Optimisation of renewable energy resources in New Zealand for process heat: An economic and supply assessment

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Abstract

A significant amount of New Zealand's greenhouse gases are emitted through the use of fossil fuels to generate process heat. New Zealand is well-placed to provide renewable energy for process heat, with a well-established plantation forestry industry that generates large amounts of renewable biomass fuel sources, and a high percentage of renewables in the electricity generation stack. Biomass and electricity could be used to reduce and eliminate reliance on fossil fuels. The important criteria for these fuel switches are to ensure that they are economic and have sufficient supply over the coming decades.

This thesis presents a method to model and optimise the allocation of resources to give foresight around the extent biomass can provide economic process heat across regions in New Zealand. A diverse range of case studies was employed, encompassing individual sites, regional energy systems, and the South Island. These case studies were modelled and optimised in P-Graph studio and examination of the results gave key insights into several important areas: regional diversity in energy supply and demand, impact of the demand scale and temperature profile, and finally demonstrated the economic potential of interregional transport of energy dense biomass to alleviate supply deficits and reduce the Levelised Cost of Energy (LCOE).

The largest impact on the LCOE was the temperature profile of the heat demand. The more heat demand below 100°C, the lower the final cost of energy. This was due to the high Coefficient of Performance of High Temperature Heat Pumps (HTHP), which were the ubiquitous fuel switching choice for below 100°C heat demand, providing LCOEs under 11 $/GJ in 2023. At these prices HTHPs are able to match or surpass the current prices for coal at 10 – 14 $/GJ. For heat demand above 100°C, biomass was the dominant choice as it provided much better economics. However, there was a wide range of LCOEs for biomass energy. This was caused by the wide range of resource, collection, and transport costs for the various biomass sources. These LCOEs ranged from 13 – 14 $/GJ for processor residues, to over 25 $/GJ for low grade export logs.

As the size of a plant or region increases, the demand exhausts the supply of low cost biomass and must source from a larger radius, or from more costly biomass sources. This resulted in a large spread of LCOEs for the regions in the South Island, with Otago, the West Coast, and Nelson-Marlborough seeing some of the lowest weighted average LCOEs for above 100°C heat demand of between 20 and 22 $/GJ, whilst the three largest energy users, Southland, South Canterbury, and North Canterbury saw LCOEs of between 26 and 28 $/GJ for 2023.

A key trend was established that regions with higher biomass supply saw lower LCOEs for heat demand above 100°C. Interregional transport of energy dense biomass was able to reduce the LCOE in the three regions of high demand and low biomass availability, bringing the weighted average for above 100° demand down to between 25 and 27 $/GJ for 2023. The use of interregional transport also saw the proportion of biomass used for heat demand above 100°C rise from 60% to over 90% in 2023. Supply constraints impact the use of biomass in 2037 and see the maximum economic use of biomass in heat demands above 100°C drop to 72%.

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List of Abbreviations

BFB – Bubbling Fluidised Bed boiler.

CCC – Climate Change Commission

CCUS – Carbon Capture, Utilisation, and Storage

CHP – Combined Heat and Power

COP – Coefficient of Performance

EDB – Electricity Distribution Businesses

EECA – Energy Efficiency and Conservation Authority

GHG – Greenhouse Gases

GIS – Geographic Information System

GXP – Grid Exit Point

HEN – Heat Exchanger Network

HP – Heat Pump

HTHP – High Temperature Heat Pump

HVDC – High Voltage Direct Current

IRT – Interregional Transport

IS – Industrial Symbiosis

LCA – Life Cycle Analysis

LCOE – Levelised Cost of Energy

LPG – Liquified Petroleum Gas

MAC – Marginalised Abatement Cost

MBIE – Ministry for Business, Innovation, and Employment

MDF – Medium Density Fibreboard

MPI – Ministry for Primary Industries

MPP – Meat Processing Plant

NEFD – National Exotic Forestry Description

NMT – Nelson/Marlborough/Tasman

NZ – New Zealand

PI – Process Integration

PO – Process Optimisation

RES – Renewable Energy Sources

RETA – Regional Energy Transition Accelerator

SED – Small End Diameter

SRF – Short Rotation Forestry, Bioenergy Forestry

t/h – Tonnes per hour

t/y – Tonnes per year

t_{powder}/h – Tonnes of milk powder per hour

VHTHP – Very High Temperature Heat Pump

VRE – Variable Renewable Energy

WAF – Wood Availability Forecast

Chapter 1 Introduction

1.1 Overview

Climate change is a global challenge, one that has been highlighted in recent years by the increase in global temperatures, and detrimental changes in weather patterns leading to flooding, heat waves, and droughts (Allen et al., 2018). The World Health Organization forecasts that from 2030, over 250,000 unnecessary deaths will occur each year due to increases in disease and coastal flooding (World Health Organization, 2023). Increasing prominence of these issues has prompted international action, with many governments pledging to reach net zero carbon emissions by 2050, with the goal of limiting global temperature rise to 1.5°C beyond preindustrial levels (IEA, 2021). New Zealand (NZ) is one of these nations, and has identified the energy sector, as an area where major gains can be made, and in order to reach net zero, two important intermediate goals have been set: phasing out of coal boilers by 2037, and the conversion of the electrical grid to 100% renewable energy sources. However, a shift to net zero emissions will require a complete paradigm shift in the way energy is produced and used on a global scale. Major challenges are presented to today's engineers, governments, and citizens, just some of the hills to climb are the cost to replace energy infrastructure, security of supply, and technological feasibility.

Industrial process heat is the thermal energy used in the physical and chemical transformation of materials for industrial purposes, covering a wide variety of uses, largely in the manufacturing of goods. Process heat is a vital component in the world today; in NZ it drives the top export of dairy products to contribute over $35 billion to the economy (Stats-NZ, 2022). Beyond financial returns, it is responsible for the cement and wood for homes and hospitals; milk, and meat for consumption; and metals for life saving medical equipment. As vital as process heat is, it consumes vast amounts of energy, largely through combustion of fossil fuels, the emissions of which contribute to climate change. Indeed, one fifth of the world's emissions are derived from process heating (IEA, 2019). As part of NZ's target of net zero by 2050, the government has enacted a series of milestones to enable this goal to be attained including the removal of all coal boilers by 2037, and the transitioning of the electrical grid to 100% renewable energy sources. Most of these emissions reduction will be achieved by switching to a renewable source of energy and will help to bring about greater sustainability to NZ's energy system. However, sustainability is only one pillar of the energy trilemma, and the two remaining pillars, security and economic supply of energy, can be made more challenging by eliminating fossil fuels. To ensure that all three aspects of the energy trilemma are maintained, the fuels switches must be made in a way that is both economical and provides long-term security of supply.

1.2 Process heat in New Zealand

Heat is required across many sectors in NZ: in the industrial sector, it is used to dry food and timber, produce metals, clean, start or maintain a chemical reaction, and generate power through steam turbines or pistons. The bulk of the heating in NZ takes place in the industrial sector, accounting for 84% of the energy use, the remaining heat is consumed by the commercial and public sectors, with applications such as space heating of buildings, and sterilising equipment in medical facilities (MBIE, n.d.-b).

New Zealand's economy is largely based on the primary industries, with several of these making up the largest energy users. In 2016 some of the largest energy users were the wood products and pulp and paper industry at 55 PJ, dairy products at 30 PJ, meat products at around 7 PJ, and other food and beverages at around 6 PJ (MBIE & EECA, 2016). Process heating spans a wide array of temperatures in NZ, outlined by the Sankey diagram in Figure 1-1; natural gas (44%) and coal (16%) provide most of the energy at around 60%, with the remainder largely filled by the two prominent renewables of wood (18.5%) and electricity (17%) (EECA, 2023b).

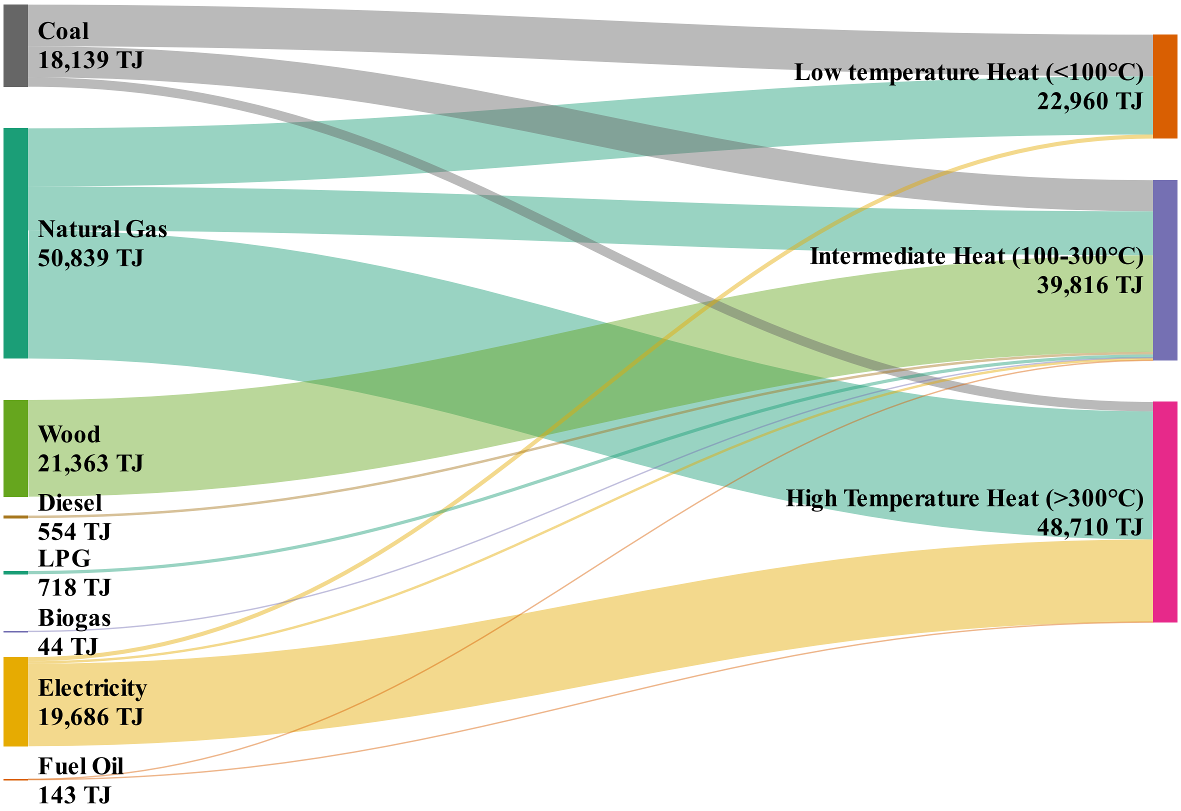

Figure 1-1: Diagram of NZ's process heat fuel sources and temperature distribution (EECA, 2023b)

1.3 Fuel switching options

As outlined above, there is a need to shift New Zealand’s process heat away from fossil fuels, and towards low carbon energy sources. There are several Renewable Energy Sources (RES) options that are competing for use across the world. These energy sources are varied both in the source of their energy, as well as the practicality of use in different sectors. Principally the viability of a RES for fuel switching will be based on its economics, technological readiness, long-term supply availability, and whether it has the support of national and local legislation. In NZ, this eliminates some prominent energy sources, in particular, nuclear energy as NZ has maintained a nuclear-free zone since 1987 (NZ History, n.d.). Green hydrogen has received much interest in recent years as an energy vector from renewable electricity, however for the purposes of industrial process heat, hydrogen is deemed uneconomic and the modelling conducted by Concept (2019) indicated that no carbon price could lead to positive economics when compared to direct electric heating or biomass. More recent economic modelling by Ernest and Young (2023) confirmed that in New Zealand, hydrogen has potential to provide fuel switching options in some hard to abate areas such as heavy transport and steel production, however it is not likely to be competitive with electrically or biomass fuelled process heat.

Solar thermal is another potential source of process heat, though it is also not considered due to unfavourable economics, with some analysis reporting the lowest Levelised Cost of Energy (LCOE) at just under 40 USD/GJ (Ingenhoven et al., 2023). Geothermal already has some direct use for heating in NZ (8 PJ), as well as providing around 17% of the country’s electricity, however the use of geothermal energy is highly location specific, as well as having large upfront costs and so is not included in this work (MBIE, n.d.-d).

The two remaining options that are considered in this report for wide-spread supply of process heating are renewable electricity, and biomass. These fuel sources are already used within NZ, though until recently these were not economically competitive with fossil fuels outside of industries where wastes from manufacturing processes were cheaper to use as fuel for combustion than to dispose of it, or in specific applications such as the Tiwai Point aluminium smelter where electricity was provided at a low cost. Both of these RES have substantial infrastructure already in place within NZ to facilitate their distribution and use, and the technological barriers are low.

The term biomass has several definitions depending on the field and context and there is no standard terminology for bioenergy. For the purposes of this research terminology will follow common use in industry; biomass refers to solid woody biofuel such as wood chips and wood pellets, biofuels refer to liquid fuels such as biodiesel and bioderived sustainable aviation fuels.

Of these two energy sources, electricity has a very well-established market for energy, its pricing is well monitored and understood (em6, n.d.), and substantial investment and legislation is in place to facilitate the installation of large amounts of new generation (Beehive.govt.nz, 2023a). Further research is required in this area to maximise the uptake of renewables into the national grid (Electricity Authority, 2023b); however, this is beyond the scope of this current work. Biomass on the other hand, is still in its infancy as an energy product in NZ, outside of the wood processing sector where it has been used as a fuel source for many decades in pulp and paper processing and drying of timber. Both industries generate significant waste, outlined in Section 2.2.4, which they utilise in boilers for their heating needs. Industrial users of process heat are motivated to switch to RES, though there are areas of concern around making these large leaps; these were highlighted in market research conducted by EECA and Mafic (2021) which identified key factors being the uncertainty around the supply and economics of biomass, the regional variation of this within NZ, and that this impacts the ability to make long-term decisions. The report also detailed that costs to secure a connection to the electrical grid with sufficient capacity are a large unknown and difficult to factor into fuel switching estimates.

Challenges for biomass in NZ

Biomass has no technological barrier to application for process heat in NZ, however, there is competition for the resource itself outside of energy use. New Zealand has significant plantation forestry outlined in the Wood Availability Forecast (WAF), (MPI, 2021), and displayed in Figure 2-5 on page 31, the harvest of which generates a wide variety of products, as well as waste from the manufacturing of these, which in turn typically become feedstock for further products. A basic outline of some of the product flow for harvested wood in NZ is outlined in Figure 1-2, showing some of the existing use for process residues such as animal bedding, and Medium Density Fibreboard (MDF) production.

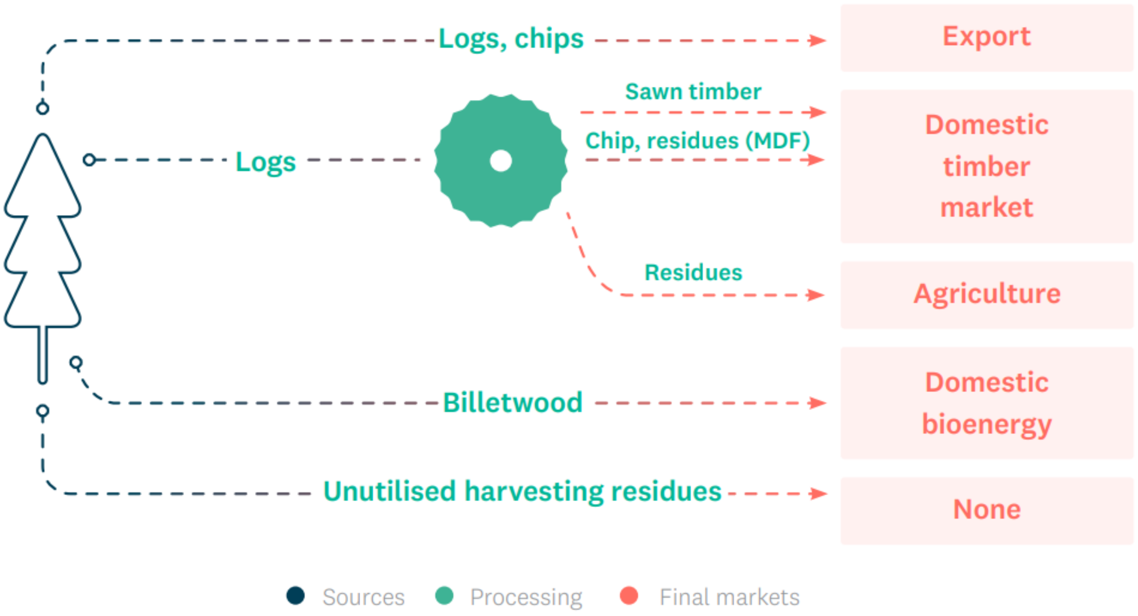

Figure 1-2: Typical wood flow to markets of a harvested tree in NZ (EECA, 2022).

Figure 1-2 also outlines a key source of residues that is underutilised, residues that remain on forestry ground after harvest of timber. Previously, the collection of these has been deemed uneconomical as there was no demand for them except for small amounts of residential firewood, though the demand for biomass is rising as pressure mounts to remove coal boilers and a new economic fuel source is sought. Whilst the resource cost for these residues might be low, as they have no current market, their collection and transportation costs can be a barrier, as these residues are often in difficult to access areas. In addition to unutilised residue sources, some biomass resources may be able to be diverted from their typical markets, as long as there are favourable economic conditions to incentivise this: low grade export logs, domestic pulp logs, processor residues, and wilding pines are all potential sources of energy. However, the nascent market means that there is uncertainty in resource availability, with annual yield estimates ranging from 15 PJ in 2050 (Bioenergy Association NZ, 2018), 57 PJ (Hall, 2010) to 150 PJ (Bioenergy Association NZ, 2022c). In addition to the resource availability over the coming decades, questions remain about how much it will it cost to collect, process, and deliver to the user. The purpose of this work is to fill these knowledge gaps by providing industry with foresight into the long-term future of fuel switching decisions in NZ.

It is proposed that there is significant biomass resource potential in NZ owing to the substantial forestry and processing levels. Improving the field of knowledge available to industry in NZ by comparing the two prominent fuel switching options and accounting for regional supply and infrastructure variation specific to NZ will allow greater foresight into the long-term future of renewable process heat in NZ.

1.4 Thesis aim

The objective of this research is to evaluate to what extent solid woody biofuels can supply New Zealand’s industrial process heat, assessing the economic viability, and ability to provide long-term supply for the country’s process heat demands.

1.5 Research approach

Using the P-Graph framework, P-Graph Studio software and scenario-based case studies, this study will focus on the South Island of New Zealand and its regions of Southland and North Canterbury to establish the impact regional diversity, existing resources and energy infrastructure have on fuel switching economics. The primary objective is to compare the economic and logistical challenges associated with biomass against other renewable energy sources focusing on cost, and supply security in the coming decades. Using the most current data on resource availability, and infrastructure upgrades to optimise resource allocation in the case study regions through the P-Graph methodology, giving foresight to industry on the best fuel switching pathways for their region. It is important to note that the intention of this study is not to provide forecasts or make predictions but to examine how the regional variation in NZ might impact the economics of fuel switching and on-going costs of energy.

1.6 Thesis outline

This thesis has been structured to reflect the workflow required to accurately model and optimise the energy systems in the case studies and then to be able to interpret their results. As many fuel switching decisions and renewable energy sources are location specific, the energy system of New Zealand is outlined to give context to the challenges and opportunities available.

Chapter 2 reviews the current literature on decarbonisation, and this builds an understanding of where fuel switching fits into this process. Attention is directed at the two leading renewable energy sources for process heating in NZ, biomass and electricity. The application of many renewable fuel sources are often location specific, hence biomass and electricity are examined in the context of the NZ energy system. This presents the challenges and opportunities for both energy sources. P-Graph Studio is introduced as the tool used to model and optimise resource allocation in NZ, and to quantify the economic potential and challenges of each fuel source.

After the knowledge base was established in Chapter 2, Chapter 3 deals with the data sourcing and methods used to construct the P-Graph energy models. The use of the data and methods outlined in this chapter allows these models to be tailored for each case study. Chapter 4 presents the cumulation of the model construction and data sourcing by using these models in case studies of several energy systems. These systems range in scale from individual sites, through to the entire South Island of NZ. These case studies are outlined in each section of this chapter and the results of the optimisation presented for analysis.

Chapter 5 conducts the analysis of the case studies and discusses how each case provided answers to the questions posed in the aim, and to what extent these fuel switching options can be used to provide solutions to the challenges outlined in the introduction. Chapter 6 draws the study to a close and highlights the key findings of this work. The work closes by addressing the foci of future work that was conceived during the course of this study.

Chapter 2 Literature review

The previous chapter highlighted the consequences of climate change and the growing, urgent need to eliminate the carbon emissions of process heat. Bringing about the necessary evolution in infrastructure and thinking requires a broad knowledge base and understanding of the synergies between energy sources and industries to carve out a roadmap towards sustainable industry. Industrial decarbonisation is the overarching goal for this research, and this chapter will outline key mechanisms to facilitate this and consider the challenges particular to renewable energy sources. Process Integration (PI), Process Optimisation (PO), fuel switching, and industrial symbiosis are key pillars of industrial decarbonisation and underpin this work, leading into and facilitating a focus on fuel switching. As stated in the introduction above, the fuel switches that are considered economic and practical in New Zealand in the immediate future are forestry derived biomass, and utility electrification. The principal focus of this research is the optimisation of the use of biomass resources in the regions of New Zealand, the opportunities and challenges of which will be elaborated on in the latter half of this chapter, before finally introducing P-Graph methodology as a framework for optimisation.

2.1 Industrial decarbonisation

Industrial decarbonisation is the process of designing or retrofitting a system to reduce and eliminate its impact on its environment. The mechanisms of industrial decarbonisation were outlined by Fischedick et al. (2014) as improving material and energy efficiency, fuel switching to a lower carbon intensity fuel source, and finally offsetting or capturing and storing any remaining emissions. The field of process engineering has an established framework that has focused on improving material and energy efficiency which can readily be applied to the reduction of carbon emissions in industry. The hierarchy of process design presented by Klemes et al. (2011) is represented by the onion diagram in Figure 2-1. The inner layers of the onion contain the key processes that dictate the needs to the outer layers. By optimising the inner layers, the demands on the outer layers can be reduced, which translates to greater material and energy efficiency, reduced load on utility systems, and reduced capital costs when fuel switching to a new heat plant. Once these inner layers have been optimised and integrated, fuel switching can be considered, as the majority of carbon emissions in industry are from fuel use (Griffin et al., 2018; MBIE, 2021): switching to a RES is going to provide the greatest reduction in carbon emissions. In the outermost layer, extending beyond a single factory is industrial symbiosis, either within a cluster of sites, or further afield to neighbouring communities, which can be a useful tool to increase the utilisation of mass and energy as well as providing benefit to surrounding communities.

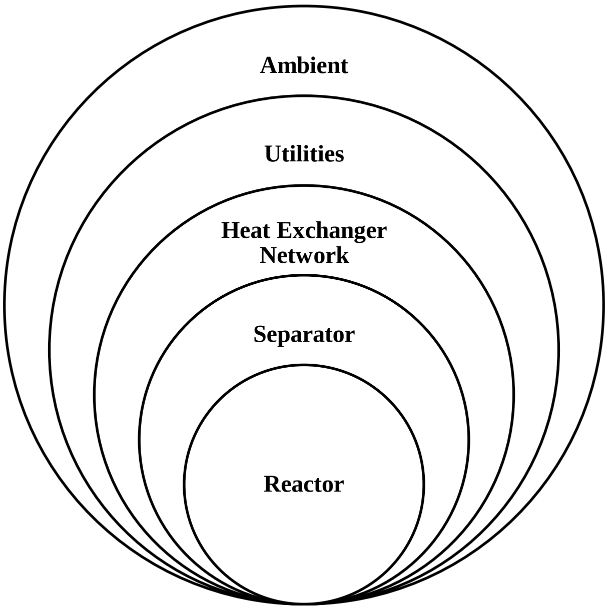

Figure 2-1: Onion diagram of the hierarchy of process design adapted from (Klemes et al., 2011).

Carbon Capture, Utilisation, and Storage (CCUS) is the final mechanism and should be employed after all other pathways have been explored. CCUS includes physical, chemical, and biological methods, and is not considered in this work though it is noted that the carbon utilisation portion has potential for industrial symbiosis (Cuéllar-Franca & Azapagic, 2015), especially for many of NZ’s industrial sectors to replace sources of CO_2 previously derived from petrochemicals (Ara Ake, 2022).

Successful decarbonisation requires a systematic approach considering the specific challenges and opportunities of each industry. This research focuses on fuel switching though it is clear from the hierarchy in Figure 2-1 that it cannot be viewed in isolation. Within this section, the mechanisms of decarbonisation will be outlined by stepping through the design hierarchy to lay a foundation for fuel switching, as well as demonstrating the interconnectivity of industrial sites both currently and in the future, as hybrid and circular renewable systems increase in prominence and importance.

2.1.1 Demand reduction and process integration

Beginning with the inner layers of the onion (Figure 2-1), a bottom-up approach should be taken to reduce the energy demand of processes, thus reducing the strain on RES. Reducing the demand for energy reduces the extent to which more costly and challenging methods need to be applied further down the line: heat plants could be reduced in size, and electrical upgrades eliminated. Demand reduction covers a variety of mechanisms and processes concerned with optimising processes from the bottom up. Because of the fluctuations in some renewables such as electricity from wind and solar sources, and the current absence of grid or large scale storage of electricity, processes in the future will need to become more dynamic, considering the storage of energy, and control of processes to allow optimal usage of energy (Atkins et al., 2010). There are several well-established methodologies aimed at reducing the overall demand on utilities and by extension the demands on the wider regional and national energy systems. A key group of these are Process Integration (PI) tools, outlined by Klemes et al. (2011) as a collection of optimisation methodologies aimed at reducing resource consumption and emissions of processes. The three major tools of PI are: pinch analysis, which focuses on optimisation of Heat Exchanger Networks (HEN) (Linnhoff & Hindmarsh, 1983); Total Site integration, which links the whole site, or sites by a central utility network (Dhole & Linnhoff, 1993; Friedler, 2010); and mathematical programming, which covers a wide variety of linear and non-linear methods. These methodologies have all progressed since their inception and have been applied to a wide variety of situations. Many deal with the fluctuating nature of renewables; batch optimisation, and emissions targeting have been a part of pinch analysis for many years (Linnhoff, 1993), and Total Site has integrated storage, and time slice modelling to account for variable energy supply and demand (Liew et al., 2014; Nemet et al., 2012).

Process optimisation is concerned with producing the optimal solution to a given problem that is constrained by different parameters. It is an adjacent field to PI and can be highly industry and case specific, extending into a wide variety of areas. Often the optimisation of more than one parameter is desired; this is multi-objective optimisation, and has been used to allow greater integration of hybrid renewable energy systems, balancing technical, economic, and environmental objectives (Eriksson & Gray, 2019). Process optimisation can often become much more specific to the system being studied. HVAC system optimisation for example, can have its own programs and systems in place either from manufacturers or third-party companies, especially with the use of smart technology to enable greater connectivity between demand centres and users, and the source or supply (Kim, 2020).

2.1.2 Fuel switching

The act of fuel switching to a RES is generally going to have the greatest impact on reducing carbon emissions, though these can exacerbate or add new challenges that were not present in fossil fuel systems. In NZ, there are two main fuel switch options for the heat utility systems for industrial processes that have suitable economics, technology readiness, and resource capacity. These are electric heating, and combustion of biomass. The major challenges involved with the two options in NZ are the increased temporal and spatial variation in supply, the lower energy density of biomass sources, and the need for supportive policies.

<u>Regionality of energy sources and infrastructure</u>

Areas with an abundance of resources have drawn industries and population to them so they can take advantage of low-cost and reliable energy. With the rise of Net Zero initiatives, the attractiveness of regions for industries is shifting towards those which have the highest potential for low carbon energy sources. Samadi et al. (2023) examined how energy intensive industries are drawn to areas with large renewables potential, a term they have labelled ‘renewables pull’. In their paper, they noted that around a dozen facilities in the ammonia and iron reduction industries have already made decisions that shift their production towards regions with high renewables. These renewable sources are focused on wind and solar for electricity generation, where the industries will be able to take advantage of demand flexibility in their production, and cheap electricity supply in times of high wind and sun. The authors indicated that relocations may enable low carbon industries to compete economically with traditional production methods.

Capital costs of infrastructure vary across different regions, influenced by several factors such as the cost of labour, transport of equipment, and proximity of expert knowledge. Schyska and Kies (2020) discuss the impact of this in the European context. Their investigations determined that assuming a homogenous capital cost in Europe tended to be too conservative, and that countries with more favourable financing conditions such as Germany benefited from lower capital costs of infrastructure. When nonhomogeneous capital cost factors were applied in their modelling, these countries benefitted from larger and more secure energy infrastructure, resulting in them becoming exporters of energy. Their modelling also found that nonhomogeneous cost factors favoured wind generation over solar. New Zealand, unlike Europe, is not connected to neighbouring countries' electrical grids, however within regions and under different council regulations the cost of infrastructure may vary if regional planning favours capital investment in renewable generation infrastructure. Consideration of different capital costs in this work is limited to the average estimates taken from the Regional Energy Transition Accelerator (RETA) reports conducted by the Energy Efficiency and Conservation Authority (EECA) as indicators of potential higher investment costs in some regions (EECA, 2022, 2023c, 2023d, 2023e, 2023f, 2023g). However, these are taken as the basis for scenarios only and not intended to be indicators or projections of true infrastructure costs.

An interesting study by Wang et al. (2019) examined the link between resource abundance in regions in China, and their emissions efficiency. Key findings from their study were that there was a negative correlation between the concentration of resources and the emissions efficiency of a region; regions that had higher security of resources were less incentivised to increase their efficiency. These principles mirror the driving forces behind the development of many of the modern PI techniques, highlighted by Klemeš and Kravanja (2013) in their reflection on 40 years of PI were they stated that much of the PI methodologies came about in response to energy shortages kickstarted by the oil crisis of the 1970s. The inference of these two studies is that scarcity promotes greater efficiency in the utilisation of resources.

Temporal supply changes

One of the major differences between fossil fuels and some RES is the time period over which supply fluctuations occur. Biomass can be relatively easily stored, and its availability predicted several years or decades in advance, though a large challenge is the time lag between planting and harvesting of forests for trees to grow. Changes in timber markets can also affect the timing of harvests and in turn the availability of harvest residue. Electricity generated from wind, and solar radiation – Variable Renewable Electricity (VRE), is dependent on weather conditions and daylight hours, and can fluctuate every few seconds (Lamsal et al., 2019). Hydroelectric generation does not experience the same degree of variability as VRE due to most lakes, and hydroelectric power station ability to provide some storage, though these are still subject to weather conditions and prolonged dry periods can result in shortages. In NZ these dry years have occurred around twice a decade (MBIE, 2023d). The most recent, in 2021 inflated NZ electricity prices by over 70% of the previous year's average spot price (Electricity Authority, 2024). Variable Renewable Electricity will make up a larger percentage of electricity generation in the coming decades, accounting for 80% of planned increases in global generation capacity over the next five years (IEA, 2022b). New Zealand also plans much greater inclusion of VRE, with wind predicted to increase from 6% to 31% by 2035 (EECA, 2021), which will likely introduce greater volatility in electricity availability and pricing.

Though this volatility presents challenges, greater inclusion of VRE into electrical grids can lead to lower spot prices when supply of wind and solar is high, and if energy systems are moved towards higher flexibility and there is sufficient storage, will help to negate the much higher prices in times of low supply (Kirkerud et al., 2017). One method to manage volatility is the use of a hybrid renewable energy system, which would use more than one RES with the goal of reducing energy costs and increasing security by being able to take advantage of low electricity prices using electrical heat plants, and solid fuels in times of low VRE supply (Walmsley et al., 2023). Another method is load shifting, which aims to increase demand flexibility in order to shift demand from a process to take advantage of lower electricity spot prices (Tveten et al., 2016).

Energy storage is a popular solution to address supply fluctuations and can work especially well with VRE as a method of firming. A range of storage capabilities has been studied, ranging from short-term use of battery electric storage (Santos et al., 2022), through to long-term storage to account for seasonal or yearly shortages (Dowling et al., 2020). The findings of Dowling et al. (2020) indicate that long-term storage is proving to be necessary in order to increase the penetration of renewables for electricity to 100% and alleviate risks of seasonal and yearly variation. Biomass is a potential method of energy storage that is being explored, Johansson et al. (2019) determined that biomass in combination with natural gas turbines and carbon capture was an economic support to wind and solar generation when supplying 20% of the electricity in Sweden. Uchino et al. (2023) simulated the integration of a thermochemical storage system, storing excess VRE to supplement power generation from biomass powered Organic Rankine cycle and they determined that the storage medium was able to mostly absorb the fluctuation in VRE.

Biomass energy density and storage life

Biomass for heating is a well-established technology, its use predates fossil fuels and for the majority of biomass fuels is a step back in energy density. Lower energy density presents problems of transport and associated emissions from using current fossil fuel powered transport infrastructure. There is substantial heterogeneity in the forms of biomass used in industry, ranging from P100 hog fuel at 7.4 GJ/t (Azwood, 2023), to 18 GJ/t for DINPlus standard wood pellets (Narra et al., 2012). Whilst wood pellets can rival the energy content of low grade lignite coal (14-19 GJ/t,), these conventional wood fuels still fall short of sub-bituminous (19-24 GJ/t), and bituminous (24-32 GJ/t) (Miller & Tillman, 2008). To overcome transport issues, highly modified wood pellets have been developed, with two dominant technologies reaching calorific values of 27-31 GJ/t for torrefied, and 22 GJ/t for steam exploded (Arous et al., 2021).

Higher moisture content of biomass limits energy content and limits storage life because wood hosts microbes which degrade the fuel, digesting it and releasing gas and heat (Fernando, 2012). In addition to their higher heating value, highly modified pellets can have greater durability than conventional pellets, which enables them to be stored outside for an extended period of time in a similar manner to coal. Genesis Energy (2022) has indicated that steam exploded pellets have potential to be a long-term storage method for use as dry year cover for electricity generation in New Zealand. Both Arous et al. (2021) and Genesis Energy (2022) note that steam exploded pellets have the best durability for storage.

Policy and top-down influences

In addition to bottom-up challenges of integrating fluctuations of supply into the existing demand fluctuations of industry, in most cases RES are not the prevailing energy system and require additional infrastructure to facilitate their use, resulting in costs for new plant, and generally higher fuel costs on top of this. These economic barriers require top-down approaches to incentivise investment. Support is most keenly called for in the electrification field with a number of papers highlighting the importance of policy and carbon unit pricing to facilitate uptake of renewable electricity (Nilsson et al., 2020; Philibert, 2019; Rightor et al., 2020; Roelofsen et al., 2020).

Application of biomass for process heating can be an economic solution for the wood industry sector where combustion of their waste products provides energy at low or zero cost, though for the majority of other industries the cost of biomass outweighs the cost of fossil fuels and top-down support is required to enable fuel switching, Mandova et al. (2018) highlighted this in their global study of countries' suitability to integrate biomass in the production of ferrous metals. They found that in addition to significant steel production, and forestry stands, national policies are necessary to lead to the uptake of a more costly and often less efficient fuel source, especially as these industries have tight profit margins subject to international competition. Olsson and Schipfer (2021) conducted a broad overview of the role of bioenergy in process heat, outlining that there is a large role for policy to support a bioenergy economy, from innovation and investment through to research and development, and market incentives such as carbon unit pricing. A large gap highlighted by Creutzig et al. (2012) is that in addition to requiring economic support to enable fuel switching and reduction of gaseous emissions, there is a need for policy to ensure that further environmental damage is not carried out through land-use changes that are often incurred through afforestation of production forestry.

2.1.3 Electrification

As the capital cost of solar Photovoltaic (PV) and wind generation has fallen in recent decades, a viewpoint has arisen that one must simply electrify everything, and carbon reductions will appear (Olsson & Schipfer, 2021). In many countries, this may be an effective way to reduce industrial emissions when switching from fossil fuels. However, electrification is not always a silver bullet, and the degree to which electrification reduces emissions varies depending on location, as many nations have low percentages of renewables in their electrical generation stack. Schoeneberger et al. (2022) demonstrated this by modelling the US grid, determining that if all boilers in the US converted to electricity on the current grid, only 7% of counties would see a reduction in emissions. Similar results were found for Germany’s electrical grid by Schüwer and Schneider (2018) who showed for the current projected grid operation, an increase in electrification of energy intensive industries over the coming decade would not result in decreased emissions. Under this scenario they also found that energy consumption increased. In countries whose electrical grids are highly reliant on fossil fuel powered thermal plants, electrification of a plant often merely shifts the location of the emissions and adds line losses. Schüwer and Schneider (2018) elaborate on the electrification of industry in Germany; their projections made with expert interviews and their own modelling highlight that electrification has long-term potential, but that in isolation does not necessarily equate to a reduction in emissions or even of energy expenditure. They highlight the importance of High Temperature Heat Pumps (HTHPs), effective electrical storage of VRE, and supportive policies to enable permeation of electrification into industry in a way that lowers emissions and provides good economics for users.

Despite challenges, electrification will make up a large number of decarbonisation fuel switches in industries across the globe. A large reason for this is the range of benefits that process and utility electrification can provide. These benefits were summarised by Wei et al. (2019), including load flexibility, low footprint, improved local air quality, faster start up, and potential integration with distributed generation. Challenges that electrification faces were also summarised as: fuel and infrastructure costs and constraints, risk aversion in industry, and exposure of low profit margin industries to international markets.

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Heat pumps

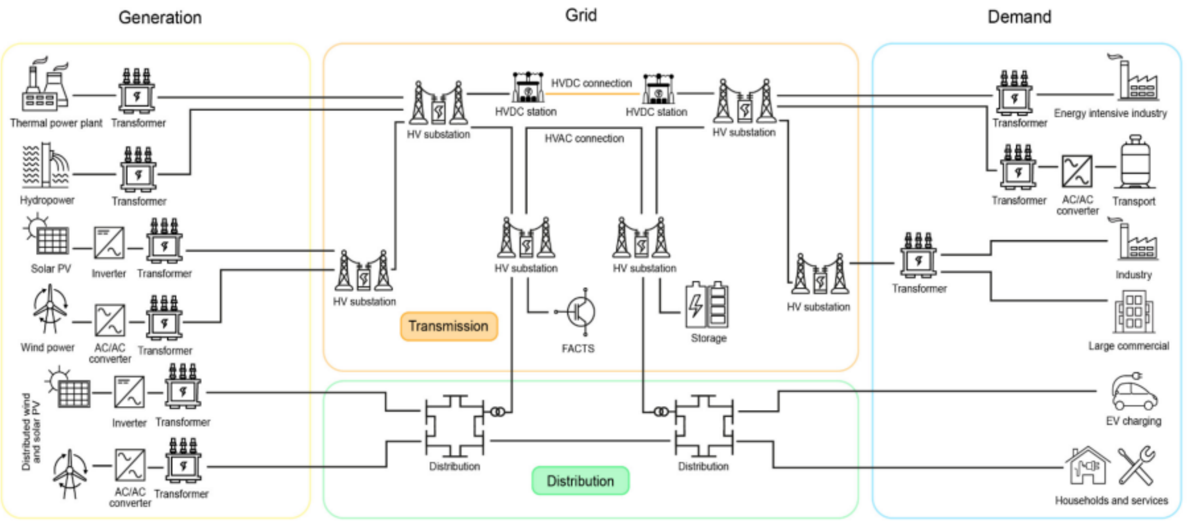
The introduction of Heat Pumps (HP) straddles fuel switching and process integration; they can operate as standalone heat plants or be integrated into existing processes to upgrade sources of waste heat to higher, more useful temperatures. Heat pumps with ambient source temperatures and sink temperature of up to 100℃ are well-established, commercially available today, and have a range of effective uses within industry (IEA, 2023a). Through high efficiency production of heat, they have considerable potential to decarbonise sectors at a range of temperature requirements. Jesper et al. (2021) provided nomenclature and terminology outlines for HP based on their sink temperature; conventional HP operate to 80°C, high temperature between 80-100°C (HTHP), and very high operate over 100°C. The temperature sink of very high temperature heat pumps is dependent on the temperature lift and working fluid. Some higher sink temperatures can be reached, though for a much reduced temperature lift (Kosmadakis, 2019).

Heat pumps are different from conventional heat plants. Generally, HPs use a working fluid to extract heat from a low temperature source and, with the input of a relatively small amount of energy this fluid is moved through a cycle to increase its temperature and then transfer this to an area of heat demand (IEA, 2022a). Because this technology operates differently to conventional heat plants, their performance is measured using a Coefficient of Performance (COP) rather than an efficiency. The COP specifies the ratio of work input to the cycle, to the useful thermal energy output at the heat sink. Typical COPs of industrial HTHPs between 3 and 5 are common; though these depend on the temperature lift, to which the COP is inversely proportional (Jesper et al., 2021). Heat can be sourced from the ambient air, the ground, water, or for many sites from waste heat that results from the cooling of process streams, or rejection from refrigeration. This heat is amplified with the input of another energy source to produce heat at a range of useful temperatures. Use of HTHPs in academia and industry is well established (Arpagaus et al., 2018) and their integration into processes should be considered with the integration and optimisation of the HEN before fuel switching (Schlosser et al., 2019), in line with the hierarchy of process integration outlined in the onion diagram in Figure 2-1 on page 8.

Infrastructure upgrades

Many studies that consider fuel switching focus on the end use costs for the user and much less attention is paid to infrastructure needs. In examining the literature around this topic, the general trend was observed that costs associated with increases to generational capacity and grid carrying capacity are ignored in modelling. The capital costs for generation infrastructure are reasonably established, and the plummeting cost of wind and solar generation are often repeated in government policy, though academic sources will note the caveat that LCOE for VRE require closer scrutiny to ensure their effective use (Keay, 2013; Neuhoff et al., 2018). Grid transmission, connection, and upgrade costs are a complex issue that is highly location and case dependent. In studies of electrification of industry these are often not mentioned (Roelofsen et al., 2020), or are explicitly excluded from costing databases (Schröder et al., 2013). Tsiropoulos et al. (2018) did account for connection of generation infrastructure to the grid in their cost projections, though grid transmission upgrades are not mentioned, and the National Renewable Energy Lab (2023) only accounted for grid connection costs in the offshore wind section of their database. Gaur et al. (2022) investigated the electrification of the residential heating sector in Ireland, with a focus on the economics of grid expansion and optimum placement of new generation. Biomass fuels featured in their analysis though not as a direct heating method and heat pumps were found to be the optimum heat source for residential temperatures. Fitiwi et al. (2020) accounted for network infrastructure upgrades in their modelling of the electrical grid in Ireland, though did not compare different forms of energy for industry.

Generation and distribution account for most of the electrical grid, as seen in Figure 2-2, the complexity and list of unknowns of which are likely the rationale that these areas slip out of scope in modelling that is focused on industrial energy users. There is significant complexity and diversity in the electrical generation stacks of most countries, and to ensure accurate costing of each potential upgrade or new connection requires detailed and specific analysis to be carried out. Generally, the nature of these upgrades means that they will be highly dependent on the location of the plant, and the distance and nature of terrain to the nearest Grid Exit Point (GXP), and the amount of spare capacity this GXP has.



IEA. CC BY 4.0.

Figure 2-2: Key components of electricity grids (IEA, 2023b).

Generally this data is not easily obtainable, however recent reports conducted by EECA provide up to date costing of potential grid infrastructure upgrades for sites in regions of the South Island of NZ (EECA, 2022, 2023c, 2023d, 2023e, 2023f, 2023g). Analysis of these costs across multiple regions shows that there is very little correlation between the size of new electrical demand, and the cost of the upgrade, as seen below in Figure 2-3.

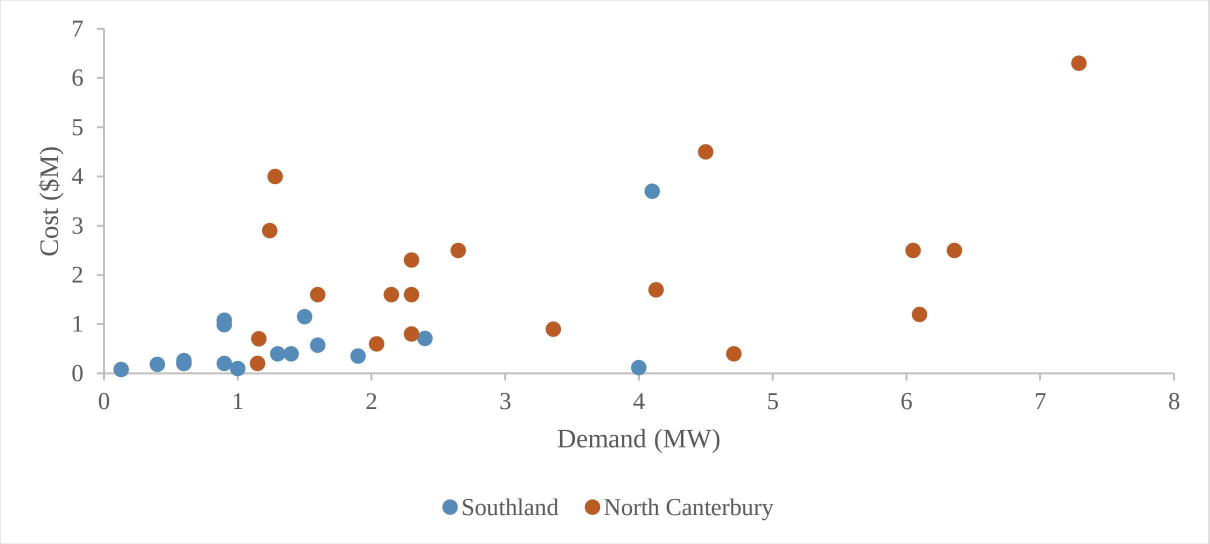


Figure 2-3: Transmission upgrade costs in Southland and North Canterbury (EECA, 2022, 2023e).

Despite the lack of concrete generalised costing methods for grid upgrades that can be as easily applied as those for plant equipment (Bouman et al., 2004), the need and cost of these upgrades cannot be overlooked. There are sectors drawing attention to these challenges, particularly those that are less concerned with individual plants and more with the overall trends for nations. The IEA (2023b) has highlighted the importance of electrical grids for successful energy transitions, and that there is a global need for substantial infrastructure upgrades of capacity to transmit and distribute electricity in order to accommodate large rises in demand. A key finding in the report from the IEA (2023b) states that in order to reach national decarbonisation goals, globally over 80 million kilometres of network need to be added or refurbished, the equivalent of the entire global network in 2023. Beyond Zero Emissions (2023) estimated investment of $20 billion is required over the next five years to accommodate renewables targets in an Australian national supergrid.

2.1.4 Industrial symbiosis

In many ways Industrial Symbiosis (IS) is an extension of PI total site methods. It offers opportunities for energy use reduction and waste minimisation by utilising the waste energy or byproducts of one industry as the fuel or feedstock for another, with the goal of achieving benefits for more than one site. The concept has roots in industrial clusters at the end of the 1980s where utilities were shared and district heating provided for nearby communities (Frosch & Gallopoulos, 1989). The degree of symbiosis spans a wide range, from the optimisation of complex systems across multiple sites, to a circular economy approach where the waste products of one industry can serve as fuel for another. Clustering of industrial sites has been shown to reduce carbon emissions by 10.8% when compared to the same sites in the absence of IS in China (Yu et al., 2015). Cioccolanti et al. (2021) show that waste heat from the Italian pulp and paper sector can be used for district heating and reduce reliance on natural gas.

Neves et al. (2020) provided a comprehensive review of IS and its use across the globe, highlighting large potential that has not yet been achieved, but that as resources become more costly and countries seek ways to reduce their emissions, IS is becoming more prominent and the potential benefits extend beyond the factory gate and into communities. They note that manufacturing facilities provide good examples and potential for IS as they often have large amounts of waste products and heat that need removal. A challenge to IS is often the complexity and economic cost to integrate sites. This was highlighted by Pakarinen et al. (2010) in their examination of the development of IS in the Finnish forestry industry over a 110 year period. They determined that the main drivers for IS were economic, and the barrier to wider adoption of IS was the inability of the economic potential to overcome the logistical barriers. Neves et al. (2019) echoed this in their review of IS implementation in Portugal, stating that despite potential for higher efficiencies and lower emissions, more top-down action is needed in the form of facilitators, policy, funding, and the use of some industries as anchor tenants to contribute to wider use of IS.

Industrial symbiosis in the wood processing sector

Biomass is an agreeable candidate for symbiosis with application as both a manufacturing and energy feedstock. Naturally, wood processing facilities have long been making use of the concepts underpinning IS, with sawdust, offcuts, and black liquor fuelling thermal plants in the industry. Investigations into sector coupling of biomass has yielded promising results as shown by Karlsson and Wolf (2008) where the coupling of a saw mill, pulp mill, district heating, and biofuel facility were optimised using linear programming. This coupling was shown to give better economics, and a more stable system than standalone sites.

Biorefineries offer potential in New Zealand for greater integration of IS by combining industrial clusters around a wood processing site. A biorefinery is a facility that converts biomass into – ideally – multiple products; fuel sources, chemicals, and other useful products such as pulp and paper (SCION, n.d.-a). Existing examples can be found in the Central North Island of NZ, where pulp and paper mills convert low grade wood into products, as well as using the biomass byproducts to provide heat for their processes. Expansion of these facilities to produce additional products through IS has been proposed. Atkins et al. (2015) examined the extent to which additional production could be integrated at existing kraft mills and sawmills. Products such as urea, bioethanol, and syngas using biomass as their feedstock, as well as using excess heat to produce milk powder were examined for their integration potential using Total Site methodology. They determined that several of the processes had pinch temperatures too low and close to the existing pinch temperature of the mills and so offered little benefit. However, production of syngas and urea through gasification of biomass, with the potential integration of geothermal steam could provide beneficial integration with the existing cluster as these processes generated high quality heat which could then be used for processes in the mills.

Fahmy et al. (2021) explored a generalised methodology to optimise industrial symbiosis of wood processing facilities, with case studies centred on the wood processing site in Kawerau. The authors found that production of laminated wood products, tannins, plywood, and bark briquettes could prove suitable for integration with the existing Kawerau processing cluster, and they noted that price volatility has a reasonable impact on the economics of this integration.

The potential to produce liquid biofuels from biorefineries has been of some interest in the past two decades. Whilst the potential for these fuels for use for light vehicles in NZ is not as high as it was due to the impacts of policy change (New Zealand Government, 2023), future use of liquid fuels in difficult to abate marine and aviation sectors remains a reasonable possibility if national goals of net zero carbon are to be achieved (Air New Zealand, 2021). Demand for liquid biofuels represents a source of potential competition for direct combustion of solid biomass if domestic production of liquid fuels was established. Suckling et al. (2018) conducted significant investigation cumulating in a roadmap outlining the potential for liquid biofuels in NZ. Their modelling analysed several scenarios and they estimated that the average LCOE for liquid biofuel was just under 1 $/L for drop in petrol and diesel in an optimised scenario producing a range of fuels. At the landed fuel prices in 2018 of around 0.85 $/L this was not economic. The estimates for marine biofuel were 0.86 $/L, compared to 0.72 $/L for fossil fuel, and to 2.21 $/L for drop in jet fuel, compared to 0.87 $/L for fossil jet fuel. The estimate for drop in jet fuel was notably high due to the method of production having higher processing requirements and costs when a single fuel was optimised for. Including the other biofuels in the optimisation would reduce this cost but was not specified in SCION's report. Suckling et al. (2018) noted that the production of liquid fuels would compete with direct combustion of solid biofuel for process heating especially for forestry and processor residues, but that herbaceous crops would be an option to increase supply.

2.2 Forestry for bioenergy

Forestry-derived wood for energy is a large contributor to renewable process heat, and it has increased in the past decade from 8.2 EJ in 2010 to 11.1 EJ in 2022 (Bains et al., 2023). Though much of this use has largely been restricted to wood processing industries as they tend to produce reasonable amounts of combustible waste, and the use of biomass outside these industries has generally not been economically competitive with fossil fuels. In order to meet net zero goals however, the IEA (2023c) predict it will increase to 15.3 EJ by 2030, accounting for around 9% of total industrial energy demand. Despite these increases, the biomass market in still in its infancy compared to fossil fuel derived heat and electricity, and established renewables such as hydro, wind and geothermally sourced electricity. The nascency of this market causes uncertainty for potential industry users who need to make fuel switching decisions that are economic and have secure long-term supply solutions.

Within both literature and industry, there is a lack of certainty in the biomass market, though there is a mixture of optimism and scepticism for its future. Optimism abounds as biofuels can replace each use of fossil fuels with varying levels of processing, though also with varying levels of economic feasibility (Olsson & Schipfer, 2021). The scepticism arises over concerns about the carbon release from combusting biomass that might have otherwise sequestered carbon as a building material or continued to absorb it from the atmosphere had it not been removed from the forest. The following section outlines the current and historical use of biomass in industry before establishing the challenges and opportunities for successful uptake of biomass for process heat, focusing on the economics, long-term supply and constraints, and examining the concerns of carbon fluxes and land usage.

2.2.1 Biomass definitions, sources, and fuel types

Biomass sources

There are several sources of solid woody biomass available in NZ. Ranging from waste products such as harvest and processor residue through to timber logs. The biomass sources displayed below in Table 2-1 are categorised based on their origin, or standard log specifications used in NZ. Log specifications are concerned with several parameters that classify the quality of the log, most importantly the Small End Diameter (SED) and the size of the knots in the log caused by branching.

Table 2-1: Wood resource definitions, adapted from (Forme, 2019).

Resource	Definition	Minimum SED (mm)	Knot diameter (mm)
Harvest residue – Roadside	Easily accessible debris left near forestry access roads, skid sites and harvest sites.	N/A	N/A
Harvest residue – Cutover	Not easily accessible residues on harvest sites, may be steep or remote terrain.	N/A	N/A
Processor residue	Sawdust, wood chips, black liquor.	N/A	N/A
Pulp log	The lowest grade of harvested logs.	80	Any
Roundwood	Posts, poles, retaining walls.	100	Various
KIS	Export log grade	140	Any
KI	Export log grade	260	<200
K	Export log grade	220	<100
A	Export log grade	300	<100
Pruned	High log grade used for framing and visual appearance	300	None

The resources in Table 2-1 above are arranged in descending order of their typical cost, exclusive of collection and transport. In NZ there is currently little existing use for harvest residue outside of firewood (EECA, 2022), largely due to its lower value and, as is especially the case for cutover residue, difficulty to access and collect the resource. However, as demand for biomass grows these residues present a great opportunity to those industry users with boilers capable of utilising lower grade fuels with higher moisture or ash contents. Modern Bubbling Fluidised Bed (BFB) boilers are capable of combusting a diverse array of fuels with moisture contents up to 65% (Windsor Energy, 2023a), meaning harvested biomass does not even require drying before combustion (Visser, Berkett, et al., 2010). Processor residues are good fuels for boilers, they are often reasonably dry and already reduced in size. Because of this, the wood processing industry utilises the majority of these for their internal use. Depending on regional availability there will be existing use for this resource such as MDF production or animal bedding. A large portion of NZ's harvested logs (62% in 2019, (MPI, 2023b)) are exported; these are generally exported as rough logs that are then processed overseas. There is potential for a portion of the lower grade export logs to be diverted to domestic bioenergy use (EECA, 2022).

Biomass fuel types

Biomass fuels come in a range of different forms, either for ease of processing, or to cater to more specific user requirements. In general, the cost of biomass increases relative to the level of processing. Exceptions arise if long transport distances are required, in which case it can be more efficient to upgrade the quality of the fuel as this will lead to a reduction in transport cost per unit of energy. The types of biomass that are investigated or discussed in this work are outlined in Table 2-2 below.

Table 2-2: Solid biomass fuel descriptions adapted from (Bioenergy Association NZ, 2022a).

Fuel type	Description	Attributes	Typical energy content
Hog fuels	Produced by mechanical crushing tools such as rollers and hammers.	Higher moisture content, broad spectrum of particle size.	7-8 GJ/t (Azwood, 2023)
Wood chips	Produced by mechanical cutting using sharp tools. Often dried in a drum dryer.	Higher quality fuel than hog fuel with narrower spread of particle size and lower moisture content.	8-13 GJ/t (Bioenergy Association NZ, 2022a)
Conventional/white wood pellets	Wood is reduced to a fine particle size before being extruded through a die to form a pellet.	Pellets have consistent size and low moisture content (10%) leading to higher energy density than chip or hog.	16-18 GJ/t (Bioenergy Association NZ, 2022a)
Black wood pellets	Similar to conventional pellets, except the particles are heat treated before pelletisation.	Heat treatment greatly reduces moisture content (<2%) and can improve mechanical strength and storability.	22-31 GJ/t (Arous et al., 2021)

Wood chips, hog fuels, and white wood pellets are all produced in NZ and have established use; black wood pellets are not produced domestically though interest is growing from industry groups (Genesis Energy, 2023a). Hog fuels are low quality, with larger irregularity of particle size, and higher moisture contents, and are used where transport is not a restrictive factor in biomass costs, and boilers capable of combusting this fuel are installed. Conventional wood pellets have established use in residential heating as well as at industrial scale, because their energy density overlaps with the range provided by some coal fuels, and they can be integrated with existing coal fired boilers after some modification to the fuel handling systems. Retrofitting these existing coal boilers may be a practical option if these boilers have a long service life remaining, though the economic feasibility is uncertain and is dependent on the specific boiler and quality coal combusted. Black wood pellets have greater processing requirements, though their higher energy density and mechanical properties means they can work as drop-in replacements for high performance coal powered boilers with minimal modifications (Genesis Energy, 2023b). A difficulty with conventional wood pellets is that they are hydrophilic and will break down when stored outside and exposed to moisture, meaning that storage and handling costs are high as they need to be protected from the elements. Steam exploded pellets are a heat-treated pellet and have greater resistance to degradation compared to conventional wood pellets. These pellets still exhibit levels of decay, though lower than conventional pellets, Yu et al. (2022) indicated that research on this fuel source is still limited. Graham et al. (2017) compared the storage capabilities of conventional and heat treated pellets, indicating that steam exploded pellets sampled on the outside of storage piles with no weather protection increased in moisture content from 2.7% to 22% after three months, pellets in the middle of the pile increased from 2.7 to 10.7% over the first nine months with low rainfall, increasing in moisture with winter rainfall to 20% after 12 months.

2.2.2 Biomass in the global context

Biomass has well-established application for high temperature heat within the wood processing sector, in large part due to the abundance of residues that arise as a byproduct of production, with as much as 55% of the log going into a sawmill becoming residue (Dudziec et al., 2023; Lock & Whittle, 2018). The challenge to increasing the use of biomass and extending it beyond processing residue has been to do it in an economic and sustainable manner.

Over the past 15 years use of wood fuels has been gradually increasing. Of high prominence are wood pellets which have been sought after by large companies such as Drax in the UK to provide electricity (LeBlanc & Vlosky, 2023). A large portion of these pellets are traded internationally, with major exporters: USA, Vietnam, Canada, Latvia, Russia, and Estonia, and importers: the UK, South Korea, Japan, Denmark, the Netherlands, and Italy (Ireland, 2022). These wood pellets are still generally a product of waste residues from the wood processing sector, and very few examples of strict bioenergy forestry exist in markets today (Jones et al., 2023). Lack of diffusion beyond the wood processing sector demonstrates that there are challenges with expanding the bioenergy market; these challenges are mainly concerned with the economics of different feedstocks, and the fact that demand has not arisen to make the recovery of more challenging feedstocks feasible.

Currently global demand is focused within industries that take advantage of residues generated by their own manufacturing, those who have obtained low-cost forestry residue, or who have been proactive in decarbonisation efforts. Thus far, the demand for wood fuels sits under the threshold of wood processor wastes, as many net zero carbon programmes have started only in recent years and long lead times are given to industries to transition to carbon neutral fuel sources. Some early adopters have jumped on favourable supply agreements where they had capital available to invest in a fuel switch. These companies will get the advantage of cheap feedstock and potentially long supply agreements that guarantee both supply and quality into the future.

As for the existing examples, the wood processing industry has used wood fuel because it is abundantly available in the forms of saw dust, offcuts, and black liquor in the pulp sector, all of which can be combusted. On top of simple thermal use, there are examples of Combined Heat and Power (CHP) providing electricity for use on site and for neighbouring communities, and to sell to the grid. Walmsley et al. (2023) state that CHP is the most exegetically efficient way to use solid wood fuels. Finland and Sweden have relatively high levels of electricity in their national grids derived from biomass fuelled CHP, at 15%, and 8% respectively (IEA Bioenergy, 2021a, 2021b). The UK also generates a relatively high portion of electricity through combustion of biomass at 10.9%, though this is not from CHP (IEA Bioenergy, 2021c).

2.2.3 Economics

Expanding on the previous section, Lenz et al. (2020) summarised that the lack of penetration of biomass into the industrial sectors is due to the abundance and low cost of fossil fuels until recently. “Exceptions only occur, if (i) the use of combustible production residues is cheaper than external disposal plus fuel costs or (ii) customers have a focus on renewable or CO_2-friendly production and producers react to this demand” (Lenz et al., 2020). The aim of top-down initiatives such as carbon emission pricing and subsidies for low carbon fuel sources and energy saving opportunities are to encourage the uptake of RES that would otherwise be uneconomical on their own. Biomass residues such as those left behind following forestry harvests are viewed as waste products, and have previously been of little use to the forestry industry outside of replenishing some of the nutrients to the soil lost by growth of trees (Harvey & Visser, 2022). The main costs associated with these feedstocks is in their collection and transport, especially on steepland where the removal of larger residue wood takes just as much effort to attach it to a cable based harvest system as high quality wood but yields far less economic return and is therefore not worth the time taken to remove it from the forest (Hall, 2023b). As demand for wood fuels increases due to the influence of climate policy, the economic viability will increase for these residues, beginning with the easiest to recover sites such as roadside residues, and escalating to more difficult sites as economics, demand, and policy dictate. Carrasco-Diaz et al. (2019) highlighted this in their estimate of forest residue for energy in Mexico. Combining technical and socioeconomic approaches, they analysed recovery of residues under different scenarios considering environmental effects to the soil as well as financial compensation to the forest owner. Unsurprisingly, residue recovery was predicted to increase with the amount of compensation paid, but also forest owners showed significant concern about the ecology of their forest (63% of respondents), which can be at risk through more intensive harvest of residue.

Short rotation forestry

New Zealand is well placed to establish a dedicated bioenergy forestry system, termed Short Rotation Forestry (SRF), with the technical knowledge, established plantation forestry, and infrastructure required, though the dedicated forests require investment of both time and money, as well as confidence that the market and policy will remain in favour of bioenergy. In NZ there would be around a 15 year lag time between planting and harvesting SRF and coupled with the significant costs to establish a forestry stand, including roads, landings, and the land itself, this combination of factors may prove prohibitive. Jones et al. (2023) produced a review of the literature focusing on short rotation bioenergy forestry and residue. They stated that to enable economical land prices and avoid clashes with food production, steepland would likely be used for any SRF venture, though this often leads to much greater harvesting and transport costs as this land is often far from processing centres and difficult to access. Their view was that “Until the supply of low-cost residues are exhausted, long-term solutions such as SRF will not be economically viable on their own.” Currently the only substantial example of a purpose grown short rotation forest is in Brazil, consisting of over 6 million hectares of forests on a five to seven year rotation. These forests were planted to serve the pulp and paper industry in Brazil as a feedstock and energy source, Brazil has the fastest growing pulp and paper industry in the world, and the fourth largest currently. Their eucalyptus trees which account for 74% of their plantation forest grow extremely quickly and are ready for harvest in just five to seven years, a large factor driving their pulp and paper expansion (van der Mark & Haggith, 2017).

Transport and collection

Despite some sources of biomass such as waste residues having a low purchasing cost, several aspects contribute to their complexity and cost as an energy resource, in particular the collection from the forest and transport to processing facilities and point of use. In NZ this has been established by Hall et al. (2001) who outlined that increases in complexity from additional handling added extra cost and that the simplest transport option with the least transhipping tended to be the cheapest. Some of these complexities could be made economical if economies of scale were reached, though this again runs into the main cost hurdles of biomass. These are its low energy density and scattered supply, both across forestry and other sites within a region, as well as within individual forestry sites.

The low energy density of biomass means that the cost to transport per unit of energy is high, Sosa et al. (2015) stated that the moisture content of biomass is the most important controllable factor in transport efficiency. As much of the available and lowest resource cost form of biomass is residue and loose wood, it has lower transport efficiency than whole logs due to a lower bulk density. This means that the volume of matter transported by trucks is the limiting factor, not weight (Johansson et al., 2006). Acuna et al. (2012) also highlighted that moisture content is the most important factor in transportation, and that it affects the storability, energy content, and comminution costs and efficacy.

The predominant modes of transport for biomass are trucks, rail, and barges or ships. In their review of biomass supply logistic models, Malladi and Sowlati (2018) highlighted that trucking is the typical mode of transport, though it is only economical for short distances, and that over long distances, rail and shipping networks are the more economic solutions. The authors did highlight using rail and shipping transport solutions generally require multiple methods of transport as biomass supply points are often not within easy access of ports or railways. These intermodal transport solutions may allow economical transport over great distances, though require specific logistic and economic analysis for each case as the increase in handling and transhipment can increase cost, as referred to in the findings of Hall et al. (2001).

There has been some research into the optimisation of the location of energy densification facilities in relation to transport points. Ng and Maravelias (2016), investigated this for the production of ethanol, and found that a single large processing facility was the most economical option when a single objective was solved for, and only when optimising for a secondary objective of reducing transport emissions did inclusion of multiple facilities to increase energy density become favourable. Roni et al. (2017) obtained similar results when investigating cost minimalisation of liquid biofuel production. However, for the production of solid biofuels, the processing requirements and thus costs are lower, Akhtari et al. (2014) and Kanzian et al. (2009) determined that it was most economical to chip forestry residue at supply sources rather than at a central location, though Kanzian et al. (2009) stated that for whole logs and round wood it is more efficient to transport these first before processing. These results align with the findings of Johansson et al. (2006) around the bulk density of different biomass sources.

There is growing interest in the use of highly processed wood fuels, such as torrefied pellets which could overcome issues of low energy density for transport. Burli et al. (2023) highlighted that whilst black pellets do have higher energy density, they suffer from classic problems of new technologies including a lack of a large-scale market. Their survey indicated that power plant operators would be willing to sign contracts for torrefied pellets if suppliers could guarantee flawless operation for two years, though they indicated several leaked bids would have large cost benefits to consumers.

2.2.4 Variation in supply estimates

The supply of biomass resources has complexities for several reasons; much of low cost biomass residues are waste products from varied industries. In the wood processing sector, the rates of residue generation vary greatly depending on the industry, fibre, and techniques used. Forestry residues have been reported variously as 10% of standing volume in Norway (Rørstad et al., 2010), between 10 and 22% depending on the species in Mexico (Carrasco-Diaz et al., 2019), and 15% of total harvested volume in NZ (Visser et al., 2019), though these are average values and it has been reiterated that they vary considerably.

Mill wastes also have a large degree of variation. As much as 40-60% of the incoming log can become waste that could be used for energy purposes (Heinimö & Junginger, 2009). Proskurina et al. (2017) outlined the impact different industries of wood processing can have on the conversion of wood into non energy products in Finland. These values are displayed below in Table 2-3.

Table 2-3: Efficiency of wood conversion into non-energy products in various wood processing industries (Proskurina et al., 2017).

Wood processing industry	Wood converted to non-energy product
Plywood mills	36%
Particle and fibreboard mills	99%
Other mechanical wood processing	35%
Chemical pulp mills	52%
Sawmills	45%
Mechanical pulp mills	90%

Because NZ has a well-established forestry sector, the location, age and nature of forestry stands are reasonably well known, and the Wood Availability Forecast (WAF) provides information on the age and location of forestry stands. Using a harvest age of 28 years (standard harvest age for *P. radiata* in NZ is between 24-30 years) it is then possible to predict harvest volumes on an annual basis. In addition to this, the residues left from harvest and forestry operations are also able to be predicted by those that have sufficient expert knowledge of the sector. These figures for residue recovery are dependent on the slope of the stand which informs the method of harvest.

2.2.5 Supply estimates in New Zealand

Biomass supply data is well provided for in NZ. The Wood Availability Forecast described above has been conducted at regular intervals (MPI, 2021), which coupled with the National Exotic Forestry Description (NEFD) (MPI, 2023a), can be used to forecast the approximate location and timing of wood harvest down to the district level in NZ. These documents provide reasonable estimates of forestry supply, with the caveat that these forecasts do depend on the assumption that forests will be harvested at the average age of 28 years (Woollons & Manley, 2011). In actuality, this can be affected by international timber pricing, fuel and wage costs, and availability of personnel to harvest these forests. Using the WAF and NEFD enables the determination of overall forest volume and harvested volume. Considering recovery rates pertinent to the terrain of the forestry stand, and efficiencies of wood processing industries, the recoverable volumes of biomass can then be estimated. These estimates have been provided in studies investigating overall bioenergy potential (Hall, 2010, 2022), as well as scenario based modelling of liquid biofuels (Suckling et al., 2018).

Estimation of the economic recovery of forest residue requires in-depth knowledge of forestry workings and the terrain and accessibility of the area. Visser et al. (2018) noted that a reasonable harvest estimate in steep terrain of Gisborne, NZ would be 120 m^3/ha for a typically 500 m^3/ha harvest (24%), whilst Harvey and Visser (2022) conducted an extensive study on a range of sites in NZ's steepland forestry and whilst the average recovered volume was 88 m^3/ha, the recoverable volume ranged from zero on a raked over area, to 580 m^3/ha on an area highly damaged by windthrown timber before harvest. Harvey and Visser also stated that the harvest method contributed to variation in residues, with ground-based methods resulting in lower residue production than cable-based systems (68 m^3/ha compared to 110 m^3/ha). Despite these variations, there are indications that the increase in market interest of bioenergy coupled with reduction in costs of drone imaging will improve accuracy of quantifying residues (Harvey, 2022), and that use of Geographic Information System (GIS) software will lead to more accurate prediction of recovery volumes (Rørstad et al., 2010).

An aspect that has been previously difficult to account for is the existing demand for wood products outside of those documented such as export logs and domestic processing of timber. Processor residues for animal bedding, and modified timber products such as MDF, consume a substantial volume of the potential biomass in NZ and make it difficult to accurately forecast biomass availability based on forestry data alone. In addition to the scarcity of incumbent use data, process heat demand data was either outdated in the form of the 2011 Regional Heat Demand Database (RHDD) (CRL Energy Ltd, 2011), or not accurate enough to facilitate regional modelling (MBIE, 2022a, 2023a). The reports released by EECA under the RETA programme provide clearer outlines of both resource supply and process heat demand specific to each region, giving higher degrees of accuracy than previously available. The reason for this higher accuracy is that EECA used a combination of top-down analysis through the WAF and NEFD, coupled with a bottom-up process of interviews with industry. The interviews with industry shed light on realistic recovery rates for biomass, as well as incumbent use. It also revealed where existing users may be able to defer resources for use as biomass if favourable economics are present (EECA, 2022). Some industries are reliant on flows of low grade wood and processor residues to meet their production outputs. The presence of these industries means that in periods of low forestry harvest the supply of biomass will be restricted. These industries will endeavour to maintain their production levels by consuming wood that could have otherwise been used as biomass (EECA, 2023e).

Availability of the data presented in the RETA reports presents the most up to date and accurate picture of the potential of biomass energy in NZ and has allowed this work to provide a more well-rounded investigation into the extent of biomass use for process heat. Broadening the scope to interregional transport of resources, as well as focusing on individual sites within these regions gives more insight into how an industry's temperature demand, and the regions' location will impact the economics and viability of biomass.

2.2.6 Carbon neutrality of biomass

Of increasing prominence in the literature are concerns from global sources about the carbon neutrality of bioenergy. These concerns cover a variety of areas, including a reduction in the soil health of forestry land from heavy machinery and timber contact with the soil (Picchio et al., 2020), and competition with existing and future needs of land to grow food (Muscat et al., 2020). Norton et al. (2019) drew attention to the temporal nature of the atmospheric carbon and that in the short term the carbon concentration can increase before forest regrowth occurs to make up for this, and that this conflicts with the current narrative of urgency in policy to reduce carbon emissions.

It is reasonable to concur that the use of forestry derived biomass should not be immediately thrust into the extremes of carbon neutral categories, that its use is highly situation dependent. Several studies examine the methods of measurement and Life Cycle Analysis (LCA) demonstrating the complexities involved with the systems being studied, the impact which the assumptions made and methodologies used, can have on results. Bentsen (2017) highlighted that the methodologies used to measure carbon debt have more impact than ecological and forestry management parameters, and Talwar and Holden (2022) suggested there is a lack of understanding of the synergies and long-term circularity involved in a bioeconomy. Investigations by Agostini et al. (2014) and Zanchi et al. (2012) stressed the importance of the feedstock used, and the temporal nature of atmospheric carbon, that use of forestry for bioenergy does have the potential to increase Greenhouse Gas (GHG) emissions in the short-term but can lead to savings in the long-term though the time-frame varies from decades to centuries. In surveying the literature, it is apparent that bioenergy should be viewed through a lens specific to the parameters that pertain to the origin, transport, and use of bioenergy. A number of important factors need to be considered by both LCA studies and policy that they often inform. Calvin et al. (2021) and Camia et al. (2018) outlined a number of important parameters that should be considered: the previous land use, transport distances, end-use conversion efficiencies, process characteristics, LCA methodology, synergies with existing agricultural or processing systems, and silviculture practices.

New Zealand’s stance on biomass

In regards to the NZ context for bioenergy, domestically produced biomass is deemed carbon neutral at the point of combustion (Ministry for the Environment, 2022). Jones et al. (2023) highlighted that despite international concerns about the carbon payback time of long-rotation forestry bioenergy, and the transport distances of internationally traded biomass such as wood pellets, NZ was not likely to experience the same issues, as NZ has the advantage of a well-established forestry sector with a stable forest volume, and relatively short transport distances domestically.

The government’s stance on carbon neutrality of biomass in New Zealand is complemented by the consistent level of plantation forestry, which serves as an indicator of the long-term sustainability of forestry and biomass use. If forest area and standing volumes are consistent over time, the carbon balance can be considered neutral, as carbon released by harvest is conserved through replanting. New Zealand has had a reasonably consistent forestry area since the 1990s, in which there was a large increase in afforestation, growing from 1.3 M ha in 1990, to 1.7 M ha in 2022 (MPI, 2023a). Rates of replanting have also been relatively consistent in this time (Forest Owners Association, 2023). Afforestation rates of production forestry had been low until 2020, in which there was a sharp increase, potentially due to the increase in the carbon unit price in that year (Te Uru Rākau, 2022a). Large increases in 2021 and 2022 can be seen in Figure 2-4 below in which there was over 110,000 ha of new production forest established in NZ, and the national surveys of forestry owners indicated that substantial afforestation is expected to continue throughout the 2020s (Manley, 2023).

In addition to large areas of new forestry, the replanting of existing forests is expected to continue, with deforestation rates continuing to remain at very low levels (Manley, 2023). A large incentive for this is that under the emission trading scheme, deforestation typically results in the land owner surrendering carbon units that amount to the stock of carbon within the forested area. For a mature forest this can be tens of thousands of dollars per hectare ("Climate Change (Forestry) Regulation 2022," ; Ministry for Primary Industries, n.d.).

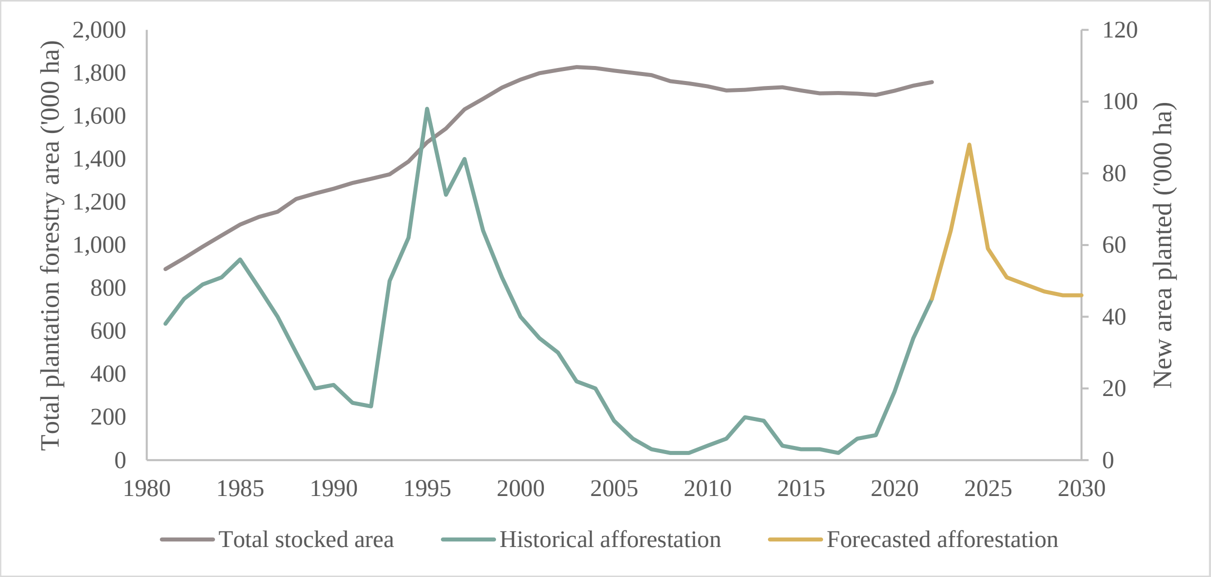


Figure 2-4: NZ's total area of plantation forestry, with historic and forecasted rates of afforestation (Manley, 2023; MPI, 2023a).

2.3 New Zealand's regional energy infrastructure

New Zealand has an abundance of resources with which to generate energy: coal fields, natural gas and oil deposits, geothermal activity, forests for biomass, and rivers for hydropower have all contributed to NZ's industry output. These resources are dispersed throughout the country and their relative concentrations have played a significant role in the energy and industry clusters in each region. New Zealand has several areas where industry has accumulated and been able to take advantage of either a supply of energy, or by filling an area of demand. An overview of the important regions follows.

2.3.1 Energy sources and infrastructure

South Island

Throughout the lower and middle of the South Island are many high-volume rivers which have been utilised for the generation of hydroelectricity. Over the past 50 years, these have helped form the backbone of the nation's electricity supply, averaging 57% over the past ten years. One of the largest hydro dams, on Lake Manapouri, is an exception, as it supplies most of its electricity to the aluminium smelter at Tiwai Point in Southland. The Manapouri dam generates around 13% of the nation's electricity and provides around 18 PJ of energy to the smelter each year (EECA, 2023b; MBIE, 2022b), the continued supply of which is subject to favourable electricity contracts. If this was to be discontinued it would lead to an abundance of electricity in the market and as a result far lower prices. Forecasting published by EECA (2022) indicated the prices could be 50% lower if the smelter were to close, though the likelihood of closure is debatable, as indicated by the central pricing scenario in their modelling which has been assumed to be a most likely case, that the supply of Tiwai Point will continue for the foreseeable future.

The South Island is also home to some of NZ’s large coal fields, with fields in Otago and Southland containing mostly lignite with some higher quality scattered in these regions. The West Coast has a long history of coal mining, extracting over 125 million tonnes since 1864, and consists mostly of higher quality bituminous coals, a large portion of which is exported as coking coal (NZ Petroleum and Minerals, n.d.). Coal is responsible for 94% of industrial heating emissions (EECA, 2022, 2023c, 2023d, 2023e, 2023f, 2023g), and for the majority of industries its abundance and low cost has made it by far the most economical method to produce heat.

Though the North Island contains 70% of the country’s plantation forestry, and a smaller land mass means that it contains almost three times the concentration of forested area as the South Island (MPI, 2023a). The South Island still has substantial forestry, as seen in Figure 2-5. The largest concentrations of forestry in the South Island are within Otago, the Tasman-Marlborough regions, and Southland. Canterbury does have forestry area to equal some of these regions, though due to its size the transport of these resources is more costly. There are several facilities taking advantage of the existing supply of low-grade wood in the South Island; two large MDF factories consume several hundred thousand tonnes of pulp wood and processor residue each year. They are also users of bioenergy as they combust part of these resources to provide heat for their manufacturing. Much of NZ’s forestry is exported, 62% in 2019 (MPI, n.d.), and the higher prices of export logs incentivise forest owners to prioritise silviculture techniques that maximise the quality of wood rather than the quantity of biomass. End use of harvested wood fluctuates each year, reflecting changes in global and local demand, trade agreements, exchange rates, logistical considerations, and consumer preference. Changes in these factors, as well as providing more certainty and demand for domestic biomass energy will give incentive for forestry owners to divert products away from export markets which would positively impact NZ’s ability to supply renewable process heat.

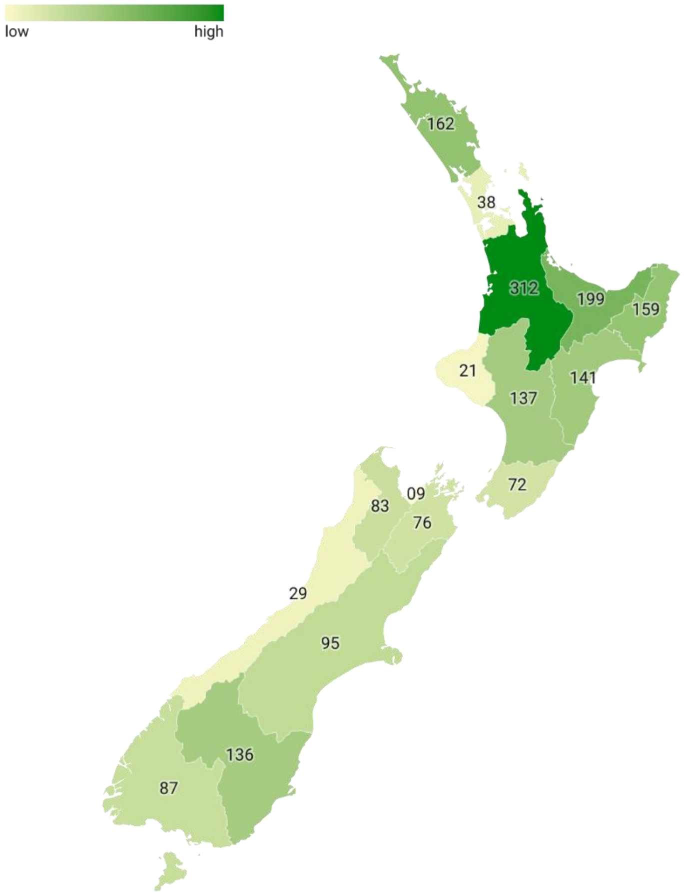


Figure 2-5: Area of forestry in NZ regions (‘000 ha) (MPI, 2023a).

North Island

The North Island mirrors some of the energy sources in the South, and it also contains substantial hydroelectric capacity and coal reserves, though some large differences are present, principally the use of natural gas, geothermal, and greater supply of forestry.

The largest difference between the two islands is the widespread availability of natural gas in the North Island, originating in the wells off the coast of Taranaki, from where it is distributed in high pressure pipelines throughout the North Island. Around 139 PJ of natural gas was used in NZ in 2022 (MBIE, 2023c), with around 51 PJ of this in the industrial sectors for process heating, and a further 31 PJ used as feedstock for chemical production (MBIE, 2022a). At 16% of the total primary energy supply in NZ, natural gas use is substantial, though its use has fallen from the average of the previous ten years (175 PJ (MBIE, 2023c)), largely due to restrictions on gas exploration (Beehive.govt.nz, 2018), and the phasing out of fossil fuels from industry (MBIE, n.d.-b). Natural gas is employed across the North Island in the key sectors of industry, electricity generation, commercial, and residential, where it has flourished due to its relatively high efficiency, small plant footprint as the pipeline eliminates the need for fuel storage, and quick response times. These factors make natural gas valuable as peaker plants that deal with fluctuating electricity demand (Contact Energy, n.d.). The largest power station in NZ, Huntly power station, houses a 400 MW combined cycle gas turbine and three 250 MW gas/coal units. Of these, one unit is typically held in long-term storage but can be activated during electricity shortages (Genesis Energy, n.d.).

Geothermal is a resource that is highly dependent on location, and is used at large scale in the Taupo Volcanic Zone in the central North Island, where it is responsible for 18% of the nation's electricity generation, (EECA, n.d.-c). Direct use of geothermal energy is also common in the area, used in industrial applications in the wood processing sector, as well as space heating for Rotorua hospital, and milk spray drying (MBIE, n.d.-d).

As stated above and displayed in Figure 2-5, the North Island is home to the majority of NZ's forested areas, in particular, Waikato, Bay of Plenty, and Hawkes Bay, and each of these regions also contains large processing facilities. The scale of forestry in these areas has already seen some large fossil fuels power industry plants convert to biomass. Notably, Fonterra's Te Awamutu, and Waitoa have shifted some or all their energy generation away from coal and into biomass. The Te Awamutu plant has made use of wood pellets, which because of their relatively high energy density, meant their existing heat plant could be used with minor modifications to fuel handling systems (EECA, n.d.-b). Fonterra's Waitoa plant chose a different route with their fuel switching to biomass, opting to construct a new boiler to supplement their utility system and begin phasing out coal. The new boiler is of the bubbling fluidised bed type and can take high moisture content fuels, meaning the Waitoa plant can utilise presumably lower cost hog fuels at 55% moisture content (Windsor Energy, 2023b).

Coal in the Noth Island is less plentiful than in the South, though the Waikato region currently extracts 850,000 tonnes each year and these coal seams are of reasonable quality at sub bituminous level (NZ Petroleum and Minerals, n.d.). The majority of this coal currently supplies the steel mill at Glenbrook, dairy plants in the Waikato, and the Huntly power station. Each of these facilities has plans to phase out coal usage (Beehive.govt.nz, 2023b; Fonterra, n.d.; Genesis Energy, 2023a).

2.3.2 Transport

Transport of energy sources into and throughout NZ depends on the type of energy and the specific locations involved. Despite its relatively small size, New Zealand has a diverse range of geography, with many of these features adding logistical and economical challenges to the distribution of energy between regions. The basic geographical outline of the country can be seen in Figure 2-5 on the previous page, and it is comprised of two relatively long and narrow islands with a body of water – the Cook Strait – in between them, which restricts transport options, as well as adding time and financial costs. In terms of transport options, energy sources can be separated into three main categories, electrical, liquid/gaseous transport, and solid fuels.

Electricity

Transfer of electricity between the two islands is enabled through the High Voltage Direct Current (HVDC) link, built in 1965 and extending from Benmore Dam in Southern Canterbury to Haywards junction near Wellington, connection of the two main islands provides greater electricity security for NZ. The HVDC line operates at 350 kV, with a capacity of up to 1050 MW (Electricity Authority, 2023a). New Zealand's electricity is transferred via the national grid, with a central backbone of high voltage alternating current lines running much of the length of NZ, connecting generation centres to areas of load, from industrial users through to residential properties. The national grid is managed by the state-owned enterprise Transpower, responsible for the substations, transmission lines, and transformers that transfer electricity from generators to distribution companies, and some larger industrial users. Transpower is also responsible for co-ordinating generation and ensuring that load and demand are balanced. Distribution companies then distribute electricity to customers and are in charge of maintaining the equipment for doing so (MBIE, n.d.-c). There are several components to the cost of electricity, shown below in Figure 2-6. These percentages are typical for most customers, though for large industrial users connected directly to the grid these may differ.

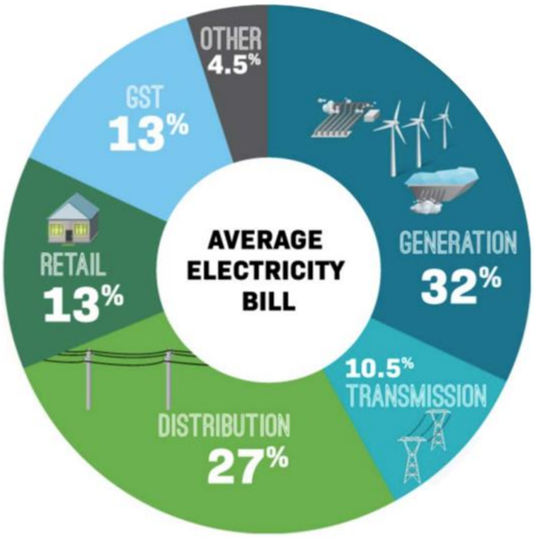


Figure 2-6: Components of a typical electricity cost (EECA, 2023e).

Natural gas

Natural gas is transmitted through a high pressure pipeline originating in Taranaki, and extending south to Wellington, east to Hastings and Gisborne, and north to the Waikato, Bay of Plenty, Auckland, and as far north as Whangārei (First Gas, n.d.). The gas is extracted from the wells and processed before being compressed and distributed across the island. The price of natural gas has increased in recent years, beginning in the June 2020 quarter; these increases may be linked to scarcity of supply as oil wells' production fluctuated, as well as the carbon unit prices which increased dramatically during that time (MBIE, 2023b). Liquified Petroleum Gas (LPG) is a fuel derived from natural gas used in New Zealand in places that do not have access to the natural gas pipeline but have processing needs that benefit from the use of a gaseous fuel. The fuel is compressed to increase its energy density and it can be transported either by rail, road or sea transport in several different sized containers depending on the mechanism of transport. There are some users of LPG in the South Island, in total only 4% of the total demand for process heat is met through LPG, though in Otago this is much higher, at 24% (EECA, 2022, 2023c, 2023d, 2023e, 2023f, 2023g).

Solid fuels

Solid fuel transport, which in NZ consists of coal, and biomass, can be achieved either via road, rail, or sea depending on the location and economics of the fuel market. Most of NZ’s high quality coal is exported overseas, as well as being used in applications outlined earlier in this work. Its high energy density and relatively lower cost has made it economical to transport over longer distances (MBIE, n.d.-a). Biomass typically has a lower energy density than coal, except for some highly processed fuels, and this restricts the distance over which transport of the fuel is economic. Fortunately, NZ has substantial forestry in many of its regions meaning that transport distances for the most part are not as significant as those observed in the intercontinental transfer of biomass into Europe and the UK (Jones et al., 2023). Transport of biomass in NZ consists of its removal from forest landings to a processing site, and distribution from this processing site to the user. The costs related to this transport fluctuate and are impacted by larger economic factors of oil prices, wage increases, and inflation, all of which have greatly increased the cost of biomass transport in recent years, with one industry expert stating that currently cost estimates older than a year are already outdated (Hall, 2023b). Factors involved with transport of biomass will be discussed in more detail in Chapter 3.

2.4 P-Graph

Process graph, or P-graph was developed by Friedler et al. (1992) to overcome problems associated with mathematical optimisation methods for process network synthesis that suffered as problem complexity grew because of the increasing computational requirements of mathematical methods. These challenges were overcome by utilising a graphical framework to restrict the search for the optimum network to structures that were feasible solutions to the problem. The framework provides the basis for P-Graph Studio (*P-Graph Studio*, 2022), the software tool that can be used to synthesise networks in a graphical editor. P-graph is a framework that uses a bipartite graphical structure consisting of operating units represented by horizontal bars, and circles for the process materials or energy. These are connected by directional arrows that represent flows from inputs through the operating units, to outputs, informed and guided by a set of theorems derived from five axioms that can be found in detail from Friedler et al. (1992). A key advantage of P-Graph is its ability to generate both optimal and near-optimal solutions to a system, which allows greater depth of analysis and the ability for the user to understand the impact of particular factors on the overall problem (Varga et al., 2010). The benefits to analysing the near optimal solutions can allow for secondary objectives to be achieved in the network, Vance et al. (2013) demonstrated this in their synthesis of sustainable supply chains for heat and power; with a 1.5% increase in cost compared to the business as usual scenario, the environmental impact could be reduced by 78%.

Since its inception over 30 years ago, the P-Graph framework has proven to be a flexible tool and has been applied to several different areas. Nagy et al. (2001) integrated P-Graph with methods for HEN synthesis, and Fan et al. (2020) showed greenhouse gas emissions could be reduced by implementing a circular economy approach in treatment of solid waste. Lam et al. (2010), used P-Graph to optimise regional energy supply using RES, and Ong et al. (2017) integrated Total Site methodology and P-Graph to optimise heat and mass flows. The multiperiodic functionality in P-Graph was used by Ji et al. (2023) to optimise renewable energy systems with hydrogen and battery storage. Multiperiod functionality of P-Graph can divide a year into hourly time slots and has applications for further work investigating the impact of seasonal electricity price variation on fuel switching decisions but is less pertinent for the biomass sector as its variations occur over a greater period. Development of a P-Graph tool that extended this functionality to cover resource and cost variation over multiple decades would be a useful tool for future investigations into biomass markets.

2.5 Summary

This chapter was written with two primary objectives: firstly, to critically examine the current literature and identify key gaps in information concerning the economics of fuel switching in NZ, and secondly; to establish the foundational knowledge necessary for building energy systems models and optimising resource allocation within NZ context. Initially this chapter defined decarbonisation and elucidated the tools and methods to decarbonise process heat. This exploration supported the decision to focus on fuel switching as the method of decarbonisation that is capable of the greatest reduction in carbon emissions. The two feasible fuel options of biomass and electricity were examined within the context of NZ’s energy system. Finally, this chapter culminates with the introduction of P-Graph as an effective method for modelling and optimising these energy systems; aiming to attain the best economic outcome of resource allocation.

The examination of literature yielded several gaps in the knowledge of fuel switching in NZ, leading to three key areas for further investigation:

1. The regional diversity of biomass availability and energy infrastructure.
2. The temperature profile of a region or site’s heat demand on the Levelised Cost of Energy
3. The economic feasibility of interregional transport of energy dense biomass.

These three foci shape the following chapters which deal with the sourcing of data, construction and optimisation of the models in several case study scenarios, and finally the analysis and discussion of the results.

Chapter 3 Methods and working

This chapter outlines the parameters with which the regional models were constructed. It sets the scene by providing a background on the data available for the NZ energy systems, before presenting the visual representation of these system generated using P-Graph Studio, which will be used as a framework to outline the data inputs required for each node of the model.

The previous chapter highlighted previous efforts to model the energy systems in New Zealand. A key theme present in these previous works was that a model is only as good as the data it is given. This chapter presents the most current data and research pertinent to the energy systems in NZ and outlines the P-Graph modelling and optimisation software.

3.1 An introduction to P-Graph

3.1.1 Model inputs

Process graph or P-Graph is a modelling technique used to design and analyse complex systems. It does this by creating a graphical representation of the system in P-Graph Studio (*P-Graph Studio*, 2022) and uses the combinatorial nature of the graphical connections to frame and constrain the problem.

Nodes and arcs

The graphical components operate in a bipartite methodology with two types of nodes; the first set of nodes represent materials. Materials represent what is flowing through the system; this can be actual materials, energy, money, and more. The other node represents operating units which transform the materials in some way; this can be a traditional operating unit such as energy transformation, or may be an arbitrary unit representing a unit conversion (Éles et al., 2021). These two nodes are connected by arcs which show the direction of material flow (*P-Graph*, n.d.). The different types of nodes used in P-Graph Studio are displayed below in Figure 3-1. The material nodes are differentiated by their position in the system which must begin at a raw material, and flow to a product material with at least one operating unit. Intermediates are not a requirement, though a model without these is not likely to be a complex system.

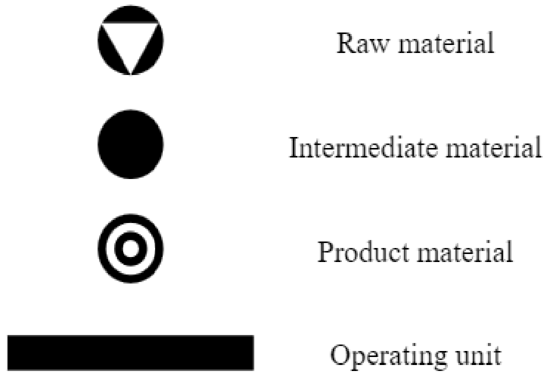


Figure 3-1: P-Graph node types.

Each of these nodes has input requirements to set up constraints within the P-Graph methodology that allow it to operate. For materials these are its type, e.g. volume, mass, energy, its unit of measurement, m^3, kg, GJ, or cost in the designated currency. From these, constraints on the flow can be applied to each node as the minimum or maximum annual resource flow.

The operating units also have inputs for both costs and flow. Cost functions cover both capital and operational expenditure though are limited to linear cost functions. Like the material nodes, the minimum and maximum flows of operating units can also be stipulated. Efficiencies can be applied to arcs on the outlet of an operating unit; this differs from other prominent process simulation software in which efficiencies are built into or calculated within operating units.

Simplified fuel switching example

An understanding of these basic principles behind the two nodes and how they interact is best conveyed with an example. The following example details a simplified version of a fuel switching decision in which the aim is to provide 100 TJ/y of steam to a plant at the lowest cost. The resources available to this plant are biomass and electricity, as outlined in Table 3-1 below.

Table 3-1: Resource parameters for basic P-Graph example.

Resource	Cost	Quantity
Low grade wood	50 $/t	10,000 t/y
High grade wood	150 $/t	10,000 t/y
Electricity	100 $/MWh	No limit

Additional inputs to this system are efficiencies of operating units, and the investment and operational costs associated with the operating units. For the investment costs it is also necessary to stipulate a payback period for the capital expenditure, in this work; 17 years was used to align with the value used in the RETA documents (EECA, 2022). Efficiencies for heat plants are outlined in Table 3-10, on page 46 and are applied as a ratio of the material leading into each operating unit to that at its outlet. Operating unit cost parameters are displayed below in Table 3-2. Calculation of investment costs on an annual throughput basis is detailed further in Section 3.2.1

Table 3-2: Cost parameters of operating units in fuel switching example.

Parameter type	Unit	Rate
Capital cost	Biomass boiler	33,333 $/TJ
Capital cost	Electrode boiler	16,500 $/TJ
Operating cost	Wood chipper	15 $/t

3.1.2 Model outputs

The maximal structure for this fuel switching example is displayed below in Figure 3-2. Material nodes and operating unit labels have been displayed for this simple example; larger examples have their label omitted as the number of nodes make labels difficult to read. Some general labels have been added to larger examples for clarification.

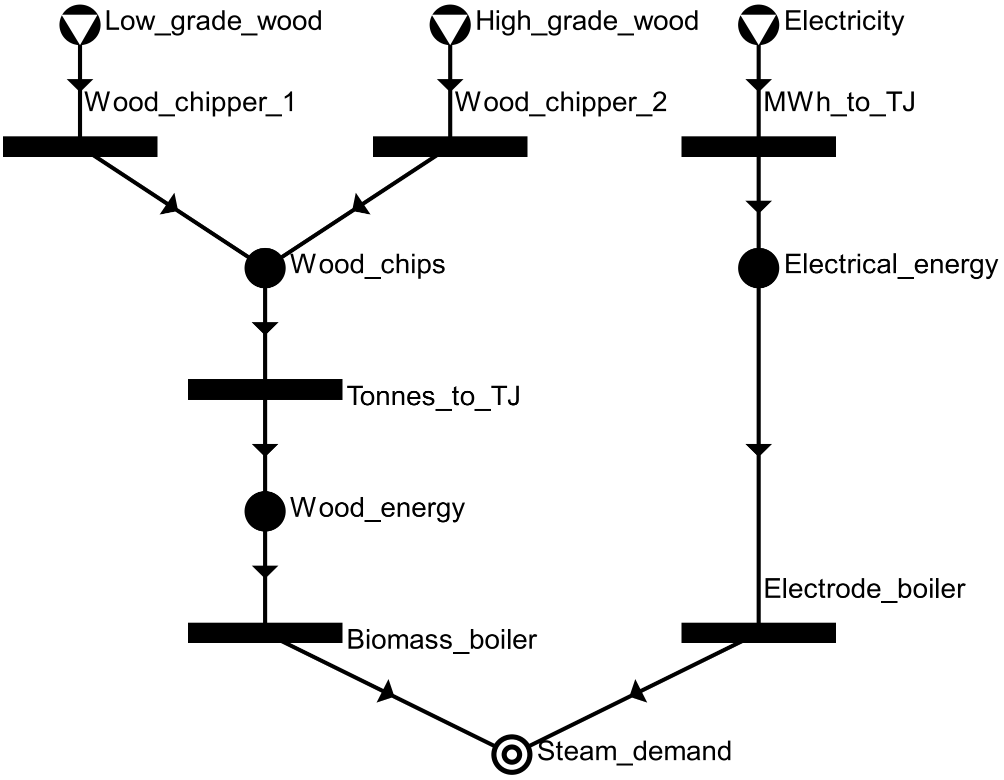
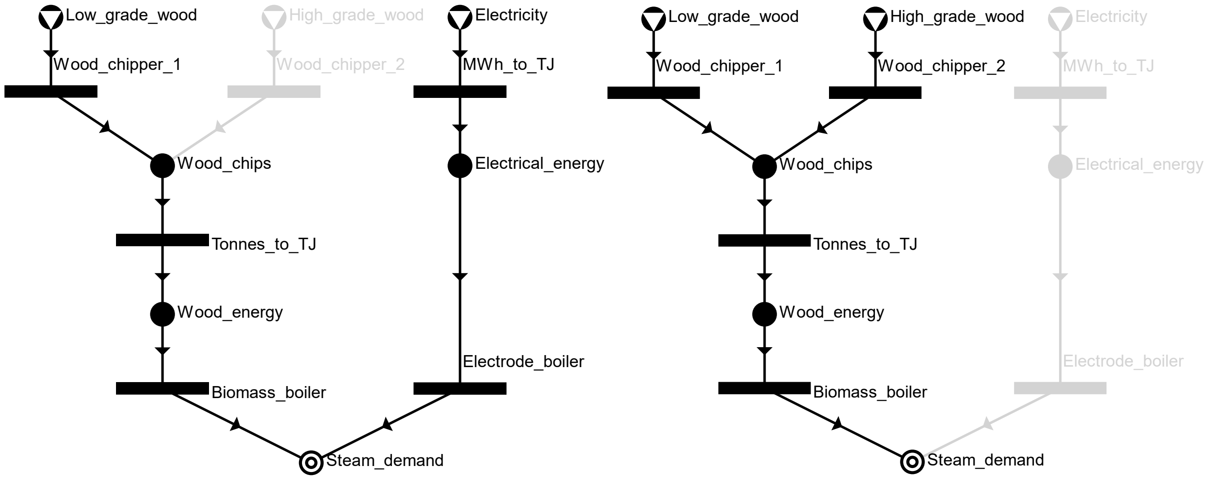


Figure 3-2: Basic P-Graph maximal structure example.

Beginning at the raw material inputs at the top of the diagram, the resources are transferred through a series of operating units, being transformed to different intermediate materials each time. The biomass side on the left for example is chipped and converted to an energy unit before being fed into the boiler where it becomes steam to meet the demand.

Optimal and near optimal structures

Once the algorithm has been run, the optimal and near optimal solutions can be analysed; these are the feasible structures. The number generated depends on the number of feasible solutions, or the solution limit, whichever is lower. The optimal solution for this system is displayed below in Figure 3-3 (a), with the closest near optimal solution (b). Pathways displayed in the structures in black are included in the solution, whilst those greyed out are not.



(a) (b)

Figure 3-3: Feasible solution 1 (a), and feasible solution 2 (b).

The above optimal structure in Figure 3-3 (a), shows that for this system it is most economical to use a combination of the low grade wood, and electricity to meet the steam demand. Analysing the list of feasible solutions indicates that for the alternative solution structures, there is not enough low grade wood to meet the entire steam demand, meaning that the more expensive resources of electricity and high grade wood are required. In the near optimal solutions it can be seen that a heat plant operating on biomass, or electricity alone is more expensive than a mixed fuel system, under these conditions.

Results

Outputs of the model are specified for each feasible solution, giving breakdowns of the cost components of each operating unit, the material input, and product output. As the systems modelled in this work are focused on meeting an energy demand which has no product value associated with it in these theoretical scenarios, the costs incurred for the system are the Levelised Cost of Energy (LCOE)[1] and are used as the minimum sell price of the energy for these systems. A full example of a detailed cost breakdown summary for the optimal solution in this example can be found in Appendix A in, Table

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[1] Levelised Cost of Energy refers to the price that energy must be sold for to break even with the costs incurred over its lifetime MBIE. (n.d.-e). *Interactive Levelised Cost of Electricity Comparison Tool*. Retrieved 02/02/2024 from https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-modelling/interactive-levelised-cost-of-electricity-comparison-tool/.

A-1, and Table A-2, A summary of costs for the three feasible solution structures in this example is presented below in Table 3-3.

Table 3-3: Costs for solution structures in the basic example.

Solution structure	Operating costs ($/y)	LCOE ($/GJ)
Solution 1	2,056,100	20.56
Solution 2	2,190,990	21.91
Solution 3	2,875,820	28.76

The above information shows that the optimal solution will provide energy at a LCOE of 20.56 $/GJ using a mixture of biomass and electricity, whereas the nearest optimal solution uses only biomass and because it needs to use a higher grade of wood, incurs higher costs. The third feasible solution uses only electricity and has much higher costs due to the higher cost of this energy source.

3.2 Outline of parameters in this work

Expanding on the previous section where the basics of P-Graph were outlined, this section will provide specific parameters and the methodology behind these that went into constructing the P-Graph economic models in this work. The regional model of North Canterbury’s process heat energy system will be used as an exemplar and visual guide to the materials and operating units required. The maximal structure for North Canterbury is displayed below in Figure 3-4. The collections of material nodes and operating units are highlighted in this figure: specific parameter inputs required for the models used in the case studies will be discussed in this section.

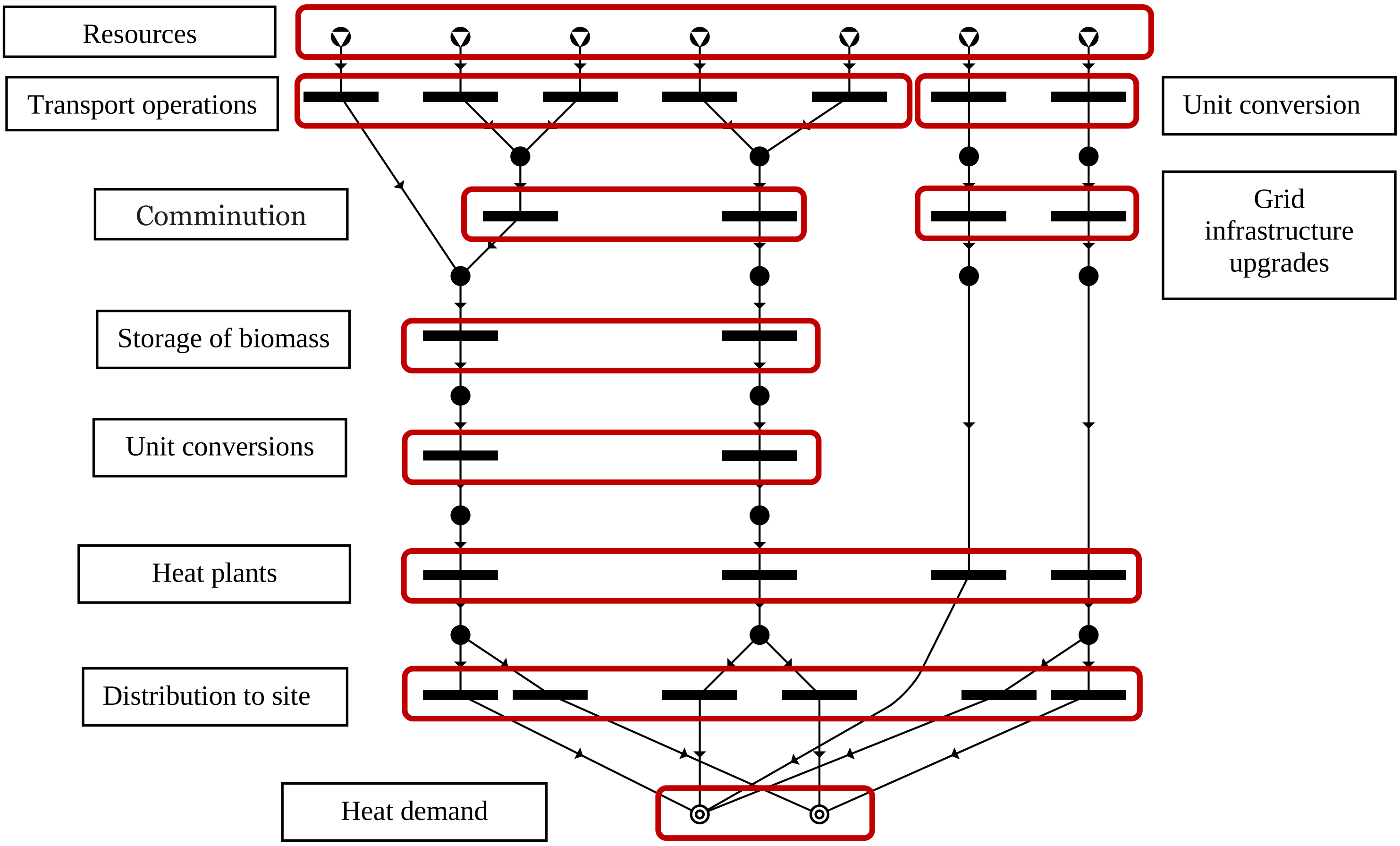

Figure 3-4: Example of maximal structure of a regional energy system modelled in P-Graph Studio.

3.2.1 Assumptions and factors involved in designing the models

The majority of the data and assumptions for these models and optimisation was sourced from the RETA reports by EECA (EECA, 2022, 2023c, 2023d, 2023e, 2023f, 2023g). Because these reports are based on a NZ context and are the most recently released information, they offer the most accurate basis for the model parameters. Where needed, additional values were used to either reinforce the RETA numbers, or to elaborate in areas that go beyond the focus of the released RETA reports. Costs are an evolving and in many cases a fluctuating feature of industry, with a range of factors influencing these from international timber markets, oil prices, hydro lake levels and electricity spot pricing through to government policy and carbon unit pricing.

Wood processing costs were calculated on a mass basis and heat plant capital expenditure on an energy basis to align with industry standards and available data. The energy density of biomass varies considerably due to moisture and wood composition. A generalised value was used matching that used by EECA for *P. radiata* of 7.815 GJ/t (EECA, 2022). This corresponds to a moisture content of 55% equivalent to a freshly harvested log.

3.2.2 Energy resources supply and costing

Costs

The cost of the source of energy generally has the largest impact on the overall process heat costs, as can be seen in the overall price summary graph below in Figure 3-5. For each of the regions in this study there is a variation in biomass feedstock cost due to its availability and difficulty of collection. The full cost breakdown and supply of each biomass type in this work can be found in Table A-3 in Appendix A. Indicative biomass pricing for North Canterbury is displayed below in Table 3-4.

Table 3-4: Biomass feedstock and collection costs for North Canterbury (EECA, 2023e).

Biomass Source	Cost of biomass source ($/t)	Harvest and collection ($/t)	Source plus harvest ($/t)
Processor residues	17.90	0.00	17.90
Roadside residues	10.00	23.00	33.30
Minor species	10.00	27.00	37.30
Cutover residues	10.00	40.00	49.90
Export KI/KIS	92.80	0.00	92.80
Export K	102.90	0.00	102.90
Export A	115.40	0.00	115.40
Pruned sawlogs	159.90	0.00	159.90

The above table demonstrates the diversity of pricing for resources, and also that harvest and collection impact the price of the resource considerably. In several regions - including North Canterbury - the collection and transport of cutover residues increases the resource price to almost as high as the lower grade export KIS logs. Higher grade export logs and pruned sawlogs were not included in the analysis but are displayed here for the purpose of comparison.

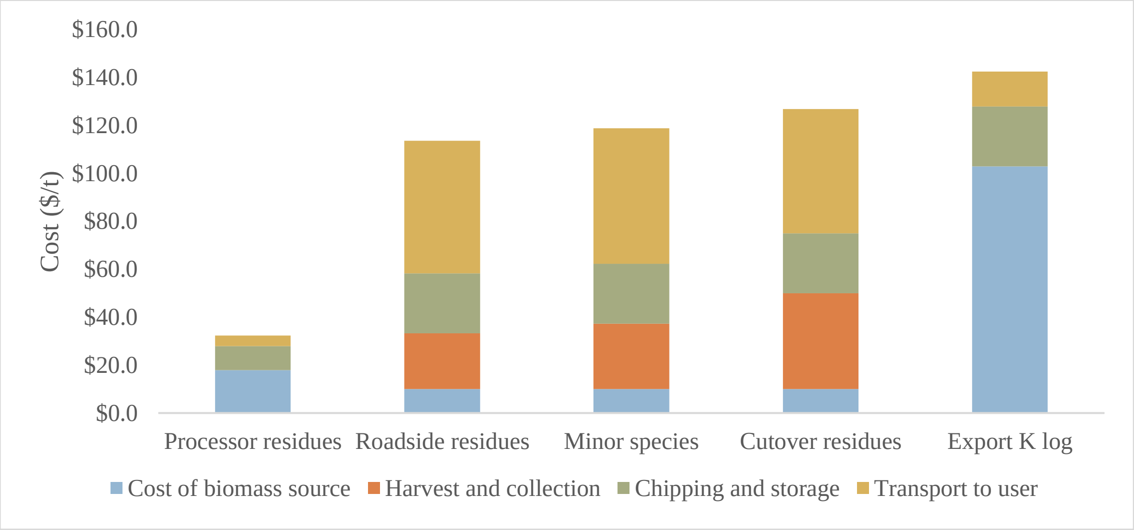

Figure 3-5: Cost breakdown of delivered biomass for North Canterbury in 2023 (EECA, 2023e).

Supply level

Outlines of the regional biomass availability were made available by EECA and, coupled with the reports detailing the incumbent demand, the resulting resource availability for the years 2023 through to 2037 was calculated and used to inform this research. The full outline of the resource availability can be found in Appendix A in Table A 3. The relatively lower supply estimates in the early 2030s are largely a result of the lower planting in the early 2000s period explained in the previous section. In North Canterbury, EECA estimates that the low supply of pulp logs will mean that the Daiken MDF plant will need to source low grade export logs to sustain their output, further squeezing biomass supply in this period. The resulting supply levels shown in Figure 3-6 begin at 179,000 t/y in 2023, dropping to under 100,000 t/y for the years 2029 – 2032 before rising steadily again to 157,600 t/y in 2037.

Figure 3-6: Biomass availability for North Canterbury 2023 - 2037 by type (EECA, 2023e).

Electricity

South Island electricity price forecasting was obtained from the RETA reports, displayed below in Figure 3-7. The forecast begins in 2026 where the central price scenario used for modelling shows a relatively steady increase. Assumptions included in the central pricing scenario are that Tiwai Point remains open for the foreseeable future, gas and coal prices are middle of the road at 85$/t, and government investment behaviour is neutral. More detail can be found in the RETA reports (EECA, 2023e). The electricity price used in this work for 2037 was $130/MWh, slightly higher than the exact number forecasted, but it was noted that the price will rise to this level in 2038 and is expected to continue rising steadily beyond this. As 2037 is the deadline for phasing out coal boilers, it is likely to lead to larger demand on the electrical network due to the potential of a number of new electric heat plants being commissioned. Electricity pricing in 2023 was set at $100/MWh based on the average spot price for the lower South Island over the past five years of $119/MWh (Electricity Authority, 2024), and assumes that an industrial user negotiating a supply agreement would likely be able to obtain a lower price. EECA notes that these electricity prices include only the generation and retail component of the customer price, they do not include network and transmission charges. Transmission and network charges can be a significant cost, as indicated by Figure 2-6 on page 33, and the inclusion of these costs should be considered for future research. Though EECA used different price forecasts for regions in the north and south of the South Island, the pricing for 2037-2040 in both central scenario prices was around \$130/MWh, and this value was used for all case studies set in 2037.

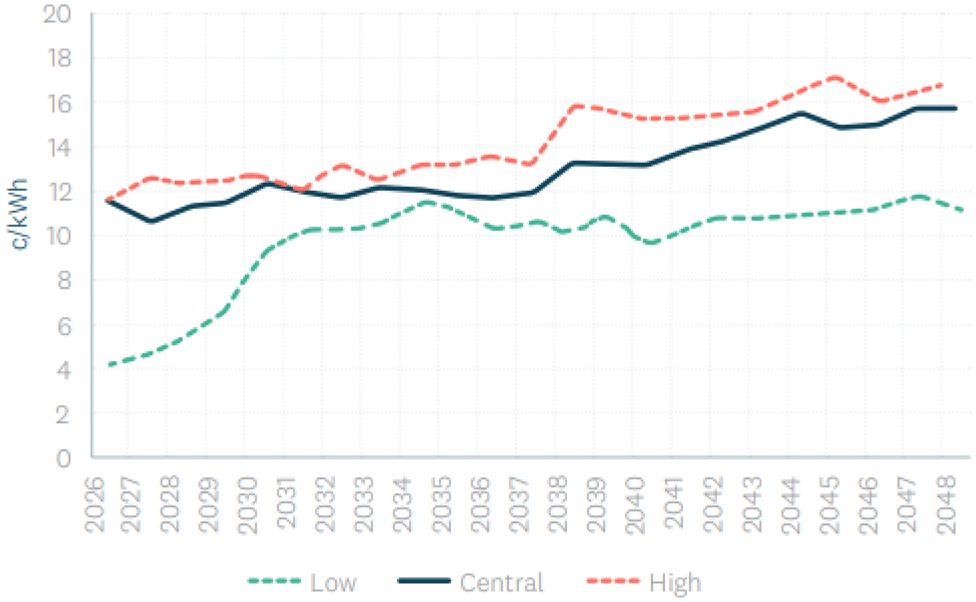

Figure 3-7: Electricity price forecast scenarios for North Canterbury (EECA, 2023e).

3.2.3 Processing

To convert a harvested log or residue into a fuel source this must be made into a form that suits the boilers being used in industry. As outlined in Section 2.2.1 above, there are different types of biomass fuels, depending on their level of processing. Processes include size reduction, drying, and pelletisation. These are displayed below in Table 3-5. Costs for heat treated pellets were not considered in this work.

Table 3-5: Process operation costs.

Process	Cost (\$/t)
Chipping/hogging	15 (EECA, 2023e)
Storage	10 (EECA, 2023e)
Pelletisation	139[2] (Gifford, 2013)

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[2] Pelletisation cost was adjusted for inflation using the Producer Price Index for Wood products Stats-NZ. (2023a). *Producer Price Index - NZSIOC Level 4: Wood Product Manufacturing*. https://infoshare.stats.govt.nz/Default.aspx

3.2.4 Transport

In earlier RETA reports i.e. Southland, and South Canterbury, the presented biomass costs used one average transport cost for all resources. In these two regions, to simulate the relationship between demand and transport cost, the transport cost was distributed across three operating units in P-Graph studio with costs set according to distances, and the operating bounds of each unit estimated based on the resource capacity in the region. An example of this for the Southland and South Canterbury regions is displayed below in Table 3-6. Distribution of biomass and its transport cost bracket was estimated based on what was viewed as a reasonable assumption, and an approximation in distribution observed in Hall and Palmer (2020). EECA uses a linear transport cost rate for road transport of biomass of \$0.30/tkm (EECA, 2022).

Table 3-6: Transport price brackets used for Southland and South Canterbury.

Transport distance	Low (30 km)	Medium (60 km)	High (120 km)
Rate (EECA, 2023c)	\$11/m^3	\$18/m^3	\$33/m^3
Proportion of total volume	25%	50%	25%

Because these models represent the energy system of a region, simplifications were necessary to accommodate the data available and timeframe of this work. In regions that pertained to the latter RETA reports (Otago, North Canterbury, the West Coast, and Nelson/Marlborough/Tasman) singular transport costs were used for each resource. As transport costs have increased significantly in recent years, impacted by diesel prices, wages, and inflation (Hall, 2023b), the individualised costs for each resource may have been used by EECA to account for this increase as well as potentially improving accuracy based on forest and wood processing facility locations. In reality, transport costs are highly specific to a plant’s proximity to forestry and wood processing facilities and the supply level of these industries. To obtain greater accuracy of costs and supply levels individual studies should be conducted for each site. As biomass demand grows, it will be sourced either from an increasing radius around the processing facility, or from more difficult or costly areas. These costs for North Canterbury are shown in Table 3-7.

Table 3-7: Transport costs for biomass feedstocks in North Canterbury (EECA, 2023e).

Biomass Source	Transport to user (\$/t)
Processor residues	4.40
Roadside residues	55.30
Minor species	56.50
Cutover residues	51.90
Export log	14.50

Some existing biomass users do not need to transport fuels because they are waste products from another area of the plant; other resources such as diverted export logs have their price reduced in EECA's latter reports as their purchase price includes transport (EECA, 2023e).

Interregional transport

Transport of biomass over long distances generally incurs high costs due to the low energy density of these fuels. Across larger distances and where logistics allow, rail transport can be an economical method to transport goods and was selected as the best candidate to test the economic potential of interregional transport of biomass. Rail journeys were assumed to operate along established railways between main hubs in each region, with a cost rate of \$0.122/tkm (2020 pricing) obtained from Sanderson and Robertson (2020), and updated for 2023 prices (0.156 \$/tkm) (Stats-NZ, 2023b). Relative distances were calculated using Google maps (Google, n.d.). An overview is detailed in Table 3-8.

Table 3-8: Rail transport costs between hubs.

Origin	Destination	Distance (km)	Cost ($/t)
Invercargill	Lyttleton	570	89.00
Invercargill	Timaru	402	72.70
Milton	Invercargill	150	23.40
Milton	Lyttleton	420	65.50
Milton	Timaru	252	49.30
Greymouth	Lyttleton	250	39.00
Greymouth	Timaru	370	67.70
Blenheim	Lyttleton	315	49.20
Blenheim	Timaru	480	84.90
Milton	Invercargill	150	23.40

3.2.5 Heat plants

Capital cost

The P-Graph models were constructed around an annual throughput basis, whereas typical capital costing functions are for MW of peak output of heat plants. The conventional peak output costing was approximated as an annual throughput cost based on a 6,000 hour per year operating schedule typical of a dairy plant with a capacity factor of 90% (Atkins, 2023). Because the P-Graph operational units base their costing on an input basis rather than conventional heat plant costing, the costing rates were adjusted to accommodate this. It is noted that the use of peak demand-based capital costs applied to values for annual throughput introduces inaccuracies and this will be discussed in Chapter 5. Capital costs for each heat plant are displayed in Table 3-9 below.

Table 3-9: Heat plant capital costs.

Heat plant	Value \$M/MW (Atkins, 2023)	Cost \$/TJ/year
BFB	2	58,333
Biomass boiler (chip/pellet)	1	33,33
HTHP	1	145,833
Electrode boiler	0.4	16,500

Efficiency

The efficiency of a boiler is dependent somewhat on its design, but largely on the quality of fuel it is burning. Moisture content and particle size variation are two factors that have a large impact on biomass boiler efficiency and are considered in this research. For biomass derived from pine wood, the energy content as related to its moisture content can be estimated using Equation 1 below. This aligns with the values used by EECA for their work and are repeated in this study. Heat plant efficiencies are displayed in Table 3-10 below. As forest residue is a lower grade resource with variable moisture, ash and energy content, it was deemed that it would likely become hog fuel and thus require a BFB boiler.

$$Energy\left(\frac{GJ}{t}\right) = 18.9 - 21.3 * (moisture\ content\ (\%))$$

Equation 1 (Visser, Hall, et al., 2010)

Table 3-10: Efficiency assumptions for Heat plant operating units.

Heat plant	Efficiency/COP
Heat pump	3.5 (COP) (Atkins, 2023)
Electrode boiler	99% (EECA, 2023c)
BFB boiler	70% (Windsor Energy, 2023b)
Chip fuel boiler	80% (EECA, 2023c)

Energy content of biomass was estimated using typical values from EECA (2022) for freshly harvested wood, for pellet fuel, energy values were taken from Bioenergy Association NZ (2022b). These are displayed below in Table 3-11.

Table 3-11: Energy content of biofuels.

Biomass	Energy value
Chip or hog fuel	7.18 GJ/t
White pellets	16.5 GJ/t

3.2.6 Electricity transmission infrastructure upgrades

As electricity will be a large part of NZ's transition to zero carbon by 2050, demand on the electrical grid will increase, driven by both electrification of industry as well as residential and commercial users. Large upgrades to both the electricity grid's generational and carrying capacity will be required. The costs for increasing generation were not included in this work; it has been assumed that this will have been accounted in the forecast in Figure 3-6 on page 44.

Infrastructure upgrade costs were included as an indicator of the additional costs that electrifying heat plants will incur beyond the factory gate. EECA (2023c) note that these upgrade costs do not include estimates of equipment within the plant such as new cables and switchboards, and so these costs are only estimates of what is required to get the electricity to the factory gate. Examples of cost estimates were provided as part of each RETA report for individual sites within each region. It is noted that the costs involved have large degrees of variation and the increase in capacity required does not always proportionally increase cost. As stated in Section 2.1.3, there is a lack of literature on the fuel switching economics that considers both capital and operational infrastructure, and that unless the electrical network was the focus of the paper, infrastructure upgrades were generally left out of economic evaluations of electrification. Regional averages of infrastructure costs was taken across all sites with costing data in the RETA reports. These values were converted to annualised throughput values using the conversions outlined in Section 3.2.5.. The costing rates are displayed below in Table 3-12.

Table 3-12: Electrical infrastructure upgrade costs (EECA, 2022, 2023c, 2023d, 2023e, 2023f, 2023g).

Region	$M/MW	$/TJ/year
Southland	0.56	25,696
Otago	0.34	15,956
South Canterbury	0.35	16,425
North Canterbury	0.75	34,795
West Coast	0.20	9,242
Nelson, Marlborough, Tasman	0.39	18,172

3.2.7 Demand

It was important to estimate the temperature requirements for process heat within the regions as this affects which heat plant was able to be used. Estimates were made for the process heat temperature distribution of each industry, and these are displayed in Table 3-13. These are estimates applied to the entire industry and do not account for variation of individual sites. For example, the same split is applied across the entire meat processing sector regardless of whether they conduct rendering at the site or not. This greatly affects the temperature of their heat requirements as one site will require steam whilst the other does not.

Table 3-13: Estimations of temperature profile distribution by industry (Atkins, 2023).

Industry sector	>100°C	<100°C
Dairy	60%	40%
Meat	50%	50%
Commercial	0%	100%
Industrial	30%	70%

Annual demand for process heat in each region was obtained from the RETA reports; an example of this for North Canterbury is displayed below in Table 3-14.

Table 3-14: Process heat demand in North Canterbury 2023 (EECA, 2023e).

Industry	Number of sites	Annual demand (TJ)	> 100°C (TJ)	< 100°C (TJ)
Dairy	5	2,588	1,553	1,035
Meat	6	104	52	52
Industrial	34	871	261	610
Commercial	35	702	0	702

Demand increases

Estimates of the process heat demand in 2037 were made by examining the historical growth trend of industrial energy use from the past 30 years (MBIE, 2023e) and forecasting this to 2037. This resulted in the increases presented below in Table 3-15.

Table 3-15: Process heat demand increases across regions in the South Island.

Region	> 100°C 2023 (TJ)	< 100°C 2023 (TJ)	> 100°C 2037 (TJ)	< 100°C 2037 (TJ)
Southland	2,742	2,209	3,016	2,429
Otago	137	568	151	624
Mid-South Canterbury	2,487	2,390	2,735	2,628
North Canterbury	1,702	2,188	1,872	2,406
West Coast	468	387	515	426
Nelson/Marlborough/Tasman (NMT)	326	513	358	564

Individual sites

Two industries were examined at the individual site level, a dairy plant operating spray dryers, and a Meat Processing Plant (MPP) with a rendering plant. The operating parameters used for these individual case studies are outlined below.

Dairy plant

The dairy site data was estimated using the paper from Walmsley et al. (2018) and recommendations from Atkins (2023), to simulate a plant typical of those found in NZ. The parameters are displayed below in Table 3-16. Temperature load distributions were determined by examining the Grand composite Curve in (Walmsley et al., 2018).

Table 3-16: Operating parameters for dairy spray drying plant.

Parameter	Value	
Number of dryers	2	
Dryer capacity	15	t_{powder}/h
Specific energy value	6.5	GJ/t_{powder}
Operating hours	5,500	h/y
Operating load	90	%
Total annual demand	965	TJ/y
>100℃ demand proportion	62.5	%
<100℃ demand proportion	37.5	%
>100℃ demand	603	TJ/y
< 100℃ demand	362	TJ/y

Meat processing plant

The meat processing facility data was obtained from (Klinac, 2023) and details a Meat Processing Plant (MPP) that processes sheep and beef and has a rendering plant that processes material from several sites in other regions. Data was extracted from a year’s energy demand and is displayed below in Table 3-17.

Table 3-17: Energy demand of MPP.

Temperature level	Annual demand (TJ)	Proportion of total
> 100℃	118	77%
< 100℃	36	23%
Total	154	100%

3.2.8 Short rotation forestry

Short Rotation Forestry (SRF) costs were developed to provide an estimate for what this resource could cost as a purpose grown energy forest product from newly established forestry land. These estimates were developed with assistance from Hall (2023a), and MPI and Nanayakkara (2023). The list of cost assumptions is displayed below in Table 3-18, resulting in a resource cost per tonne of $77.40.

Table 3-18: Short Rotation Forestry costing assumptions.

Parameter	Value	Source
Stocking rate	1,100 stems/ha	(MPI & SCION, 2023)
Tree cost	$0.50	(MPI & Nanayakkara, 2023)
Planting	$0.80	(MPI & SCION, 2023)
Land cost	7000 $/ha	(realestate.co.nz, n.d.)
Payback period	3 rotations	(Hall, 2023a)
Roading establishment	3,000 $/ha	(Hall, 2023a)
Landing establishment	400 $/ha	(Hall, 2023a)
Spraying	350 $/ha	(MPI & SCION, 2023)
Harvest	45 $/t	(Te Uru Rākau, 2022b).
Management	15%	(MPI & SCION, 2023).
Yield	133 t/ha	(EECA, 2022).
Planting area	30,000 ha	Planting area for a harvest of 2000 ha/y.
Planting area	60,000 ha	Planting area for a harvest of 4000 ha/y.

3.2.9 Inflation of costs

Costs of all resources in this work are expected to rise, both because of higher demand on these resources, as well as secondary costs such as wages and transport. Electricity price increases are based on the values in Figure 3-7 on page 44, with pricing for 2037 reflecting the likely increase seen in the years immediately following it. As the estimates of price increases are beyond the scope of this work and indicative only, the rate of increase for biomass feedstock, and other operational costs were aligned to increase linearly at the same rate as the overall increase in electricity price from 2023 to 2037. This rate was calculated to be approximately 1.9% per year using the exponential cost function (Equation 2), cost rates used for 2037 can be found in Table 3-19 below.

$$Final = Initial * (1 + rate)^{years} \qquad \text{Equation 2}$$

Table 3-19: Inflation of operational costs.

Operational unit	2023	2037
Storage ($/t)	10.00	13.00
Chipping/hogging ($/t)	15.00	19.50
Pelletisation ($/t)	138.90	180.80
Rail transport ($/tkm)	0.016	0.20
Road transport ($/tkm)	0.30	0.39

3.3 Summary

This chapter presented and outlined the substantial quantity of data that is required to effectively model an energy system. Data was obtained from the most current and accurate sources, with particular attention given to use information pertinent to the context of the NZ energy system. The data from this chapter goes on to inform the models constructed and presented in the following chapter.

Chapter 4 Case Studies

This section outlines the case studies that help to build an understanding of how supply and demand can influence the extent of biomass use in an energy system. All case studies use data from both 2023 and projected estimates of 2037 to investigate how the changes in supply levels will impact these energy systems. Southland and North Canterbury are presented as the regional case studies, followed by focusing on two individual sites to investigate how the temperature load profiles of different industries might impact their resource optimisation. Finally, the South Island is modelled and optimised with a focus on how interregional transport (IRT) of high energy density wood fuels might be able to smooth supply variation between regions.

4.1 Southland regional case study

Southland in the context of the RETA reports is the region extending from Milton in South Otago down to Bluff and across to the west coast of Fiordland (Figure 4-1) Southland is the first of two regional case studies in this work, and is presented in a similar manner to the structure of Section 3.1 and 3.2 The maximal structure is presented first, followed by the data inputs for operating units and material nodes for both the 2023 and 2037 operating parameters. The latter half of this section outlines the optimal structures and cost breakdowns for each year, followed by a brief discussion of the results. Comparisons of the case studies and greater analysis will be discussed in Chapter 5.

Figure 4-1: The Southland region.

4.1.1 System setup

Maximal structure

Figure 4-2 displays the simplified visual representation of Southland's process heating energy system known as the maximal structure. Like the example system of North Canterbury (Figure 3-4 on page 41), this system has a similar flow, though with some variations around the transport operating units. These variations are from both the different resources available, and the different methods that transport data was presented across the RETA reports. The impact of this will be discussed in the following chapter, though for this case study it is important to note that the transport costing was determined using assumptions intended to provide a more realistic insight into how transport of biomass works in actuality. The method of this is detailed in Section 3.2.4.

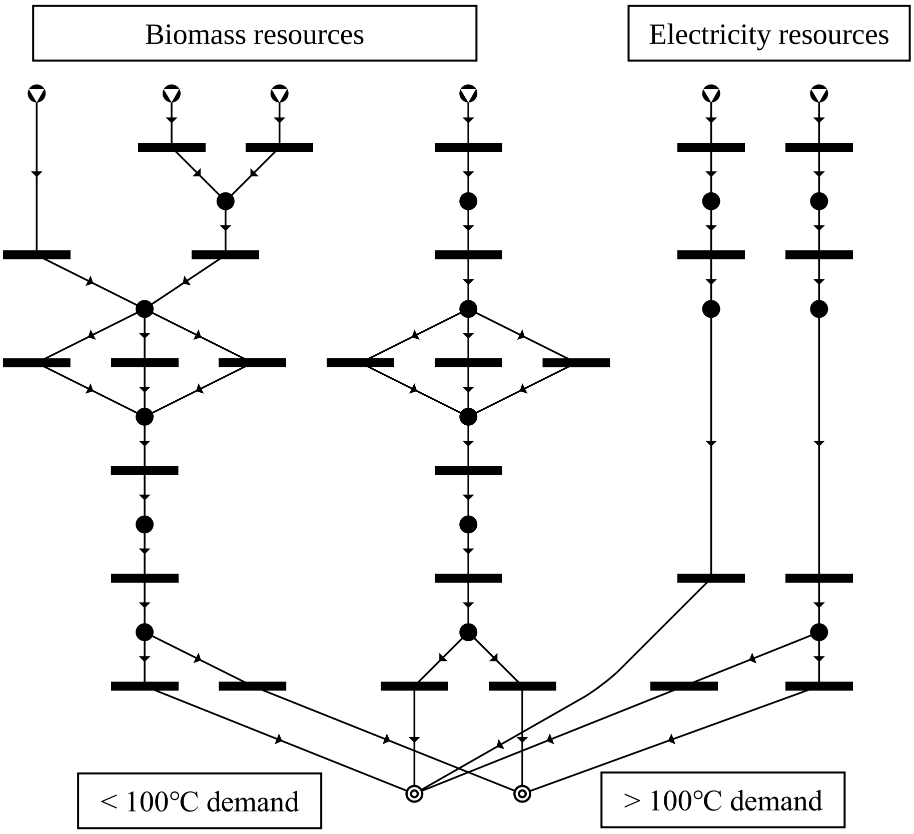

Figure 4-2: Maximal structure for Southland.

Resource cost breakdown

Southland has four different types of biomass feedstock available to it, based on the work conducted by EECA (2022). Table 4-1 details the resource availability for Southland in 2023 and 2037 after incumbent use has been accounted for. The projected cost of resources in 2037 was estimated based on the methodology outlined in Section 3.2.9. on page 51.

Table 4-1: Biomass resources for the Southland region.

Resource	2023 (t/y) (EECA, 2023a)	2023 ($/t) (EECA, 2022)	2037 (t/y) (EECA, 2023a)	2037 ($/t)
Wood processor residue	3,920	40	3,920	52.00
Chip log	50,000	62	50,000	80.70
Export log	250,000	110	250,000	139.20
Harvest residue	83,000	41	85,200	53.40

Operating units

The processing units considered in this system are wood chippers, hogging machines[3], and storage. These three operations have cost rates consistent with those outlined in Table 3-5 on page 44. All operating units have the same inputs as those outlined in Section 3.2; the electricity infrastructure upgrade cost is that stipulated for Southland in Table 3-12. The transport unit operations follow the methodology outlined in Section 3.2.4 for the regions of Southland and South Canterbury. The biomass availability and proximity scenarios for Southland are displayed below in Table 4-2. Low, medium, and high terms relate to the relative transport cost detailed in Table 3-6 on page 45. The wood chip resources are those derived from processor residues, chip logs, and export logs which are of reasonable quality to be chipped, whereas forest residue is more likely to be a lower quality fuel source and so is treated as hog fuel. This assumption was made early on in this work and carried through in much of the working for case studies. In the final stages of this work, it was realised this assumption may not be correct in all cases. The impact of assumptions will be discussed in Chapter 5.

Table 4-2: Resource proximity scenarios for Southland

	Availability 2023	Availability 2037
Wood chips	(t/y)	(t/y)
Low	75,980	75,980
Medium	151,960	151,960
High	75,980	75,980
Hog fuel		
Low	20,752	21,288
Medium	41,504	42,576
High	20,752	21,288

---

[3] Hogging machines are similar to wood chippers except they reduce particle size through blunt tool impacts, rather than the sharp tools of a wood chipper.

Demand breakdown

A total of 40 sites were included by EECA in the Southland RETA as producing significant heat demand, a summary of which is displayed below in Table 4-3. The demand distributions were calculated using the industry operating temperature profiles found in Table 3-13 on page 49. For more information on how EECA determined which sites to include in each region see (EECA, 2022, 2023c, 2023d, 2023e, 2023f, 2023g)

Table 4-3: Process heat demand for Southland 2023 (EECA, 2022).

Industry	Number of sites	Thermal Capacity (MW)	Annual demand (TJ)	>100°C demand (TJ)	<100°C Demand (TJ)
Dairy	5	205	4,205	2,523	1,682
Meat	7	68	922	461	461
Industrial	4	16	144	43	101
Commercial	24	46	194	0	194

Process heat demand for 2023 and 2037 was calculated using the methodology outlined in Section 3.2.7: the adjusted demand specific to each sector is not specified here or in the model as this does not affect the optimisation. The values shown (Table 4-4) are the result of the initial demand for Southland, less the value of reductions that will be made due to increase in efficiencies indicated by EECA (2022)

Table 4-4: Resulting process heat demand for Southland in 2023 and 2037.

Heat demand	2023 (TJ)	2037 (TJ)
<100°C	2,209	3,016
>100°C	2,742	2,429

4.1.2 Results

Optimal solution structure

Once these parameters are specified in the model, the P-Graph algorithm can be run to generate the optimal solution, as well as the designated number of near optimal solutions. The structure of the optimal solution is displayed below in Figure 4-3; the pathways that are a part of the optimal structure are highlighted in black, whilst those in grey are not part of the structure.

Here both the optimal solutions in the 2023, and 2037 models utilise the same pathways to meet the heat demand. As these structures are identical, they were not repeated. Note that electricity resources were separated into electricity for electrode boilers, and electricity for HTHPs in the P-Graph models only for the ease of data extraction and individual cost calculations.

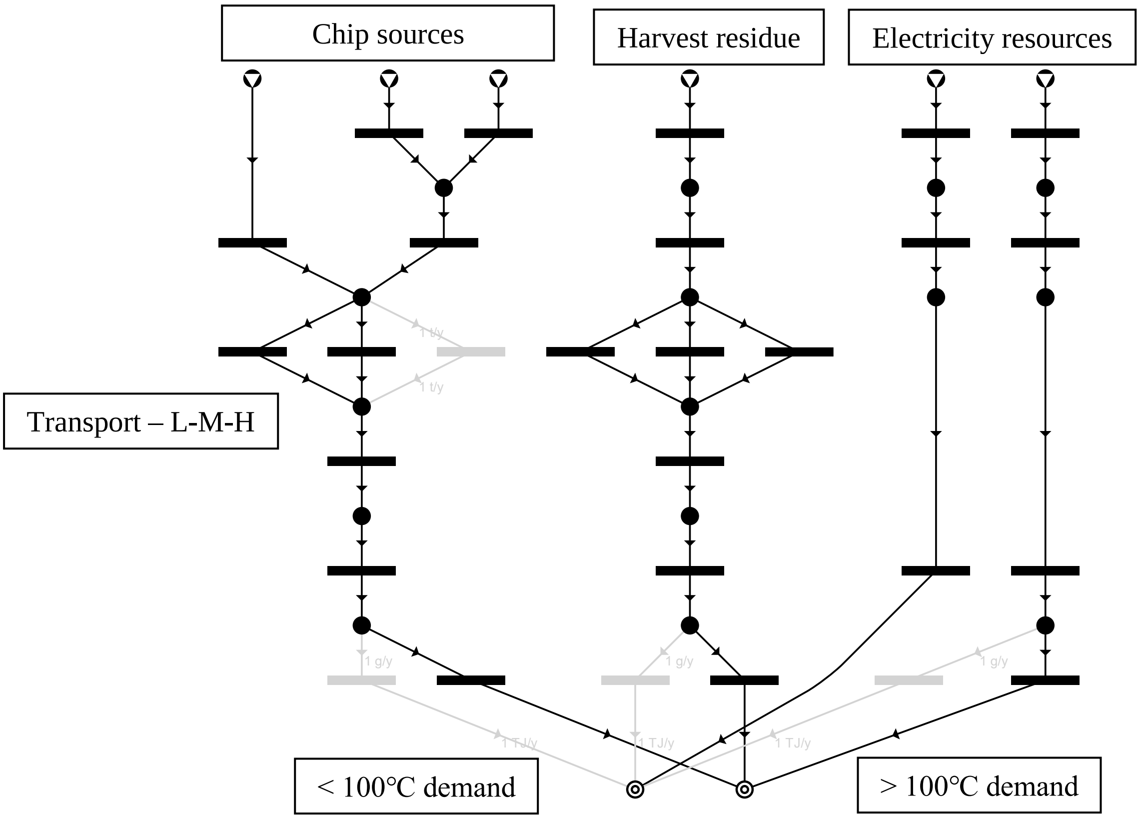

Figure 4-3: Optimal solution structure for Southland 2023, and in 2037.

Cost breakdown – Southland 2023

Figure 4-4 displays the optimal resource and energy flows for Southland in 2023. Note that for all cost breakdowns in this chapter, the energy values given for annual demand of resources are total demand and not the delivered energy.

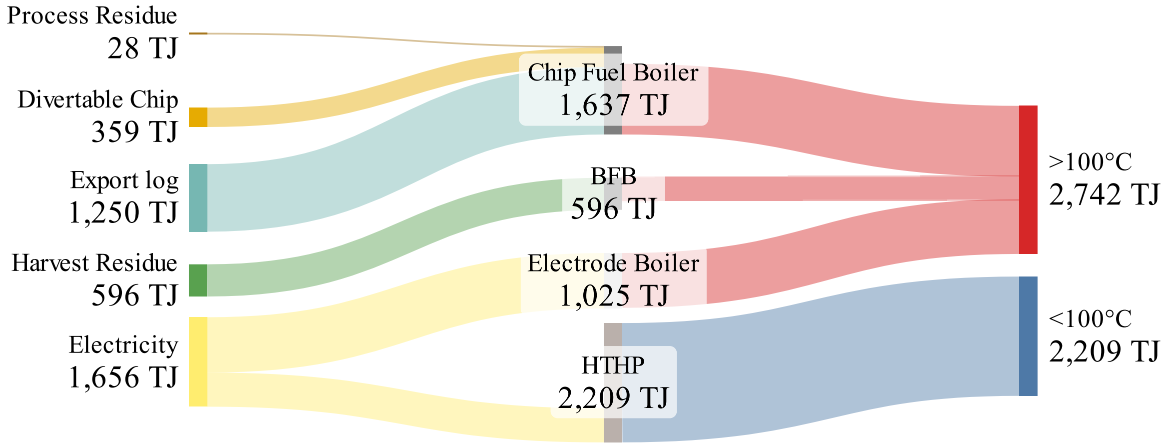

Figure 4-4: Optimal resource and energy flows in Southland 2023.

Table 4-5 below contains the energy cost breakdown of the optimal solution structure for Southland in 2023. A full breakdown of the material and operating costs for this case study is available in Appendix A in Table B 1, Table B 2, Table B 3, and Table B 4. Full breakdowns are provided for this first case study to give a through example of the output of P-Graph Studio, though are omitted for the remaining case studies. Note that for all cost breakdowns in this chapter, the energy values given for annual demand of resources are total demand and not the delivered energy.

Table 4-5: Resource supply and cost breakdown for Southland in 2023.

Individual energy costs	Annual demand	Transport distance	Delivered cost $/GJ	LCOE $/GJ
Processor residues	3,920 t (28 TJ)	Low	8.49	13.06
		Medium	9.46	14.28
Harvest residues	83,008 t (596 TJ)	Low	10.72	20.21
		Medium	11.69	21.60
		High	13.78	24.59
Chip log	50,000 t (359 TJ)	Low	13.64	19.50
		Medium	14.61	20.72
Export log	174,020 t (1250 TJ)	Low	20.32	27.33
		Medium	21.29	28.55
Electrode boiler	284,667 MWh (1025 TJ)	-	27.78	30.57
HTHP	175,317 MWh (631 TJ)	-	27.78	10.82

Cost breakdown – Southland 2037

Figure 4-5 presents the optimal resource flows for Southland in 2037, this shows the overall demand increase and shift in the ration of biomass and electricity towards electricity. This shift is both due to increased energy demand, and the lack of an increase in biomass supply.

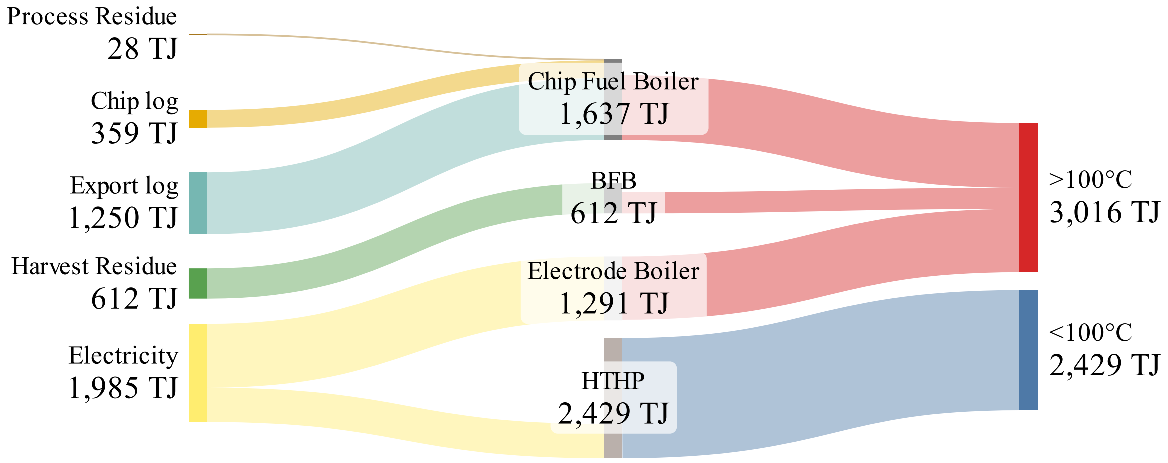

Figure 4-5: Optimal resource and energy flows in Southland 2037.

Table 4-6 presents the cost breakdown and resources required in the optimal solution structure.

Table 4-6: Resource supply and cost breakdown for Southland in 2037.

Individual energy costs	Annual demand	Transport distance	Delivered cost $/GJ	LCOE $/GJ
Processor residues	3,920 t (28 TJ)	Low	11.05	16.26
		Medium	12.32	17.85
Harvest residues	85,152 t (612 TJ)	Low	13.95	24.82
		Medium	15.21	26.63
		High	17.94	30.53
Chip log	50,000 t (359 TJ)	Low	17.76	24.65
		Medium	19.03	26.23
Export log	174,020 t (1250 TJ)	Low	25.92	34.84
		Medium	27.18	36.43
Electrode boiler	358,522 MWh (1291 TJ)	-	36.48	39.35
HTHP	192,778 MWh (694 TJ)	-	36.11	13.20

Near optimal structure analysis

As expected, heat below 100°C is far cheaper to produce due to the lower thermal requirements, but also because of the performance of HTHPs. The cost saving benefits of HTHPs are well highlighted by the full list of other feasible structures for both models, in which the top 176 structures all utilise the HTHP to provide the entirety of sub-100°C heat. The remaining several hundred structures that were calculated do not use HTHP, and consequently there is a cost jump of around 40%, as highlighted below in Figure 4-6.

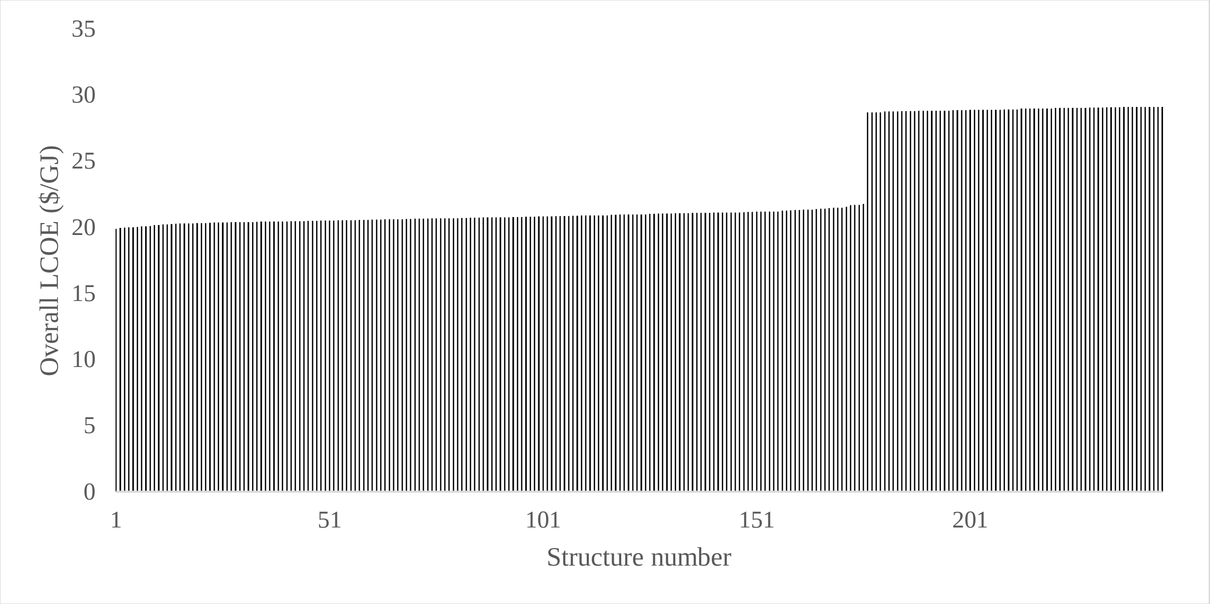

Figure 4-6: The first 250 feasible structures for Southland 2023.

The large jump from structure 176 at $104 million, to structure 177 at $143 million, highlights the importance of HTHP. There is not a great deal of difference in the final cost between the other solution structures. Of note is that solution 176 is the least cost all-electric structure with HTHP supplying all heat under 100°C, and electrode boilers supplying all heat above it. Structure 176, all electric, has a delivered LCOE of 20.98 $/GJ, an increase of 8% over the optimal structure.

4.1.3 Summary

Table 4-7 below presents the summary of costs for the optimal solution structures for Southland in both 2023, and 2037. This table shows that the LCOE for heat demand above 100°C increases substantially from 2023 to 2037, at a greater rate than the LCOE for heat demand below 100°C (increase of 28% compared to 22%). This is due to the higher proportion of electricity used for heat demand above 100°C in 2037 which is more expensive than the biomass alternatives, however the biomass supplies were exhausted by the increase in process heat demand.

Table 4-7: Summary of costs for Southland

Item	Cost 2023	Cost 2037
Total cost of materials	$71,278,630	$104,687,340
Total cost of operating units	$27,115,000	$32,504,702
Overall cost of solution	$98,393,630	$137,192,042
LCOE <100℃	10.82 $/GJ	13.20 $/GJ
LCOE >100℃	27.17 $/GJ	34.86 $/GJ
Overall LCOE	19.87 $/GJ	25.20 $/GJ

4.2 North Canterbury regional case study

4.2.1 System setup

North Canterbury extends from the Selwyn district north to Kaikoura (Figure 4-7), Christchurch is the major urban centre and the region encompasses an array of industries, businesses, schools, and medical facilities that need heating. For broader detail on the specific sites involved in this region see EECA (2023e). North Canterbury has a similar size of process heating requirements as Southland, though differing forestry resources, and the two provide an interesting comparison which will be discussed further in Chapter 5. Again, the data from 2023 is presented alongside estimated demand for 2037 to give insight into the energy flows during these periods.

Figure 4-7: Outline of the North Canterbury region (EECA, 2023e).

Maximal structure

The maximal structure for North Canterbury (Figure 4-8) follows a similar overall flow to that of the Southland system (Figure 4-2) as individualised transport costings for each biomass resource was available in the North Canterbury RETA. These individualised costing included discounts for export logs, as the purchase price for this resource typically includes transport to a centralised location

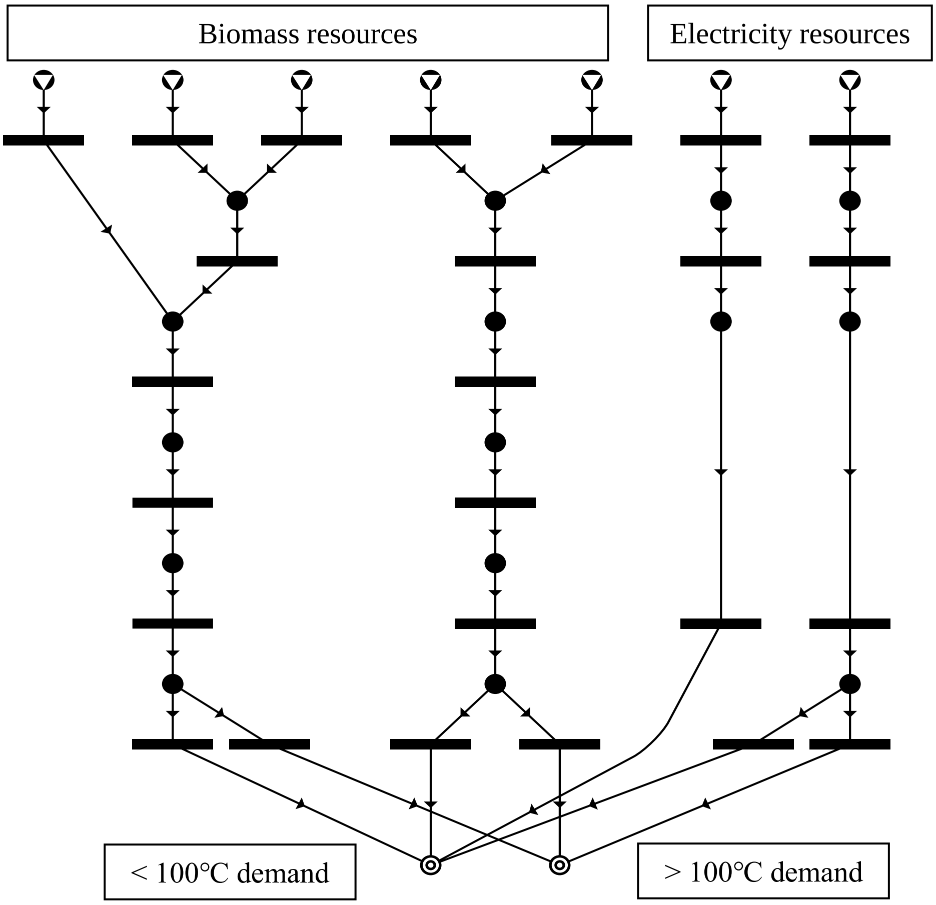

Figure 4-8: Maximal structure for North Canterbury.

Resource cost breakdown

Five different types of biomass feedstocks are expected to be available in North Canterbury (EECA, 2023e). These resulting available feedstocks, after accounting for incumbent use, are displayed below in Table 4-8. Resource costs for 2037 have been estimated using the methods outlined in Section 3.2.9.

Table 4-8: Biomass resource availability and cost in North Canterbury.

Resource	2023 (t/y) (EECA, 2023a)	2023 ($/t) (EECA, 2023e)	2037 (t/y) (EECA, 2023a)	2037 ($/t)
Wood processor residue	10,854	17.90	10,854	23.30
Roadside residue	47,289	33.30	17,306	43.30
Cutover residue	28,505	49.90	15,562	64.90
Minor species	12,635	37.30	73,990	48.60
Low grade export log	79,863	102.90	39,847	133.90

Notably in North Canterbury, the supply of both low grade export logs and residues is expected to be very low in 2037 due to the lack of forestry harvest around this time, EECA (2023e) note that in addition to low harvest levels, the Daiken MDF factory will likely compete for resources with biomass users, eating into the supply of low grade export logs.

Operating units

The processing units and their cost rates used in this system are consistent with those outlined in Table 3-5 on page 44; price increases follow the inflation estimates outlined in 3.2.9. These costs (Table 4-9) are much higher than those in the Southland RETA. At the transport cost assumed in the RETA documents of 0.30 $/tkm (EECA, 2023e), the transport distances are much higher in this region and thus incur higher costs.

Table 4-9: Process costs for operational units in North Canterbury.

Process	Cost 2023 ($/t) (EECA, 2023e)	Cost 2037 ($/t)
Chipping/hogging	15.00	19.50
Storage	10.00	13.00
Processor residues transport	4.40	5.70
Roadside residues transport	55.30	72.00
Minor species transport	56.50	73.50
Cutover residues transport	51.90	67.50
Export log transport	14.50	18.90

Demand breakdown

For a comparable energy demand, North Canterbury has twice as many sites as Southland, indicating a larger number of smaller industrial and commercial sites. The breakdown of industry sectors is displayed below in Table 4-10. Again, the demand distributions were calculated using the industry operating temperature profiles in Table 3-13 on page 49.

Table 4-10: Breakdown of heat demand in North Canterbury (EECA, 2023e).

Industry	Number of sites	Thermal Capacity (MW)	Annual demand (TJ)	>100°C demand (TJ)	<100°C Demand (TJ)
Dairy	5	149	2,588	1,553	1,035
Meat	6	20	104	52	52
Industrial	34	96	871	261	610
Commercial	35	92	702	0	702

Process heat demand for 2023 and 2037 was calculated using the methodology outlined in Section 3.2.7. The values shown in the table below are the result of the initial demand for North Canterbury, less the value of reductions that will be made due to increase in efficiencies indicated by EECA (2022, 2023e)

Table 4-11: Resulting process heat demand for North Canterbury in 2023 and 2037.

Heat demand	2023 (TJ)	2037 (TJ)
<100°C	2,188	2,406
>100°C	1,702	1,872

4.2.2 Results

Optimal solution structure

Both 2023, and 2037 have the same optimal structure (Figure 4-9), where all biomass resource pathways are utilised in addition to electrodes boilers to provide the over 100°C demand, and all heat demand below 100°C is provided by HTHP.

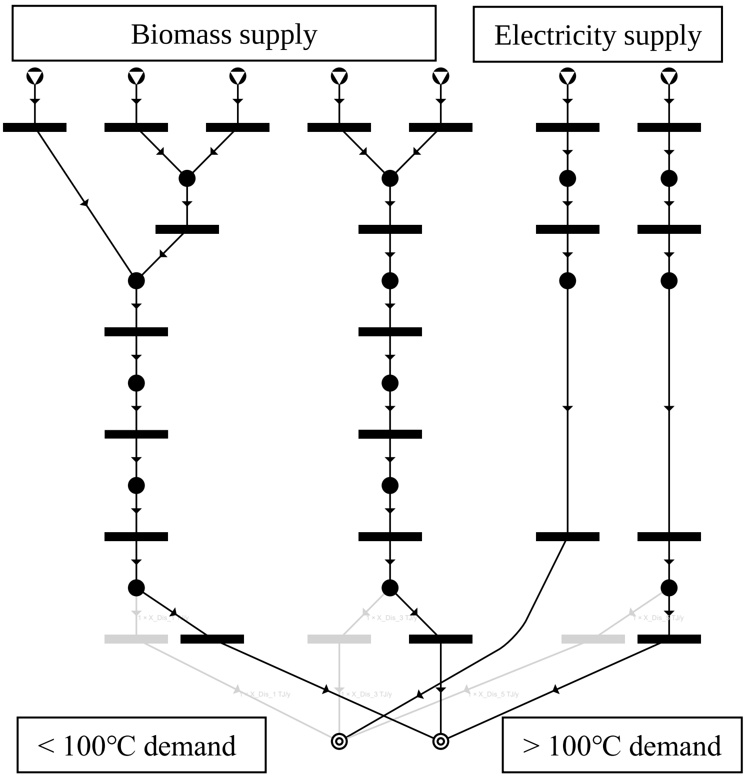

Figure 4-9: Optimal solution structure for North Canterbury in 2023 and 2037.

Cost breakdown – North Canterbury 2023

The cost breakdown for the individual components (Table 4-12) gives insight into the potential make up of the energy system in North Canterbury. All available biomass resources are used in this scenario to provide steam (>100°C heat) as these resources are at a lower cost than the electrical alternative, even if only by a small amount in the case of cutover residues. For low temperature heat (<100°C) HTHP remains the leading choice of heat plant with the processor residues the only biomass resource that could compete economically. Figure 4-10 shows the optimal resource and energy flows in North Canterbury for 2023.

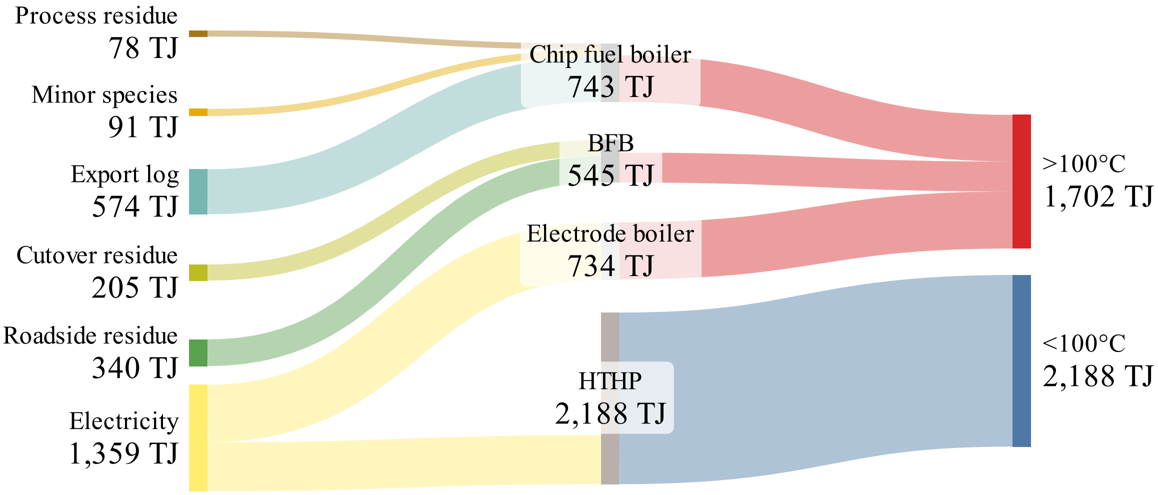

Figure 4-10: Optimal resource and energy flows in North Canterbury 2023.

Table 4-12: Resource supply and cost breakdown for North Canterbury in 2023.

Individual energy costs	Annual demand	Delivered cost $/GJ	LCOE $/GJ
Processor residues	10,854 t (78 TJ)	4.50	8.07
Roadside residues	47,289 t (340 TJ)	15.81	27.49
Cutover residues	28,505 t (205 TJ)	17.65	30.11
Minor species	12,635 t (91 TJ)	16.53	23.12
Export log	79,863 t (574 TJ)	19.82	27.22
Electricity (Electrode boiler)	203,946 MWh (734 TJ)	27.78	31.11
Electricity (HTHP)	173,651 MWh (625 TJ)	27.78	10.97

Cost breakdown – North Canterbury 2037

Naturally the costs increase again for the 2037 scenario. In North Canterbury the supply of biomass is overall lower, though the supply of minor species increases and provides a lower cost alternative to low grade export logs. Figure 4-11 shows the optimal flow of resources and energy in North Canterbury for 2037.

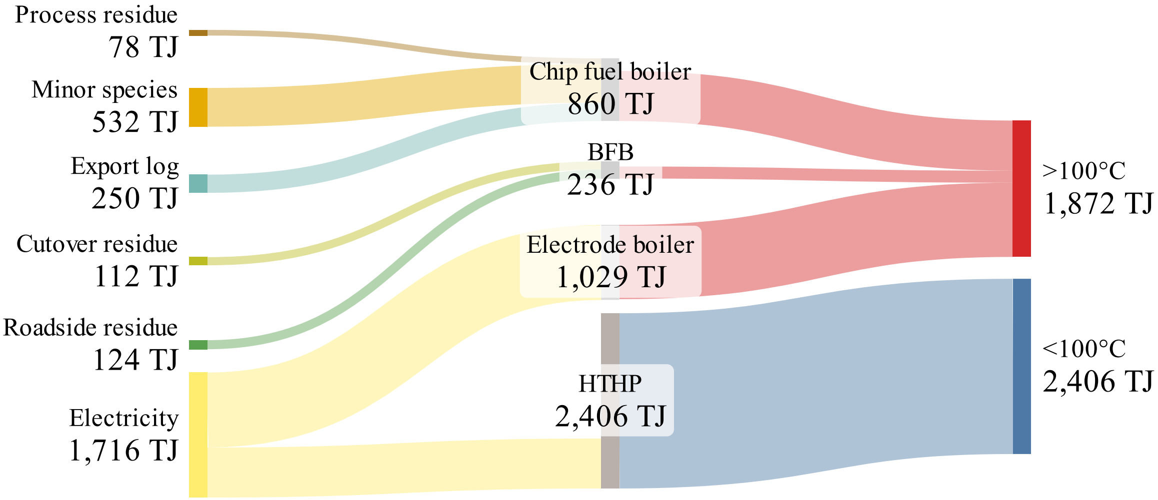

Figure 4-11: Optimal resource and energy flows for North Canterbury in 2037.

The breakdown of costs is provided in Table 4-13.

Table 4-13: Resource supply and cost breakdown for North Canterbury in 2037.

Individual energy costs	Annual demand	Delivered cost $/GJ	LCOE $/GJ
Processor residues	10,854 t (78 TJ)	5.85	9.76
Roadside residues	17,306 t (124 TJ)	20.57	34.29
Cutover residues	15,562 t (112 TJ)	20.86	34.71
Minor species	73,990 t (532 TJ)	21.52	29.35
Export log	34,847 t (250 TJ)	25.79	34.69
Electricity (Electrode boiler)	285,866 MWh (1029 TJ)	36.11	39.52
Electricity (HTHP)	190,952 MWh (687 TJ)	36.11	13.35

Near optimal structure analysis

Consistent with the trend observed in the Southland 2023 structures (Figure 4-6, page 60) there is a large jump in costs when HTHP is removed from the system. Shown below in Figure 4-12 this jump in costs occurs between structure 36 with an annual cost of 19.68 $/GJ, and structure 37 at 29.87 $/GJ.

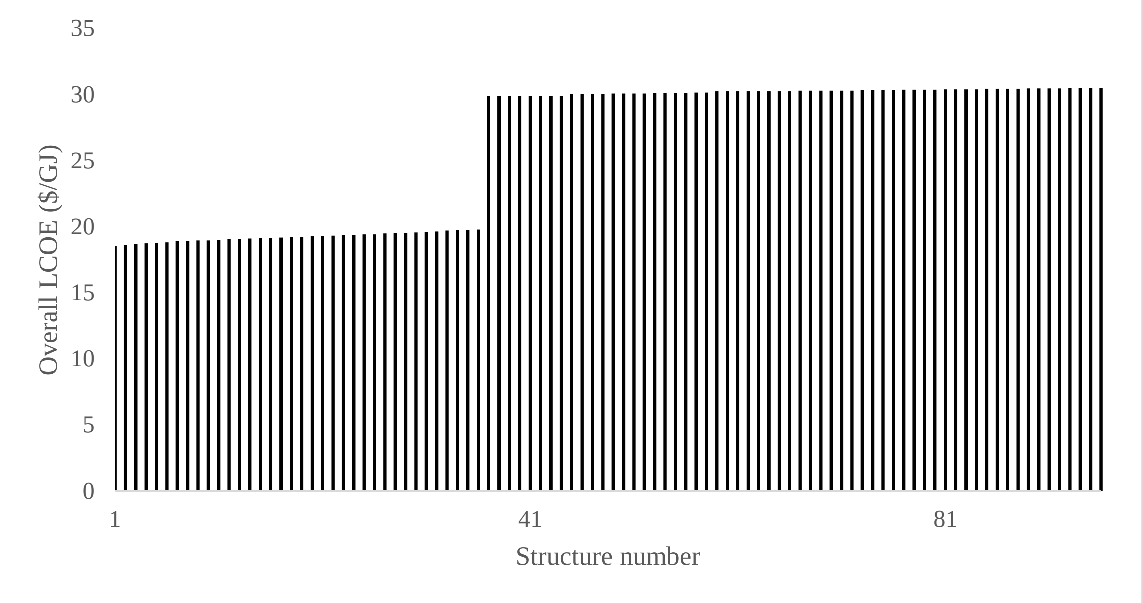

Figure 4-12: The first 100 feasible structures for North Canterbury 2023.

4.2.3 Summary

Table 4-14 below contains an overall summary of the costs within the optimal solution structures for North Canterbury in 2023, and 2037.

Table 4-14: Summary of costs for North Canterbury

Item	Cost 2023	Cost 2037
Total cost of materials	$49,640,292	$72,260,438
Total cost of operating units	$22,511,796	$26,107,178
Overall cost of solution	$72,152,088	$98,367,616
LCOE <100°C	10.97 $/GJ	13.35 $/GJ
LCOE >100°C	28.29 $/GJ	35.38 $/GJ
Overall LCOE	18.55 $/GJ	22.99 $/GJ

Material costs and the increase in demand drive much of the overall cost increase, and both temperature range energy costs exhibit a 30% increase in costs, reflecting the estimated increase presented in EECA (2023e) that also informed the biomass price estimates.

4.3 Dairy plant case study

As dairy is one of the most important industries within New Zealand, it was important to understand how the different regions and demand profiles would affect fuel switching economics. In this section, an overview is given of the plant setup and how the demand was generated. The demand profiles are then applied to the Southland and North Canterbury 2023 regional heat demand systems and the results presented in the second half of this section.

4.3.1 System setup

The two individual site case studies presented in this section utilise much of the same setup as the regional case studies presented earlier in this chapter, the demand data and profiles are adjusted to reflect individual sites. The maximal structure for Southland can be found in Figure 4-2 on page 54, and North Canterbury in Figure 4-8 on page 62, resource supply and costs can be found for Southland in Table 4-1 on 55, and for North Canterbury in Table 4-8 on page 63. Transport parameters for biomass resources in Southland are presented in Table 4-2 on page 55, and in Table 4-9 on page 63 for North Canterbury.

Dairy plant demand and setup

As stated in Section 3.2.7, the site data for the dairy plant was estimated using data from Walmsley et al. (2018) and recommendations from Atkins (2023). The final energy demand and temperature profile is displayed below in Table 4-15**.**

Table 4-15 : Energy demand and temperature levels for the dairy plant.

Temperature level	Annual demand (TJ/y)
<100°C	362
>100°C	603

4.3.2 Southland

Optimal solution structure

Figure 4-13 is the optimal system structure to supply the dairy plant in Southland; the lower cost biomass resources are used to supply heat above 100°C, and electricity powers HTHP for demand below 100°C.

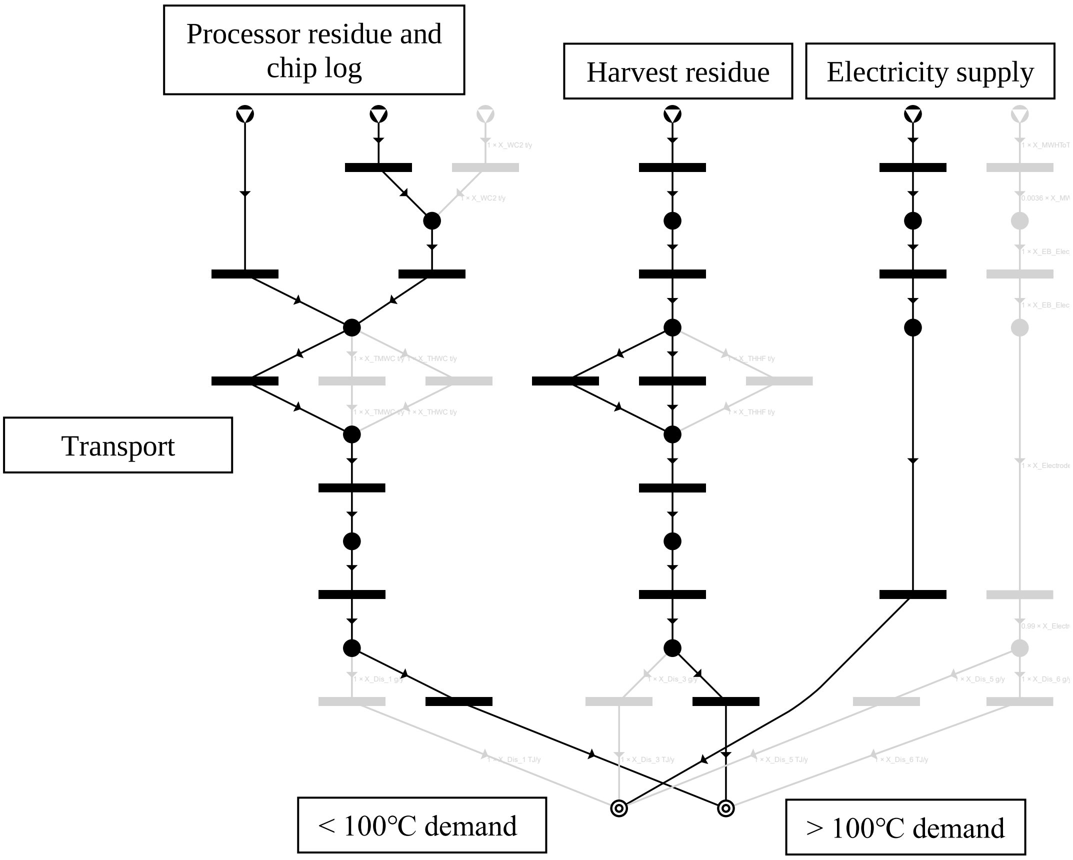

Figure 4-13: Optimal structure of the Dairy plant case study in Southland 2023.

Cost breakdown – Dairy plant in Southland

The cost breakdown for the individual components in Table 4-16 below shows the resources required to supply the dairy plant in Southland. As the total demand is smaller than for the Southland regional case, only the lowest cost resources are required and thus will give a lower LCOE for above 100°C heat. Below 100°C heat prices are unaffected as the same resource and heat plant is used (electricity and HTHP), and the size of the demand does not affect the electricity pricing.

Table 4-16: Resource supply and cost breakdown for the dairy plant in Southland.

Individual energy costs	Annual demand	Transport distance	Delivered cost $/GJ	LCOE $/GJ
Processor residues	3,920 t (28 TJ)	Low	8.49	13.06
Harvest residues	58,287 t (419 TJ)	Low	10.72	20.21
		Medium	11.69	21.60
Chip log	50,000 t (359 TJ)	Low	13.64	19.50
HTHP	28,730 MWh (103 TJ)	-	27.78	10.82

Figure 4-14 shows the optimal flow of resources in Southland to supply the dairy plant with heating. Despite the optimal solution determining that both a BFB, and a chip fuel boiler would be required on a single site, it is uncertain whether the operators of a single site would want to add complexity to fuel handling, increasing storage requirements and potential capital and maintenance costs that may arise. There would have to be significantly better economics to enable this to occur.

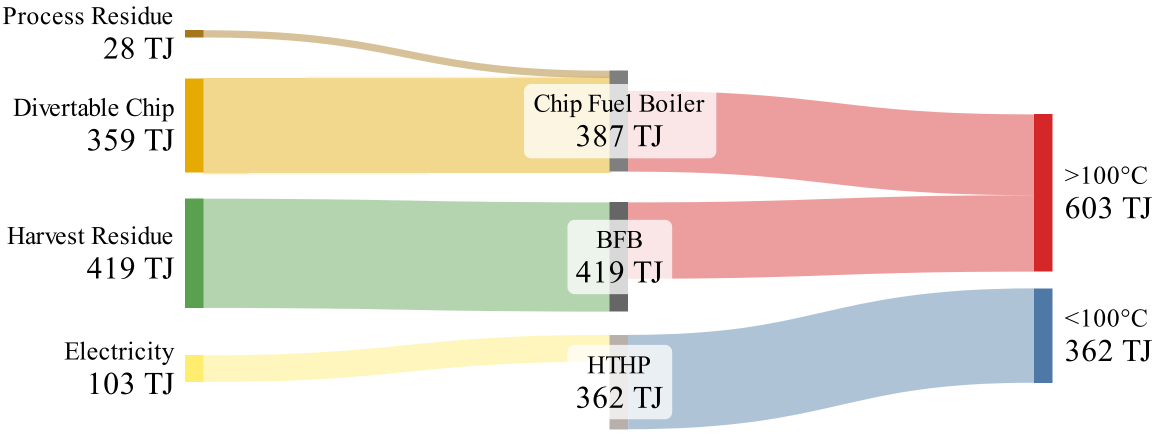

Figure 4-14: Optimal resource and energy flow in Southland for the dairy plant case study.

Near optimal structure analysis

Figure 4-15 shows the first 200 optimal structures for the dairy plant case study in Southland, notably the lowest cost all-biomass solution is solution number 157 at 22.50 $/GJ, the lowest cost all-electric is solution number 189 at 23.16 $/GJ.

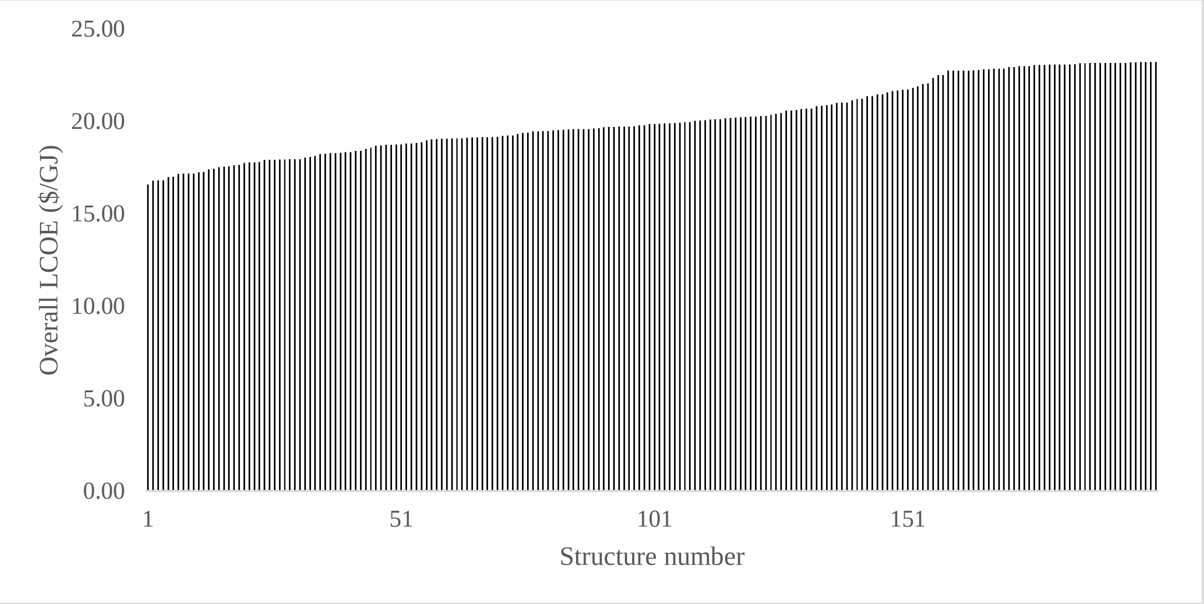

Figure 4-15: The first 200 optimal structures for the dairy plant case in Southland.

4.3.3 North Canterbury

Optimal structure

The optimal structure for the dairy plant in North Canterbury is displayed below in Figure 4-16. The HTHP supplies all heat demand below 100°C, and biomass supplies the above 100°C demand.

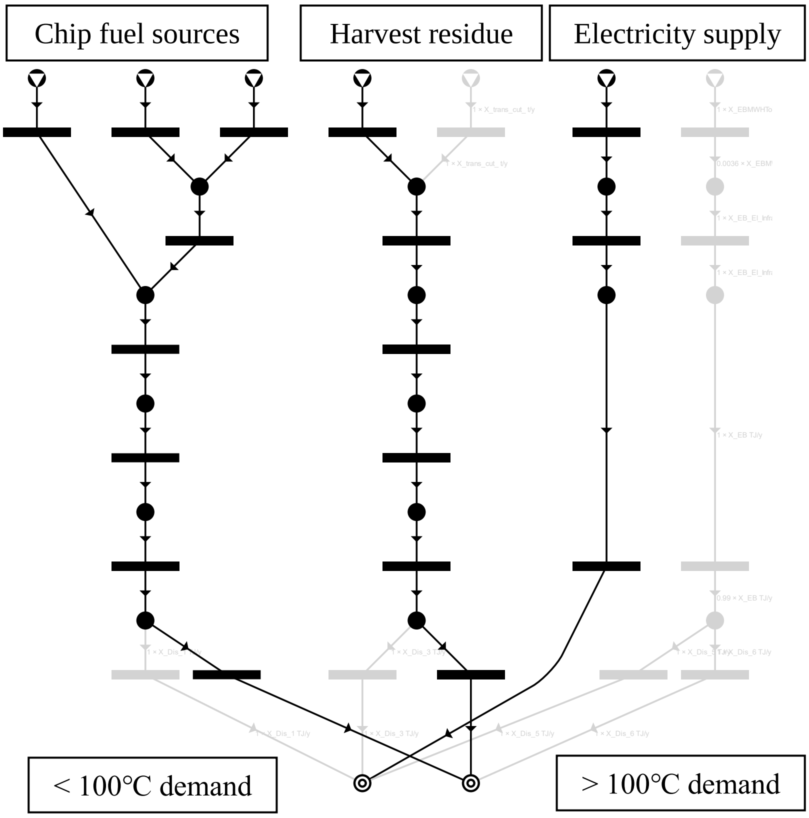

Figure 4-16: Optimal structure for dairy plant case in North Canterbury.

Cost breakdown – Dairy plant in North Canterbury

The breakdown of costs provided in Table 4-17 below shows the resources required to operate the dairy plant in North Canterbury. Notably this dairy plant consumes a significant portion of the biomass resources in the region (59% on a mass basis), and as the lowest cost of these biomass resources are not residues, shows that recovery of residues in North Canterbury may be economically challenging.

Table 4-17: Cost breakdown by resource for dairy plant in North Canterbury.

Individual energy costs	Annual demand	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	10,854 t (78 TJ)	4.50	8.07
Roadside residues	1,793 t (13 TJ)	15.81	27.49
Minor species	12,635 t (91 TJ)	16.53	23.12
Export log	79,863 t (574 TJ)	19.82	27.22
Electricity (HTHP)	28,730 MWh (103 TJ)	27.78	10.97

Figure 4-17 shows the optimal flow of resources and energy in North Canterbury to provide energy for the dairy plant. Whilst this is the optimal flow of resources as dictated by the P-Graph optimisation, in reality the use of both a chip fuel boiler, and a BFB boiler is not likely at a single site especially for such a small quantity of residues.

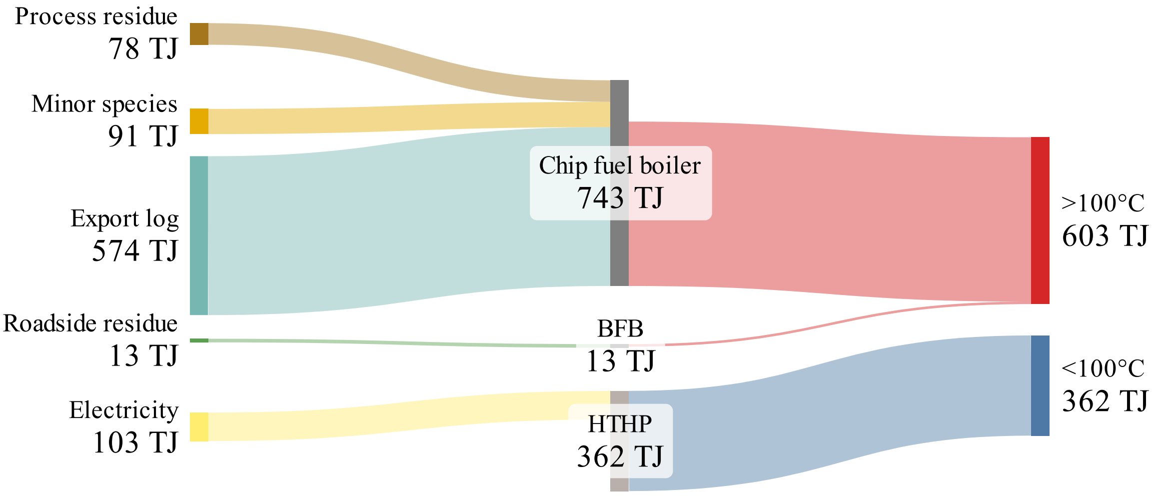

Figure 4-17: Optimal resource and energy flow in North Canterbury for the dairy plant case study.

Near optimal structure analysis

Figure 4-18 shows the top 200 optimal structures for the dairy plant in North Canterbury. The notable jump in LCOE from structure 32 at 23.55 $/GJ, which is supplied entirely by electricity, to structure 33 which is an entirely biomass solution structure at 26.14 $/GJ shows the relatively larger cost of supplying biomass in North Canterbury.

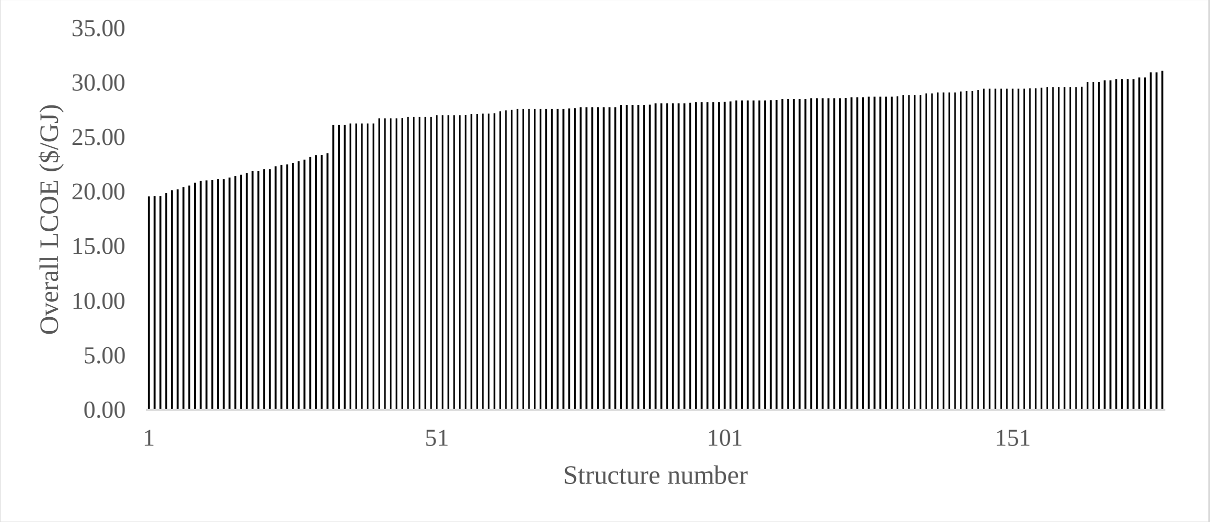

Figure 4-18: The first 200 optimal solution structures for the dairy case in North Canterbury.

4.3.4 Summary

Table 4-18 below contains an overall summary of the costs for optimal solution structures of the dairy plant case study.

Table 4-18: Summary of costs for the dairy plant case study.

Item	Southland	North Canterbury
Total cost of materials	$8,519,570	$11,816,191
Total cost of operating units	$7,483,296	$7,083,563
Overall cost of solution	$16,002,866	$18,899,754
LCOE <100°C	10.82 $/GJ	10.97 $/GJ
LCOE >100°C	20.04 $/GJ	24.76 $/GJ
Overall LCOE	16.58 $/GJ	19.59 $/GJ

From the table above it can be seen that the higher biomass resource costs drive higher energy prices in North Canterbury, though the operating cost is slightly lower, which may be the higher proportion of Southland’s biomass resources that are derived from residues which are only combusted in the higher capital cost BFB boiler. The annualised cost of solid fuel heat plants in Southland (BFB, and wood chip boilers) totals $2.2 million, as opposed to $1.5 million in North Canterbury. Over 95% of the projected solid fuel boilers in this case study for North Canterbury are chip fuel boilers which tend to have half the capital investment of BFB boilers (Table 3-9, page 47).

4.4 Meat processing plant case study

4.4.1 System setup

The meat processing plant (MPP) case study presented in this section has the same set up as the dairy plant individual case study, in this section the demand data and profiles are adjusted to reflect an individual MPP and to examine how the location of this in either Southland or North Canterbury affects the energy prices and resource usage. The maximal structure for Southland can be found in Figure 4-2 on page 54, and North Canterbury in Figure 4-8 on page 62, resource supply and costs can be found for Southland in Table 4-1 on page 55, and for North Canterbury in Table 4-8 on page 63. Transport parameters for biomass resources in Southland are found shown in Table 4-2 on page 55, and in Table 4-9 on page 63 for North Canterbury.

Meat processing plant energy demand and temperature profiles

Data for this case study was obtained from Klinac (2023), this data contained a year of operating data for a site located in the South Island of New Zealand. This site has several processing lines including beef, lambs, fellmongery, casings, and a rendering plant; of these lines, the rendering plant is the only one that requires heat over 100°C. A brief summary of the heat demand, and temperature distribution is presented in Table 4-19 below.

Table 4-19: Temperature distribution and energy demand of the MPP.

Temperature level	Annual demand (TJ)	Proportion of total
> 100°C	118	77%
< 100°C	36	23%
Total	154	100%

4.4.2 Southland

Optimal solution structure

The optimal structure for the MPP in Southland is presented below in Figure 4-19. As the energy demand is relatively small in comparison to the regional case studies and dairy plant case study, few resources are required.

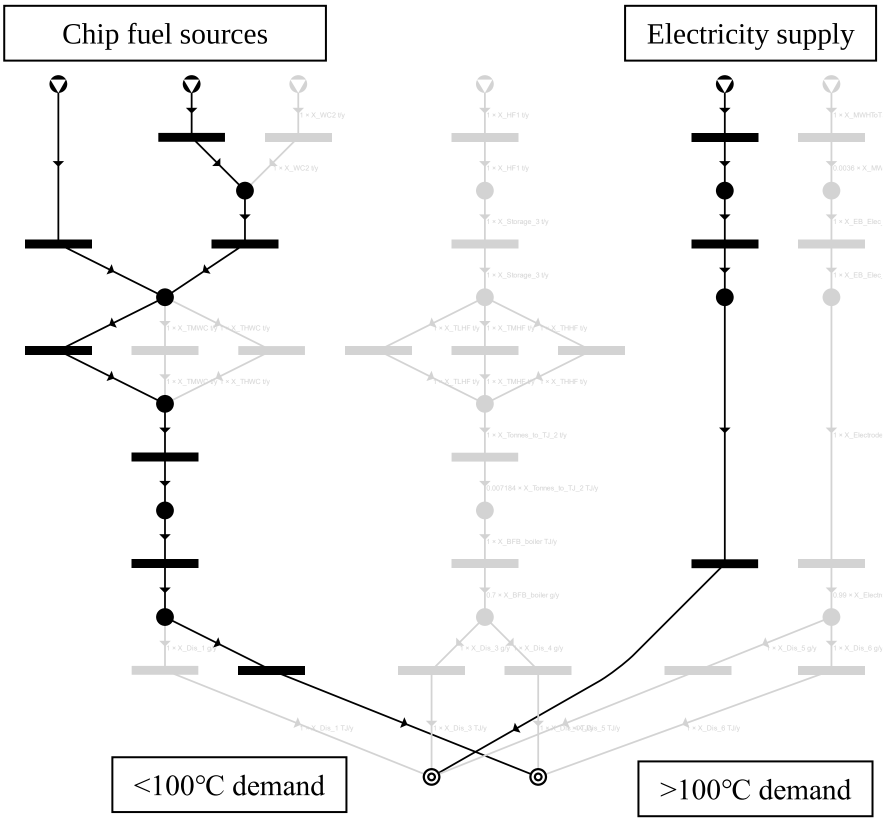

Figure 4-19: Optimal solution structure for the MPP in Southland.

Cost breakdown – Meat processing plant in Southland

Presented in Table 4-20 below are the required resources to meet the energy demand of the MPP in Southland and their relative costs.

Table 4-20: Resource supply and energy cost breakdown by resource for the MPP in Southland.

Individual energy costs	Annual demand	Transport distance	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	3,920 t (28 TJ)	Low	8.49	13.06
Chip log	16,612 t (119 TJ)	Low	13.64	19.50
HTHP	2,857 MWh (10 TJ)	-	27.78	10.82

Figure 4-20 below shows the resource and energy flows to supply the meat processing plant in Southland. In this case, only two heat plants are theoretically required.

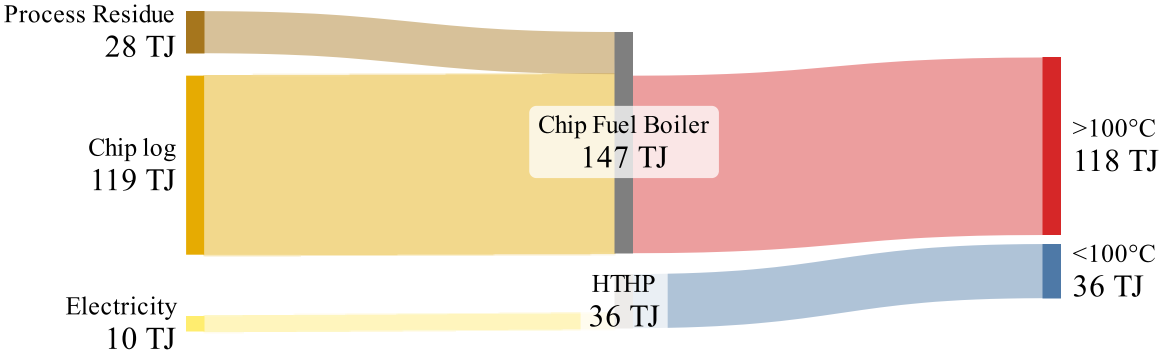

Figure 4-20: Optimal resource and energy flows for the MPP in Southland.

Near optimal structure analysis

As the demand is relatively small for this plant, the small quantity of low-cost process residues make up a more significant portion of their resource supply which greatly reduces the overall cost of energy. There is only a small amount of processor residues available region wide, and it can be seen in Figure 4-21 below that the overall energy cost is relatively more sensitive to the availability of these cheaper resources than a larger plant. The increase in LCOE across the first ten structures is notably steeper than for other case study scenarios and suggests that the relatively lower energy cost for this case study is dependent on securing the small quantity of low-cost processor residues.

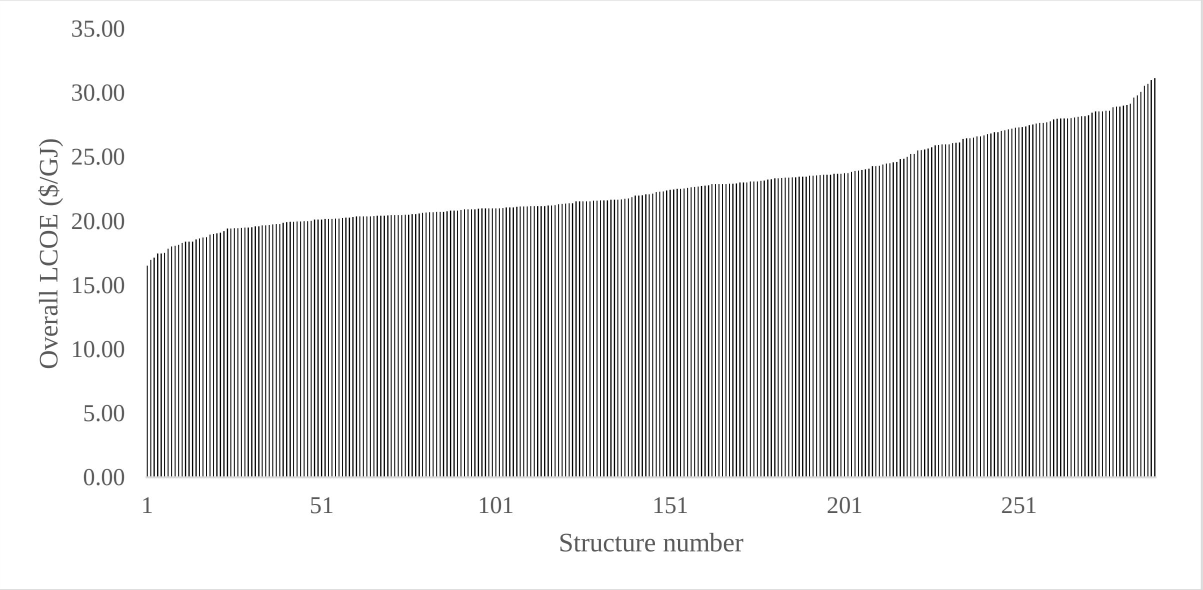

Figure 4-21: The first 300 optimal structures of the MPP in Southland.

4.4.3 North Canterbury

Optimal solution structure

The optimal structure for the MPP in North Canterbury is presented below in Figure 4-22.

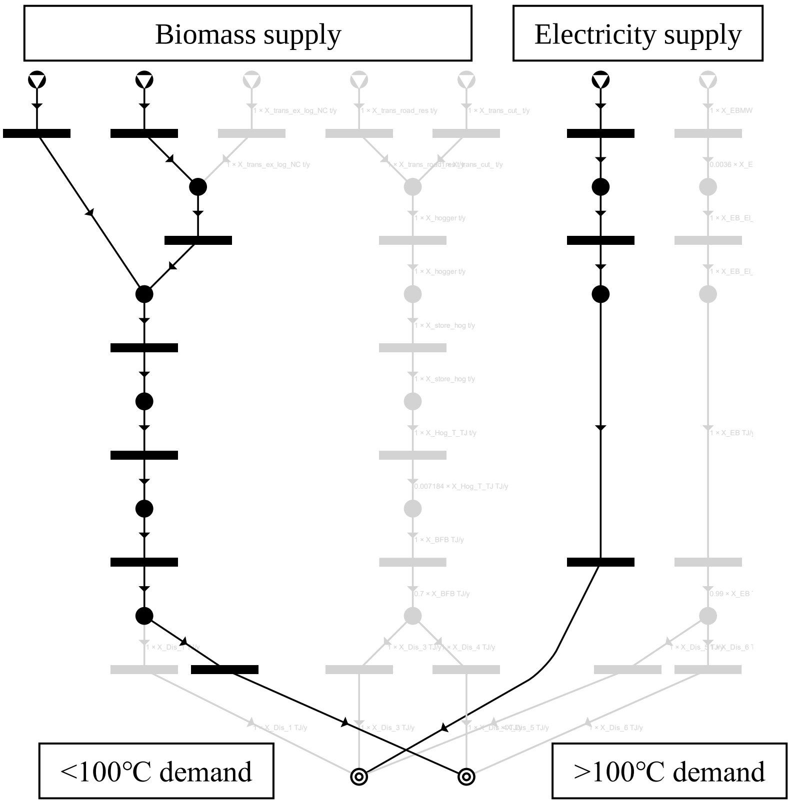

Figure 4-22: Optimal structure for the MPP in North Canterbury.

Cost breakdown – Meat processing plant in North Canterbury

Figure 4-23 below shows the resource and energy flows to supply the MPP in North Canterbury. Similar to the Southland system (Figure 4-19 on page 77), this system would optimally be a hybrid heat plant setup in which a solid fuel boiler supplies the heat demand at temperatures over 100°C, and a HTHP for all heat below 100°C.

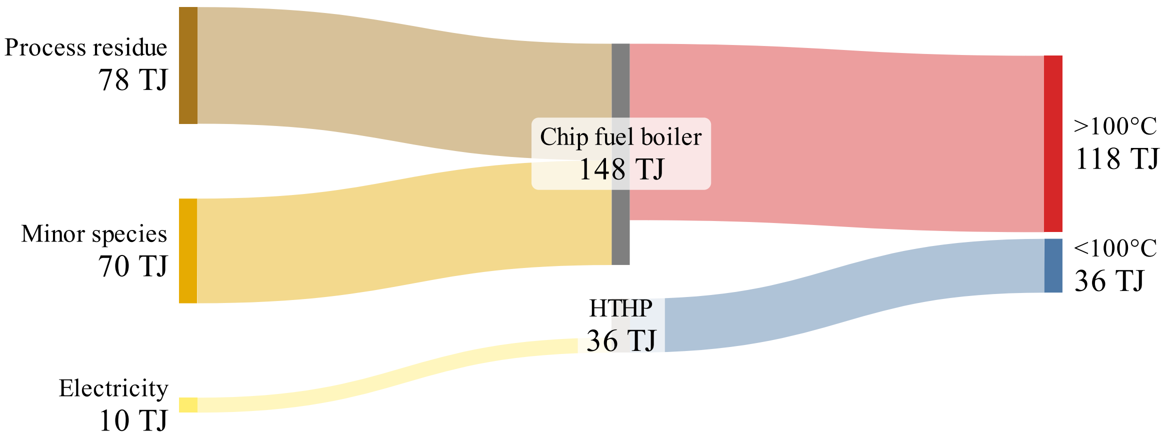

Figure 4-23: Optimal resource and energy flows for the MPP in North Canterbury.

The supply of resources required and the cost breakdown for the MPP in North Canterbury is shown below in Table 4-21.

Table 4-21: Resource supply and cost breakdown for the MPP in North Canterbury.

Individual energy costs	Annual demand	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	10,854 t (78 TJ)	4.50	8.07
Minor species	9,678 t (70 TJ)	16.53	23.12
Electricity (HTHP)	2,857 MWh (10 TJ)	27.78	10.97

Near optimal structure analysis

Notably for both regions, in the absence of these low cost processor residues, which are in small supply in both regions, the costs increase across the nearest optimal structures quickly as shown in Figure 4-21 on page 78, and Figure 4-24 below.

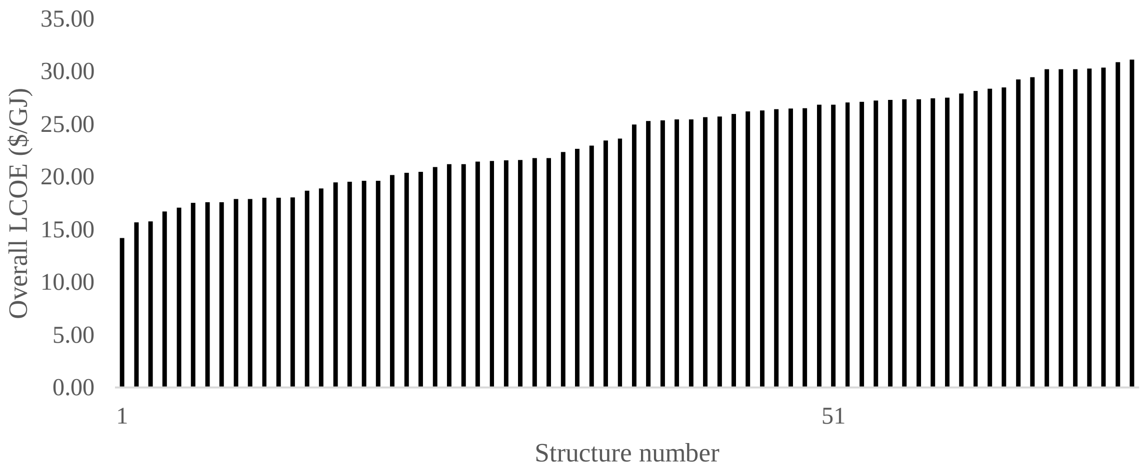

Figure 4-24: The first 80 structures for the MPP in North Canterbury.

In contrast to the earlier case studies, the North Canterbury system can produce energy at a much lower cost than Southland, almost $400,000 cheaper each year on an annualised cost basis. Processor residues in North Canterbury were priced much cheaper in the estimates made by EECA (2023e) than for Southland, and the smaller energy demand found in this case study gives a lower LCOE.

4.4.4 Summary

Again, similar to the Southland MPP case study, this system has the potential to produce energy at a relatively low cost if the plant can take advantage of a smaller quantity of cheap biomass sources (processor residues), though without these low cost resources, such as in the case of competition within the region, the costs increase steeply across the top five structures (Figure 4-24).

Table 4-22: Summary of costs for the MPP case study.

Item	Southland	North Canterbury
Total cost of materials	$1,472,444	$840,981
Total cost of operating units	$1,073,337	$1,343,533
Overall cost of solution	$2,545,781	$2,184,514
LCOE <100°C	10.82 $/GJ	10.97 $/GJ
LCOE >100°C	18.27 $/GJ	15.17 $/GJ
Overall LCOE	16.53 $/GJ	14.19 $/GJ

4.5 South Island case study

The previous two case studies investigated regions as isolated entities; the ability of a site to source biomass for its energy needs was restricted to the regional boundaries. Figure 4-25 below shows the process heat demand and biomass supply for each region in the South Island. This graph shows that there are several regions with high energy demand, but relatively low levels of biomass. The motivation for this case study is to determine the economic feasibility of transporting energy dense biomass resources between regions in the South Island to reduce the overall LCOE and increase the potential for biomass use.

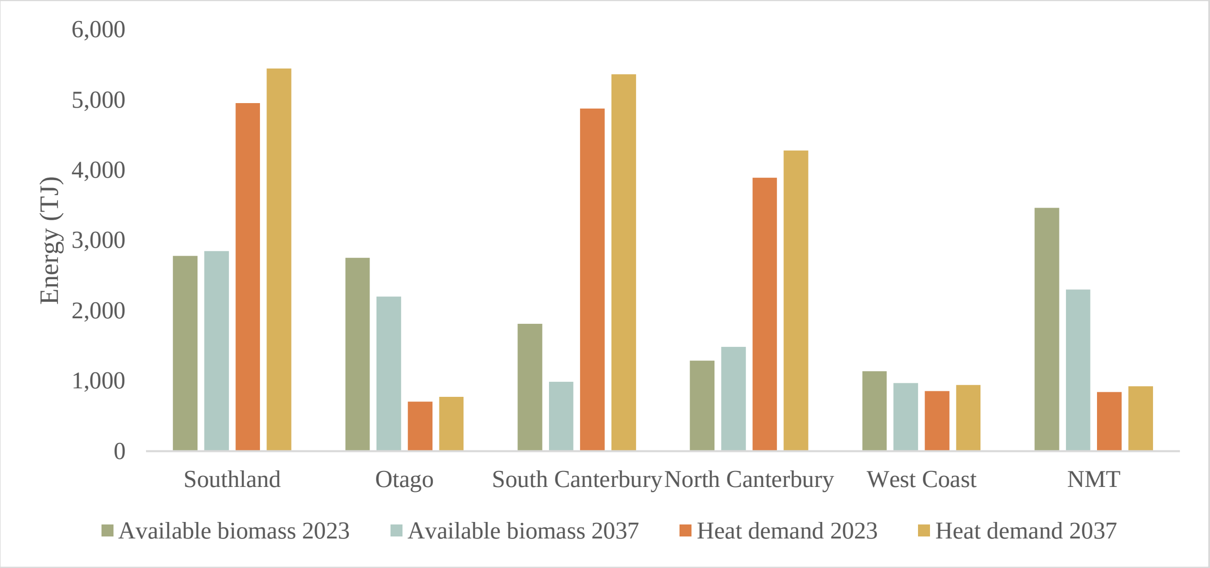

Figure 4-25: Biomass availability and heat demand across the South Island for 2023 and 2037 (EECA, 2022, 2023a, 2023c, 2023d, 2023e, 2023f, 2023g) .

4.5.1 System setup

The energy demands for each region were obtained from their respective RETA reports (EECA, 2022, 2023c, 2023d, 2023e, 2023f, 2023g). Temperature demand profiles were generated for each region using the breakdown of industry types and method in Section 3.2.7 to obtain estimates of the demands above and below 100°C. These are displayed below in Table 4-23.

Table 4-23: South Island regional energy demand.

Region	>100°C (TJ)	<100°C (TJ)	Region total (TJ)
Southland	2,742	2,209	5,465
Otago	137	568	749
Mid-South Canterbury	2,487	2,390	5,731
North Canterbury	1,702	2,188	4,266
West Coast	468	387	1,087
Nelson/Marlborough/Tasman	326	513	997
Total	7,863	8,255	16,118

A P-Graph model was constructed to represent the South Island regions by placing the individual region models side by side, and adding interregional transport operating units that connect regions of higher forestry production (Otago, Southland, West Coast, and NMT) with regions that have high demand (Southland, South Canterbury, North Canterbury). Transport options include rail transport of both wood chips and wood pellets to neighbouring regions. Costs and relative distances between hubs are outlined in Table 3-8 on page 46. The energy content of wood pellets used was 16.5 GJ/t (Bioenergy Association NZ, 2022a).

Pelletisation costs and rail transport

Industrial scale pelletisation plants have emerged in NZ in the past decade, though cost breakdowns for this process are not widespread and this is a more complex process than the creation of wood chips which likely leads to less certainty around the exact cost requirements of the process. Costing data for the estimation of pelletisation production costs was obtained from Gifford (2013) and the costs updated for price inflation for 2023 using the producer price index (Stats-NZ, 2023a). A summary of cost assumptions and an example of pelletisation costs is found below in Table 4-24. The final pellet cost was calculated in P-Graph studio using the method outlined in Equation 3.

Table 4-24: Pelletisation and interregional transport cost example.

Item	Cost
Pelletisation – per tonne of product	139 \$/t
Wood required – per tonne of product	2
Resource cost	50 \$/t
Transport to processing facility	40 \$/t
Transport interregional NMT to North Canterbury	49.20 \$/t
Energy content of pellets	16.5 GJ/t

$$\begin{aligned} Pellet\ cost = {} & wood\ required * (transport\ to\ processing\ facility + resource\ cost) \\ & + pelletisation + interregional\ transport \end{aligned} \quad \text{Equation 3}$$

For the example above the resulting delivered pellet cost would be 22.31 \$/GJ delivered from NMT to North Canterbury. This delivered price is several dollars per GJ more expensive that the most expensive biomass source in North Canterbury (Table 4-12 on page 66). However, this is substantially cheaper than the delivered cost of electricity at 100 \$/MWh (27.78 \$/GJ), which makes interregional transport of wood pellets economically competitive with electricity.

Constructing the interregional model

Figure 4-26 on the following page displays the maximal structure for the South Island in both 2023 and 2037. Individual structures for each region were constructed and arranged according to their neighbouring region; the labels in Figure 4-26 outline the sections of the maximal structure which correspond to each region. To reduce the complexity of the model, interregional transport operating units were only established to connect appropriate regions. The purpose of this was to connect regions of high energy demand that exceeded the economical collection of biomass with regions of excess biomass supply. The list of these regional connections is outlined in Table 3-8 on page 46. In early calculations it was determined that rail transport of wood chips could be more economical over certain distances than for wood pellets. Therefore, the interregional connections included the transport of both wood chips, and wood pellets.

Table 4-25 presents the biomass supplies for the South Island in both years of the case study. For a full breakdown by resource type, and resource cost see Table A-3 in Appendix A.

Table 4-25 Summary of biomass supply for 2023 and 2037 in the South Island EECA (2023a).

Region	Available biomass in 2023 (TJ/y)	Available biomass in 2037 (TJ/y)
Southland	2,780	2,849
Otago	2,751	2,201
South Canterbury	1,811	989
North Canterbury	1,287	1,483
West Coast	1,138	969
NMT	3,461	5,075

Figure 4-27 on the following page displays the optimal solution structure. Due to the size and detail of these figures, they have been reproduced on the final page of the appendix in a larger page size for easier viewing, these figures are available as Figure B-1 and Figure B-2.

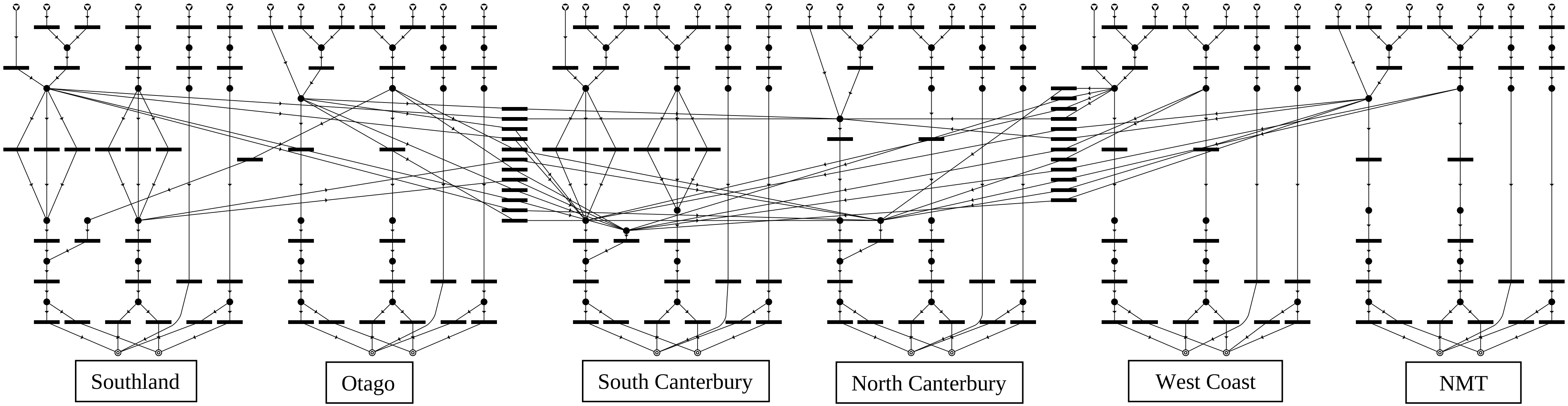

Figure 4-26: Maximal structure of the interregional case study of the South Island.

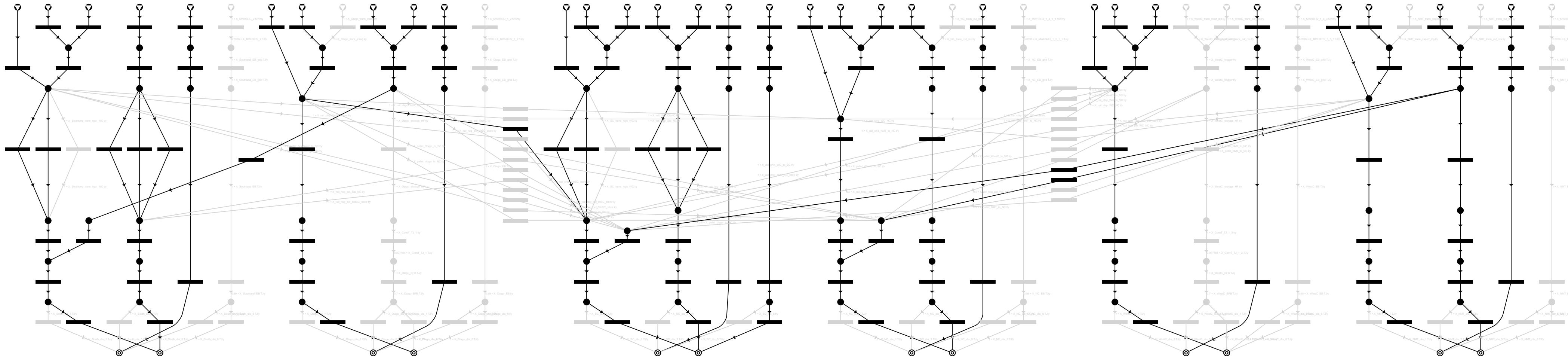

Figure 4-27: Optimal structure of the interregional case study of the South Island.

4.5.2 Results

South Island 2023 with no interregional transport

Figure 4-28[4] displays the optimal resources flow for the South Island without interregional transport of biomass. The proportion of biomass in the overall energy mix without interregional transport is just under 30%. Excluding heat demand under 100°C, this percentage rises to 61%. Figure 4-28 shows that electricity makes up substantial amounts of the heat demand above 100°C for three regions in the South Island, where Southland, South Canterbury, and North Canterbury are the three highest energy consumers. North and South Canterbury also have low forested area, compared to their total land mass. For these three regions, the low ratio of biomass to energy demand means that any low cost biomass resources are exhausted, and more costly feedstocks are required. This will in turn drive up the overall energy prices for the region, both because more expensive biomass must be used, but also because electricity is needed to fill the gaps that the regional supplies of biomass cannot.

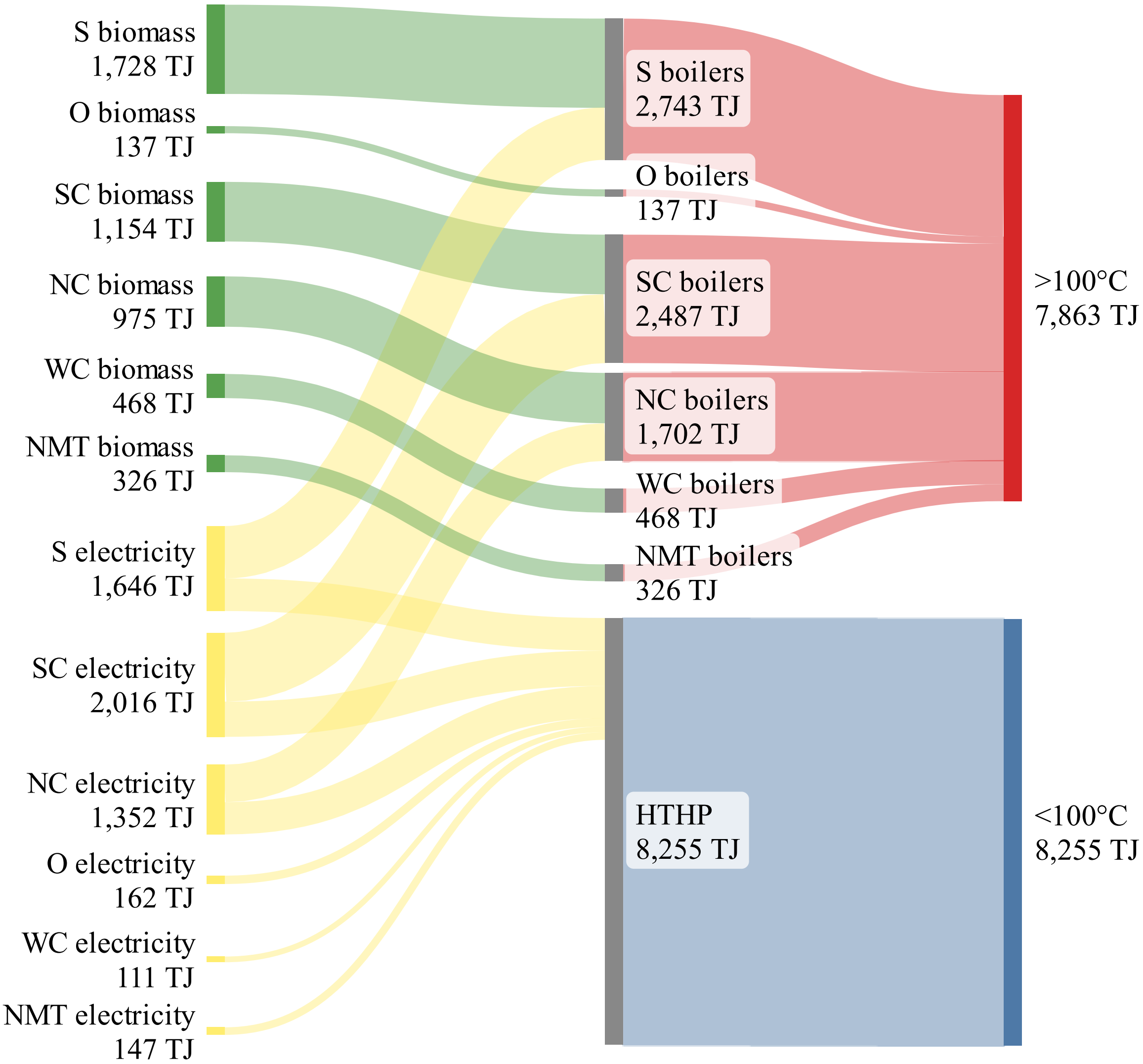

Figure 4-28: Optimal resource and energy flows for the South Island without IRT.

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[4] Key for the diagrams in Figure 4-28 and Figure 4-29: S – Southland; O – Otago; SC – South Canterbury; NC – North Canterbury; WC – West Coast; NMT – Nelson/Marlborough/Tasman.

Summary of the 2023 case study without interregional transport

Table 4-26 below displays the overall summary of costs and fuel switching proportions in the optimal structure of the South Island in 2023 without IRT. The LCOEs presented are weighted averages for the temperature range in each region. These LCOEs for the above 100℃ temperature range represent a large range across all regions; notably the lowest of these prices are found in regions with high biomass proportions for heat above 100℃.

Table 4-26 : Summary of the South Island for 2023 without IRT.

Region	Heat demand type	LCOE $/GJ	Biomass proportion >100°C	Biomass proportion overall
Southland	<100°C	10.82	63%	35%
	>100°C	25.95		
Otago	<100°C	10.66	100%	19%
	>100°C	18.10		
South Canterbury	<100°C	10.66	46%	24%
	>100°C	27.25		
North Canterbury	<100°C	10.97	57%	25%
	>100°C	28.29		
West Coast	<100°C	10.78	100%	55%
	>100°C	21.26		
NMT	<100°C	10.69	100%	39%
	>100°C	21.95		

South Island 2023 with interregional transport

Figure 4-29[5] below displays the large changes in the energy mix that occur with the inclusion of IRT. This impact is most keenly seen in the high energy demand regions of Southland and North Canterbury where biomass from Otago and NMT has displaced the use of electricity in all heat demand above 100°C. South Canterbury still uses 655 TJ to meet its demand above 100°C, though this is a large reduction from the 1333 TJ that is required without IRT. Despite IRT adding cost to biomass, these energy sources are more economic than electricity at 100 $/MWh.

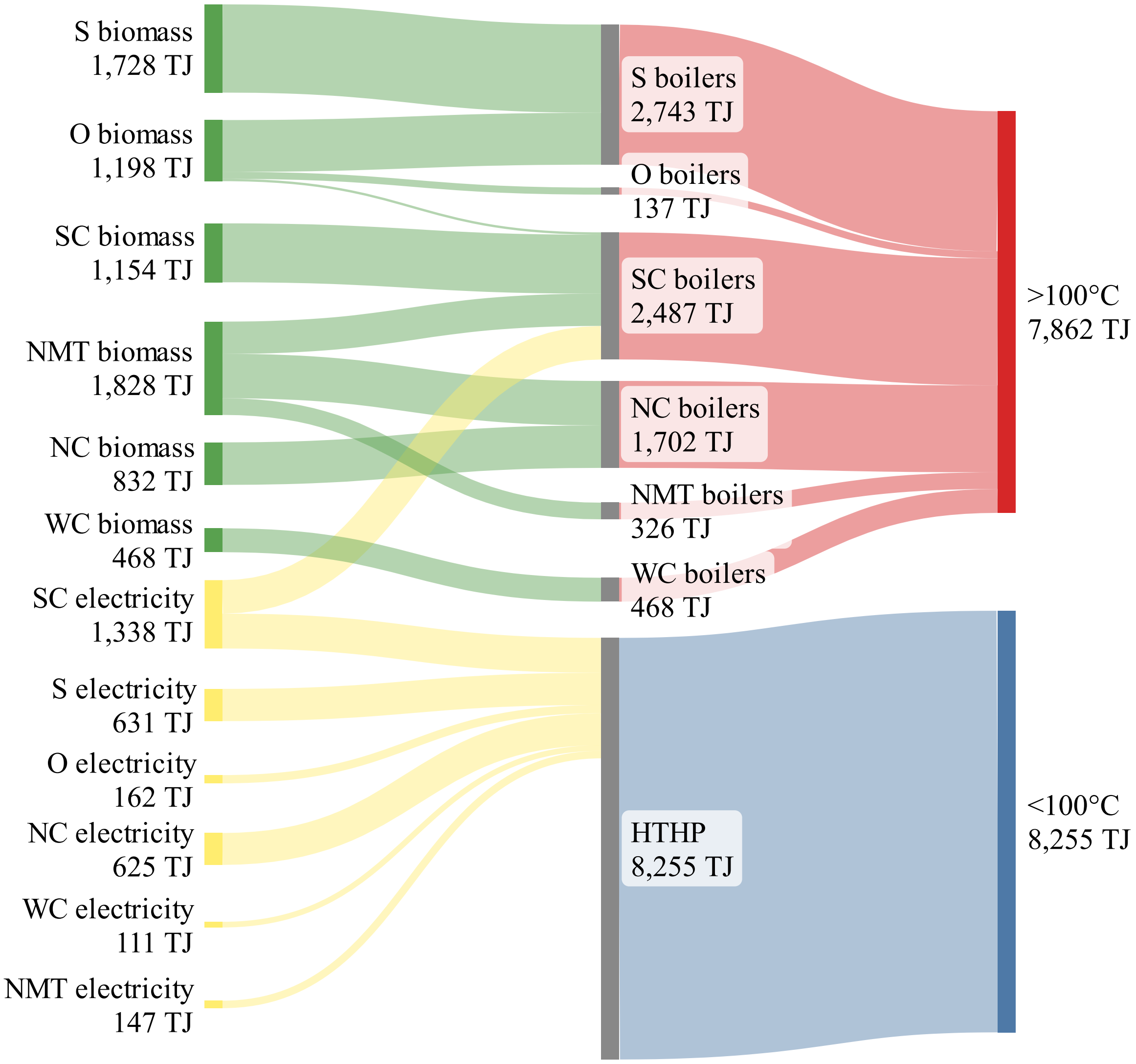

Figure 4-29 : Optimal resource and energy flows for the South Island 2023 with IRT.

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[5] For the South Island case study Sankey diagrams in Figure 4-28, Figure 4-29, Figure 4-30, and Figure 4-31, the resources flows of biomass and electricity into boiler for >100°C heat demand were adjusted from the raw material required for efficiency of the boiler to reduce the size and complexity of the diagram.

Summary of the 2023 case study with interregional transport

Table 4-27 below presents the summary of LCOEs for each region in the South Island in 2023 with IRT case study. North Canterbury has seen a substantial reduction in its average LCOE for heat demand above 100°C, from 28.29 $/GJ without IRT, to 25.41 $/GJ with IRT. This reduction in price is due to the importing of wood pellets derived from forest residue from NMT. Southland and South Canterbury also see reductions in their LCOE for above 100°C heat demand. For Southland this reduction is relatively significant at 0.93 $/GJ, however South Canterbury only sees a reduction by 0.11 $/GJ. This small reduction indicates that the costs required to import biomass are not significantly lower than to use electricity.

Table 4-27 : Summary of the South Island in 2023 with IRT.

Region	Temperature level of heat demand	LCOE $/GJ	Biomass proportion >100°C	Biomass proportion overall
Southland	<100°C	10.82	100%	55%
	>100°C	25.02		
Otago	<100°C	10.66	100%	19%
	>100°C	20.47		
South Canterbury	<100°C	10.66	74%	38%
	>100°C	27.14		
North Canterbury	<100°C	10.97	100%	44%
	>100°C	25.41		
West Coast	<100°C	10.78	100%	55%
	>100°C	21.26		
NMT	<100°C	10.69	100%	39%
	>100°C	21.95		

South Island 2037 without interregional transport

Figure 4-30 presents the optimal resource and energy flows for the South Island in 2037 without IRT. Compared with the South Island 2023 without IRT case study (Figure 4-28 on page 86), electricity makes up a much greater portion of the heat demand above 100°C. As the heat demands were estimated to increase for the 2037 case studies, more resources are needed to meet these demands. Regions with smaller demands, and larger forestry production are able to meet these increased demands with biomass. However, for Southland, South Canterbury, and North Canterbury, the increased demands and lack of IRT sees their heat demand above 100°C largely supplied by electricity (Table 4-28).

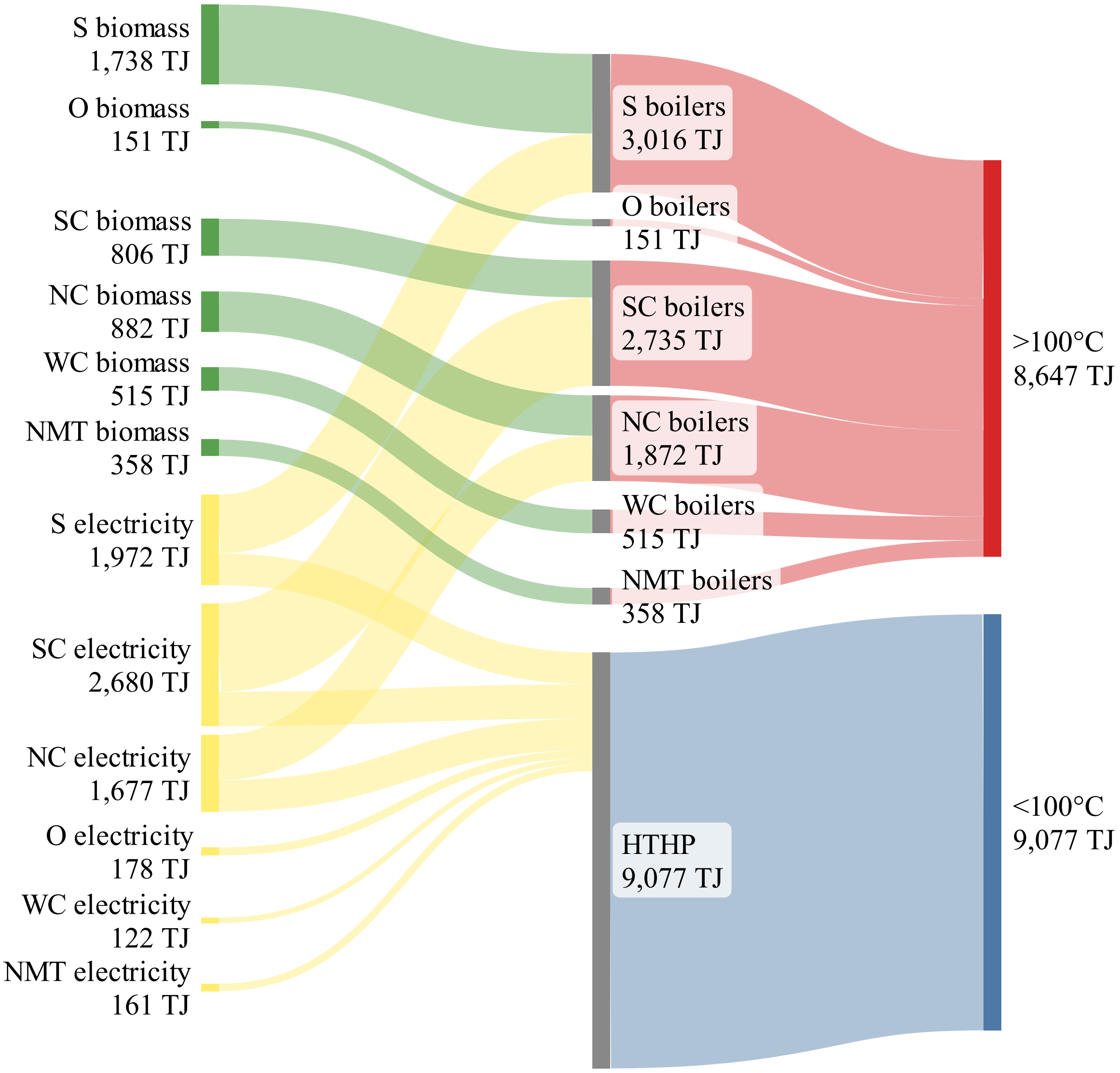

Figure 4-30 : Optimal resource flow for the South Island in 2037 without IRT.

Summary

Table 4-28 below shows a summary of the South Island 2037 without IRT case study. The increases in heat demand see South Canterbury's proportion of biomass drop to low levels. The LCOEs for heat demand above 100°C of South Canterbury, and North Canterbury are closer in price in this scenario. North Canterbury's LCOE closed this gap due to a higher reliance on electricity for heat demand above 100°C; this region has the most expensive electricity transmission upgrade costs which leads to the higher electricity prices (EECA, 2023e).

Table 4-28: Summary of the South Island in 2037 without IRT.

Region	Temperature level of heat demand	LCOE $/GJ	Biomass proportion >100°C	Biomass proportion overall
Southland	<100°C	13.20	58%	32%
	>100°C	34.84		
Otago	<100°C	13.04	100%	19%
	>100°C	23.23		
South Canterbury	<100°C	13.04	29%	15%
	>100°C	35.87		
North Canterbury	<100°C	13.35	47%	21%
	>100°C	35.29		
West Coast	<100°C	13.16	100%	55%
	>100°C	26.25		
NMT	<100°C	13.07	100%	39%
	>100°C	27.92		

South Island 2037 with interregional transport

Figure 4-31 presents the optimal flow of resources and energy in the South Island 2037 with IRT case study. The use of IRT shows a large reduction in the use of electricity and because of this, lower LCOEs across the South Island compared with the No IRT case study (Table 4-28 and Table 4-29). A major difference compared to the South Island 2023 with IRT case study is that Southland's energy demands have grown too large for the heat demand above 100°C to be supplied economically by biomass from within Southland or from neighbouring Otago. Notably Otago's predicted supply of forest residues declines from 2023 to 2037 (Table A-3 in Appendix A); these residues were able to meet Southland's above 100°C demand in 2023. In a similar trend, the supply of forest residue from NMT also declines which results in the supply of wood pellets to South Canterbury being much reduced.

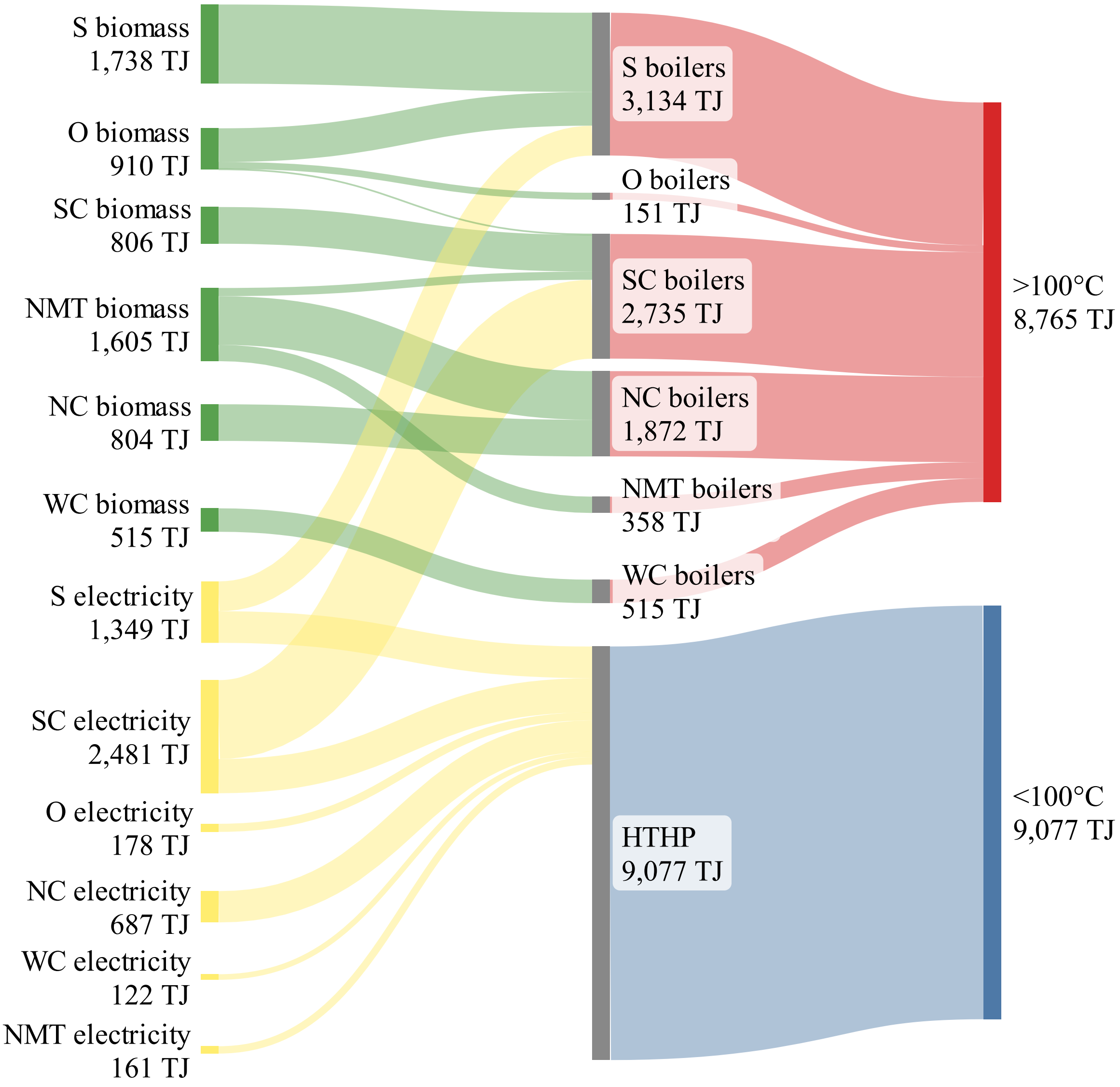

Figure 4-31: Optimal resource and energy flows for the South Island in 2037 with IRT.

Summary

Table 4-29 presents the summary of the South Island 2037 with IRT case study. As stated above, a major difference for this case study compared to the 2023 with IRT case study is the amount of electricity required for both Southland and South Canterbury for their heat demands above 100°C. This change sees the proportion of biomass used for heat demand above 100°C drop substantially, from 100% to 61% in Southland, and from 74% to 38% in South Canterbury (Table 4-27). The LCOEs for each region, as well as the overall weighted average for the South Island (Table 4-30) are still lower than without IRT. However, it is clear that the increased energy demands in 2037 coupled with lower biomass availability put a strain on resources in the South Island, leading to increased energy prices.

Table 4-29: Summary of the South Island in 2037 with IRT.

Region	Temperature level of heat demand	LCOE $/GJ	Biomass proportion >100°C	Biomass proportion overall
Southland	<100°C	13.20	61%	26%
	>100°C	32.73		
Otago	<100°C	13.04	100%	43%
	>100°C	23.23		
South Canterbury	<100°C	13.04	38%	19%
	>100°C	34.40		
North Canterbury	<100°C	13.35	100%	44%
	>100°C	31.19		
West Coast	<100°C	13.16	100%	55%
	>100°C	26.25		
NMT	<100°C	13.07	100%	39%
	>100°C	27.92		

4.5.3 Summary

Table 4-30 presented a brief summary of the energy prices for each South Island case study. From these predictions it is clear the IRT of biomass can positively influence process heating energy prices across the South Island. However, for this to occur there needs to be good communication and collaboration between energy users, and biomass suppliers so that long-term fuel supply agreements can be reached. This long-term planning is key as the constraints on biomass in the year examined (2037), as well as throughout the 2030s could lead to supply shortages in some regions if a large number of heat plants switched to biomass before this period. A full outline of the cost break down for each region in the South Island case study under both IRT scenarios for 2023, and 2037 can be found in Appendix B.

Table 4-30 : Summary of the South Island case studies.

Case study	Temperature level	Weighted average LCOE ($/GJ)	Biomass proportion >100°C	Biomass proportion overall
South Island 2023 with IRT	<100°C	10.79	91%	45%
	>100°C	25.18		
South Island 2023 without IRT	<100°C	10.79	61%	39%
	>100°C	26.24		
South Island 2037 with IRT	<100°C	13.17	72%	35%
	>100°C	32.12		
South Island 2037 without IRT	<100°C	13.17	51%	25%
	>100°C	34.26		

Chapter 5 Analysis and discussion

The previous chapter presented the results of the P-Graph model optimisation for several case studies. In this chapter the implications of these case studies will be discussed, and the regions compared to determine the key aspects that influence the extent of biomass use and the associated costs. The impact of the biomass supply over time will also be discussed, and how interregional transport can be used alongside energy densification of biomass to alleviate the supply and demand differences between regions. Creating a substantial biomass market is difficult as it becomes a chicken and egg situation; industry does not want to commit to a fuel source without guarantee of long-term supply, and potential suppliers are reluctant to expand production without guarantee of biomass purchases. The potential impact of a lack of biomass uptake by industrial heat users will also be discussed and how this will impact the wider energy sphere. A key factor in this work is the pricing levels given to resources and their transport: a sensitivity analysis is undertaken to determine how changes in costs would impact electricity and biomass in the energy mix. Other factors that may impact fuel switching decisions such as demand flexibility are discussed. Several assumptions were made during the course of this work and these impact the results. The nature of this impact is examined, and potential solutions are proposed.

5.1 Regional case study analysis

Both regional case studies focused on regions that had significant energy demand. After accounting for the energy efficiency reductions estimated by EECA, Southland and North Canterbury would require 4,951 TJ, and 3,890 TJ respectively to meet their current heating demands, compared to low demand regions such as Otago (705 TJ), and NMT (839 TJ). All regions will require large-scale fuel switching action, though the scale of the infrastructure required will be much larger in some regions than others. These fuel switches will also bring a large amount of secondary infrastructure such as wood processing plants and storage facilities for biomass, and new generation equipment, transmission lines, and substations for electricity. These two regions also have different levels of production forestry, relatively lower than for neighbouring regions, which results in tighter markets for biomass. Both of these regions contain large MDF plants which further constrain biomass supply as an MDF plant will consume hundreds of thousands of tonnes of low grade wood and processor residue each year (EECA, 2022, 2023e).

A summary of the regional energy cost estimates for Southland[6] and North Canterbury across both 2023 and 2037 are displayed below in Table 5-1, and Table 5-2. A summary of the weighted average LCOE for each temperature range is displayed in Table 5-3. Note that for all cost breakdowns in this chapter, the energy values given for annual demand of resources are total demand and not the delivered energy.

Table 5-1: Summary of Southland regional energy costs.

Resource	2023		2037	
	Annual demand	LCOE $/GJ	Annual demand	LCOE $/GJ
Processor residues	3,920 t (28 TJ)	12.60 - 13.80	3,920 t (28 TJ)	15.80 - 17.40
Harvest residues	83,008 t (596 TJ)	20.20 - 24.60	85,152 t (612 TJ)	24.80 - 30.50
Chip log	50,000 t (359 TJ)	19.00 - 20.20	50,000 t (359 TJ)	24.20 - 25.70
Export log	174,020 t (1250 TJ)	26.80 - 28.10	174,020 t (1250 TJ)	26.60 - 30.50
Electricity >100℃ (Electrode boiler)	284,667 MWh (1025 TJ)	30.60	358,522 MWh (1291 TJ)	39.40
Electricity <100℃ (HTHP)	175,317 MWh (631 TJ)	10.80	192,778 MWh (694 TJ)	13.20

Table 5-2: Summary of North Canterbury regional energy costs.

Resource	2023		2037	
	Annual demand	LCOE $/GJ	Annual demand	LCOE $/GJ
Processor residues	10,854 t (78 TJ)	7.58	10,854 t (78 TJ)	9.27
Roadside residues	47,289 t (340 TJ)	27.49	17,306 t (124 TJ)	34.29
Cutover residues	28,505 t (205 TJ)	30.11	15,562 t (112 TJ)	34.71
Minor species	12,635 t (91 TJ)	22.63	73,990 t (532 TJ)	28.86
Export log	79,863 t (574 TJ)	26.73	34,847 t (250 TJ)	34.20
Electricity >100℃ (Electrode boiler)	203,946 MWh (734 TJ)	31.11	285,866 MWh (1029 TJ)	39.52
Electricity <100℃ (HTHP)	173,651 MWh (625 TJ)	10.97	190,952 MWh (687 TJ)	13.35

Table 5-3: Overall LCOE comparison between Southland and North Canterbury in 2023.

Item	Southland 2023	North Canterbury 2023
LCOE <100℃	10.82 $/GJ	10.97 $/GJ
LCOE >100℃	27.17 $/GJ	28.29 $/GJ
Overall LCOE	19.87 $/GJ	18.55 $/GJ

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[6] The range of prices for the biomass resources in Southland refers to the range of transport distances required. For full details see Section 3.2.4, Table 3-6.

Impact of resource price

As these prices were calculated using the information from the RETA reports, the base energy cost that accounts for operational costs matches the values given by EECA in both the Southland RETA (EECA, 2022), and the North Canterbury RETA (EECA, 2023e). There is some slight variation in the Southland costs due to the method of transport cost allocation outlined for Southland in Section 3.2.4, though the average aligns well. Where the energy costs differ is in the LCOE, as this also accounts for heat plant and infrastructure upgrades across the sites in this region. For sites using a solid fuel chip boiler for wood chips, this adds an additional 2.45 $/GJ, and for a fluidised bed boiler it adds 4.90 $/GJ.

Of note is that in North Canterbury the biomass resource costs are generally more expensive than for Southland with the exception of processor residues which are only available in a relatively small quantity, less than 10% of overall supply potential. These larger costs will tend to push up energy prices in the region by a little over a 1.10 $/GJ for demands above 100℃ (Table 5-3), though it is only a 4% increase in the average cost, extrapolated out over years, and for a large site or entire region this is a significant increase in costs. For example, a dairy plant that consumes 900 TJ each year would see their annual energy bill increase by almost a million dollars.

Both regions will likely see substantial use of electrically generated heat above 100°C as the supply of biomass is not high enough within each region to meet the demand. Southland will require 1,014 TJ, and North Canterbury 727 TJ, at a cost of around 30 $/GJ, which will be a huge increase from current fossil fuel prices. The standard fuel used by a majority of industrial sites in the South Island is coal, the price of which is indicated by EECA (n.d.-a) to be between 10 and 14 $/GJ at a carbon price of 70 $/t. Most of the fuels considered within this work have costs above this price and mean that any fuel switch will require both large capital investment and a large increase in operating fuel costs for businesses and industries.

Supply distribution

Both regions have a similar ratio of biomass resources to their energy demands which results in similar splits between biomass and electricity for heat demands above 100℃ of 63% for Southland, and 57% for North Canterbury. For the overall heat demands these percentages drop to 35%, and 25%, the lower value for North Canterbury reflecting that this region has more demand at temperatures below 100℃ compared to Southland.

In terms of overall resources used in each region, North Canterbury consumes all available biomass resources in both modelled years 2023, and 2037, the remaining energy demand is filled by electrification of utilities. In Southland, almost all biomass resources are used, the exception occurs for low grade export logs in which only 70% (174,020 t) of the estimated availability of this resource (250,000 t) is used. Where this cut-off occurs is due to the transport cost distribution that was applied for Southland. The final 25% of resources were estimated to need to be sourced from a much larger distance and thus given higher transport costs as seen in Table 3-6 on page 45. The impact of this higher transport cost which reflects a transport distance of 120 km and 33 $/t pushes the LCOE up to 31.68 $/GJ which is greater than the LCOE for electricity above 100℃ in this region of 31.11 $/GJ. In reality this split would likely not be so distinct: a site that has made the fuel switch to biomass will be locked into using this resource and their supplier would use the more expensive sources to meet the demand and pass the cost to the consumer. As these more expensive sources would only be part of the overall supply, the average cost for the resource would still work out to be lower than for electricity. The average cost of export logs for bioenergy across all transport distances works out to 29.42 $/GJ, lower than electricity.

An aspect that is different for each region in the methodology used for resource costs is that of transport. In the first RETA report a transport price of 18 $/t was estimated, this was outlined as a guideline for prices within the region. At a distance of 60 km this transport price was deemed to be lower than what could realistically be expected for sites within the region. The resource and heat plant maps obtained from SCION (n.d.-b) and used to estimate the approximate distances between the industrial sites outlined in the Southland RETA document (EECA, 2022), large forest locations, and wood processing facilities. From these estimates it was determined that there was a greater spread of transport distances that would be required. The report by Hall and Palmer (2020) also informed the decision to apply different cost functions for the Southland region. As this model was for an entire region the prices are indicative only and therefore this method may have benefits as it shows there is a range of costs for biomass that depend on location. However, for more specific costs it is necessary to conduct site surveys pertaining to specific locations.

5.2 Individual case study analysis

The individual site case studies were conducted to determine how a site's temperature profile would influence its energy generation mix. These case studies gave a better understanding of the energy cost expectation for an individual site if they were able to secure long-term supply agreements in the near future. By acting quickly and securing contracts with suppliers a site would be able to guarantee a lower cost, and security of supply into the future. With demand increasing as more sites look to fuel switch to biomass, the supply will need to be sourced from further away, or from more expensive sources of biomass, resulting in higher costs to energy users.

Dairy

The dairy plant considered in this individual site case study is very large by international standards, with a total milk powder production capacity of 30 t/h: these facilities are not unusual in NZ (Atkins, 2023). Despite this, the total energy demand of this plant (965 TJ) exceeds the total regional process heat demand of Otago (705 TJ) and NMT (839 TJ). These figures demonstrate the scale of the industry in NZ, and with it the scale of decarbonisation efforts required. A summary of the individual site case study costs is displayed below in Table 5-4. It can be seen that the dairy plant follows a similar trend to the regional case study in that the overall LCOE for North Canterbury is higher than that of Southland, though in this example it is substantially higher. A reason for this may relate to the method of transport cost allocation for Southland in that the dairy site was of a size that it could obtain enough low and medium transport cost biomass resources to meet its needs. whilst the transport costs for North Canterbury were fixed and more specific to each resource. Closer examination in further detail about the specific transport distances required by a site are again shown to be hugely important.

Table 5-4: Cost summary of the dairy plant case study in Southland and North Canterbury.

Item	Southland	North Canterbury
LCOE <100℃	10.82 $/GJ	10.97 $/GJ
LCOE >100℃	20.04 $/GJ	24.76 $/GJ
Overall LCOE	16.58 $/GJ	19.59 $/GJ

Within both the Southland and North Canterbury case studies of the dairy site, to meet the high demand for heating above 100°C, two different fuel types of biomass are selected in the optimal solution structure. Partly, this is determined by the method of construction used throughout the case studies which assumed that forest residues were of low quality and would only be sufficient for hog fuel. The impact this has on the case studies and wider applications will be discussed later in this chapter. Considering just the dairy case study as presented in Section 4.3 it would be unlikely that a small plant would operate two types of boiler for different types of biomass, though a large plant such as in these case studies may see financial and logistic benefit in being able to be more flexible and operate on cheaper and more abundant fuels. This may prove especially useful if a biomass commodity market emerged. The Fonterra Waitoa site currently operates both biomass and coal boilers on a single site (Windsor Energy, 2023b): the inclusion of a biomass boiler is a step in their decarbonisation pathway but is an example of a single site using two heat plants with two different fuel sources. These boiler types (BFB and solid fuel boilers) are outlined in Section 3.2.5 and within the scope of this research affect the capital cost and efficiency of the boiler, two parameters that have sizeable impact on the final cost of energy. It was determined that the LCOE of a BFB added $4.50 for every GJ of energy output, and a solid fuel boiler $2.45. The benefit of the higher capital cost BFB boilers is that they can use lower quality and presumably cheaper biomass, though in the costing outlined in the RETA reports it was clear that the fuel sources considered lower quality i.e. forest residue, encountered high recovery costs and meant their overall delivered cost often exceeded low grade chip logs, as seen in the regional case study in North Canterbury (Table 4-12, page 66).

Meat processing plant

By comparison, the meat processing plant (MPP) had a lower overall LCOE than the dairy sites in both regions. This is due to the scale of these sites; as the MPP is much smaller its demand is filled selectively by the cheapest resources. As demand grows, more expensive resources are required; hence the far larger demand of the dairy site requires a much higher proportion of the more costly resources. Table 5-5 displays a summary of the MPP case study.

Table 5-5: Cost summary of the MPP case study in Southland and North Canterbury.

Item	Southland	North Canterbury
LCOE <100℃	10.82 $/GJ	10.97 $/GJ
LCOE >100℃	18.27 $/GJ	15.17 $/GJ
Overall LCOE	16.53 $/GJ	14.19 $/GJ

In contrast to the larger dairy plant, and the regional cost trend observed from Southland (Note that for all cost breakdowns in this chapter, the energy values given for annual demand of resources are total demand and not the delivered energy.

Table 4-5, page 58) to North Canterbury (Table 4-12, page 66), the smaller MPP had a substantially lower LCOE in North Canterbury. A major contribution to this is the availability of low-cost processor residues in North Canterbury (LCOE of 7.58 $/GJ) which made up more than half the above 100°C heat demand (78 out of 148 TJ). These residues carry a transport cost estimated by EECA (2023e) of just 4.4 $/t which indicates that this final cost would be dependent on the location of the MPP. These case study comparisons show that even though the overall trend for biomass prices in a region may be higher, there are good possibilities for businesses to arrange more economic supply contracts based on the location of the plant and wood processing facilities, and the cost of resources.

5.2.1 Impact of temperature profile

Naturally the HTHP is able to provide the lowest cost heat for temperatures under 100°C due to its COP of 3.5. As this technology matures further, the ability of Very High Temperature Heat Pumps (VHTHP) to achieve higher temperature lifts will become more economic through increasingly efficient process and design. This will allow a much greater use of VHTHP in industry and provide greater economics for the decarbonisation of heat above 100°C. There have been several studies investigating the use of VHTHP in literature (Adamson et al., 2022; Arpagaus et al., 2018; IEA, 2023a; Kong et al., 2024). Several VHTHPs are already commercially viable and used in industry; it is likely that there use will become more prominent in NZ as major companies are already entering partnerships to design and implement these technologies (Fonterra, 2023). However, in the current state of play electrically derived heat for applications above 100℃ remains one of the most expensive sources of energy at current electricity prices.

This study agrees with the prevailing views of industry and academia that for heat applications below 100℃, HTHPs are likely going to provide the greatest economics. As stated earlier in this work; this is due to their ability to produce three or four units of useful heat energy for every one electrical unit. The LCOEs presented in this work are capable of rivalling or surpassing coal energy prices of $10 - $14 per gigajoule; therefore, these technologies are highly likely to achieve economic viability for heat applications below 100℃. In addition to the electrical energy input to a heat pump, they require heat energy, either from the air or waste heat from a process; an expansion of this could be that a HTHP could work in tandem with a solid fuel boiler. What this could look like for heat applications over 100℃ would be the HTHP completing the heating work up to 100℃ or the most economic temperature, and the solid fuel boiler taking over from there to upgrade the heat to the required level of the plant. This would take advantage of the high efficiency of the HTHP and that it could upgrade waste heat from the plant. Using waste heat additionally reduces cooling demands for the site. There are some examples of studies investigating the upgrading of waste heat from biomass boilers (Hebenstreit et al., 2014), though the concepts are not well established regarding the use of air source heat pumps which use heat pump and biomass hybrid systems. Further work is needed with site specific investigations to determine the economic feasibility and whether the increased CAPEX would be balanced by reduced OPEX in these hybrid systems. These analyses would need to consider more detailed data that goes beyond the scope and timeframe of this work. Factors specific to industries and sites such as the timing of processes, waste heat upgrade potential and transfer distance of heat utility would all need to be considered.

Another nascent area of research is the use of hybrid energy systems that optimise which fuel source is used based on economic conditions. This has been referenced by Walmsley et al. (2023) and is concerned with the use of hybrid biomass-electric heat plant systems. These systems would be able to switch between heat plants and fuel sources depending on the electricity spot price of the region. Additionally, this process could be expanded and used for energy storage either in battery electric systems, thermal storage such as steam accumulators, or other means such as pumped hydro storage.

5.3 Interregional case studies

The interregional case studies present a what-if scenario to explore how best supply gaps could be filled by neighbouring regions. In terms of overall available biomass, supply in the South Island is 13.2 PJ (EECA, 2023a), while the total heat demand above 100°C is 7.86 PJ and that below 100°C is 8.23 PJ (EECA, 2022, 2023c, 2023d, 2023e, 2023f, 2023g). These numbers signify that there is sufficient biomass to supply all heat demand above 100°C without affecting domestic markets. From the regional case studies and the South Island study without interregional transport (Section 4.5.2) it was seen that the heat demands could not be met economically using only biomass for heat demand above 100°C. The interregional case study considered the economic feasibility of energy densification and longer distance transport as a strategy to achieve greater incorporation of biomass in NZ's renewable energy mix and a more economical fuel switch.

As stated previously there are only two main contenders for fuel switching considered in this work; generally electrification is the more expensive energy source compared to solid fuels and natural gas. However, as has been seen in several of these case studies, there are instances where the transport cost of biomass becomes great enough that it exceeds the cost of electricity. There are methods to reduce the transport cost, and those that were considered were the densification of fuel sources through pelletisation, and the use of the more efficient and cheaper transport method of rail. The use of rail transport alone was able to alleviate some supply and demand mismatches in the South Canterbury region by transporting wood chips from Otago. Modelling of rail transport was treated as an additional transport on top of that required to move the resource from the forest to a processing centre, and to distribute it to site. Even though rail transport is a lower cost per km that trucking, it is still an overall higher cost than if the resource was to be used within the region. The cost ratio used for rail transport was 0.156 \$/tkm (2023 price adjusted (Stats-NZ, 2023b)) (Sanderson & Robertson, 2020), whilst that for trucking was the same as the RETA reports at nearly double rail freight 0.30 \$/tkm (EECA, 2023e). It is also fortunate for the South Island that many major wood processing facilities are located near the main rail networks. For a full list of these locations and their transport costs see Table 3-8 on page 46. Pelletisation of biomass is beneficial for both transport and combustion efficiency reasons. Transporting a tonne of wood pellets at a typical minimum energy content of 16.5 GJ/t will transport twice as much energy as the same mass of lower quality biomass such as hog fuel which is between 7 and 8 GJ/t. As these energy values are higher, combustion efficiency will also be higher within boilers (Visser, Hall, et al., 2010). However, the additional processing and transport required to achieve greater economics for long distance transport comes with higher upfront costs that are only more effective after a certain transport distance has been reached. An example of the higher relative cost comparisons between road and rail is displayed below. Cost parameters for this example are in Table 5-6, and the resulting cost curves in Figure 5-1.

Table 5-6: Wood pellet and wood chip mode of transport comparison parameters.

Item	Cost ($/t)
Resource[1]	50
Transport within region	40
Wood chipping and storage	25
Wood pelletisation (Gifford, 2013)	139
Rail transport (Sanderson & Robertson, 2020)	0.156 /km
Road transport (EECA, 2023e)	0.30 /km
Final pellet cost	318.90
Final wood chip cost	115.00

1- Two tonnes of wood are required to produce one tonne of wood pellets.

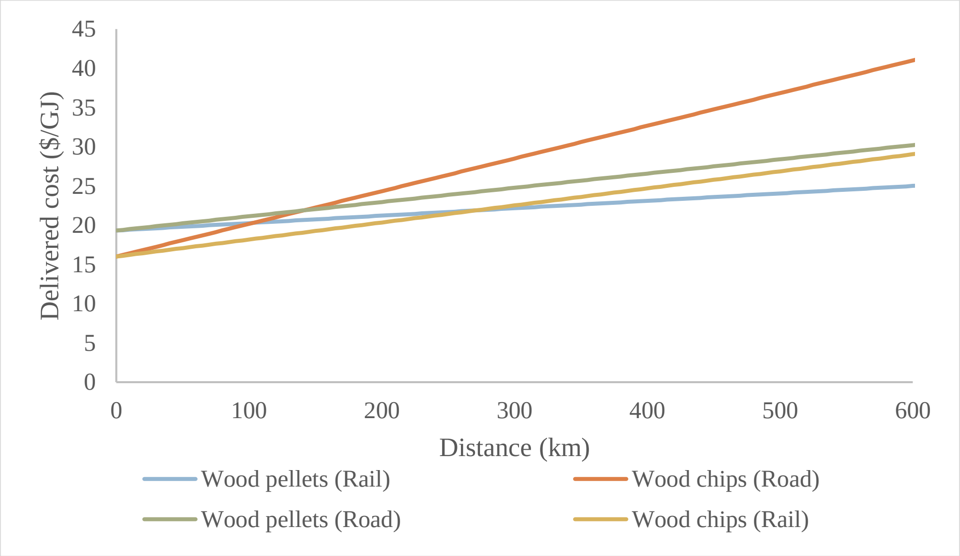


Figure 5-1: Relative cost of wood pelletisation against chipping, and modes of transport

Figure 5-1 shows that road transport of wood chips are more cost effective for a shorter transport distance, though beyond 100 km this quickly becomes far more costly than the alternative solutions. The use of rail transport for shorter distances has less practicality due to the added costs of transhipment and that many industrial sites still require road transport for delivery of biomass as they may not be located directly on a railway line. Transport of wood chips via rail has better economics in this example compared to wood pellets until approximately 270 km, and wood pellets become cost effective to transport by road when compared to wood chips after 150 km.

As electricity pricing and infrastructure is relatively consistent across each region and electricity can be easily transferred across the country due to the national grid, by comparison; the pricing of biomass is highly location dependent and largely subject to transport costs.

5.3.1 Sensitivity analysis

As the prices offered to industries across different regions and sectors will vary, a sensitivity analysis was conducted to determine the extent of biomass in >100°C heat relating to various factors including the price of electricity and the cost of transport via rail and road freight networks.

Electricity

Based on the prices of interregional transport and the resulting price of transported chip and wood pellets it would be expected that a reduction in the price of electricity by 10 and 20% would see substantial changes in the proportion of biomass in the energy mix. Reductions in price by 10 and 20% were chosen as arbitrary figures to give reasonable understanding of how these prices could affect the results. However, the price increases above the base case (100 $/MWh) were chosen because they represent the average electricity spot price for the lower South Island in the past five years. As stated earlier in Section 3.2.2, the electricity price forecasts presented by EECA do not account for transmission and network charges. This increase the cost of electricity for users and so the assumed base case of 100 $/MWh may be lower for the majority of users who pay retail prices. The higher price includes the dry year of 2021 (119 $/MWH), while the lower (106 $/MWh) is the average of the past five years with the 2021 dry year removed. Analysis was conducted on the 2023 interregional case study model and only the price of electricity for heat applications above 100°C was altered. The results of this sensitivity analysis can be seen in Figure 5-2 which shows that the proportion of biomass in the energy mix is very sensitive to the electricity price.

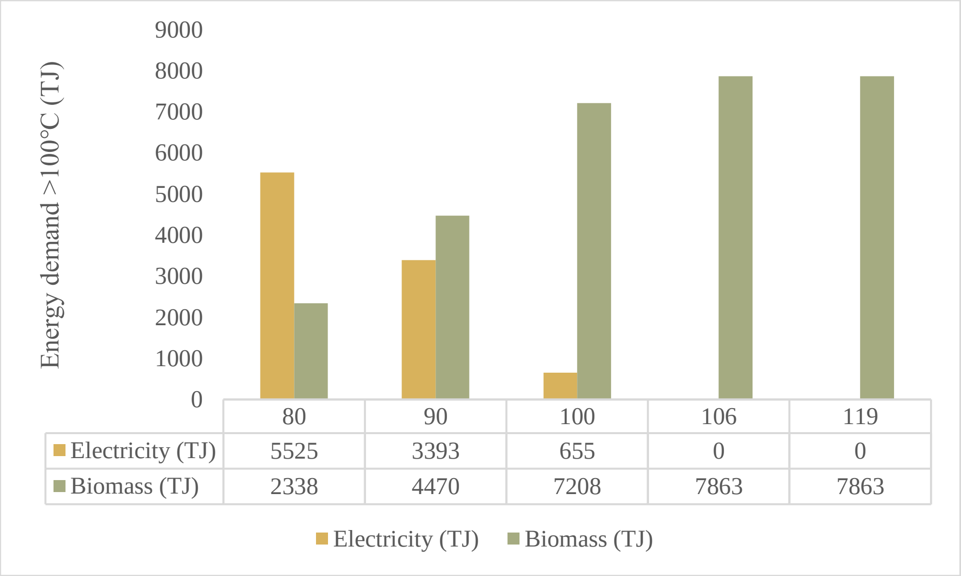


Figure 5-2: Results of the sensitivity analysis of the impact of the electricity price on the energy mix in heat demand above 100°C.

A decrease in electricity price by 10% sees the proportion of biomass drop from 91% to 57% for heat demand above 100℃, and a further reduction by 20% to 80 $/MWh sees this percentage drop further to 30% (Table 5-7). Whilst the electricity price had a large effect on the overall cost of energy and the use of biomass when the electricity price is reduced, there is far less impact when this is increased. An increase of just 6% to the five year average dry year removed sees no electricity use in the above 100℃ heat demand and only increases the overall LCOE by 0.01 $/GJ. A further increase to the true five-year average sees no further change in these figures.

Table 5-7: Summary of sensitivity analysis of electricity price.

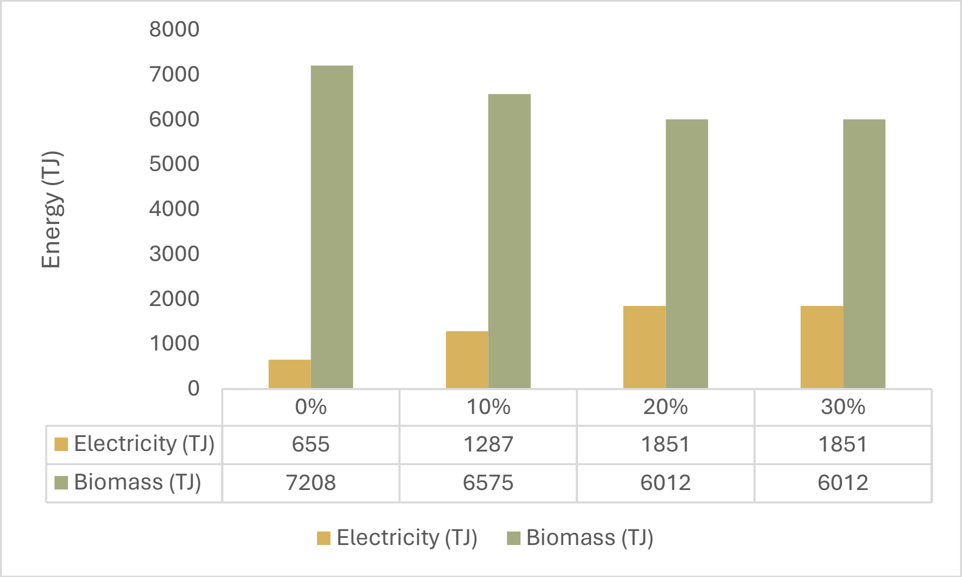
Electricity price ($/MWh)	Electricity (TJ)	Biomass (TJ)	Biomass proportion	LCOE electrical >100℃ ($/GJ)	Overall LCOE ($/GJ)
80	5525	2338	30%	25.01	17.05
90	3393	4470	57%	27.78	17.90
100	655	7208	92%	30.56	18.24
106	0	7863	100%	32.23	18.25
119	0	7863	100%	35.84	18.25

The application of a value of 50 $/MWh was attempted for the South Island case study; this would be in line with the low electricity price scenario outlined by Ergo in EECA (2023e). However, due to unknown issues with the P-Graph studio software the model did not solve in a timely manner consistent with the writing of this report and the exact results were unobtainable. At a purchase price of 50 $/MWh this would result in a LCOE for heat demand below 100℃ of just 16.67 $/GJ, and it is estimated to be cheaper than 85-90% of biomass sources. Figure 3-7 on page 44 displays the cost scenarios presented by Ergo. Assumptions included by Ergo in the low-price scenario are that the Tiwai Point aluminium smelter closes at the end of its contract in 2024, carbon unit and coal prices remain low, and large investment in new generation is undertaken by the government and private parties. In the near future, some of these factors are unlikely for several reasons: interest rates are high in order to combat inflation which reduces borrowing power (Reserve Bank of New Zealand, n.d.), and Tiwai is looking to continue operations far past in current 2024 contract end date (Daalder, 2023). Though this low-price scenario is still a possibility, the amount of infrastructure that would be required to connect new businesses to the grid for this increase in power would be immense. Lines companies have indicated that they will struggle to build enough transmission infrastructure in Waikato just to keep up with projected increase in demand from electric vehicle charging (Coffey, 2024) and it is fair to assume that this would be the case for the majority of networks across the country. Considering this, the addition of thousands of TJ each year on top of typical yearly increases will either result in a lack of service or massive cost increases for industries and consumers for transmission and grid connections beyond that outlined in the RETA reports (Radio New Zealand, 2023).

Transport

In recent years, the cost of transport has increased greatly, expanding from 25% of the delivered energy costs of biomass, to around 40% (Hall, 2023b), and these costs are reflected in much of the biomass price breakdown given previously in this work. A major focus of this work is on the regional variation of energy sources and in large part this is impacted by the transport requirements for each region and within the region itself. Expert opinions (EECA, 2023e; Hall & Palmer, 2020) reiterate that individual studies for each business should be considered to determine more accurate pricing for transport of biomass as this will fluctuate both according to proximity to forests and processing facilities, and to the annual supply variations in forests as different areas of forest reach maturity and are harvested.

Sensitivity on the cost of transport was analysed and increases of 10 – 30% were applied to both rail and road freight methods to determine the impact these would have on the proportion of biomass in the energy stack and the delivered cost of energy. These results are displayed below in Figure 5-3 and show that increases in transport costs have less impact on the final energy mix compared to the same increase in the cost of electricity. A lower impact is to be expected as transport is only a portion of the total cost of biomass.



	0%	10%	20%	30%
■ Electricity (TJ)	655	1287	1851	1851
■ Biomass (TJ)	7208	6575	6012	6012

Figure 5-3: Results of the sensitivity analysis comparing percentage transport cost increase and biomass in the above 100℃ energy mix.

An interesting result of the increases in transport costs was that even at the highest level of increase, there was still IRT between two regions. This transport was of wood pellets and suggests that this higher energy dense fuel source is more robust to the impacts of transport cost increases than that of the lower energy density wood chip. The increase in transport costs of 10% saw IRT of pellets from NMT to South Canterbury, and wood chips from Otago to South Canterbury become uneconomic, and electricity was used in place of these biomass sources. However, there was an increase in IRT of pellets from NMT to North Canterbury. This displaced some intraregional transport of residues, likely because the road freight for residues was more heavily impacted than rail transport of a more energy dense fuel. The 10% increase from the base case scenario resulted in a reduction in the portion of biomass in >100°C energy from 92 to 84% as the use of electrode boilers became more economic in South Canterbury than to importing biomass from other regions.

The increase from 10 to 20% saw the portion of biomass drop further to 76% of above 100°C heat demand. A reduction in transport of wood pellets from Otago to Southland was responsible for this, dropping from 76,860 t/y to 37,650 t/y. This number corresponds to the amount of cutover residue from Otago that was being pelletised and transported to Southland. As the cutover residue costs more to recover, the combination of the increase in transport costs made its transport to Southland uneconomic.

These transport options were pellets from Otago to Southland, and from NMT to North Canterbury. Both the 20 and 30% increase cases had the same proportion of electricity in the energy mix of heat demand above 100°C though there was an increase in the overall average LCOE as seen in Table 5-8.

Table 5-8: Summary of transport cost sensitivity analysis.

Transport cost increase	Electricity (TJ)	Biomass (TJ)	Biomass proportion	Overall LCOE ($/GJ)
0%	655	7,208	92%	18.24
10%	1,288	6,575	84%	18.49
20%	1,851	6,012	76%	18.72
30%	1,851	6,012	76%	18.91

5.3.2 The extent of biomass use

The graph below in Figure 5-4 describes the biomass utilisation on an annual basis for each of the regions in the South Island. The blue column is the usage without IRT, the orange column is with IRT, and the green column is the total available biomass. Only North Canterbury in the case study without IRT uses all available biomass. For most other regions there is a large amount of untapped resource potential, especially in NMT and Otago.

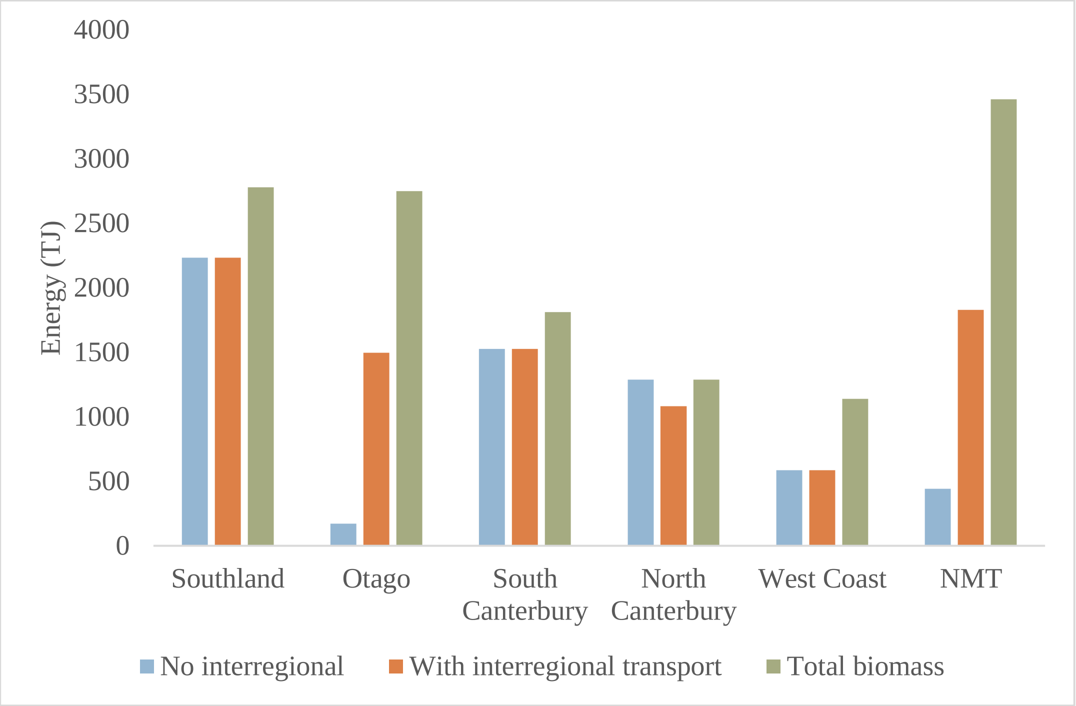


Figure 5-4: Biomass utilisation across the South Island case study in 2023.

5.3.3 Short rotation forestry

Purpose grown bioenergy forestry could offer additional solutions to providing dispatchable renewable energy for high temperature applications. There are no technical barriers to implementing a Short Rotation Forestry (SRF) growing regime and using it to drive a high-quality biomass market that could offer greater security to energy users both in terms of price and long-term security of supply. However, the major catch to these programs is that they would take around 15 years to reach maturity in NZ’s climate (Jones et al., 2022). This situation again reiterates the chicken and egg scenario that surrounds the nascent biomass market. Landowners will likely not want to invest the time and money if there is uncertainty regarding demand. In 2024, the demand for biomass does not exceed the available supply and it is possible that it never will. If site operators only made fuel switching decisions if they were certain that supply security was guaranteed into the future, long-term scenarios would likely not include building a new heat plant only to run out of fuel in ten years. Therefore, the supply of biomass in the future would dictate the installation of new biomass heat plants. A possible exception for this would be for a large agency, either a large energy user that has access to potential spare land from farmers, or the government which has the power to borrow money at low rates over long periods of time, to enact their own SRF scheme. In the case of Fonterra this could be done to secure their supply of biomass indefinitely. For the government it could be to incentivise and guarantee the supply of biomass for process heat users, or to act as dry year storage of energy in a biomass powered Huntly (Genesis Energy, 2023a).

Instead of the establishment of large amounts of new forest land specifically for bioenergy, what is more likely is what occurred in the South Island case study of this thesis. Biomass would be pelletised and transported from areas of excess forest residues to areas of high demand. This may be more expensive than for purpose grown bioenergy forestry, however, the absence of a 15 year wait time makes this option a lot more palatable. There may still be some time lag to construct sufficient pellet manufacturing capacity though this would likely be measured in low single digit years rather than decades. Another aspect that favours pellet transport over SRF is that forest owners will have more security that their product will have a market by using the well-established silviculture techniques to produce higher quality timber wood. This method still sees a substantial quantity of by-products created as well as forest residues for bioenergy.

An estimate of costs for SRF was made to give an idea of how much the resource cost could be. Under the assumptions outlined in Table 3-18 on page 51 which were made in consultation with Hall (2023a), and MPI and Nanayakkara (2023), the resource cost of SRF could be in the range of 75 – 80 \$/t or 10.40 – 11.10 \$/GJ excluding transport and comminution. These costs accounted for a range of establishment costs for a new forestry block including roading, landings, and purchase of the land. Costs for an existing forestry block could be much less, as low as 50 \$/t. These costs in comparison to several of the resource costs outlined for the regions in Table A-3 of Appendix A would be very competitive. Pruned logs generally sell for more than twice these values: EECA (2023e) estimates a value of 160 $/t, however these logs take a full 25 – 30 year rotation to grow. The ability to harvest at 15 year intervals may be very attractive to forestry owners, though will incur the costs to replant, harvest and care for the land twice as often as for conventional silviculture.

5.3.4 Summary

In short, IRT has the potential to enable over 90% of heat demand above 100℃ in the South Island to be sourced from biomass. When considering that fuel switches must be made to RES by 2037, and that the two technologically and economically feasible options are biomass and electricity, biomass is typically going to be the lowest cost option for above 100℃.

A greater use of biomass would allow electricity to be used in areas where biomass is either not feasible or not economic, or in hard to abate sectors. A greater use of biomass would reduce reliance on electrical infrastructure and greatly reduce the cost of electricity for consumers across the board from industry to residential. It would also serve to diversify the energy mix and in doing so would give greater security of energy supply in the future.

Overall, this work shows that the widespread use of biomass to supply over 90% of the South Island's energy needs above 100℃ is economically and logistically feasible. The energy densification of biomass into wood pellets gives robust transport characteristics and a wide range of applications, however the availability of biomass and its subsequent transport cost varies depending on the region. This study considered to some degree the impact of intraregional transport in the case of Southland (Section 3.2.4), but this still needs further exploration and the relative abundance and proximity of biomass for each site needs to be considered.

5.4 Limitations of the study

5.4.1 Forest residue quality

A decision that has likely impacted a large part of this work was built around the idea that forest residue was a low-quality fuel source due to it being left on the harvest site and contaminated with dirt, metal and stones. Anecdotal evidence from industry groups also lead to this assumption as a dairy plant operator stated that their boiler output would undergo fluctuations due to the quality of forest residue derived hog fuels that was used to fuel it. The construction of the P-Graph studio models was initially built around two types of biomass fuel, wood chips, and hog fuel, and these each of these fuels restricted in the model to specific boilers. Wood chips were assumed to be combusted in a solid fuel chip boiler with higher efficiency (80%) based on wood chips being considered higher quality fuels due to their particle uniformity and lower moisture content (Bioenergy Association NZ, 2022a). Hog fuels derived from forest residue on the other hand were assumed to require a BFB boiler which could handle fuels with higher moisture content, producing a lower efficiency (70%), and requiring double the capital investment compared to solid fuel chip boilers ($2M/MW compared to $1M/MW (Table 3-9, page 47)). As stated earlier in this chapter, the higher capital cost of the BFB boilers contributes almost an additional 2 $/GJ to the LCOE over a 17-year payback period. If these fuels did not require such a costly boiler, the economics of biomass fuel switching would be positively impacted and could lead to an even higher proportion of biomass in the energy mix.

One aspect that will likely see the increase in quality of biomass from forest residue is the growing market for biomass as an energy source. A large part of the reason that forest residue can be a poor energy source is that there has been no demand for forest residue and it was uneconomic to remove from the forest and was therefore left to decompose. However, the growing interest in biomass energy has led to EECA (2023e) and Margules Groome suggesting the creation of an E-grade (energy grade) log. Margules Groome suggests that this could lead to several benefits including improving the quality of the fibre recovered from forest residue due to lower contamination, improving ecological outcomes for the harvested area, and providing more competitive harvesting rates (EECA, 2023e). An E-grade log could provide a good market for forestry residue especially in combination with new regulations that require the removal of sound wood greater than 2 m long and a SED greater than 10 cm from orange and red zoned forestry land ("Resource Management (National Environmental Standards for Commercial Forestry) Regulations 2017," 2023). Both of these factors could help to facilitate a greater market and a higher quality biomass source from forest residue, a previously largely untapped resource.

Forest residue quality will vary depending on the region where it is collected. Soils around the Taupo Volcanic Zone are high in pumice which can wear down comminution machinery such as wood chippers and pellet plants, however the use of forest residue to create wood pellets in other regions of NZ is possible (McBrearty, 2024). The implication is that forest residue does not need to be confined to a more expensive BFB boiler, and that it can serve as a potentially lower cost source of fibre to create wood pellets. Both these factors would impact the results of this work but only the ability of residues to be used for wood pellets was implemented due to time constraints.

The use of residues for wood pellets proved to be a major factor in the interregional model suggesting that biomass can achieve positive economics for over 90% of fuel switching decisions that require heat above 100℃. Without interregional transport of wood pellets, the proportion of biomass drops to just 61% (Table 4-30, page 94), so if it was to be assumed that 90% of fuel switches over 100℃ could be made to biomass, a third of this relies on positive economics of pelletisation and long-distance transport using rail freight.

The sensitivity of biomass in the energy mix to increase in freight costs was tested in Section 5.3.1. An increase in both rail and road freight costs did reduce the economic viability of biomass as would be expected, though even with a 30% increase in freight costs, biomass accounted for 76% of the energy demand over 100°C. Changes in fuel switching optimisation occurred in the increase from base case to 10 and then 20% though the jump to 30% showed no further change compared to that at 20% increase. Surprisingly, the increase in freight costs by 10% actually saw an increase in the amount of wood pellet transported from NMT to North Canterbury, the quantity of pellets transported between these regions remained the same at further increases in costs. This surprising change highlighted the greater efficiency of rail transport and if interregional transport of wood pellets is undertaken in the South Island the use of rail transport for distances greater than approximately 250 km is likely to be a necessity (Figure 5-1, page 103).

5.4.2 Capital costing of heat plants

An additional assumption made in this work was for the capital cost of heat plants and electricity infrastructure upgrades. As stated earlier in Section 3.2.5 typically heat plants' CAPEX is determined by the maximum peak energy demand that the plant can service. Because this optimisation is considered in yearly time periods, energy demand was for a yearly period and did not consider the fluctuations in demand that can occur within plants. For example, a 10MW plant operating for 12 hours a day would consume the same amount of energy as a 5 MW plant operating for 24 hours; by conventional capital cost estimates, the 10 MW plant would cost about twice as much as the 5 MW plant. However, this work annualised these costs to align with the supply and demand data because a major focus was on the overall consumption of energy. In this work, both plants would be allocated the same CAPEX because they consumed the same amount of energy over an annual period. This is a limitation of this work which may mean that the costing will not be as accurate for industries with large fluctuations in demand and thus requiring large peak capacity heat plants. The working in Section 3.2.5 outlines some aspects that were adjusted to reduce potential discrepancies between conventional peak capacity capital estimates, and annual throughput estimates used in this work. A 90% capacity factor was used to reduce the overall CAPEX estimates as the majority of boilers would not be operating at their maximum capacity all the time. Each annualised CAPEX value also assumed 6,000 operating hours which was intended to reflect the dairy industry i.e. the largest energy use sector in most regions (EECA, 2022, 2023c, 2023d, 2023e, 2023f, 2023g). Again, this highlights that this study was conducted to give a better understanding of the overall energy use and an indication of relative costs. For greater accuracy each site would need to undertake economic and feasibility studies to determine the optimum fuel switching decision for them.

5.5 Demand flexibility

An aspect that is of growing interest to the energy community is that of demand flexibility. The average electricity spot price over the past five years for the lower South Island was 119 $/MWh (Electricity Authority, 2024), which means that 50% of the time the price was lower than 119 $/MWh. Businesses that can shift the timing of their processes, or store energy when electricity prices are cheap for use at times of high demand may see substantial economic benefit. Electricity prices are already offered over separate time periods that reflect the wider demand in the market and incentivise businesses to reduce their use when demand is high (EECA, 2023e). As discussed in Section 2.1, the integration of more VRE into the electricity grid brings greater fluctuation in prices as the supply of solar and wind fluctuations will not always coincide with the existing demand patterns of industry. Industries will likely adapt their demands to take advantage of periods with an abundance of electricity and thus lower prices and reduce demand in times of low VRE supply. It may also be likely that Electricity Distribution Businesses (EDB) will look to incentivise businesses to shift their electricity demand, especially in times where the residential demand is typically high. Load shifting could more effectively reduce the amount of new generation and transmission infrastructure that needs to be installed in the coming decades, both reducing costs for NZ and the embodied carbon emissions that come with large infrastructure projects.

If load shifting became the industry standard it could see many fuel switching decisions swing towards electrification to achieve greater economics. However, this could mean unconventional operating hours for businesses which may be unfavourable for employees or unviable for many industries and sites and so the trade-offs of greater economics would be weighed against whether processes could be time shifted and tolerated by employees.

5.6 Energy security

A significant trend that this work investigated was the impact of falling harvest volumes in the 2030s. Lower harvest volumes translated as expected to a constrained supply of biomass in the 2037 studies. Instead of the over 90% of heat demand above 100℃ being supplied by biomass for the South Island with IRT in the 2037 case study, this value could only reach 72%. The impact of growing energy demand, and lower biomass supply led to a much lower proportion of biomass used for heat demand above 100℃, and therefore a higher overall weighted average LCOE for the South Island. This higher LCOE was driven by increases in energy costs in the three major energy users as they would need to rely on more costly electrical energy to meet their demands. Increased energy prices for heat demand above 100℃ would likely not be felt for those regions that have sufficient biomass; Otago, the West Coast, and NMT.

In addition to providing greater economics, IRT of biomass, and the resulting increased use of biomass provides greater energy security to the South Island through the diversification of energy sources. This also reduces strain on the upgrades required for the electricity network and its generational and transmission infrastructure. Planting of substantial areas of short rotation forestry would be another method to greatly increase the energy security of NZ in addition to providing stable prices for energy users. However, as stated earlier in this chapter; an effective SRF scheme requires long-term commitments from both energy users and forest owners and this relationship has not been observed outside of small portions of crown-owned land used for SRF trials. The shorter time frame required to establish pellet plants and transport pellets interregionally would likely fill most of the gaps in the energy demand without the 15 year lag required for SRF to mature.

Of particular interest to lines companies is that the addition of interregional transport has the potential to almost halve the required investment in upgrades to the electricity transmission network. For 2023 in the South Island case study; total investment required to accommodate all the electricity network growth was over $128 million, when IRT was used this dropped to just $68 million. Substantial investment is still required to provide the necessary infrastructure for the transition to net zero carbon over the coming decades, however the greater use of biomass for heat demands above 100°C would heavily reduce the economic and time investment required. This could also result in lower electricity prices for all users, as the cost of building new infrastructure is generally passed to the user through network and transmission pricing.

Chapter 6 Conclusions and recommendations for future work

6.1 Conclusions

This study was undertaken in response and to support NZ in achieving Net Zero carbon emissions by 2050. The aim of this study was to provide novel methods to evaluate the extent that biomass could economically supply NZ's process heat users by modelling and optimising the allocation of renewable energy resources in NZ. The conclusions of this work were derived from a range of case studies that investigated the optimum allocation of resource in the regions of the South Island of NZ.

The key findings of this study relate to the foci of each case study: the impact of regional resource and energy infrastructure diversity; the impact of temperature and scale of plant size on its energy cost; and the economic potential of IRT to reduce energy costs and increase energy security in the South Island.

Regional variation in biomass supply

In the regional case studies, it was determined that those regions with a high supply of biomass, and low energy demand would see the lowest LCOEs for heat applications above 100°C. The LCOE for heat demand below 100°C largely showed little fluctuation due to the complete prevalence of HTHPs. The ability of a HTHP to produce upwards of three or four units of heat from only a singular unit of electrical energy (as well as the input of heat from the air, or waste process heat) gives this technology highly competitive economics that will be able to meet or surpass the current cost of coal derived heat below 100°C. The transport and collection costs of low energy dense fuels was found to be a large contributor to the final LCOE, and in some regional case studies, constrained the use of biomass for demands above 100°C in favour of electrically derived heat.

Scale and temperature profile of the demand

The individual site case studies demonstrated that both the scale and temperature demand profile of a plant will impact its final LCOE. A plant's scale will impact the LCOE for heat demand above 100°C; as the plant's energy demand grows, it exhausts the supply of the lowest cost sources of biomass, and must then source from either an increasing radius, or increasingly expensive sources of biomass. Depending on the scale of the energy demand, individual sites will not necessarily follow regional energy price trends. This was observed for the MPP which saw a lower weighted average LCOE in North Canterbury as opposed to Southland, which was in contrast to the trends of the much larger dairy plant, and of the regional case studies.

The impact of a plant’s temperature demand profile echoes the previous paragraph when using HTHPs to provide heat for below 100℃ applications. The greater the proportion of a plant, or region’s heat demand that is below 100℃, the lower the overall LCOE. The economics of HTHPs to provide this heat are typically superior to the economics of any biomass source.

Economics of interregional biomass transport

The case studies concerning IRT indicated that the majority of fuel switches for heat demands above 100℃ could be most economically provided by biomass once energy dense biomass sources were transported from neighbouring regions. The use of IRT saw the proportion of biomass in heat applications above 100℃ rise from 60%, to over 91% in the 2023 case studies of the South Island. This also saw the weighted average LCOE of the three largest energy consuming regions drop; the largest impact was in North Canterbury which saw a 10% reduction in the LCOE for heat demand above 100℃. The IRT case studies for 2037 saw similar trends in the reduction of LCOE for the three largest energy users. In both the 2023 and 2037 case studies, the use of interregionally transported biomass displaced the more expensive electricity in these regions.

6.2 Recommendations for future work

Analysis of supply level year by year

This work constrained its focus to just two years for the case studies; 2023, and 2037. These provided foresight of a snapshot in time, however supply varied across all regions between these two years, especially during the 2030s which sees very low harvest levels. Whilst P-Graph does not allow for multiyear analysis, it does have functionality for multiperiod analysis. One method could be to divide the model into monthly periods but treat each month as a year in P-Graph with the corresponding supply levels and energy demands. This could provide insight to supply constraints over multiple years, and capital cost rates could potentially be scaled to account for the change in time period. Alternatively, functionality could be added into P-Graph Studio to allow for multi-year periods.

Spatial model

A limitation of this work was that it applied generic transport cost rates. In several areas of this study the importance of transport costs, and how specific they can be to each site, was highlighted. Models do exist to predict these levels in NZ (Hall & Palmer, 2020), though they are not publicly available. A model that incorporated GIS layers of forestry supply, as well as the location and demands of energy users, could be combined with temporal data to give more accurate estimates of the energy supply and demand over time. This model could also make use of terrain data to estimate the quantity of residue collected from each harvest site, building on the work of Hall (2022) and Harvey (2022).

Biomass moisture content and transport

This work considered that all biomass with the exception of wood pellets was transported at a moisture content of 55%. This aligned with the work conducted by EECA and simplified the complexity of the modelling and optimisation. As transport costs are greatly affected by moisture content, the effects of drying biomass before transport should be investigated. It has been shown that the moisture content can be greatly reduced over three to four months on site (Visser, Hall, et al., 2010). If space, time and economics allowed for this to be applied to all biomass, the transport costs could be reduced by 40 -50% on an energy basis.

Integration of hybrid energy systems

There is growing interest in the use of hybrid renewable energy systems (Eriksson & Gray, 2019; Guelpa et al., 2019; Walmsley et al., 2023). Integration of multiple energy systems such as a biomass-electrode boiler hybrid or dual heat plant system could see great benefits for energy users in both economics and supply resilience. These systems could also account for each other's shortcomings, for example electrode boilers have very quick ramp up periods which can be used to respond to demand fluctuations far better than biomass boilers. Integration of these systems into a larger costing optimisation would be complex as it increases the number of factors and 'moving parts', though could be explored at smaller scale before being applied to regional or national models.

Use of electrical load shifting

Electricity spot prices fluctuate heavily, and there are periods where the wholesale electricity price is close to zero (Electricity Authority, 2024). For businesses that do not operate on a spot market price, pricing is still allocated on a time of use basis, with cheaper rates offered in times of low demand to incentivise businesses to shift their demand away from periods of high grid demand (EECA, 2023e). As pressures on the electricity network grow, and more variable renewable electricity sources such as wind and solar are integrated, prices too will fluctuate to a greater extent. Load shifting would entail energy users incorporating more flexibility into their utility systems or processes, turning these down in periods of high demand, and taking advantage of times of low electricity prices by increasing production or energy storage. This could be incorporated into a P-Graph model either by applying historic spot price data to an energy system or using the multiperiod function to simulate daily price brackets offered to businesses.

Very High Temperature Heat Pumps

As mentioned in Chapter 5, VHTHPs are increasing in prominence in NZ. Their use to produce low temperature steam demand could see great economic benefit to industry users, both as standalone heat plants, and integrated as hybrid systems. This would change the optimal resource allocation, and modelling in the future could account for these advancements, whilst acknowledging that these VHTHPs tend to require greater levels of expertise than traditional boilers, and their capital costs are likely to be greater.

Ecological considerations

The use of biomass for combustion has carbon neutral status in NZ (EECA, 2023e), however there is growing scepticism globally about the true carbon neutrality of biomass. This should be critically examined in the NZ context to determine how NZ’s production forestry and ecological factors impact and are impacted by more combustion of biomass.

There are also additional factors that must be taken into account when fuel switching. Particle emissions, spatial footprint both for storage and heat plants, and fuel handling all need to be taken into account and have not been considered in this work. These factors will differ by location and may impact the North Island more so than the South. This could be due to the higher population density which could limit particle emissions and restrict the use of biomass boilers. There is also presumably less space available for many businesses that operate gas boilers, which have no need for fuel storage if they are connected to the natural gas pipeline, so the addition of large areas for biomass storage and handling would be a challenge. This could mean that electricity is the only practical fuel switch for many businesses.

Hot water biomass boilers and electricity pricing

This work only considered biomass boilers with capital costs indicative of steam producing boilers. Lower cost hot-water biomass boilers are available and could potentially be used where sources of cheap biomass are available, or if electricity prices were high.

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Appendix A Supplementary information

Table A-1: Material parameter inputs for the basic P-Graph example.

Name	Type	Price		Flow		Cost ($/y)
Electrical energy	Intermediate Material	0.00	$//TJ	0.00	TJ/y	0.00
Electricity	Raw Material	100.00	$/MWh	11,888.90	MWh/y	1,188,890.00
Low grade wood	Raw Material	50.00	$//t	10,000.00	t/y	500,000.00
Steam demand	Product Material	0.00	$//TJ	100.00	TJ/y	0.00
Wood chips	Intermediate Material	0.00	$//t	0.00	t/y	0.00
Wood energy	Intermediate Material	0.00	$//TJ	0.00	TJ/y	0.00
Total cost of materials ($//y)						1,688,890.00

Table A-2: Operating unit cost breakdown for solution 1 in the basic P-Graph example.

Name	Size factor	Operating cost		Investment cost		Overall cost		Cost ($/y)
		Fixed charge ($/y)	Prop. constant ($/y)	Fixed charge ($/y)	Prop. constant ($/y)	Fixed charge ($/y)	Prop. constant ($/y)	
Biomass boiler	71.50	0.00	0.00	0.00	41,667.00	0.00	2,451.00	175,246.00
Electrode boiler	42.80	0.00	0.00	0.00	16,667.00	0.00	980.41	41,961.60
MWh to TJ	11,888	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tonnes to TJ	10,000	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wood chipper 1	10,000	0.00	15.00	0.00	0.00	0.00	15.00	150,000.00
Total cost of operating units ($/y)								367,207.60

In Table A-3 below, biomass costs and availability for 2023, and availability for 2037 were sourced from (EECA, 2022, 2023a, 2023c, 2023d, 2023e, 2023f, 2023g), whilst the costs for 2037 were estimated using the method outlined in Section 3.2.9 on page 51.

Table A-3: Biomass availability and costs for 2023 and 2037 in the South Island.

Region	Resource	2023		2037	
		Supply	Cost ($/t)	Supply	Cost ($/t)
Southland	Processor residue	3,920	40	3,920	52.06
Southland	Harvest residue	83,008	41	250,000	53.36
Southland	Chip log	50,000	62	50,000	80.69
Southland	Export log	250,000	107	85,152	139.26
Otago	Processor residue	11,365	20.6	11,365	26.81
Otago	Roadside residue	75,299	31.77	49,734	41.35
Otago	Cutover residue	83,590	45.56	62,462	59.30
Otago	Minor species	20,429	34.94	18,240	45.47
Otago	Export log	192,145	87.9	156,257	114.40
S. Canterbury	Processor residues	19,625	42	19,625	54.66
S. Canterbury	Roadside residue	28,539	46	9,442	59.87
S. Canterbury	Cutover residue	64,933	55	39,978	71.58
S. Canterbury	Wilding pines	25,432	73	25,432	95.01
S. Canterbury	Export/pulp log	113,572	102	51,997	132.75
N. Canterbury	Processor residues	10,854	17.9	10,854	23.30
N. Canterbury	Roadside residue	47,289	33.3	17,306	43.34
N. Canterbury	Cutover residue	28,505	49.90	15,562	64.94
N. Canterbury	Minor species	12,635	37.30	73,990	48.55
N. Canterbury	Export log	79,863	102.9	39,847	133.92
West Coast	Processor residues	51,479	45.85	59,757	59.67
West Coast	Roadside residue	12,831	33.30	10,476	43.34
West Coast	Cutover residue	12,856	49.9	10,496	64.94
West Coast	Minor species	18,145	31.55	47,190	41.06
West Coast	Export log	63,143	102	56,284	132.75
NMT	Processor residues	10,399	16.2	10,399	21.08
NMT	Roadside residue	266,323	33.30	241,373	43.34
NMT	Cutover residue	68,261	49.9	62,258	64.94
NMT	Minor species	12,495	47.30	6,116	61.56
NMT	Export log	124,166	102	-	132.75

Appendix B Case study data

Table B-1: Materials cost breakdown for Southland 2023.

Resource	Price		Flow		Cost ($/y)
Processor residues	40.00	$/t	3,920	t/y	156,800
Harvest residues	41.00	$/t	83,008	t/y	3,403,330
Chip log	62.00	$/t	50,000	t/y	3,100,000
Export log	107.00	$/t	174,020	t/y	18,620,100
Electricity	100.00	$/MWh	459,984	MWh/y	28,466,700
Total cost of materials					71,278,630

Table B-2: Operating unit costs for Southland 2023.

Operating unit	Size factor	Cost rate	Cost ($/y)
Infrastructure			
BFB Boiler	596.33	3,431.35	2,046,220
Electrical infrastructure	1,655.94	1,511.53	2,503,011
Electrode boiler	1,024.80	970.59	994,659
HTHP	631.14	8,578.41	5,414,200
Solid fuel boiler	1,637.52	1,960.76	3,210,790
Processes			
Hogging machine	83,008	15	1,245,120
Storage	310,948	10	3,109,480
Transport of biomass	310,948	Various	5,231,220
Wood chipper	224,020	15	3,360,300
Total cost of operating units ($/y)			27,115,000

In the above table of operating unit costs (Table B-2), the unit costs for infrastructure such as heat plants and electrical infrastructure are reflective of the per unit cost divided by the number of years in the payback period, in this case 17 years.

Table B-3: Material costs in the optimal solution structure Southland 2037.

Item	Price		Flow		Cost ($/y)
Processor residues	52.00	$/t	3,920	t/y	203,840
Harvest residues	53.30	$/t	85,152	t/y	4,538,602
Chip log	80.70	$/t	50,000	t/y	4,035,000
Export log	139.30	$/t	174,020	t/y	24,240,986
Electricity	130.00	$/MWh	551,300	MWh/y	71,669,000
Total cost of materials					104,966,402

Table B-4: Operating unit costs for Southland 2037.

Operating unit	Size factor	Cost rate	Cost ($/y)
Infrastructure			
BFB Boiler	611.73	3,431.35	2,099,070
Electrical infrastructure	1,984.68	1,511.53	2,999,900
Electrode boiler	1,290.68	970.59	1,252,720
HTHP	694.00	8,578.41	5,953,420
Solid fuel boiler	1,637.52	1,960.76	3,210,790
Processes			
Hogger	85,152.00	19.5	1,660,460
Storage	313,092.00	13.1	4,101,502
Transport of biomass	313,092.00	Various	6,858,450
Wood chipper	224,020.00	19.5	4,368,390
Total cost of operating units ($/y)			32,504,702

B.1 South Island case study data

This appendix presents the resource cost breakdowns and resource flows for the South Island case study.

B.2 South Island 2023 without interregional transport

Table B-5: Resource flows and cost breakdown for Southland without IRT in 2023

Individual energy costs	Annual demand	Transport distance	Delivered cost $/GJ	LCOE $/GJ
Processor residues	3,920 t (28 TJ)	Low	8.49	13.06
		Medium	9.46	14.28
Harvest residues	83,008 t (596 TJ)	Low	10.72	15.31
		Medium	11.69	16.70
		High	13.78	19.68
Chip log	50,000 t (359 TJ)	Low	13.64	19.50
		Medium	14.61	20.72
Export log	174,020 t (1250 TJ)	Low	20.32	27.85
		Medium	21.29	29.07
Electrode boiler	284,667 MWh (1025 TJ)			30.57
HTHP	175,317 MWh (631 TJ)	-	27.78	10.82

Table B-6: Resource cost breakdown for South Canterbury without IRT in 2023.

Individual energy costs	Annual demand	Transport distance	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	19,625 t (141 TJ)	Low	8.77	13.41
		Medium	9.74	14.63
Roadside residues	28,539 t (205 TJ)	Low	11.41	21.21
		Medium	12.39	22.60
		High	14.47	25.58
Cutover residues	64,933 t (467 TJ)	Low	12.67	23.00
		Medium	13.64	24.39
		High	15.73	27.37
Wilding pines	25,432 t (183 TJ)	Low	15.17	21.41
		Medium	16.14	22.63
Export logs	73,915 t (531 TJ)	Low	19.21	26.46
		Medium	20.18	27.68
Electrode boiler	374,072 MWh (1347 TJ)	-	27.78	30.01
HTHP	189,683 MWh (683 TJ)	-	27.78	10.66

Table B-7: Resource cost breakdown for Otago without IRT in 2023.

Individual energy costs	Annual demand	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	11,365 t (82 TJ)	9.55	14.39
Minor species	12,473 t (90 TJ)	15.23	21.49
Electricity (HTHP)	45,079 MWh (162 TJ)	27.78	10.66

Table B-8: Resource cost breakdown for North Canterbury with IRT in 2023.

Individual energy costs	Annual demand	Delivered cost $/GJ	LCOE $/GJ
Processor residues	10,854 t (78 TJ)	4.50	8.07
Roadside residues	47,289 t (340 TJ)	15.81	27.49
Cutover residues	28,505 t (205 TJ)	17.65	30.11
Minor species	12,635 t (91 TJ)	16.53	23.12
Export log	79,863 t (574 TJ)	19.82	27.22
Electricity (Electrode boiler)	203,946 MWh (734 TJ)	27.78	31.11
Electricity (HTHP)	173,651 MWh (625 TJ)	27.78	10.97

Table B-9: Resource cost breakdown for West Coast with IRT in 2023.

Individual energy costs	Annual demand	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	51,479 t (370 TJ)	14.18	20.17
Minor species	18,145 t (130 TJ)	15.53	21.86
Export log	11,807 t (85 TJ)	18.09	25.07
Electricity (HTHP)	30,714 MWh (111 TJ)	27.78	10.78

Table B-10: Resource cost breakdown for NMT with IRT in 2023.

Individual energy costs	Annual demand	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	10,399 t (75 TJ)	9.20	13.95
Roadside residue	38,657 t (278 TJ)	13.49	24.17
Minor species	12,495 t (90 TJ)	18.09	25.07
Electricity (HTHP)	40,714 MWh (147 TJ)	27.78	10.78

B.3 South Island 2023 with interregional transport

Table B-11: Resource cost breakdown for Southland with IRT in 2023.

Individual energy costs	Annual demand	Transport distance	Delivered cost $/GJ	LCOE $/GJ
Processor residues	3,920 t (28 TJ)	Low	8.49	13.06
		Medium	9.46	14.28
Harvest residues	83,008 t (596 TJ)	Low	10.72	20.21
		Medium	11.69	21.60
		High	13.78	24.59
Chip log	50,000 t (359 TJ)	Low	13.64	19.50
		Medium	14.61	20.72
Export log	174,020 t (1250 TJ)	Low	20.32	27.85
		Medium	21.29	29.07
Pellets from Otago	76,860 t (1268 TJ)	IRT	17.91	24.84
HTHP	175,317 MWh (631 TJ)	-	27.78	10.82

Table B-12: Resource cost breakdown for South Canterbury with IRT in 2023.

Individual energy costs	Annual demand	Transport distance	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	19,625 t (141 TJ)	Low	8.77	13.41
		Medium	9.74	14.63
Roadside residues	28,539 t (205 TJ)	Low	11.41	21.21
		Medium	12.39	22.60
		High	14.47	25.58
Cutover residues	64,933 t (467 TJ)	Low	12.67	23.00
		Medium	13.64	24.39
		High	15.73	27.37
Wilding pines	25,432 t (183 TJ)	Low	15.17	21.41
		Medium	16.14	22.63
Export logs	73,915 t (531 TJ)	Low	19.21	26.46
		Medium	20.18	27.68
Wood chip from Otago	7,956 t (57 TJ)	Interregional	20.70	25.57
Pellets from NMT	47,906 t (790 TJ)	Interregional	21.21	29.80
Electrode boiler	183,814 MWh (662 TJ)	-	27.78	30.01
HTHP	189,683 MWh (683 TJ)	-	27.78	10.66

Table B-13: Resource cost breakdown for Otago with IRT in 2023.

Individual energy costs	Annual demand	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	3,409 t (24 TJ)	9.55	14.39
Minor species	20,429 t (147 TJ)	15.23	21.49
Electricity (HTHP)	45,079 MWh (162 TJ)	27.78	10.66

Table B-14: Resource cost breakdown for North Canterbury with IRT in 2023.

Individual energy costs	Annual demand	Delivered cost $/GJ	LCOE $/GJ
Processor residues	10,854 t (78 TJ)	4.50	8.07
Roadside residues	47,289 t (340 TJ)	15.81	27.49
Minor species	12,635 t (91 TJ)	16.53	23.12
Export log	79,863 t (574 TJ)	19.82	27.22
Electricity (HTHP)	173,651 MWh (625 TJ)	27.78	10.97
Pellets from NMT	65,925 t (1088 TJ)	18.29	25.31

Table B-15: Resource cost breakdown for West Coast with IRT in 2023.

Individual energy costs	Annual demand	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	51,479 t (370 TJ)	14.18	20.17
Minor species	18,145 t (130 TJ)	15.53	21.86
Export log	11,807 t (85 TJ)	18.09	25.07
Electricity (HTHP)	45,079 MWh (162 TJ)	27.78	10.78

Table B-16: Resource cost breakdown for NMT with IRT in 2023.

Individual energy costs	Annual demand	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	10,399 t (75 TJ)	9.20	13.95
Roadside residue	38,657 t (278 TJ)	13.49	24.17
Minor species	12,495 t (90 TJ)	18.09	25.07
Electricity (HTHP)	40,714 MWh (147 TJ)	27.78	10.78

B.4 South Island 2037 without interregional transport

Table B-17: Resource cost breakdown for Southland without IRT in 2037.

Individual energy costs	Annual demand	Transport distance	Delivered cost $/GJ	LCOE $/GJ
Processor residues	3,920 t (28 TJ)	Low	11.05	16.26
		Medium	12.31	17.84
Harvest residues	85,152 t (612 TJ)	Low	13.95	24.82
		Medium	15.21	26.63
		High	17.94	30.53
Chip log	50,000 t (359 TJ)	Low	17.75	24.63
		Medium	19.01	26.22
Export log	174,020 t (1250 TJ)	Low	25.90	34.83
		Medium	27.17	36.41
Electrode boiler	358,522 MWh (1291 TJ)	-	36.11	38.98
HTHP	192,778 MWh (694 TJ)	-	36.11	13.20

Table B-18: Resource cost breakdown for South Canterbury without IRT in 2037.

Individual energy costs	Annual demand	Transport distance	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	19,625 t (141 TJ)	Low	11.41	16.72
		Medium	12.68	18.30
Roadside residues	9,442 t (68 TJ)	Low	14.85	26.12
		Medium	16.12	27.93
		High		
Cutover residues	39,978 t (287 TJ)	Low	16.48	28.44
		Medium	17.75	30.25
		High		
Wilding pines	25,432 t (183 TJ)	Low	19.74	27.12
		Medium	21.00	28.70
Export logs	51,997 t (374 TJ)	Low	25.00	33.70
		Medium	26.26	35.28
Electrode boiler	541,158 MWh (1948 TJ)	-	36.11	38.43
HTHP	208,571 MWh (751 TJ)	-	36.11	13.04

Table B-19: Resource cost breakdown for Otago without IRT in 2037.

Individual energy costs	Annual demand	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	11,365 t (82 TJ)	12.43	17.99
Minor species	14,909 t (107 TJ)	19.82	27.22
Electricity (HTHP)	49,524 MWh (178 TJ))	36.11	13.04

Table B-20: Resource cost breakdown for North Canterbury without IRT in 2037.

Individual energy costs	Annual demand	Delivered cost $/GJ	LCOE $/GJ
Processor residues	10,854 t (78 TJ)	5.85	9.76
Roadside residues	17,306 t (124 TJ)	20.57	34.29
Cutover residues	15,562 t (112 TJ)	23.03	37.81
Minor species	73,990 t (532 TJ)	21.52	29.35
Export log	39,847 t (286 TJ)	25.65	34.51
Electricity (Electrode boiler)	277,803 MWh (1000 TJ)	36.11	39.52
Electricity (HTHP)	190,952 MWh (687 TJ)	36.11	13.35

Table B-21: Resource cost breakdown for West Coast without IRT in 2037.

Individual energy costs	Annual demand	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	59,757 t (429 TJ)	18.46	25.52
Minor species	29,852 t (214 TJ)	20.21	27.71
Electricity (HTHP)	33,810 MWh (122 TJ)	36.11	13.16

Table B-22: Resource cost breakdown for NMT without IRT in 2037.

Individual energy costs	Annual demand	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	10,399 t (75 TJ)	12.87	18.54
Roadside residue	52,316 t (376 TJ)	17.54	29.95
Minor species	6,116 t (44 TJ)	20.99	28.69
Electricity (HTHP)	44,762 MWh (161 TJ)	36.11	13.07

B.5 South Island 2037 with interregional transport

Table B-23: Resource cost breakdown for Southland with IRT in 2037.

Individual energy costs	Annual demand	Transport distance	Delivered cost $/GJ	LCOE $/GJ
Processor residues	3,920 t (28 TJ)	Low	11.05	16.26
		Medium	12.31	17.84
Harvest residues	85,152 t (612 TJ)	Low	13.95	24.82
		Medium	15.21	26.63
		High	17.94	30.53
Chip log	50,000 t (359 TJ)	Low	17.75	24.63
		Medium	19.01	26.22
Export log	174,020 t (1250 TJ)	Low	25.90	34.83
		Medium	27.17	36.41
Pellets from Otago	76,860 t (1268 TJ)	IRT	23.19	31.44
Electrode boiler	150,751 MWh (543 TJ)	-	36.11	38.98
HTHP	192,778 MWh (694 TJ)	-	36.11	13.20

Table B-24: Resource cost breakdown for South Canterbury with IRT in 2037.

Individual energy costs	Annual demand	Transport distance	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	19,625 t (141 TJ)	Low	11.41	16.72
		Medium	12.68	18.30
Roadside residues	28,539 t (205 TJ)	Low	14.85	26.12
		Medium	16.12	27.93
Cutover residues	64,933 t (467 TJ)	Low	16.48	28.44
		Medium	17.75	30.25
Wilding pines	25,432 t (183 TJ)	Low	19.74	27.12
		Medium	21.00	28.70
Export logs	73,915 t (531 TJ)	Low	25.00	33.70
		Medium	26.26	35.28
Wood chip from Otago	3,331 t (24 TJ)	Interregional	26.95	36.13
Electrode boiler	485,441 MWh (1748 TJ)	-	36.11	38.43
HTHP	208,571 MWh (751 TJ)	-	36.11	13.04

Table B-25: Resource cost breakdown for Otago with IRT in 2037.

Individual energy costs	Annual demand	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	11,365 t (82 TJ)	12.43	17.99
Minor species	14,909 t (107 TJ))	19.82	27.22
Electricity (HTHP)	49,524 MWh (178 TJ)	36.11	13.04

Table B-26: Resource cost breakdown for North Canterbury with IRT in 2037.

Individual energy costs	Annual demand	Delivered cost $/GJ	LCOE $/GJ
Processor residues	10,854 t (78 TJ)	5.85	9.76
Roadside residues	17,306 t (124 TJ)	20.57	34.29
Minor species	73,990 t (532 TJ)	21.52	29.35
Export log	3,9847 t (286 TJ)	25.65	34.51
Electricity (HTHP)	190,952 MWh (687 TJ)	36.11	13.35
Pellets from NMT	80,936 t (1335 TJ)	23.81	32.21

Table B-27: Resource cost breakdown for West Coast with IRT in 2037.

Individual energy costs	Annual demand	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	59,757 t (429 TJ)	18.46	25.52
Minor species	29,852 t (214 TJ))	20.21	27.71
Electricity (HTHP)	45,079 MWh (162 TJ)	27.78	10.78

Table B-28: Resource cost breakdown for NMT with IRT in 2037.

Individual energy costs	Annual demand	Delivered cost ($/GJ)	LCOE ($/GJ)
Processor residues	10,399 t (75 TJ)	12.87	18.54
Roadside residue	52,308 t (376 TJ)	17.54	29.95
Minor species	6,116 t (44 TJ)	20.99	28.69
Electricity (HTHP)	44,762 MWh (161 TJ)	36.11	13.07

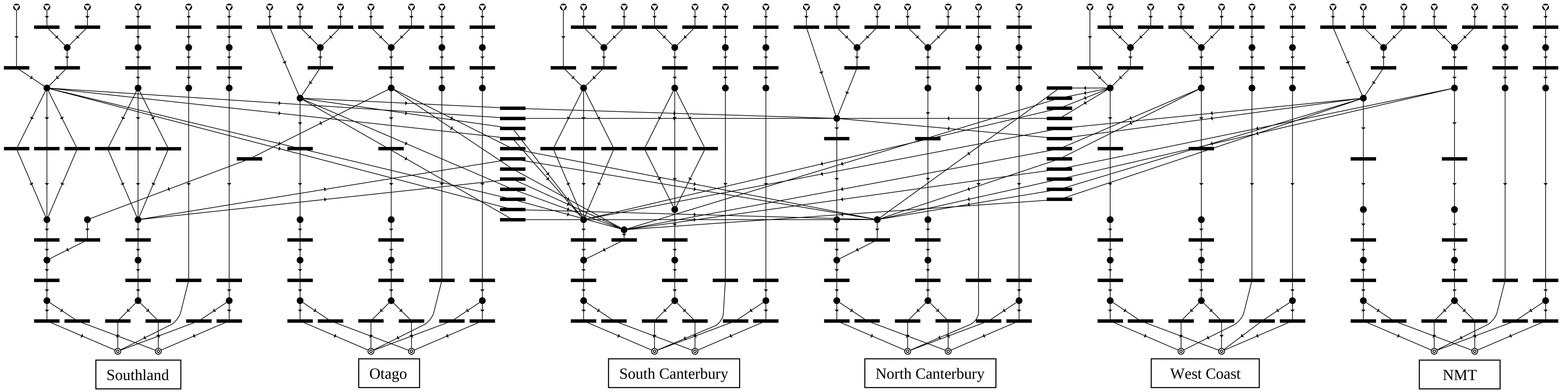

Figure B-1: Maximal structure of the interregional case study of the South Island.

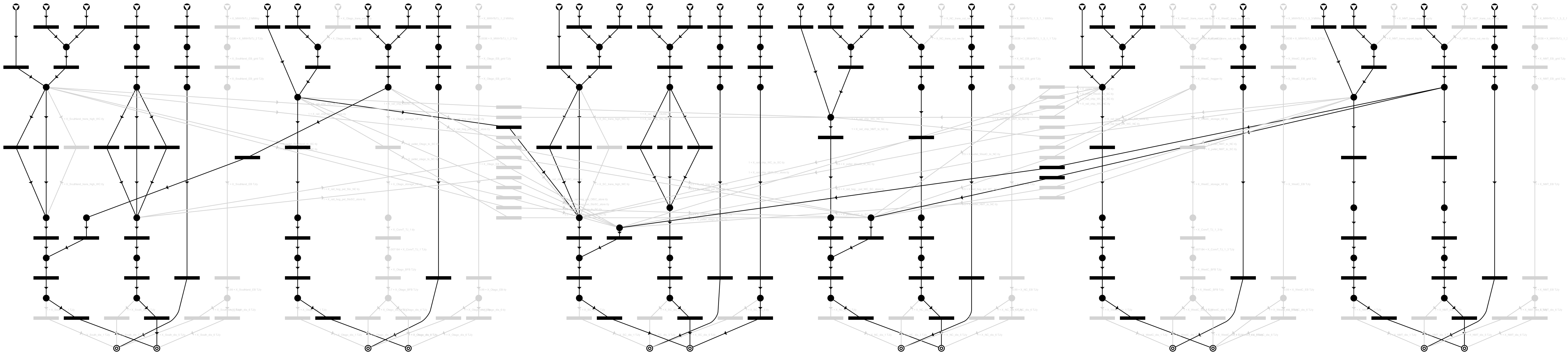

Figure B-2: Optimal solution structure for the IRT case study of the South Island.