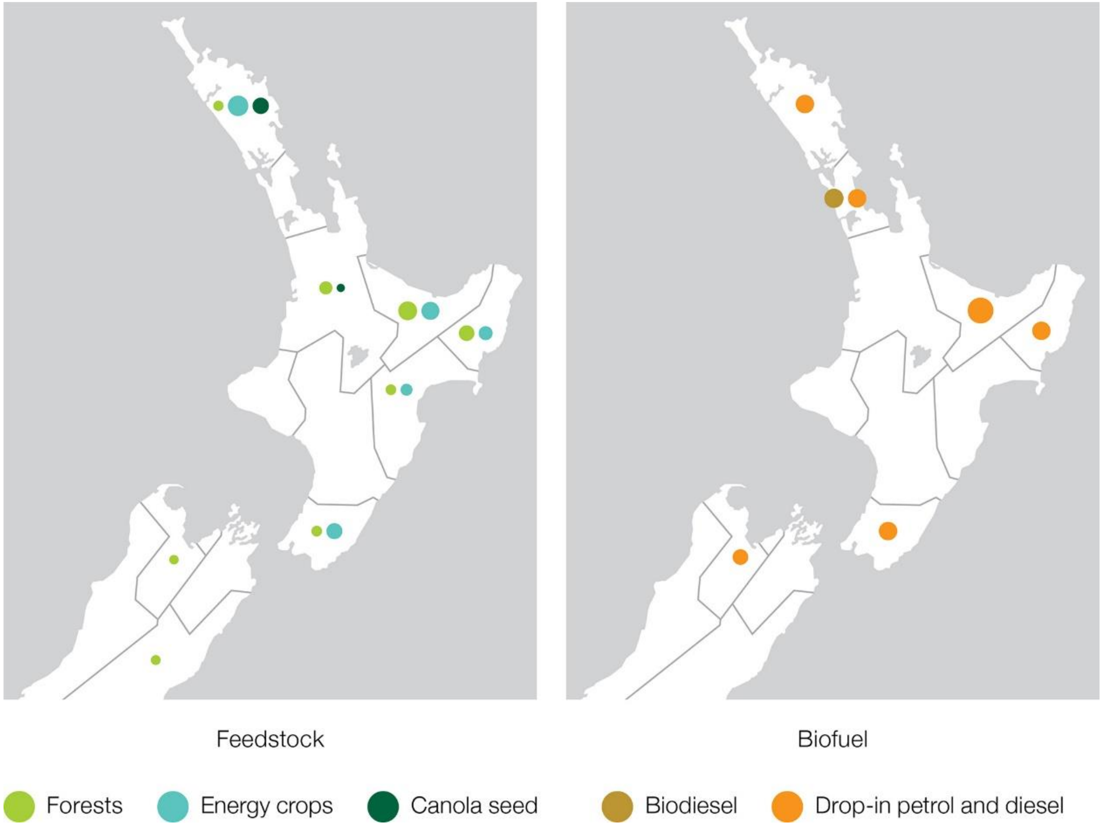


Figure 4.8: Maps showing feedstock consumed and biofuels produced for Scenario 1 (30% substitution, all land classes) in the 2031-35 period.

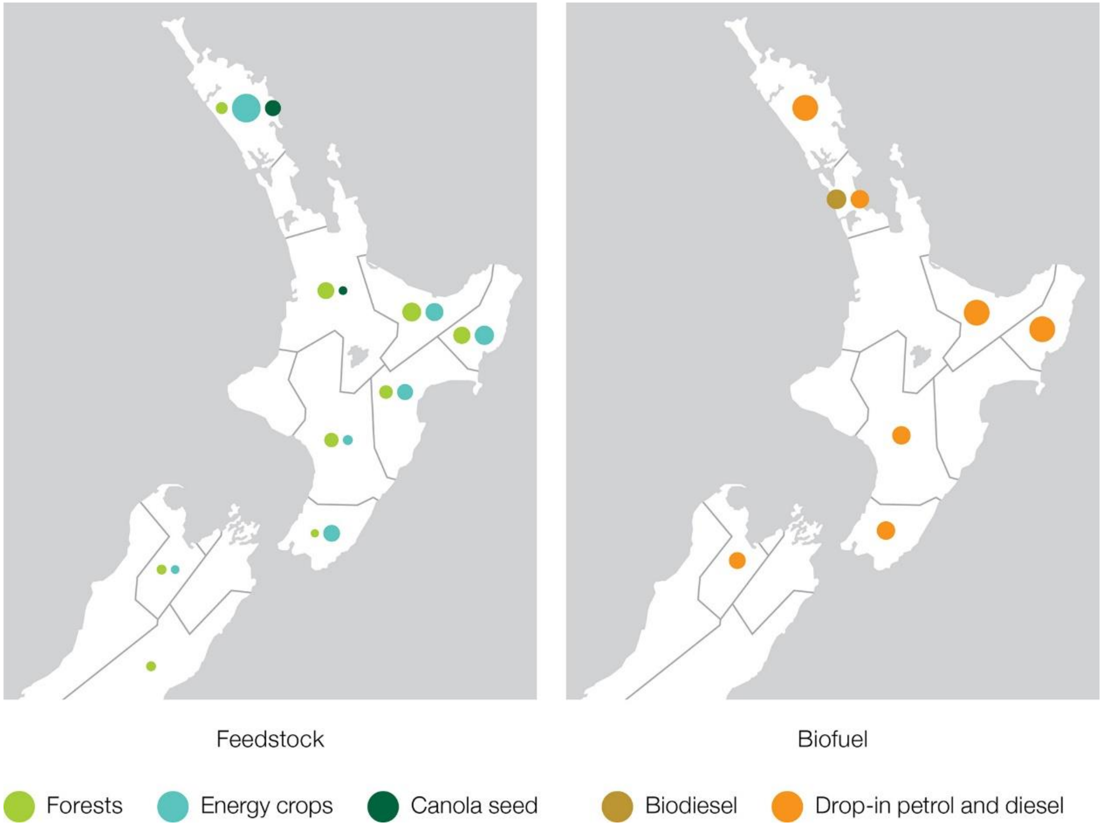


Figure 4.9: Maps showing feedstock consumed and biofuels produced for Scenario 1 (30% substitution, all land classes) in the 2036-40 period.

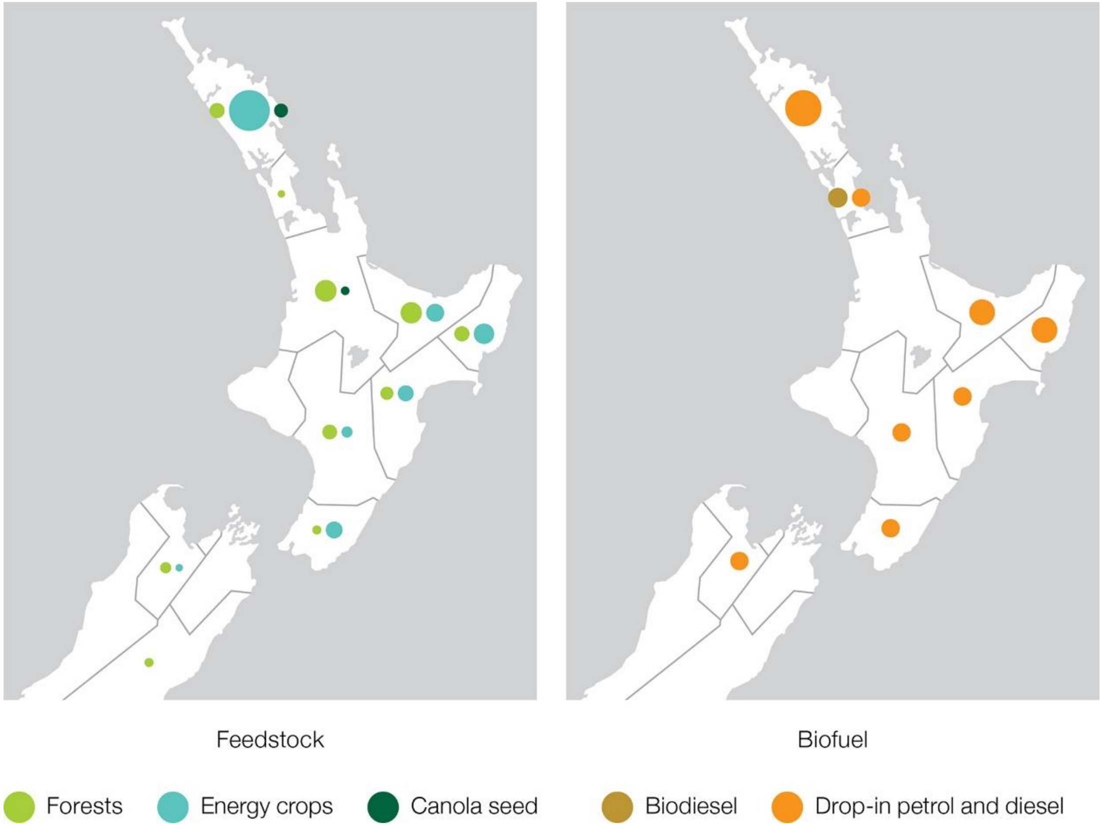


Figure 4.10: Maps showing feedstock consumed and biofuels produced for Scenario 1 (30% substitution, all land classes) in the 2041-45 period.

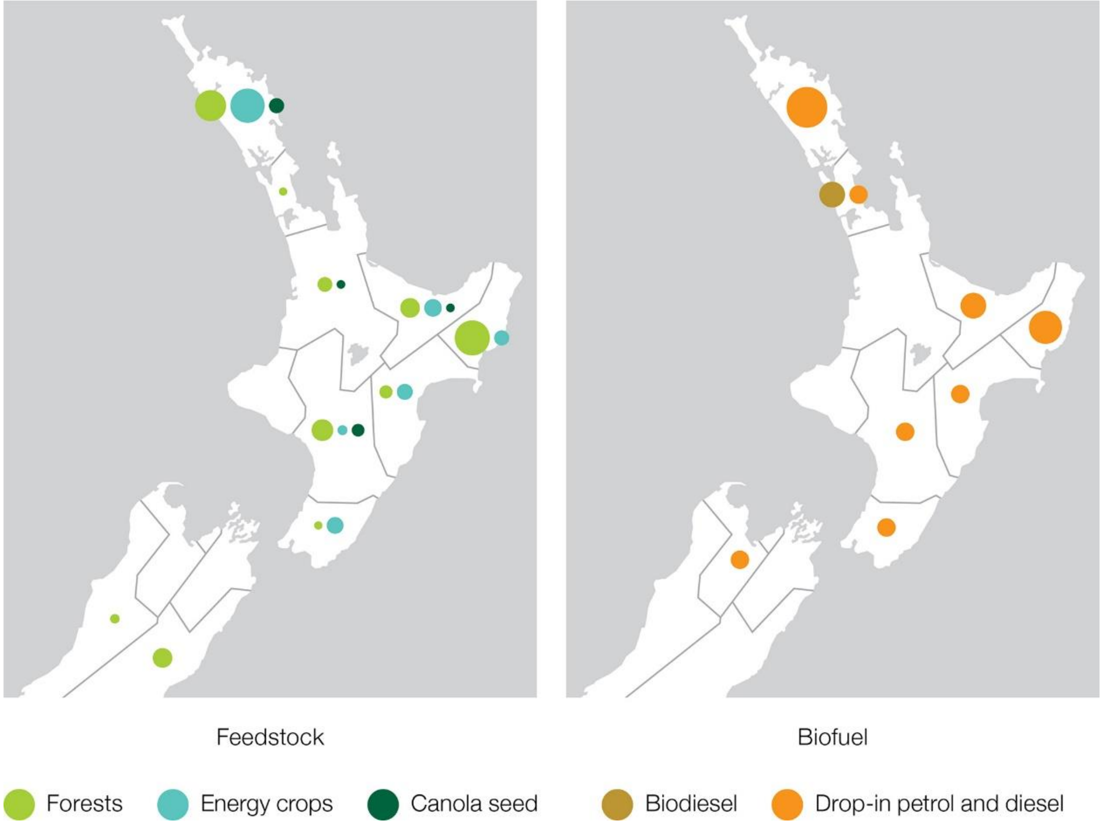


Figure 4.11: Maps showing feedstock consumed and biofuels produced for Scenario 1 (30% substitution, all land classes) in the 2046-50 period.

Crop location

The model choses to grow crops predominantly in areas such as Northland, East Coast/Gisborne and the central North Island (Figs 4.6 - 4.11). This is because the feedstock costs ($/odt) are lowest in these regions, as a result of relatively low land costs ($/ha) and higher crop yields (t/ha). Crop yields are governed by climatic conditions, explaining why the model choses to plant predominantly in the northern half of the North Island, rather than on lower-cost land in the South Island.[68]

Crops are generally planted on the lowest possible land class (*i.e.* on steep land rather than highly productive flat land) due to its lower cost. A notable exception here is for new forestry which is planted predominantly on class 4 land, rather than on class 5 land. This is because most of the class 5 land is very steep, so harvesting is expensive and residues from the cutover are expensive to gather.

Conversion plant location and scale

The model tends to minimise biomass transport costs by locating conversion plants close to where the biomass is produced, rather than close to where the final fuel is needed. This is often in less-developed parts of the country.

The reason for this is illustrated in Figure 4.12 when producing drop-in petrol and diesel by pyrolysis-upgrading of fibre logs. In this case, 1000 kg of freshly-harvested logs, containing 580 kg of water, produces 225 kg of pyrolysis oil and 78 kg of the drop-in fuels after upgrading. Therefore, transporting a single truck-load of final fuel is equivalent to transporting 13 truck-loads of wet fibre logs or almost three truck-loads of pyrolysis oil. Consequently, initial conversion of the biomass to pyrolysis oil is best carried out close to where the feedstock is grown and, if transport is required, it is best to transport the intermediate pyrolysis oil or the final fuel.

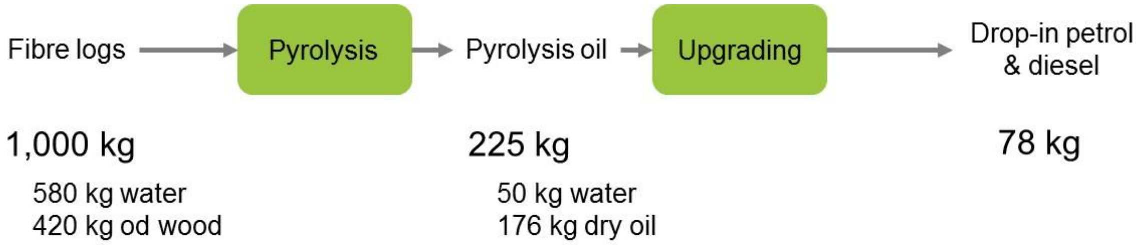


Figure 4.12: Material flows in pyrolysis-upgrading.

As discussed earlier, the cost of processing feedstocks into biofuels drops as the size of the conversion plant increases due to economies of scale. On the other hand, the cost of transporting the required volumes of biomass to the conversion plant rises with size, as it becomes necessary to draw on biomass from further away to meet demand. As a result, there is an optimal conversion plant size, which depends on the specifics of each feedstock/conversion process combination.

The modelling considers this trade-off, and for both biodiesel and pyrolysis plants it chooses the largest possible plant size - indicating that the lower capital and operating costs per litre of fuel for the bigger plants outweighs the increased cost of biomass transport.[69]

Both conversion technologies chosen in the above scenarios, biodiesel production and pyrolysis/upgrading, are examples of distributed processing (Box 8), *i.e.* where the initial feedstock is processed into a higher density intermediate close to where it is produced before transport to a larger plant for final conversion. This capability for distributed processing likely contributes to these technologies being widely chosen in the lowest-cost scenarios.

[68] The outcomes of these modelling scenarios, *i.e.* which crop is planted and where, depend heavily on modelled crop yields. While reliable crop yield data is available for crops already grown commercially in New Zealand, good data for miscanthus and willow is not available as they have only been trialled in a few places in New Zealand.
[69] Improved results could be obtained in future studies by increasing the number of scales included within the model for each plant type (a maximum of 3 scale variants are included per technology) and more accurately modelling feedstock transport.

4.3 Regional development opportunities

These scenarios represent major regional development opportunities. For example, Scenario 2 would result in an additional 75,220 hectares of new forest plantings in the Gisborne/East Coast region; an approximately 50% increase in the existing area of plantation forests. In addition, this scenario envisions construction of 4 new pyrolysis plants and 4 new bio-oil upgrading plants in the region, requiring around $936 million in capital expenditure and creating over 1,000 new direct, indirect and induced jobs.

The land use or feedstock decisions determine where the feedstocks are grown, as well as where the fuels are produced. The two maps shown in Figure 4.13 illustrate how the land class choices made in Scenarios 1 and 2 influence where the fuels are produced - and therefore where regional development would occur. [70]

Figure 4.13: Maps showing where biofuels are produced during 2046-2050 in Scenarios 1 and 2. For Scenario 1, fuel production per cell can be seen in Figure 4.14.

4.4 Infrastructure and services

Questions could be raised over whether current services and infrastructure such as roading and population would be able to support major new processing plants in less-developed parts of the country, such as in East Cape.[71] For example, a single pyrolysis oil upgrading plant of the scale envisioned here would require a capital investment of the order of $170 million and require 240 direct and indirect employees.

In particular, pyrolysis oil upgrading requires significant amounts of natural gas to generate the hydrogen required for the process. However, natural gas is currently only available in parts of the country where there is a gas grid[72,73] - which excludes the South Island, the East Coast beyond Gisborne, Wairarapa and parts of Northland.

[70] For Scenario 2 fuel production in the Waikato is split almost equally between the Taupo and Southwestern Waikato regions.
[71] Recall that the model assumes all services are available at the same price in all locations, and that all supporting infrastructure and labour is also available everywhere at the scale required.
[72] The model assumes natural gas can be used to generate the hydrogen needed for pyrolysis oil upgrading.
[73] The amounts of gas required in both cases are significant. For example, Scenario 1 consumes 22.3 PJ/yr in 2046-50, or 12% of gas consumed in New Zealand in 2015, so the long-term availability of gas might be an issue.

However, there are multiple possible ways to address such issues, including:

- restricting the location(s) where conversion plants can be built to areas close to the gas pipeline,
- extending services and upgrading infrastructure in new locations - something New Zealand has done in the past, and
- choosing conversion technologies which do not require natural gas, or producing hydrogen on-site from biomass via gasification.[74]

To explore the first option, a 30% substitution scenario was run where upgrading plants can only be located in cells where gas is available in that or an adjacent cell. While this changed the locations of the plants to some extent (Fig. 4.14), the conversion technologies and feedstocks used, and regions where feedstocks are grown remained quite similar. The levelised biofuel cost increased only slightly, from $0.77/L-e for Scenario 1 up to $0.79/L-e when the locations were restricted in this way.

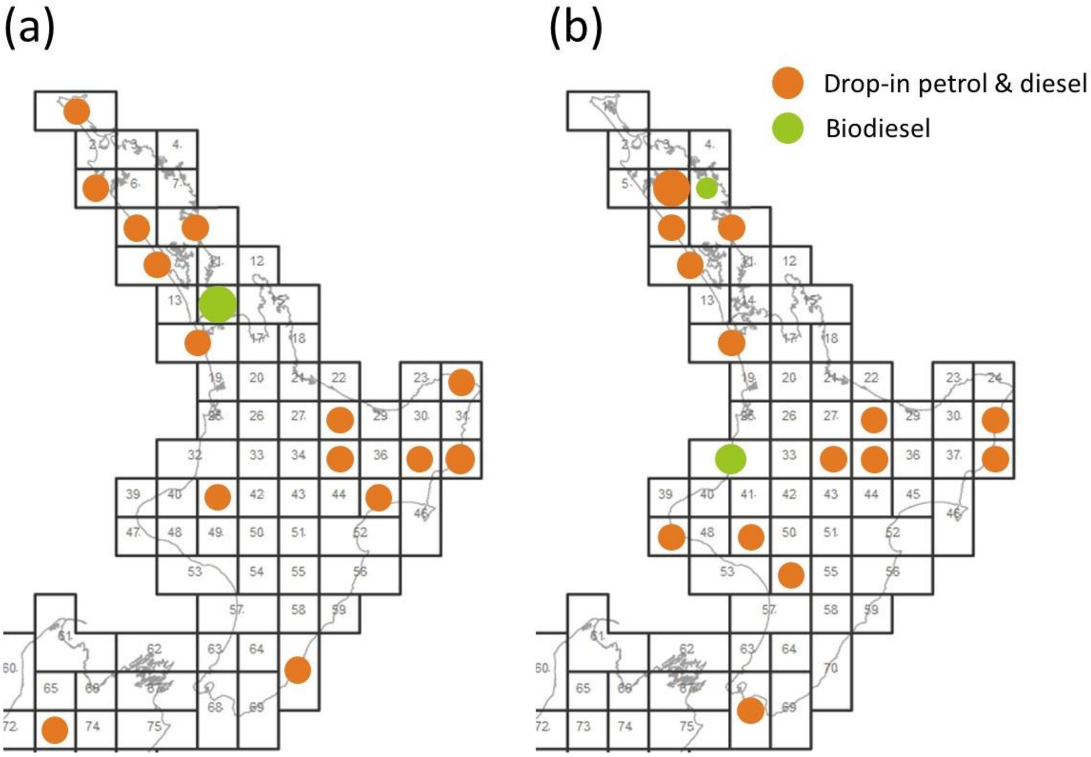


Figure 4.14: Maps comparing the locations of final fuel production in the 2046-50 period for (a) Scenario 1 (all land classes allowed) and (b) a similar scenario except that pyrolysis oil upgrading is only allowed in cells on/adjacent to the gas grid.

4.5 Fuel distribution

Biofuels produced in Northland, the central North Island and East Coast would need to be distributed to areas where the demand is, such as Auckland.

Existing fossil fuel dsitributors already have a substantial distribution infrastructure, so it would make sense to use this infrastructure.[75] A potentially attractive way to do this might be to use the existing coastal shipping network and fuel distribution terminals by transporting the biofuels to

[74] Using biomass to produce hydrogen would significantly increase both the amount of biomass required to produce a given volume of fuel and the final fuel cost. The model contains an option to use the intermediate pyrolysis oil to produce hydrogen but purchasing natural gas was the lower-cost option. Other technology choices may therefore be preferred, particularly if biomass availability was limiting the rate of biofuel deployment.

[75] A separate distribution infrastructure for biofuels would add considerably to capital costs.

these distribution terminals.[76] A new terminal at Gisborne could be one way of getting biofuels produced in the East Coast to where they are needed. Rail transport could also be an attractive option in some cases.[77]

4.6 Opportunity scale

Substituting 30% of liquid fuels with biofuels is a large undertaking, as illustrated in Figure 4.15 for Scenario 2. It will consequently have a number of significant national and regional implications.

Figure 4.15: Illustration of the scale of Scenario 2 (30% substitution, no arable land) in the 2046-50 period.

[76] Recalling that the cost of transporting a final fuel are much lower than transporting the equivalent volume of wet biomass required for its production (Fig. 4.12), final fuel distribution costs are anticipated to have only a small impact on biofuel production costs and conversion plant locations if they had been included in the model.
[77] As the locations where biofuels are produced depends on the types of feedstocks used and levels of deployment, the best way to get the biofuels to market will depend on answers to these questions.

4.7 Greenhouse gas emission reduction

In both Scenario 1 and Scenario 2, net GHG emissions reduce as the amounts of biofuels increase. As Figure 4.16 shows for Scenario 2, this is mainly because biofuels displace fossil fuels, but also partly because the model assumes the char produced during pyrolysis is used to replace coal burned for heat.

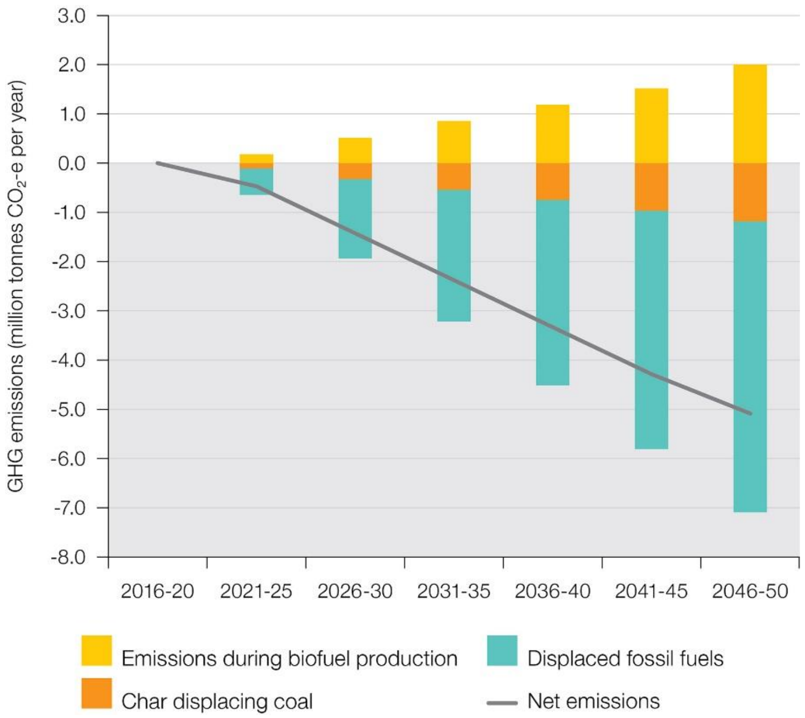


Figure 4.16: Net greenhouse gas emission reduction in Scenario 2 (30% substitution, no arable land) relative to 2015.

Table 4.2 shows that net average emissions from 30% substitution in Scenarios 1 and 2 are reduced by 80% and 88% respectively relative to the displaced fossil fuels.

Table 4.2: GHG impact for the two 30% substitution scenarios.

	Scenario 1 **No restriction on land use**	**Scenario 2** **No arable land**
Average emissions reduction, relative to displaced fossil fuels (kg CO_2-e/L-e)	-2.1	-2.3
GHG emission reduction relative to displaced fossil fuels	80%	88%
2046-50 GHG savings (% of 2015 energy sector emissions)	15%	16%
Cumulative CO_2 reduction in 2021-30 (million tonnes CO_2-e)	9.0	9.5

Thirty percent biofuel substitution in 2050 would reduce New Zealand's annual energy-related GHG emissions by 15% over 2015 levels (Table 4.2). Net GHG offsets are slightly smaller for Scenario 1 due to the use of more carbon-intensive canola production in this scenario.

The GHG reduction in 2030 under both scenarios would be much more limited. Current projections show that between 2021 and 2030, New Zealand has a gap of 220 million tonnes of CO_2-e in our actual emissions versus Paris commitments. A cumulative reduction in emissions of 9-9.5 million tonnes over this period is a step towards meeting these commitments. The real potential for GHG reduction from biofuels is however much more significant in the longer term.

4.8 Cost of biofuels

Value chain cost breakdown

All parts of the biofuel value chain contribute significantly to the cost of the fuel produced (Fig. 4.17). The relative proportions of the different parts of the value chain vary from scenario to scenario.

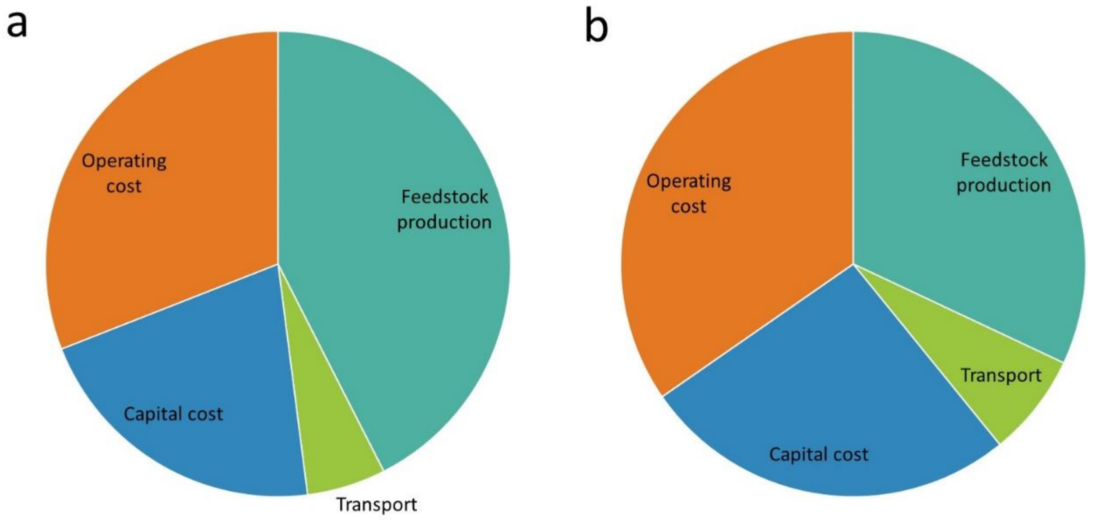


Figure 4.17: Proportion of costs across the total value chains for 30% substitution in (a) Scenario 1 and (b) Scenario 2 (non-arable land used). Co-product revenue is not included.

The opportunity cost of the land makes up a substantial proportion of the cost for producing the feedstock; 25% and 13% of the feedstock production cost for Scenarios 1 and 2 respectively.[78] The use of more expensive arable land, and greater production costs for canola explains the higher proportion that feedstocks make to the final fuel cost in Scenario 1.

Levelised biofuel cost

The levelised biofuel cost was used to compare the relative costs of biofuel production across the different scenarios. This is an economic assessment of the average per litre cost of constructing and operating the whole value chain over the timeframe modelled (*i.e.* 2016 – 2050). This type of analysis is widely used in the energy sector to compare different methods of energy production [83]. It takes into account the initial plant investment, the cost of capital, plant operating costs, co-product revenues, and all costs for feedstock production and transport.

$$\text{Levelised biofuel cost (\$/L-e)} = \frac{\text{Sum of (all costs – all revenues) discounted over lifetime modelled}}{\text{Sum of biofuels produced discounted over the lifetime modelled}}$$

Biofuel relationship to fossil fuel price

For biofuel production to be profitable relative to fossil fuels in the absence of any other incentives, then the plant gate biofuel cost must be less than the sum of the landed cost of their fossil equivalents, plus any carbon price these would incur under the ETS.[79,80]

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[78] This corresponds to 11% and 4% of the total costs of producing the biofuel in Scenarios 1 and 2 respectively.
[79] The displaced fossil fuel must be discounted to allow comparison to the levelised biofuel cost given by the model.
[80] Carbon emissions incurred during biofuel production (*e.g.* from fertilisers, fossil fuel used during harvesting/transport, or natural gas used during pyrolysis oil upgrading) and emissions mitigated via co-products (particularly char burnt as a substitute for coal) must also be accounted for.

Figure 4.18 makes this comparison for the two scenarios discussed above, Scenarios 1 and 2. It shows that when we assume the nominal[81] landed prices for fossil petrol and diesel remain constant at their 10-year average (Box 9), Scenario 1 is profitable, whereas Scenario 2, where non-arable land is used, is not profitable.[82,83]

What Figure 4.18 also shows is that while neither scenario would be profitable at current (February 2017) fossil fuel prices, there are many circumstances where biofuels would be economic given the range of fuel prices seen in the last 10 years.

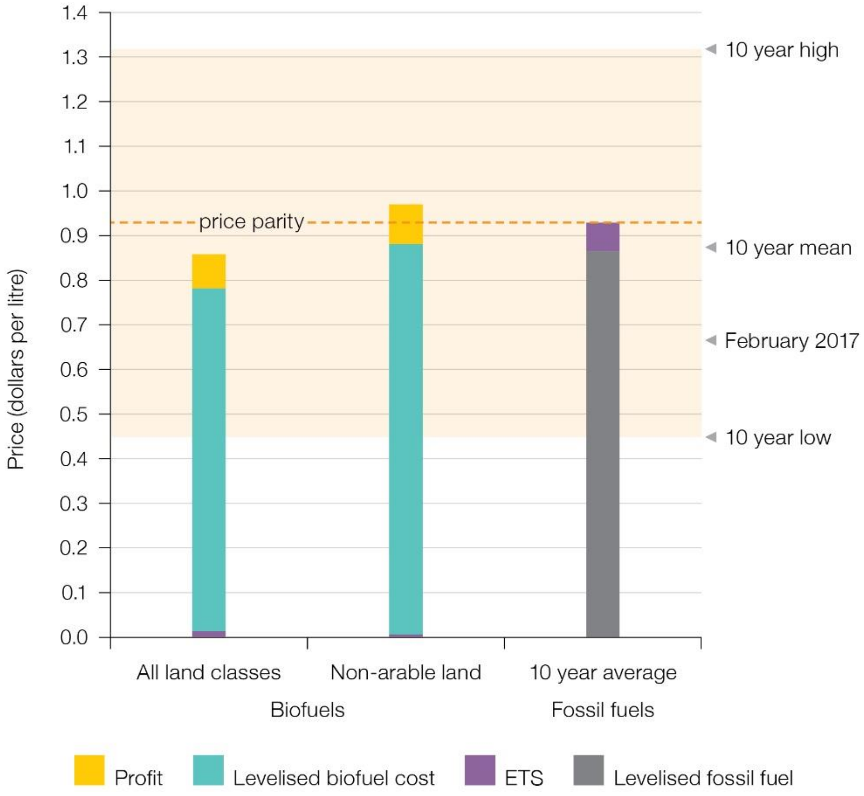

Figure 4.18: Comparison of levelised biofuel cost for the two 30% substitution scenarios against the levelised displaced fossil fuel costs.[84] The range for fossil petrol prices over the last 10 years is indicated for comparison.

Box 9: Landed fuel prices

Fuel type	Price NZ¢/L 10-yr mean (range)
Petrol	84.4 (44.1 – 130.8)
Diesel	87.8 (38.3 – 157.4)
Jet	86.9
Marine (Heavy fuel oil)	72.0

Sources: Refs [37, 84].

[81] Unadjusted for inflation.
[82] Additional assumptions here are: constant nominal prices for all inputs and co-product revenues; a constant nominal carbon price of $25/tonne CO_2-e; and an indicative profit margin to the biofuel producer of 10% of costs. In the BVCM any co-product sales revenue belongs to the whole modelled value chain, but as the BVCM is set to give both the feedstock producer and biomass transporters a profit, this is essentially the profit for the biofuel producer(s).
[83] Both these scenarios produce only diesel and petrol replacements, so both would likely be used domestically and fall within the ETS.
[84] The levelised landed cost for the displaced fossil fuel cost is for the average of the fuel mixtures produced in Scenarios 1 and 2, using 10-yr mean values for fossil petrol and diesel (Box 9).

It is important to note that even if the overall biofuel system is profitable relative to its fossil equivalent, this does not indicate that biofuel production is profitable during all time periods. In particular, our modelling assumes biofuel production costs for the immature processes reduce over time as a consequence of "technology learning", so production costs will be significantly higher in the earlier periods.

Higher landed fossil fuel prices, or higher prices for carbon within the ETS, unsurprisingly, make the domestic production of biofuel more likely to be profitable. Figure 4.19 provides a way to compare the profitability of the different scenarios presented above under a range of possible future carbon prices and landed fossil fuel prices. This covers the range of landed fossil fuel prices seen since 2010 (44 – 112 ¢/L for petrol and 38-122 ¢/L for diesel) and range of future carbon prices.

Carbon price	Landed fossil fuel price, ¢/L					
$/t CO_2-e	40	60	80	100	120	140
0	40	60	80	100	120	140
10	43	63	83	103	123	143
25	46	66	86	106	126	146
50	53	73	93	113	133	153
100	66	86	106	126	146	166
150	79	99	119	139	159	179
	39	67	95	124	152	180
	Dubai crude $/bbl					

Figure 4.19: Effect of variations in the landed fossil fuel price and carbon price under the ETS on the equivalent fossil fuel price, given in cents per litre.[85] The cross shows the equivalent fossil fuel price for the comparison made in Figure 4.18.

Equally, government incentives to biofuel producers, or mandated levels of biofuel incorporation are commonly used overseas to encourage biofuel production. These can make a big difference to the biofuel producer. For example, bioethanol and electric vehicles are currently exempt from contributions to the National Land Transport fund (59.5 ¢/L). A similar exemption for other types of biofuel would provide a substantial incentive to biofuel producers.[86]

Impact of co-products

The sale of co-products produced during biofuel production has a significant beneficial impact on the verall cost of biofuels (Table 4.3). These co-products include: canola seed meal used for stock feed; char burnt for energy; and sawlogs sold for solid wood processing. Table 4.3 shows that if co-product revenues are excluded, the cost of producing biofuels in Scenario 2 is actually slightly lower than for Scenario 1, with co-products being responsible for dropping the levelised biofuel cost for Scenario 1 by approximately 25%.

The data in Table 4.3 further suggests that revenue from selling canola seed meal and glycerine is a significant factor responsible for biodiesel production becoming one of the preferred technologies. Based on these results, log sales from conventional forests in the last period reduce the levelised biofuel cost for Scenario 1 by 8 cents, char from pyrolysis by ~3 cents and the canola seed meal and glycerine from biodiesel production by ~15 cents.

[85] An approximate crude oil price in NZ dollars per barrel is included, as this is highly correlated to the landed fossil fuel price.
[86] This would effectively increase the price a biofuel producer must meet from $0.93/L to $1.52/L for the example shown in Figure 4.18.

Table 4.3: Impact of co-product revenues on the levelised biofuel cost for the two 30% substitution scenarios.

Scenario	**Fuels**	**Co-products**	**Levelised biofuel cost $/L-e**		
			Including co-products	**Excluding log sales**	**Excluding all co-products**
Scenario 1, all land classes	Biodiesel Drop-in petrol & diesel	Canola seed meal Glycerine Char Sawlogs + fibre logs	$0.77	$0.85	$1.03
Scenario 2, no arable land	Drop-in petrol & diesel	Char Sawlogs	$0.88	$0.96	$0.99

Lignocellulosic feedstock cost

The costs of lignocellulosic feedstocks used for processes such as pyrolysis/upgrading generally rise in the order: municipal wood waste < forest residues from existing or new forests < fibre logs from existing or new conventional (30-yr) forests ~ miscanthus ~ willow < fibre logs from energy forests < sawmill chips < sawlogs.

When comparing scenarios with 30% biofuel substitution run when restrictions are placed on the allowable feedstocks we see (Fig. 4.20):

- waste wood[87] and forest residues are used in all scenarios up to the levels possible; and are introduced in early time periods (Fig. 4.2).
- the levelised biofuel costs remain very similar whether all feedstocks are permitted, or when either miscanthus, fibre logs from existing forests, or new conventional forests are excluded, indicating that feedstocks costs for these crops are all comparable.
- when arable energy crops are excluded by excluding arable land, then additional energy forests must be grown to satisfy demand. Fibre logs from energy forest have higher costs because they must cover the whole cost of growing the forest – in contrast to the conventional forests where sale of the higher-value sawlogs can offset the cost of fibre logs.
- sawmill chips or sawlogs are rarely used in these 30% substitution scenarios, and if so only in small amounts, indicating that they have higher value alternative uses.

[87] Limited amounts of municipal wood waste are available, 2.6% of feedstocks used in the 2046-2050 period in Scenario 1.

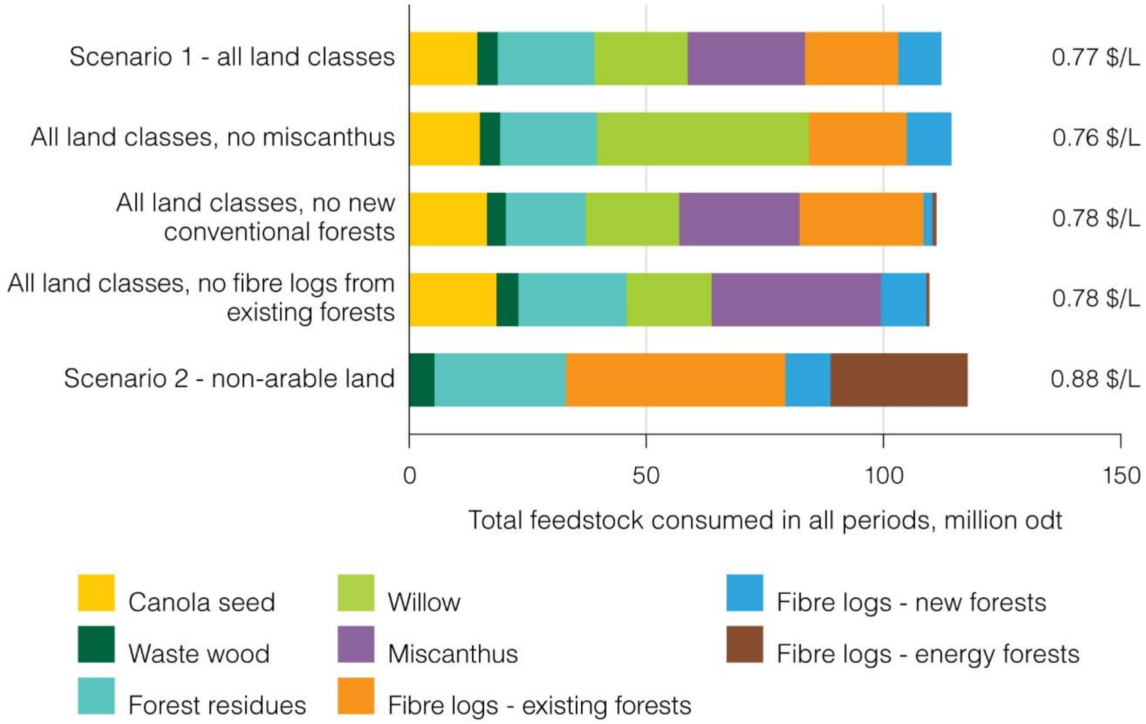

Figure 4.20. Levelised biofuel costs and total feedstock consumed in all periods for 30% substitution when different restrictions are placed on allowable feedstocks.[88]

30% substitution, no food crops

A further way in which the question of "what are acceptable feedstocks for biofuel production?" could play out is that crops which could be used to produce food are not acceptable. This would exclude the use of canola for biodiesel production or sugar beet or maize for ethanol production, but would still allow energy crops to be used.

Not unexpectedly, a 30% substitution scenario run when food crops were excluded, but arable land could still be used, gave a levelised biofuel cost intermediate between those of Scenario 1 where no restrictions on crops or land are applied and Scenario 2 which assumes no arable land is used (Fig. 4.21). In this case pyrolysis/upgrading to produce a mix of drop-in petrol and diesel is chosen, and miscanthus and willow are both important feedstocks.

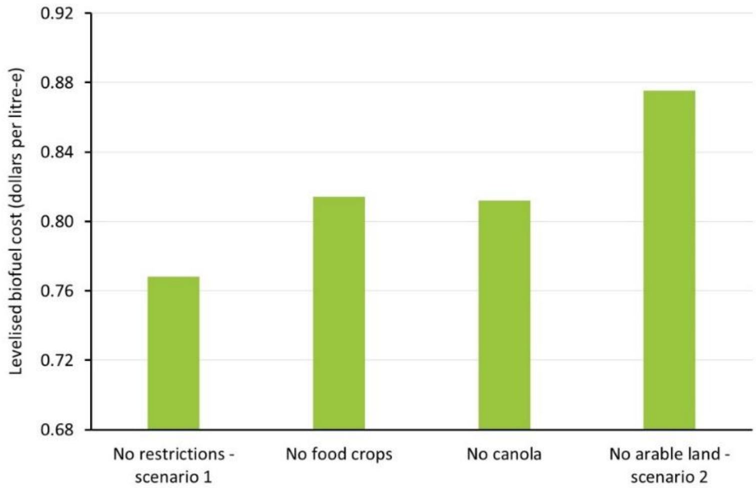

Figure 4.21. Levelised biofuel costs for 30% substitution scenarios when different restrictions are placed on allowable feedstocks.

[88] Levelised biofuel costs of $0.76, $0.77 and $0.78/L-e should not be considered to be significantly different due to the margin of error considered in the model.

5 Results of other scenarios

In Chapter 4 we focussed solely on how to deliver a minimum level of biofuel production of 30% of 2015 fuel demand by 2050. In this Chapter we present the results of scenarios assuming other levels of biofuel substitution or targeting specific fuel types.

5.1 Different levels of biofuel substitution

The implications of different final levels of biofuels substitution, 5%, 10%, 20%, 30% and 50% of 2015 fuel demand by 2050, were compared. As with the 30% substitution scenario discussed earlier, biofuel production was set to climb linearly from 0% in 2020 to the targeted level of substitution in 2050. Again, the specific fuels to be targeted were not specified and two situations were compared - all land classes available, and when no arable land could be used. This produced differing effects on feedstocks, production, cost and reduction of GHG emissions (Figs 5.1 - 5.3, Table 5.1).

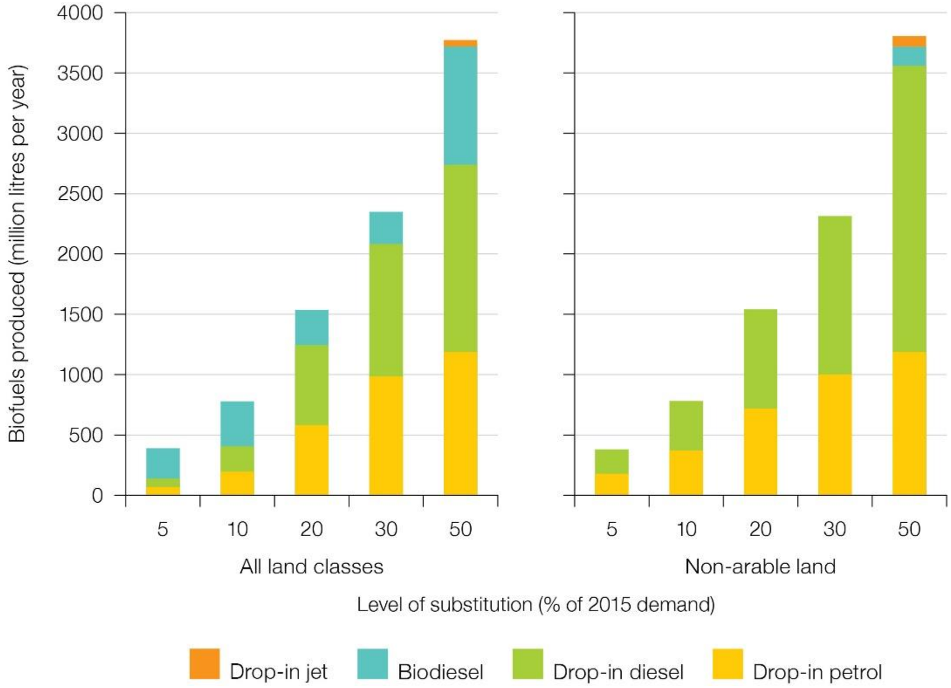

Figure 5.1: Biofuel production in the 2046-50 period for different levels of substitution when all land classes are available and when no arable land is allowed.

When all land classes are permitted and up to 50% substitution, the main biofuels are biodiesel from canola and drop-in petrol and diesel by pyrolysis/upgrading of energy crops plus fibre logs and forest residues from new and existing forests (Figs 5.1 and 5.2).

When no arable land is used, the canola and energy crops are substituted by additional feedstocks from new and existing forests (Fig. 5.2). In particular, fibre logs from energy forests, grown with a rotation age of 15 years, become increasingly important feedstocks at high substitution levels, as the volumes of fibre logs from existing forests and from new conventional forests are limited.[89] Such energy forests are often important feedstocks in the earlier time periods when fibre logs from new forests are not yet available.

[89] Fibre logs from new conventional, 30-year rotation forests, only available in the last period, are limited by the assumption that only 100,000 ha of such forests can planted in the first period, to allow for a realistic rate of expansion from recent low annual planting rates.

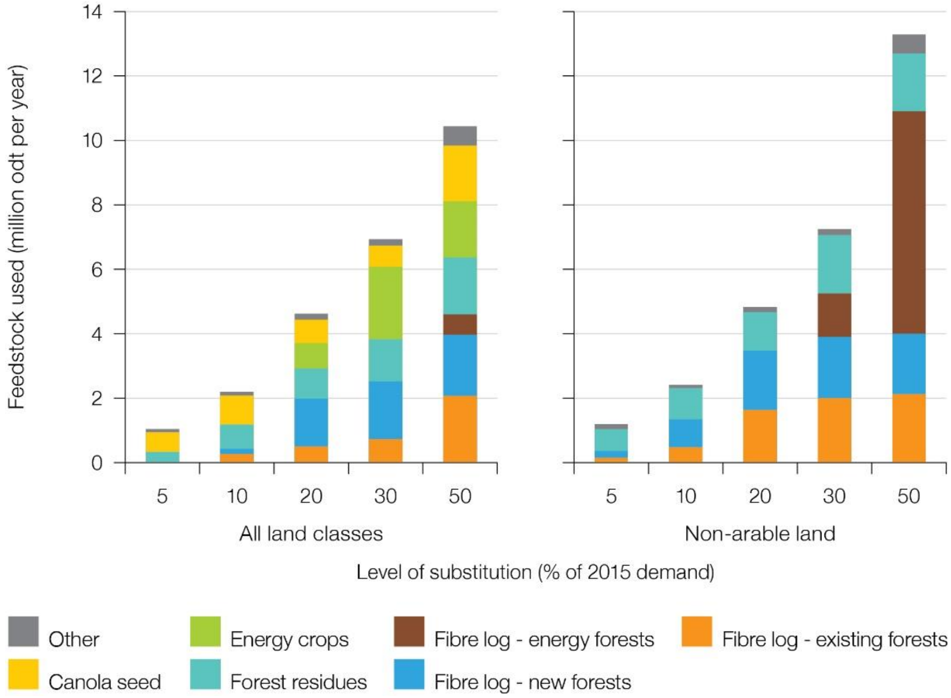

Figure 5.2: Feedstocks used for different levels of substitution when all land classes are available and when no arable land is allowed. Other includes municipal solid waste, corn, sawmill chips and sawlogs.

Figure 5.3 shows that the levelised biofuel cost increases as the level of substitution increases and is higher when non-arable land is used. The levelised cost per litre goes up mainly because at low substitution levels co-product sales (particularly logs and rapeseed meal) are higher per litre of biofuel produced. Increases in the cost of delivered feedstock and the need to use more expensive technologies also contribute to the increased per litre cost.[90] As discussed earlier, the scenarios where no arable land is used are more costly because, while feedstock costs are lower, capital and operating costs are higher and co-product revenues lower.

At 50% substitution the model was forced to produce more costly diesel and even more expensive jet fuel. This is because conversion technologies like pyrolysis/upgrading produce fuels in specific ratios and once the demand for petrol (or diesel) in the fuel demand projection is satisfied, then other more costly biofuels must be produced to target other fuel families.[91]

The higher the level of biofuel substitution modelled, the greater the net reduction in fossil GHG emissions (Fig. 5.3). Particularly at the higher substitution levels, the emission reduction is higher when no arable land is used, mainly due to the types of feedstocks employed.

[90] As the amounts of biofuels are required, increasingly expensive feedstock types (*e.g.* crops, not wastes, using energy forests), more costly land, and/or land with lower productivity must be used. This is expected for a lowest-cost optimisation model of this type.

[91] Recall we assume for this study that no biofuels are exported. This means that the maximum amount of each fuel family that can be substituted by biofuels is limited to the amount of that fuel required in the low use projection (see Figure 2.4). For example, once the demand for petrol has been satisfied, only technologies that do not produce petrol can be used. Technology developments to target different final fuel mixes, *e.g.* to produce less petrol, could consequently have a beneficial impact on costs.

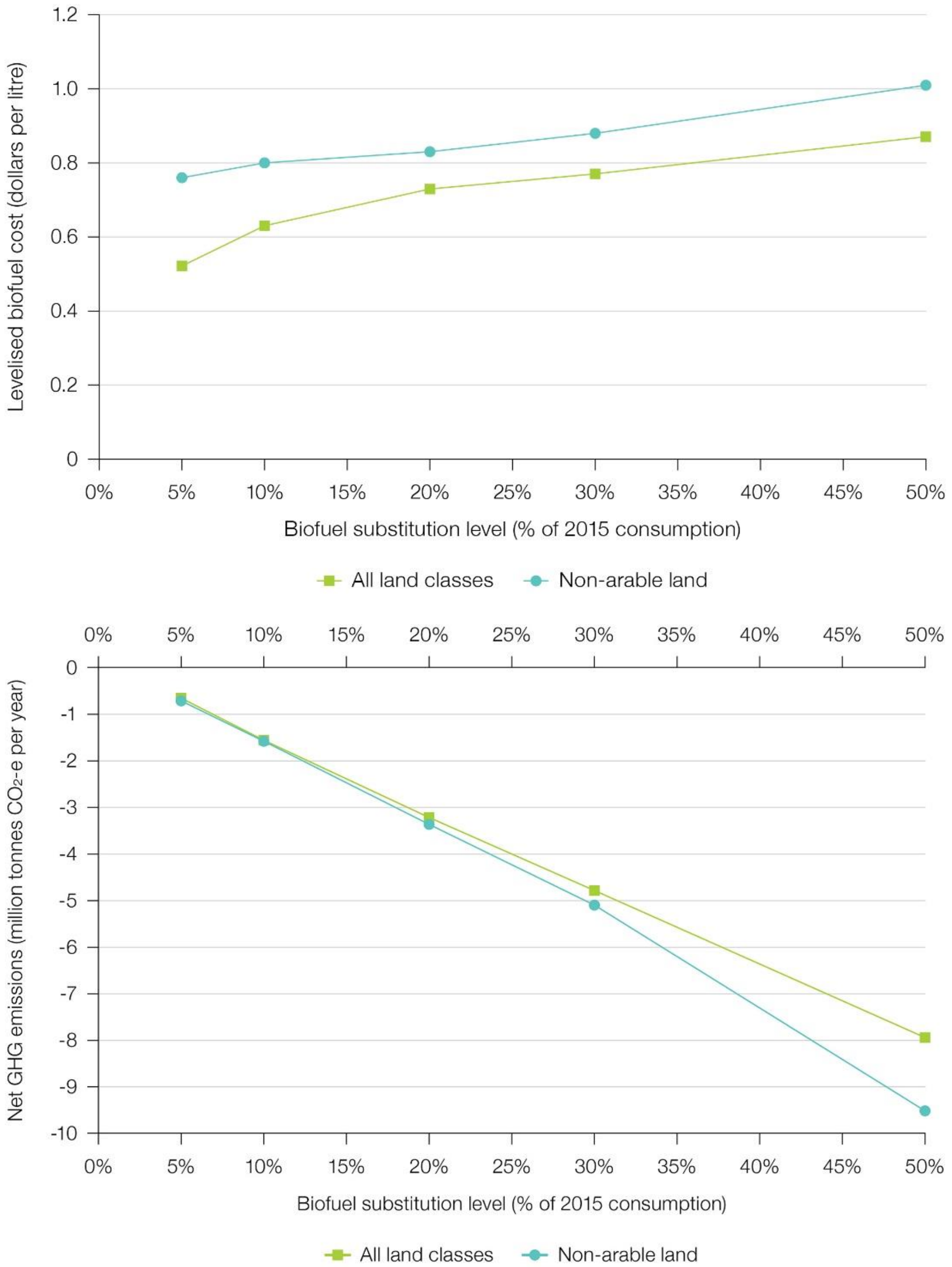

Figure 5.3: Levelised biofuel cost and net displaced greenhouse gas emission in the 2046 – 50 period for different substitution levels.

Table 5.1: Cost metrics and greenhouse gas emission reduction for different levels of fuel substitution.

Substitution level	**Levelised biofuels cost, $/L-e**		**Total capital investment, billion $ (not discounted)**		**Net GHG emission reduction in 2046-50 period, M tonnes CO_2-e per year**	
	All land classes	**No arable land**	**All land classes**	**No arable land**	**All land classes**	**No arable land**
5%	0.52	0.76	0.6	1.2	-0.7	-0.7
10%	0.63	0.80	1.4	2.3	-1.5	-1.6
20%	0.73	0.83	3.8	4.5	-3.2	-3.4
30%	0.77	0.88	6.0	6.8	-4.8	-5.1
50%	0.87	1.01	9.8	14.4	-8.0	-9.5

5.2 Complete substitution by biofuels

Finally scenarios where the model was asked to simulate total substitution of fossil fuels by biofuels by 2050 were run. This was attempted for both the high and low fuel demand projections shown in Figure 2.4. These final demand projections were modelled assuming that the amounts of biofuels of each fuel family increased linearly from 0% in 2020 to the final projected demand in 2050. This meant that a specific amount of each of the four fuel types was needed in each time period, unlike in earlier scenarios where the model was free to choose which fuel to produce in all time periods.

The levelised biofuel cost for total substitution of the two fuel demand projections are shown in Table 5.2. Key findings are:

- The biofuel production costs are significantly higher than in other scenarios discussed so far. This is not only because the delivered cost of feedstock rises as the level of biofuel substitution increases, but because it is also necessary to produce specific amounts of each fuel family in each period. As we will see in the following section, this requires more costly conversion technologies to be used, particularly for aviation fuels.
- A complex mix of feedstocks and technologies are chosen in all cases.
- When all land classes can be used, the per litre cost of producing the biofuel in the high demand projection is actually lower than that for the low demand projection, despite the total volume of fuel required being significantly higher. This is because the high use projection contains proportionately more petrol and less diesel and aviation fuel.[92] This means a greater proportion of the diesel demand can be covered by lower-cost pyrolysis/upgrading and proportionately less expensive jet fuel is required.
- When only non-arable land is allowed, not enough feedstock is available in early periods to produce the volumes of biofuel required for the high demand projection, so no solution is possible. Once all wastes, sawmill chips and fibre logs plus sawlogs from existing forests have been utilised, no further feedstock is available until the new energy forests mature in the 2031-35 period.

Table 5.2: Biofuel costs for scenarios run assuming complete replacement of fossil fuels by 2050 for the high and low projections given in Figure 2.4.

	Levelised biofuel cost, $/L-e	
	All land classes	**Non-arable land**
Low demand projection	$1.57	$1.87
High demand projection	$1.45	No solution possible

5.3 Producing specific fuel types

Nearly all the preceding scenarios left the model free to choose which biofuels to produce to satisfy the required demand at lowest cost, often a mix of replacements for fossil petrol and diesel.

Strategically it might be better to target replacements for specific fossil fuel types. For example, bio-jet fuels are one of the few options for decarbonising the aviation sector.

Table 5.3 and Figure 5.4 show the results of scenarios run where we specify that 10% substitution of fossil fuels as either petrol, diesel, jet or marine substitutes.[93,94] This showed that targeting minimum volumes of specific fuels is more expensive than producing an equivalent volume of biofuels as any fuel mixture. When one fuel is specified, flexibility is removed from the system and more expensive technologies must be used.

The high cost of bio-jet fuel is because the only practicable option in the model to make high proportions of this fuel is to make ethanol first, and convert this to a mix rich in drop-in jet fuel. This

[92] Petrol increases from 20 to 29% and jet drops from 36 to 28% of total fuel demand on going from the low to high demand projections.
[93] Again the volumes of specific biofuels were set to rise linearly from zero in 2020 to a minimum of 10% of total 2015 fuel demand in 2050.
[94] While marine fuels are projected to make up only 5 – 7% of total fuel offtake in 2050, running such single fuel scenarios at 5% substitution levels took unacceptably long times to solve (>2 weeks).

is costly. Other technologies, such as gasification/Fischer-Tropsch and hydrotreatment of oils, only make a small proportion of jet fuel together with larger proportions of other fuels. In these scenarios credit is only given for the targeted fuel type, but costs to produce all fuels produced are included.

In reality, targeting a single drop-in biofuel, as is modelled in these scenarios, is unlikely. This is because most drop-in biofuel technologies produce mixtures of drop-in petrol, diesel and jet, so a producer would sell this slate of products.

Table 5.3: Production of biofuels targeting 10% of 2015 demand as specific fuel families. Non-arable land is assumed for feedstock production.

Fuel family	Conversion technologies	Biofuels produced	Levelised biofuel cost, $/L-e
Any fuel	Pyrolysis-upgrading	Drop-in diesel	0.80
		Drop-in petrol	
Petrol	Cellulosic ethanol	Bioethanol	1.36
	Gasification/syngas fermentation	Biobutanol	
	Cellulosic butanol		
Diesel	Catalytic depolymerisation	Drop-in diesel	1.39
	Biodiesel production	Biodiesel	
	Pyrolysis-upgrading	Drop-in petrol[a]	
Aviation	Alcohol-to-jet[b]	Drop-in jet	2.21
	Cellulosic ethanol	Drop-in petrol[a]	
	Gasification/syngas fermentation	Drop-in diesel[a]	
Marine	Pyrolysis-mild upgrading	Oxygenated marine fuel	0.86

[a] Minor amounts only.
[b] Drop-in jet fuel is produced by first making bioethanol and then converting it to jet fuel.

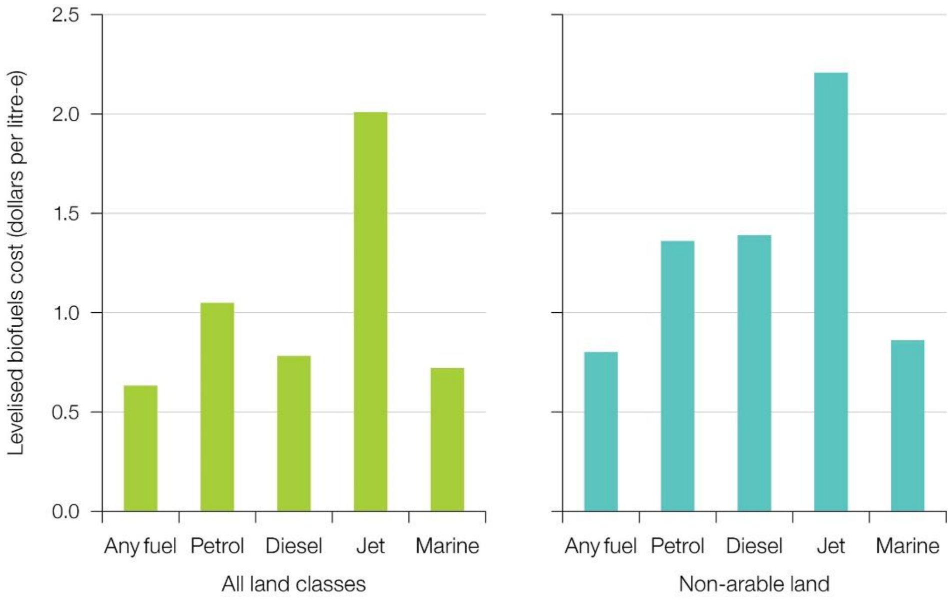

Figure 5.4: Levelised biofuel cost for production of 10% of 2015 demand as specific fuel types assuming either all land classes or only non-arable land is used.

5.4 Residuals and by-products

Current biomass wastes and process residues could be good initial biofuel feedstocks. Municipal solid waste, waste wood from construction and demolition,[95] harvest residues left in forests, and co-products from existing biomass processing such as chips from sawmills, or tallow from meat-processing are examples.

However, their potential as feedstocks for large-scale biofuel production is generally limited because (Table 5.4):

- available volumes are low compared to expected total fuel demand, making up at most 8% of 2015 fuel demand,
- while some wastes and residues are not currently being used, tallow and sawmill chips already have existing end uses and established values, often making them too costly to use as feedstocks for biofuel production, and
- it might not be technically or economically feasible to collect geographically dispersed feedstocks such as forest residues.

The model frequently chooses to use forest residues and wood waste as feedstocks in the scenario modelling because of their lower cost.

Table 5.4: Maximum potential of residuals and by-products.

	Amount produced (thousand odt/yr, 2015)	**Substitution potential (% of total 2015 liquid fuel demand)**
Tallow	178	2.2
Municipal solid waste	2358	0.7
Wood waste	229	0.8
Forest residues	1,240	4.5
Total		**8.2**

[95] Cities and towns already pay to dispose of municipal solid wastes in landfills, so a biofuel producer might be paid to take such material.

6 Additional considerations

On top of the cost of producing the biofuels and the level of GHG reduction, there are a number of additional considerations which will help to define how biofuels might best be deployed in New Zealand. This Chapter discusses a number of these.

6.1 Technical risk

Although rapid developments are occurring internationally, many of the biofuel technologies of interest, and included in the scenario modelling, are not yet commercially proven. This is particularly so for drop-in biofuel production from lignocellulosic feedstocks, including pyrolysis/upgrading, identified as one of the model's prominent options.

Before large-scale deployment of these new technologies can occur they will need to be proven to operate reliably at large scale with the identified feedstocks and to produce fuels that meet the required fuel quality standards.

Such technical risks substantially adds to the risk for an investor.[96] However, such risk will fall with time as the technologies are commercially proven. Multiple technologies to produce drop-in biofuels are under active development, reducing the risk of finding a commercially-viable solution.

Box 10: Technology readiness level scale

The state of commercial readiness of technologies is commonly described using the technology readiness level (TRL) as described below [38]. As a technology progresses from the laboratory to a pilot plant, and then on to a demonstration plant and a first commercial plant, new technical issues must be overcome at each stage. As the TRL rises the technical risk drops and costs become more certain.

TRL	Definition	Description
0	Idea	Unproven concept, no testing has been performed
1	Basic research	Principles postulated and observed but no experimental proof available
2	Technology formulation	Concept and application have been formulated
3	Applied research	First laboratory tests completed, proof of concept
4	Small scale prototype	Built in a laboratory environment
5	Large scale prototype	Tested in intended environment
6	Prototype system	Tested in intended environment close to expected performance
7	Demonstration system	Operating in operational environment at pre-commercial scale
8	First-of-a-kind commercial system	Manufacturing issues solved
9	Ready for commercialisation	Technology available for consumers

[96] Government support has been widely used overseas as a mechanism to reduce the risk to investors with immature technologies and encourage their deployment.

Figure 6.1 summarises the readiness of most of the conversion technologies considered in the scenario modelling. The technology readiness level (TRL, Box 10) puts the stage of commercial readiness into context. In practice, TRLs are only indicative and often span a wide range, as there are frequently multiple technology developers at different stages of development, and the TRLs depend on both the feedstock used[97] and scale of operation.[98]

Pyrolysis coupled with bio-oil upgrading to produce a mix of drop-in petrol and diesel is a prominent technology identified in many of the study's scenarios because of its low cost. While pyrolysis is relatively well-proven with a number of commercial-scale plants operating, upgrading of pyrolysis oil has only been demonstrated at a pilot scale.

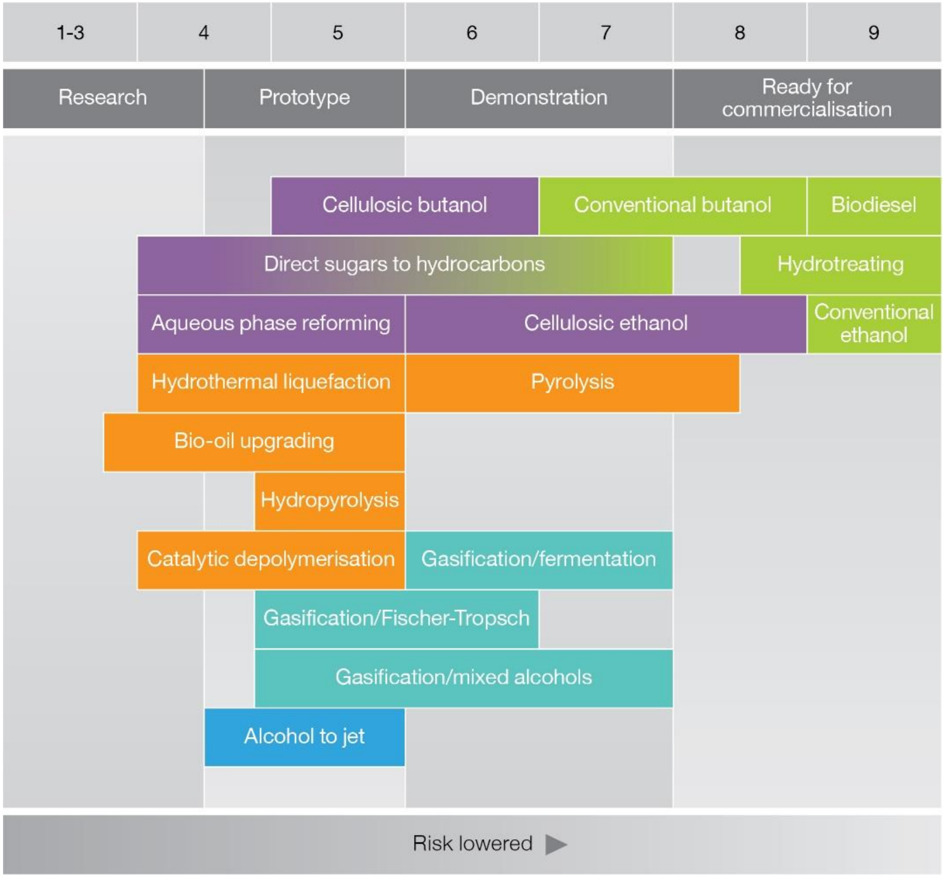

Figure 6.1: Commercialisation status of various biofuel production technologies used in this study. The TRL is shown at the top. Colours represent mature processes (green), process proceeding via sugar intermediates (purple), bio-oils (orange) syngas (light blue) or alcohols (dark blue). Adapted from ref. [38].

[97] For example, while there are several first-of-a-kind cellulosic ethanol plants operating on agricultural residues like corn stover and bagasse, these technologies would likely not be suitable for the feedstocks proposed here, particularly pine wood.

[98] For example, the direct sugar to hydrocarbons process is being used at a commercial scale by Amyris to produce cosmetic ingredients – and trial aircraft flights have been carried out using this fuel. However, this would be ranked at a much lower TRL for producing large volumes of lower-priced fuels.

Implications of using only mature technologies

Technical risk could be reduced by deploying only mature conversion technologies. A scenario run assuming 30% fuel substitution using only today's mature technologies identified biodiesel from canola plus a little tallow, and ethanol from sugar beet as the sole fuels.

However, there are a number of significant factors to consider with this scenario, including:

- the biofuel cost is considerably higher, $1.02 *vs* $0.77/L-e,
- new vehicles with modified engines would be needed,[99]
- it would require a total of 825,000 hectares of cropping land to grow the canola and sugar beet, 1.7 times the current area of cropping plus horticultural land in New Zealand, and
- sales of co-products, particularly canola meal and sugar beet pulp, are assumed to offset costs. Would there be markets for these products at this scale?

Energy crop risk

Energy crops such as miscanthus or willow have not been grown at large scale in New Zealand, and so would carry substantial technical and financial risk. As these have been identified as significant feedstocks in some scenarios, it would be prudent to obtain further information and experience on how successfully these crops can be grown at scale across the country.

6.2 Land use considerations

Land owners have choices around what they do with their land, so using land for biofuel production will always need to be evaluated against other land use options. New Zealand land use is relatively dynamic and farmers or other land owners will switch to more lucrative crops if the returns are higher and the risk not too great. It follows that if a given crop is not being grown now, it is likely not sufficiently profitable in the current market.

There are opportunities for biofuel feedstock production to replace established land uses experiencing economic challenges. For example, drystock land owners in the relatively inexpensive and flat lands of the East Coast and Northland have been looking for more profitable alternatives to sheep and cattle. If biofuel demand increased in the coming years, feedstock demand would lift, offering profitable land use alternatives to these landowners.

Furthermore, current environmental policies aiming at mitigating climate change (e.g. ETS), avoiding increasing erosion rates (e.g. Erosion Control Funding Program and Afforestation Grant Scheme) and reducing freshwater nutrient loads (e.g. National Policy Statement for Freshwater Management), may also make the case for growing biofuel feedstocks more appealing to land owners.

[99] This scenario would equate to 57% of 2015 petrol demand being substituted by ethanol and 36% of the 2015 diesel demand by biodiesel.

6.3 Timing

Timing is critical. Biofuel deployment requires coordinated implementation across the value chain at large scale. Some of the key timing considerations are given in Table 6.1 and illustrated in Figure 6.2.

Table 6.1: Key timing considerations in biofuel deployment.

Feedstock production & transport	Conversion plants	Fuel distribution and use
Time for crop/forest to grow Learning to grow new crops Expanding crop production	Consents & finance for plants Plant construction times Infrastructure upgrades Time to commission plant Time for new technologies to be commercially proven (uncertain)	Fuel demand changes Upgrading of fuel distribution infrastructure Fuel certification (*e.g.* for bio-jet) Rate new vehicles enter market (if modified engines required)

If New Zealand wanted to implement biofuel production as quickly as possible, the time required to construct the conversion plants will likely limit the rate at which biofuels could be deployed (Fig. 6.2). That would mean choosing mature technologies and a crop like canola which is already grown in New Zealand, matures quickly and could be upscaled rapidly. Likewise, the use of tallow as a biofuel feedstock is well understood. While forest residues and fibre logs from existing plantation forests or biomass wastes are available immediately, technologies to convert them to biofuels are not yet commercially proven. Collectively these issues would limit the ability of biofuels to contribute to meeting the country's 2030 GHG commitments.

In the longer term, deployment is likely to be limited by feedstock availability, particularly if forestry feedstocks are the preferred option (Fig. 6.2). The required conversion technologies would be expected to mature within this timeframe.

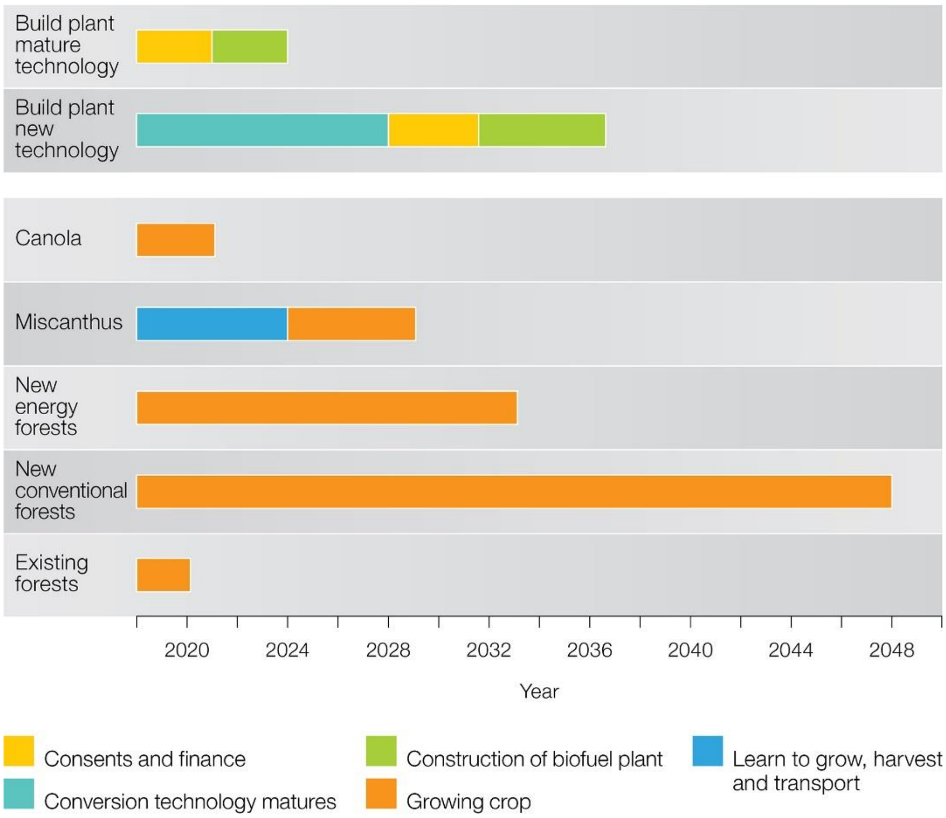

Figure 6.2: The impact of timing on biofuel implementation, assuming we start now.

Forestry feedstocks also offer timing flexibility as they can be harvested at a range of ages to match demand. They can also be grown in different ways - for energy production on a 15 year rotation, or for 25 to 30 years for a conventional forest producing sawlogs, fibre logs and forest residues.

As identified in our modelling, growing lignocellulosic crops such as miscanthus, willow, or energy forests in the early years, and then switching to fibre logs from new multi-purpose forests in later years helps get around feedstock constraints.

National leadership will be crucial to coordinate large-scale biofuel deployment given the scale of the opportunity, its complexity and the need for simultaneous implementation of all parts of the value chain. The higher the level of biofuel deployment, or the quicker biofuels are to be implemented, the more critical this co-ordination becomes.

6.4 Competition for biomass

Biofuel feedstocks would have to compete with existing and future users of biomass (Fig. 6.3).

- Existing users include the pulp and paper, particleboard, fibreboard and wood pellet industries. These are major regional employers and exporters.
- Replacing fossil coal and gas with wood waste for industrial heat is an attractive and easier to implement option to reduce New Zealand's carbon emissions – which would increase competition for this biomass.
- Production of naturally produced sustainable biochemicals for export and use in the global plastics and chemicals industries is another potential future use of biomass.

Future competition for biomass is likely to have impacts on the price of biomass feedstocks. While an important question, it is beyond the scope of this study to consider the impact of supply and demand on feedstock costs, or the best uses of biomass.

Competition for feedstocks with the forestry sector could become particularly important if crops grown on arable land are excluded as biofuel feedstocks, particularly for the lower-value fibre logs and forest residues. While slightly over half the current forest harvest is exported as logs, almost no fibre logs are exported, as they are used domestically by the current pulp and paper and panelboard industries.

One option to limit competition with the existing pulp and paper and fibreboard industries would be to exclude fibre logs from existing plantation forests as biofuel feedstocks. When a 30% substitution scenario was run assuming no fibre logs from existing forests are allowed,[100] the levelised biofuel cost remained relatively unchanged ($0.78 *vs* $0.77 in Scenario 1), with the fibre logs being replaced by more miscanthus, forest residues and canola.

Biomass competition must be considered at a regional level, as it is generally not economic to transport such feedstocks over long distances. For example, in the central North Island where 33% of current plantation forests are located, fibre logs are in short supply because there are major pulp and paper mills, whereas in areas such as the Wairarapa or East Coast fibre logs are in low demand – and may not even be collected from the forest.

There is a clear need for a national discussion on what the best uses for biomass are, balancing economic, social and environmental factors.

New energy crops such as miscanthus and willow could be seen as a way of addressing this biomass competition, but it should be recognised that these crops could also be used as biomass for industrial heat energy or even for pellet manufacture.

[100] All land classes are available.

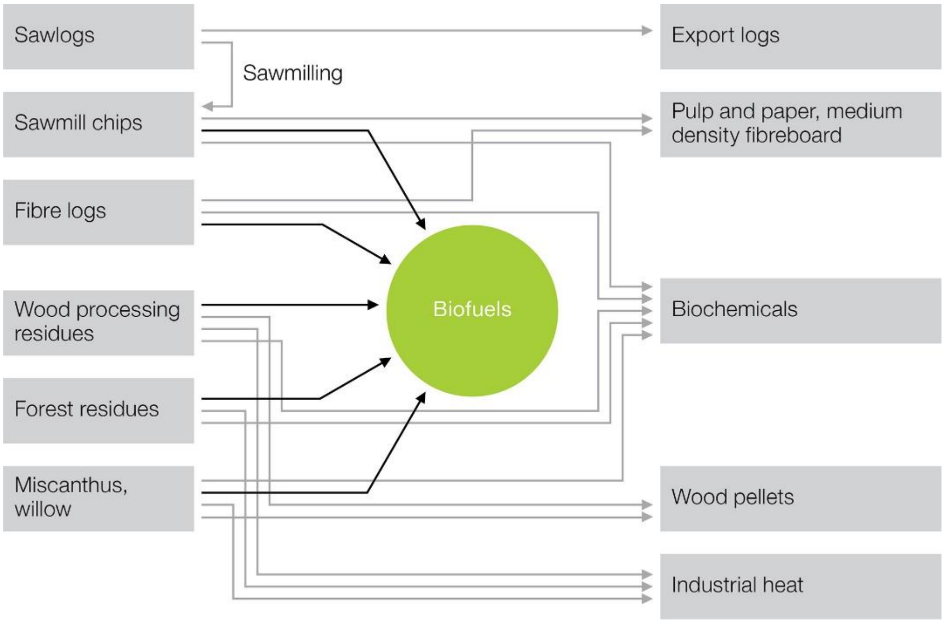

Figure 6.3: Competing uses of biomass (residuals are available in limited volumes).

6.5 Environmental and social implications

Large-scale biofuel production would have significant positive environmental and social impacts, but there are issues that need to be considered.

Under a ‘biofuels done right’ policy, pathways selected for the production of biofuels should have demonstrable and significant carbon benefits compared to fossil fuels.

Crop production areas might need to be restricted to minimise the use of water for irrigation, or halt the spread of crops into areas of high conservation or amenity value.

The general public would have to buy into the benefits of addressing climate change and the ability of biofuels to deliver these benefits. The public would also have to understand and accept the possible risks and implications of biofuel production, such as the growing of monocultures on large areas of land.

6.6 Implications across the biofuel value chain

As will already be apparent, the large-scale production and use of liquid biofuels in New Zealand would have a number of significant implications at both a regional and national level. Table 6.2, which summarises the main implications across different parts of a future biofuel value chain, highlights two key points:

- The implications depend on the choices made around deployment, *i.e.* which biofuels, which feedstocks and the level/timing of deployment.
- While a given implication might be greatest in one part of the value chain, the impact ripples across all parts of the value chain. For example, land use competition, as reflected in land value, affects were feedstocks are produced and consequently the plant locations and how the biofuel would need to be distributed.

Table 6.2: Implications of biofuel deployment. Parts of the biofuel value chain where the implications are most significant are highlighted.

	Feedstock production	Transport	Biofuel production	Fuel distribution & use	New Zealand
Land use competition	Land use competition New opportunities for landowners	Mode(s) used Location(s)	Plant location/scale	Fuel distribution	
Technical risks	New feedstock Grower knowledge	New collection & transport systems	Technology risk Services & infrastructure	Fit to vehicles Fuel distribution Fuel quality	Infrastructure
Regional impacts	Major community & employment impacts – depends on value chain(s) chosen				
Social & environmental	Land use changes Land & water impacts	Public acceptance	Public acceptance	Public acceptance	Skilled staff
Competition for biomass	Profitability Residue volumes		Feedstock availability & price	Biofuel price Competitor fuel price	
Fuel choices	Feedstock needs		Technology choice/ location	Fuel demands Fit to vehicles Fuel distribution Fuel quality	Market demands
Timing	Time to grow Grower experience		Technical risk Time to build plants		Infrastructure
Financial	Grower profitability Grower risk/return Markets for sawlogs	New trucks & infrastructure	Producer profitability Capital Co-product markets	Infrastructure upgrades	Capital Infrastructure

7 Future narratives

The preceding scenario modelling has demonstrated that credible routes exist for large-scale biofuel production and consumption in New Zealand. Biofuel use could also significantly reduce New Zealand's GHG emissions and underpin regional economic development. It also provides a basis for government, industry and communities (including project stakeholders) to explore the opportunities, issues and trade-offs associated with large-scale biofuel production and use.

Given the right strategic drivers, national consensus is needed on the answers to four key questions in order to pinpoint the best option(s) for biofuel deployment in New Zealand.

1. Which fuel families and which specific biofuels should we be targeting?
2. What are acceptable feedstocks for biofuel production?
3. What level of biofuel substitution is required and in what timeframe?
4. What are the best uses of biomass in New Zealand?

The following five 'future narratives' are included to help inform these decisions around the 'right' biofuel strategy for New Zealand.

Meeting New Zealand's Paris commitments

New Zealand decides it must implement large-scale biofuel production and use to help fulfil its commitment to meeting its 2030 GHG emission target of 57.7 million tonnes CO_2-e per year.

To achieve this

- Biofuel production is focussed on reducing national emissions, so targeting domestically-consumed fossil fuels, rather than those used internationally (which are outside the ETS framework).
- Mature conversion technologies would likely be chosen, at least initially, as a way of ensuring these biofuels are actually produced, and to reduce the technical risks of less-mature conversion technologies.
- Feedstock choices would likely be dictated by the available conversion technologies.

Likely biofuels

- Biodiesel or renewable diesel produced from canola (and tallow).
- Bioethanol from sugar beet and/or corn.

Impacts and consequences

- Feedstocks would need to be grown on cropping land. This would lead to a major expansion of cropping on flatter land spread across the country; with possible impacts on the existing dairy sector.
- Neither biodiesel nor bioethanol are drop-in fuels. The levels to which these biofuels can be deployed may be limited to the extent they can be blended with fossil petrol or diesel and still operate in the existing vehicle fleet. Production of more costly renewable diesel from canola oil could allow blend limits to be overcome.
- This may not be an optimal long-term solution. Food feedstocks may not remain acceptable feedstocks and higher levels of deployment would require vehicle fleet modifications, possibly making it difficult to meet 2050 targets due to technology and feedstock lock-in.

Biofuels from non-arable land

New Zealand decides that food or energy crops grown on land capable of producing food crops are not acceptable feedstocks for biofuel production.

To achieve this

- Feedstocks would likely mostly originate from existing and future plantation forests and wastes.
- New forests likely to be grown on steeper land incapable of growing crops, mainly where land is cheaper such as in Northland, the East Coast and the central North Island.

Likely biofuels

- Mixtures of drop-in fuels produced largely from forestry feedstocks.

Impacts and consequences

- Technologies for producing drop-in fuels from lignocellulosic feedstocks are immature - making investment problematic. But, this is an area of intense global interest, so solutions will probably eventually be found.
- Economic development and employment growth occurs in regions where feedstocks are grown and conversion plants located.
- Could potentially lead to competition for feedstocks from existing wood processors.
- Potentially, all fuel families could be replaced by biofuels, and high levels of substitution achieved without requiring engine modification.

Leave it to the market

The Government takes a hands-off approach to biofuels implementation. Fuel users make decisions based on price and are not prepared to pay a premium for biofuels over fossil alternatives.

To achieve this

- Biofuel producers and feedstock producers would only invest when the technical risks are low and biofuels are profitable.

Likely biofuels

- Decided on a case-by-case basis.

Impacts and consequences

- Level and timing of any deployment would be uncertain.
- Conversion plant investments unlikely until oil and/or carbon prices rise substantially and stay there for a significant length of time.
- First investments are built around specific opportunities such as utilising the limited amount of existing low-cost waste.
- If biofuel demand rises rapidly, the rate of deployment may be limited by access to the required feedstocks - with resulting market price responses.
- There is a risk that nothing happens until it is too late. Feedstock producers will not commit to growing a crop without a guaranteed market, while investors will not build conversion plants without a sustainable supply of feedstock. This is of particular concern for forestry feedstocks because the time to grow a crop to maturity is long.
- It could be difficult to impossible for the country to meet its GHG reduction targets.

International market pressure

Sustainability becomes increasingly important across the world, and market pressure from consumers of New Zealand goods and services (tourism in particular) about fossil fuel use drives biofuel implementation in the marine and aviation sectors.

To achieve this

- As biofuels from food crops or arable land would likely not be acceptable, feedstocks would probably mostly come from existing and future plantation forests.
- Biofuels to replace fossil marine and aviation fuels would be a priority.
- New forests on steeper land, particularly in Northland, the East Coast and the central North Island.

Likely biofuels

- Technologies producing drop-in fuels, particularly jet and marine replacements, largely from forestry feedstocks.

Impacts and consequences

- Since the marine and aviation fuel markets are global, such biofuels would need to fit with international developments, regulations and standards as they emerge.
- It might not happen if New Zealand biofuel producers target domestic road transport over international markets. Carbon emissions from fuels burnt outside New Zealand currently sit outside the ETS, so mechanisms to meet national emissions targets may provide a price premium for biofuels targeting domestic emissions.

Carbon zero by 2050

New Zealand decides there will be zero net carbon emissions by 2050.

To achieve this

- Fossil fuels must be replaced in nearly all applications.
- Electric vehicles and biofuels both need to be a significant component of the transportation energy mix.
- Long-term buy-in and commitment by government, industry and the public is required.
- Leadership is needed to plan and coordinate such a large-scale biofuel deployment.
- Long term stable government policies are essential to provide investment certainty.

Likely biofuels

- Drop-in biofuels from lignocellulosic biomass, produced by multiple technologies depending on local conditions.
- A focus on biofuels in the difficult-to-electrify transport modes of aviation, marine and heavy transport - although some bio-petrol is still required.

Impacts and consequences

- Afforestation and/or carbon capture from biofuel plants is used to compensate for agricultural emissions.
- This is a large-scale undertaking with many significant social, land use and economic implications.
- Only lignocellulosic feedstocks are used to prevent a lock-in situation.
- New Zealand leads global implementation of lignocellulosic biofuels.
- Possible competition for feedstock with use of biomass to replace coal and gas for industrial heating.

8 Study findings

1. Credible large scale biofuel production and use pathways exist for New Zealand. The country can, realistically, bring a biofuelled economy and environment into existence and general adoption.

2. Biofuels could be a large to very large longer term answer to meeting New Zealand's greenhouse gas reduction commitments. This is particularly so for sectors such as aviation, shipping and long-haul road freight, which are difficult to decarbonise through other means.

3. The biofuels opportunity is large-scale.
   - There are multiple ways to address issues raised.
   - Any solution must consider the whole value chain and its impact on other value chains.
   - Timing is important, especially at high fossil fuel substitution levels. This is particularly so if significant biomass quantities are to come from new forests - given the length of time required to grow such trees.
   - Decisions made now have a major long-term impact.

4. Biofuel production can provide strong regional economic development and employment growth.
   - Prominent biomass growing areas predicted by the model are Northland, East Coast and the central North Island, but expanding out to other regions as substitution levels increase. Biofuel conversion plants would generally be located close to where the feedstocks are grown.

5. Drop-in fuels from non-food feedstocks, particularly forestry grown on non-arable land, look to be the most attractive longer-term opportunity for New Zealand.

6. Technologies for producing drop-in biofuels from non-food feedstocks are less developed than other technologies. But it is an area of intense global research and rapid development, so viable technologies are expected within the required timeframes. From that perspective, what is being advocated is not too technically risky.
   - Pyrolysis followed by upgrading appears to be particularly attractive for producing drop-in petrol, diesel, and marine fuels; but multiple options targeting all fuel types are being developed.

7. Government policy support will be required in the short to medium term to enable large-scale biofuel production to occur. Market forces alone will not be sufficient to initiate large-scale production.
   - Currently, fossil fuel and carbon prices are too low and the technical risks still high.
   - Stable long-term policies will be critical for required investment to occur.
   - Biofuel production costs will fall as technologies and the new value chain mature.

9 Way forward

Scenario modelling, international trends and stakeholder feedback suggests the following key areas for New Zealand to focus on.

1 Produce liquid biofuels to replace fossil fuels where there are few decarbonisation options

The best option to replace fossil fuels depends on the needs of the specific fuel sectors.

Battery-electric vehicles are promising, particularly in urban settings. Travel distances are short, and the vehicles often sit idle so the recharge time is less critical. EVs also improve air quality and reduce noise.

EVs would reduce petrol demand in the first instance.

EV use may gradually spread to other sectors powered primarily by fossil diesel, but because of the distances travelled and loads transported with the associated demands on batteries, early electrification of these markets is less likely.

The high energy density of liquid fuels make them well suited to applications in remote locations where fuel consumption is high, vehicles operate for a long time and battery weight would reduce payloads.

In some situations electrification of heavy duty vehicles may make sense - such as city buses, rail, city ferries and light trucks which return to base at frequent intervals.

Biofuels are currently the only real option to significantly decarbonise aviation, and even though alternative clean propulsion techniques are in development, these alternatives are unlikely to be ready for commercial use by 2050. Aircraft also have a long life span and are very expensive, so airlines typically want to use them as long as possible before replacing them.

In the marine sector, biofuels are one of the few options for decarbonising without installing new engines, particularly for large vessels such as container ships that export New Zealand's goods.

The International Maritime Organisation has regulated to reduce sulfur levels in marine fuels from 3.5% to 0.5% in 2020. Biofuels inherently have a low sulfur content, so could be one way to reach this goal while also reducing carbon emissions. Marine engines are also tolerant of a wide range of fuels, making them an attractive biofuel option.

It should also be noted that though fossil fuel emissions from international aviation and shipping (1.4 billion litres in 2015) lie outside national climate change commitments (and New Zealand's ETS), decarbonising these sectors is strategically important to New Zealand.

As climate change increases in profile, consumers in our export markets may focus more on the carbon embedded in getting New Zealand's exports to market, or even the jet fuel used to bring tourists to the country.

For these reasons the strong focus should be on biofuel replacements for fossil jet, diesel and marine fuels.

2 Focus on drop-in biofuels that can be used in existing vehicles, ships and planes.

While the technical risks and costs of producing drop-in biofuels are presently higher than for conventional biofuels, drop-in biofuels offer substantial advantages for New Zealand. In particular, they allow both the existing fossil fuel distribution infrastructure and existing vehicles to be used, and for the biofuel to be introduced in gradually increasing levels.

These benefits are particularly compelling for international shipping and aviation where there are few viable non-drop in alternatives, and New Zealand is only a small part of global aviation and maritime fleets.

Ethanol and biodiesel, added as blends in petrol and diesel respectively, could offer short-term options to increase New Zealand biofuel use. They are proven overseas, already available in limited quantities in New Zealand, but their ultimate deployment could be limited by the need for new vehicles.

3 Reduce future market risks by focussing on feedstocks grown on non-arable land

Large-scale biofuel use in New Zealand will require consumers to be convinced they are being produced in a 'sustainable' way before they buy them.

Given the long-term nature of investments in large-scale biofuel production, it would be prudent to reduce future market risk by avoiding food crops or using land capable of growing food crops (this would also exclude most of the land currently being used for dairying).

Lower-cost non-arable land would therefore be best for biofuel feedstocks. But lignocellulosic crops such as miscanthus or willow require arable land as they need to be mechanically harvested could be an option until the required volumes of forestry feedstocks become available.

4 Plantation forest feedstocks are New Zealand's best long-term large-scale biofuel production option

Wastes and agricultural feedstocks could play a short-term role, but logs and forest residues are the best option for large-scale production of biofuels in New Zealand. Plantation forests are one of the few profitable crops for lower quality non-arable land. They also offer significant flexibility around how they are grown, when they are harvested and what they are used for.

The scenario modelling showed conventional pine forests, where higher value sawlogs are sold into existing markets and lower value fibre logs and forest residues are used for biofuel production were preferred feedstocks at longer timeframes.

5 In the short term, focus on niche opportunities to build momentum, provide early wins and create a positive perception of biofuels

Currently only small volumes of biofuels are being used and produced in New Zealand. There is also a very limited understanding of biofuels' potential to address the country's GHG emissions.

If biofuels are to be produced at large scale, it is imperative to start now to build knowledge and experience around how to make and use biofuels successfully, and to build general public confidence they can be successfully used.

Niche opportunities to produce biofuels include.

- Using currently-unused low-cost biomass wastes such as municipal green waste, municipal wood wastes and forest residues,
- Where users such as brand owners and tourism operators may be prepared to pay a premium for using biofuels,
- Focussing on large fuel users where refuelling is possible at a single point. These include mining companies and where vehicles or vessels return to base each night. This greatly reduces the investment and risks required in fuel distribution and use.
- Siting conversion plants on brownfield sites to leverage existing infrastructure and resource consents.
- Targeting marine fuels where the technical requirements for a successful biofuel are less demanding.

9.1 Next Steps

Leadership is required now to build a national consensus on the future role biofuel deployment should play in decarbonising New Zealand. Key decisions are needed on:

1. Which fuel families and which specific biofuels we should be targeting.
2. Acceptable land and feedstocks for biofuel production.
3. The level of biofuel substitution required, and in what timeframe.
4. The best uses of biomass.

Once this national consensus is in place, an implementation plan must be developed. Critical to this will be:

1. National leadership to coordinate implementation.
2. National buy-in to the trade-offs required and 'biofuels done right'.
3. Alignment of different stakeholders, taking ownership for delivering each part of the value chain.
4. Strongly leveraging international learnings and experience.

New Zealand needs to continue to explore short term niche opportunities to produce biofuels to start building momentum, provide early wins, create a positive perception of biofuels and develop New Zealand's regulatory environment.

If conventional forests are identified as the best feedstock option, planting needs to start soon to provide the large and sustainable supply of feedstock needed for future biofuels.

Further work is required to de-risk future options for rapid and large-scale biofuel implementation particularly to:

1. Increase our knowledge on the growth and suitability of energy crops such as miscanthus and willow in New Zealand,
2. Develop new forestry options grown specifically for energy applications, and
3. Better understand the suitability of different conversion technologies to New Zealand feedstocks and fuel needs.

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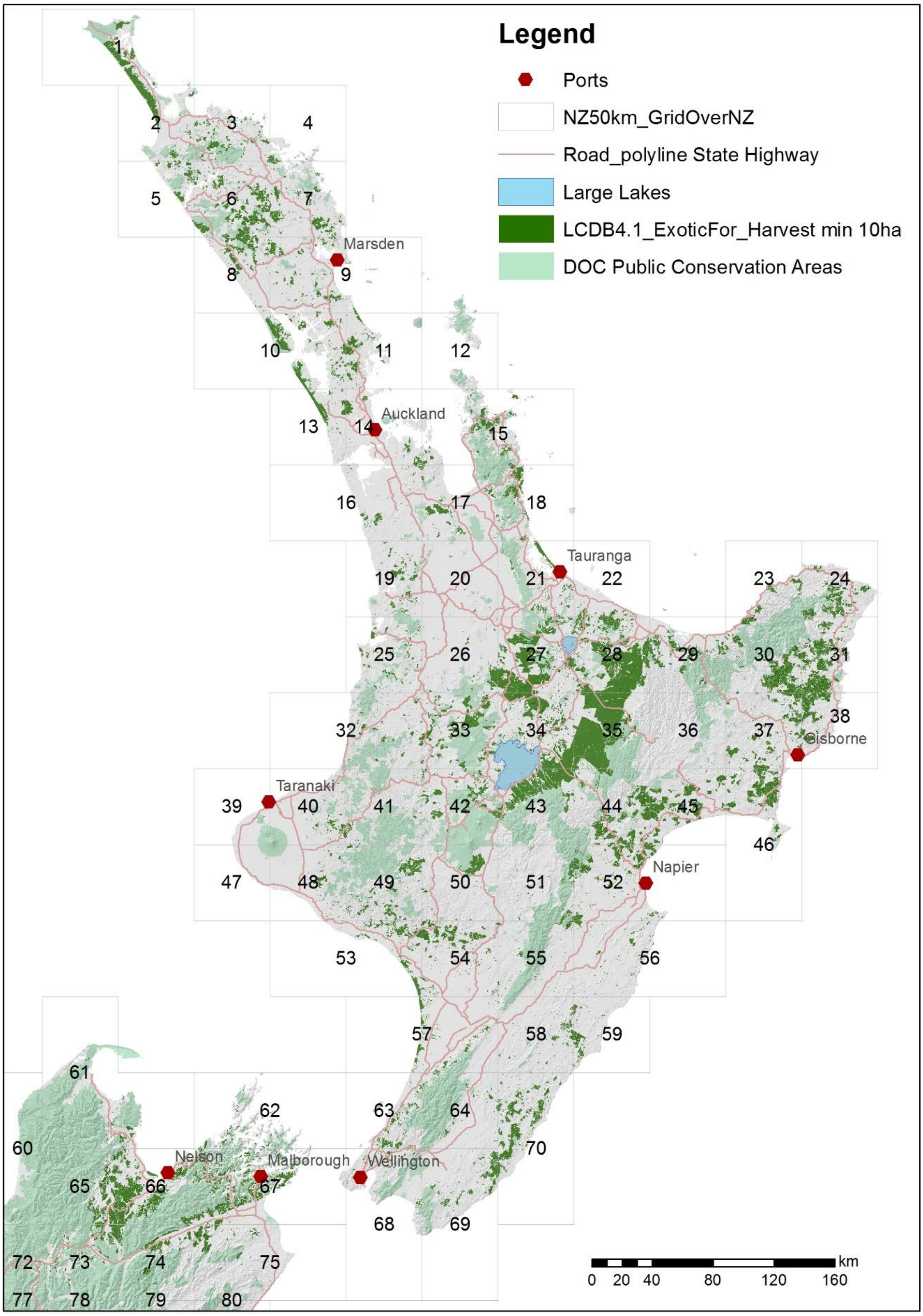
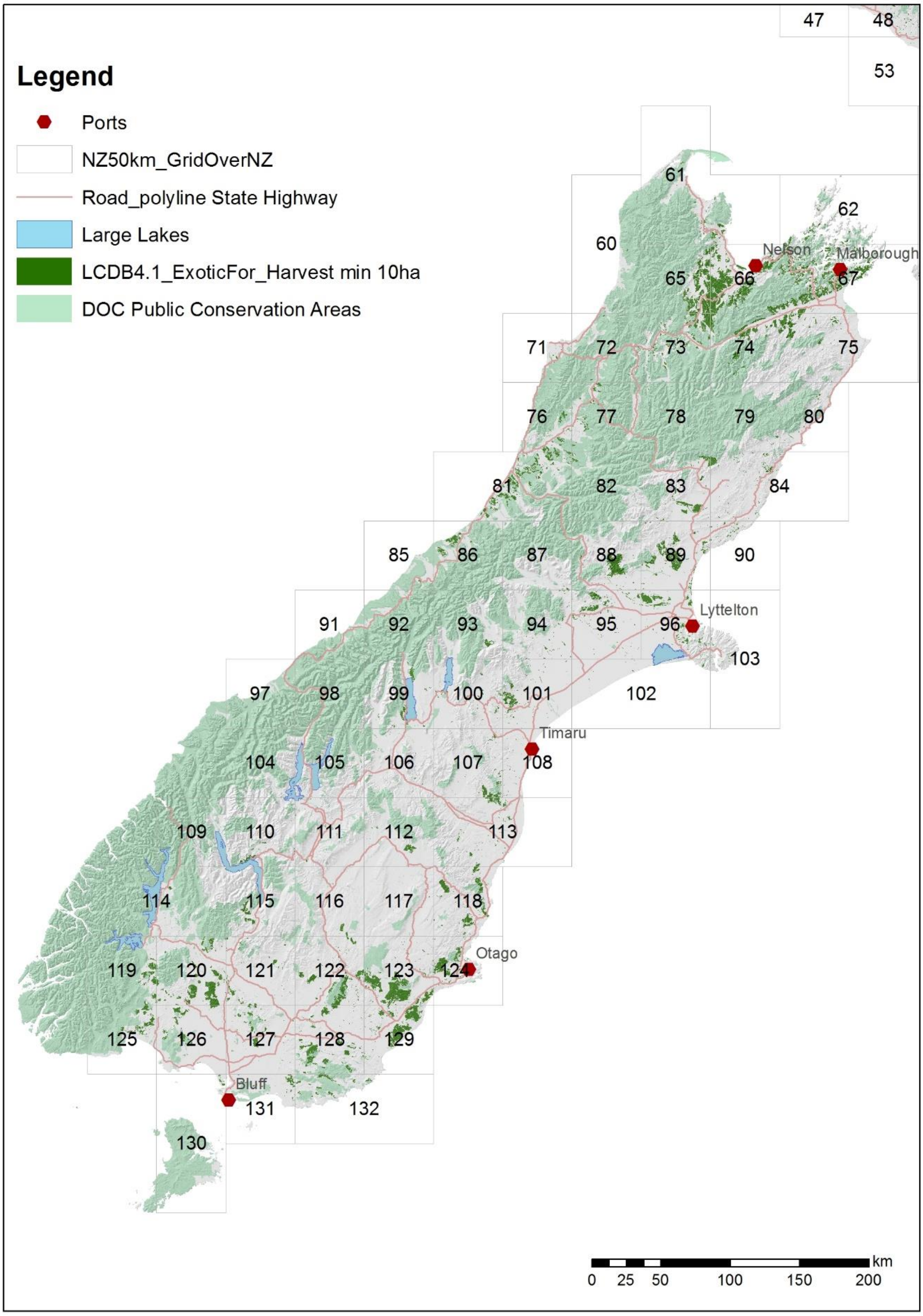
11 Appendices

11.1 Appendix 1 – Maps showing BVCM grid

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Large Lakes
LCDB4.1_ExoticFor_Harvest min 10ha
DOC Public Conservation Areas
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Malborough
Lyttelton
Timaru
Otago
Bluff
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11.2 Appendix 2 – Crops modelled

Crop	Description	Feedstock(s) produced
Arable crops		
Canola	Annual brassica crop (oilseed rape) grown for the oil in the seeds. The seeds are harvested. Requires crop rotation.	Canola seed
Corn	Shorter-growing season than maize-grain and less dependent on the weather. Grown as for silage and assumed chipped at harvest.	Corn (whole plant)
Maize	Main North Island arable crop, grown for stock feed as grain. The grain is collected at harvest. Marginal crop in the South Island.	Maize (corn grain)
Sugar beet	Annual beet crop with higher sugar and dry matter content than fodder beet used in NZ for stock feed. Requires arable land and crop rotation.	Sugar beet
Energy crops		
Miscanthus	Fast-growing perennial tall grass planted from sterile rhizomes. It is harvested annually (after drying off in winter) for about 15 years before resowing is required. Mechanised harvesting, including chipping and baling, is assumed.	[Baled] miscanthus
Willow	Hardwood tree planted as cuttings at a high density with harvesting on a three-year cycle. The rootstock is retained after harvest and new shoots appear in spring. Assumed to be mechanically harvested every third year with the yield and cost averaged over six three-year cycles.	[Chipped] willow
Forestry		
Conventional forests	Modelled assuming an unpruned radiata pine forest grown on a 30-year rotation, designed to give high yields of sawlogs plus fibre logs. Collection of either landing and/or cutover residues is optional.	Sawlogs Fibre logs Forest residues
Energy forests	Modelled assuming a 15-year radiata pine forest specifically grown to produce only fibre logs, with no recoverable residues.	Fibre logs

11.3 Appendix 3 - Feedstock descriptions

Feedstock/ intermediate	**Description**
Biocrude	The liquid oil produced on hydrothermal liquefaction of lignocellulosic biomass. This is a feedstock for bio-oil upgrading to drop-in fuels. Compared to pyrolysis oil, the yield and oxygen content of the biocrude is lower.
Canola seed	The seed produced on harvesting of the annual brassica crop (oilseed rape).
Canola oil	Produced by extraction on canola seed. It is also used by the food industry.
Corn	Chipped whole corn plants.
Cutover residues	Woody residues from harvesting left behind on the forest floor after harvesting. Generally left in the forest, but can be recovered and chipped as a biofuel feedstock.
Fibre logs	Lowest value logs unsuited to sawing or veneer production. An existing feedstock for the pulp and paper or panel board industries if a market is close enough. Commonly referred to as pulp logs.
Forest residues	Used in this study to refer to the mix of cutover residues and landing residues recovered from a conventional plantation forest.
Landing residue	Woody residues from harvesting left behind on the landing site after harvesting of conventional forests. Currently commonly left in the forest, but can be readily chipped on-site and used as a feedstock.
Maize	The maize or corn grain is used as a feedstock for conventional ethanol or butanol production.
Miscanthus	Bales of dried-off and chipped miscanthus stems.
Municipal solid waste	Non-woody biological waste from land-fills. This is mainly kitchen and green garden waste. It is assumed this has been sorted to remove inorganics and is chipped at the landfill prior to transport.
Pyrolysis oil	The liquid oil produced on pyrolysis of lignocellulosic biomass. This is a feedstock for bio-oil upgrading to drop-in fuels.
Sawlogs	Conventional *P. radiata* forests produce a mix of sawlogs and lower-value fibre logs (see Box 7). For this study we assume 3 sawlog grades, varying in quality and value. These can either be used for biofuel production or sold for a profit.
Sawmill chips	Chips are produced, along with sawn timber, as a co-product at most existing sawmills. They are important feedstocks for the pulp and paper or panel board industries. Here it is assumed any wood chips produced at a given site and not currently used at that site are available for purchase at that site.
Sugar beet	The beet harvested from growing of the annual crop sugar beet and is used as a feedstock for conventional ethanol or butanol production.
Tallow	Rendered animal fat, a by-product of the meat processing industry.
Willow	The chipped product produced after harvesting and chipping of whole willow stems.

Waste wood	Woody waste at landfills, from municipal solid waste stream plus construction and demolition waste. Assumed available at existing landfills and chipped prior to transport.

While the model includes options for chipping of logs, as well as for pelletising and torrefaction, they are not chosen in this study, so the resulting feedstocks, *e.g.* torrefied wood chips, are not included here.

11.4 Appendix 4 - Technology descriptions

Technology	Description
Alcohol to jet	Process to convert bioethanol into a range of hydrocarbon drop-in fuels with a large portion of the product being jet fuel (some drop-in petrol and diesel are also produced).
Aqueous phase reforming	Process to convert sugar beet sugar into a drop-in diesel. This process involves a series of chemical reactions involving aqueous phase reforming.
Biodiesel production	Process to convert oils and fats into biodiesel by reaction with methanol. The product is a fatty acid methyl ester (FAME).
Bio-oil upgrading	Process to convert pyrolysis oil or biocrude into a mixture of drop-in petrol and diesel. Bio-oils are reacted with hydrogen in a high pressure catalytic reactor to remove all the oxygen from the oils, producing hydrocarbons. The hydrogen can be produced either from natural gas or biomass. A variant is included which can convert the bio-oils to a drop-in marine fuel.
Catalytic depolymerisation	Process to convert biomass into drop-in diesel in a single step. The biomass is mixed with a hydrocarbon oil and heated in a reactor at moderate temperatures (200-350 °C) and low pressures in the presence of a catalyst. The generated vapours are condensed to form a drop-in diesel.
Cellulosic butanol	Process to convert lignocellulosic feedstock such as energy crops or wood into butanol. The feedstock is first treated to release the sugars from the cellulose. These sugars are then fermented into butanol in a process similar to conventional butanol.
Cellulosic ethanol	Process to convert lignocellulosic feedstock such as energy crops or wood into ethanol. The feedstock is first treated to release the sugars from the cellulose. These sugars are then fermented to ethanol in a similar process as conventional ethanol. Two different variants of this technology are included.
Chipping	Process to reduce the size of large biomass items such as fibre logs or forest residues into smaller pieces (4-7 cm) called chips.
Conventional butanol	Process to convert sugars and starches from feedstocks such as maize or sugar beet into biobutanol to be used as a blend in petrol.
Conventional ethanol	Process used to convert sugars and starches from feedstocks such as maize or sugar beet into ethanol to be used as blend in petrol. It is also known as first generation ethanol. Most bioethanol produced is made via this process.
Direct sugars to hydrocarbons	Process to convert sugar to drop-in diesel. Lignocellulosic feedstocks such as wood are first converted into sugars, which are then biologically converted to fatty acids, which are then upgraded to a drop-in diesel.
Gasification/fermentation	Process to convert a wide range of feedstocks into ethanol. Feedstocks such as waste wood, MSW or forest residues are fed to a high temperature reactor (700-1200 °C) where they are converted into a mixture of hydrogen and carbon monoxide called synthesis gas. The synthesis gas is fermented by bacteria into bioethanol.
Gasification/Fischer-Tropsch	Process to convert a wide range of feedstocks into drop-in fuels. Synthesis gas produced from a wide range of feedstocks is fed to the Fischer-Tropsch reactor where it is converted into a mixture of drop-in petrol, jet and diesel biofuels. A variant is included which produces only drop-in petrol and diesel.

Gasification/mixed alcohols	Process to convert a wide range of feedstocks into ethanol plus other alcohols. Synthesis gas produced from a wide range of feedstocks is fed into a catalytic reactor where the alcohols are formed. The bioethanol can be used as petrol blendstock while the higher alcohols are assumed to be sold.
Hydropyrolysis	Process to convert lignocellulosic feedstocks into a mixture of drop-in petrol and diesel. Biomass is rapidly heated in the presence of a catalyst and hydrogen in a first reactor. The generated vapours are further reacted with hydrogen a second reactor to produce a mix of drop-in fuels. This process does not need an external hydrogen source.
Hydrothermal liquefaction	Process to convert wet lignocellulosic feedstock into a liquid called biocrude. Wet biomass is heated under high pressure and moderate temperatures (around 350 °C) for several minutes. After cooling and depressurising, the oily biocrude is produced.
Hydrotreating	Process to convert oils and fats into drop-in diesel, or a mixture of drop-in petrol, jet and diesel. Feedstocks such as canola oil or tallow are reacted with hydrogen in a high pressure catalytic reactor producing renewable diesel (plus some drop-in petrol and energy). A variation of the process can produce mixtures of drop-in petrol, jet and diesel.
Mild bio-oil upgrading	Process to convert pyrolysis oil or biocrude into an oxygenated fuel capable of being used in a marine engine. Bio-oils are reacted with hydrogen in a high pressure catalytic reactor. Under the mild conditions used, the oils are not fully deoxygenated, and the products are only suited as a marine biofuel. The hydrogen used is assumed produced from natural gas.
Oil extraction	Process to extract oil from canola seed, producing canola oil. The seeds are crushed and extracted using an organic solvent which is recovered and reused.
Pelletising	Process to increase the energy density of bulk biomass by drying, milling and compressing the fine product into pellets. A typical pellet has a diameter of 6-8 mm and a length between 20-40 mm.
Pyrolysis	Fast pyrolysis is a process used to convert lignocellulosic biomass into a liquid called pyrolysis oil. Biomass is rapidly heated to temperatures around 500 °C. The vapours produced are quenched, producing the pyrolysis oil.
Torrefaction	Process to improve the properties of solid biomass. It consists of heating biomass to moderate temperatures (200-300 °C) in an inert atmosphere increasing the energy density of the biomass and reducing its capacity to absorb water.

11.5 Appendix 5 - Biofuels

Fuel family	Biofuel	Description	Technologies to produce it
Petrol	Biobutanol	An alcohol-based fuel, produced either from starch and sugar crops. It has a higher energy density and higher blend limits in petrol than ethanol. It can also be produced from lignocellulosic feedstocks.	Cellulosic butanol Conventional butanol
	Bioethanol	An alcohol-based fuel, produced either from starch and sugar crops and blended with petrol. It can also be produced from lignocellulosic feedstocks.	Cellulosic ethanol Conventional ethanol Gasification/fermentation Gasification/mixed alcohols
	Drop-in petrol	A hydrocarbon fuel produced from biomass which can be used as a direct replacement for petrol.	Bio-oil upgrading Gasification/Fischer-Tropsch Hydropyrolysis Hydrotreating
Diesel	Biodiesel	An oil-based fuel produced from canola and tallow and blended with fossil diesel.	Biodiesel production
	Drop-in diesel	A hydrocarbon fuel produced from biomass which can be used as a direct replacement for diesel.	Aqueous phase reforming Bio-oil upgrading Catalytic depolymerisation Direct sugars to hydrocarbons Gasification/Fischer-Tropsch
	Renewable diesel	A hydrocarbon fuel produced by reacting fats and waste oils with hydrogen, which can be used as a direct replacement for diesel.	Hydrotreating
Jet	Drop-in jet	A hydrocarbon fuel produced from biomass which can be used as a direct replacement for jet fuel.	Alcohol to jet Gasification/Fischer-Tropsch
	Renewable jet	A hydrocarbon fuel produced by reacting fats and waste oils with hydrogen, which can be used as a direct replacement for jet fuel.	Hydrotreating
Marine	Drop-in marine	A hydrocarbon fuel produced by upgrading of biocrude with hydrogen, which can be used as a direct replacement for a fossil marine fuel.	Bio-oil upgrading
	Oxygenated marine fuel	An oxygenated fuel capable of being used in a marine engine and produced from pyrolysis oil or biocrude by reaction with hydrogen at high pressure.	Mild bio-oil upgrading