The University of Auckland

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Part IV Project Final Report

Security of Supply in the New Zealand Electricity Market

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Contribution Declaration

We have been fortunate enough to have been able to use some existing code in this project.

DOASA was first developed in C++ by Andy Philpott, Ziming Guan, and Geoffrey Pritchard. It was then translated into Julia by Lea Kapelevich, and renamed as JADE. Oscar Dowson wrote much of the SDDP.jl code which implements Stochastic Dual Dynamic Programming in Julia.

The JADE model and SDDP.jl code was then extended by Shasa Foster to produce infinite horizon policies. I simulated the subsequent policies in Julia. I also wrote the VBA macros which take as inputs the results of the simulations, giving operating surpluses for each gentailer), and the macro which modifies demand to incorporate future renewable energy sources.

I have written this report myself, and the work throughout this project has been carried out by myself and Shasa, with assistance from our supervisors, except where referenced otherwise.

Abstract

The New Zealand Government recently announced that the nation's electricity should be entirely produced by renewable sources 'in a normal hydrological year' by 2035. As a result, power stations that use coal and gas are being phased out, the largest of which is Huntly Power Station. This report examines the effect of Huntly's units being shut down, and how the potential deficit in supply could be resolved.

To do this, policies of when and where to release water from New Zealand's seven largest reservoirs and how much electricity to produce by thermal means are constructed using Stochastic Dual Dynamic Programming. These policies are then simulated using historical data which captures the weekly inflows of water into each of the reservoirs. The various policies and simulations represent various combinations of electricity-producing units at Huntly being available, as well as renewable energy sources being added into the New Zealand Electricity Market.

Huntly Power Station (Huntly) has both coal and gas units and is owned by Genesis Energy, which is one of the five big electricity-generating companies in New Zealand. We investigate the role that Huntly plays in the electricity market, which companies would benefit if Huntly's coal units are shut down, and which generation sources would be best suited to making up the deficit of electricity supply.

From our analysis, it is apparent that the removal of units at Huntly increases the strain on New Zealand's hydro network. Water becomes more valuable, and this impacts the estimated distribution of operating surpluses for the five largest market participants. If Huntly were to shut down entirely, electricity shortages would become more likely.

Hence, it is clear that new generation assets will be required in order to account for the deficit in electricity supply if some or all of Huntly's units are shut down. We postulate that geothermal and wind energy are best suited to replace Huntly's coal units, and that the addition of all currently-consented geothermal and wind energy sources into the New Zealand Electricity Market would significantly decrease the carbon emissions associated with the generation of electricity.

Acknowledgements

To my supervisors - Tony, thank you for your insights, your friendly nature and your unique sense of humour. Andy, thank you for being a fountain of wisdom, and for always being willing to have a chat.

I would also like to acknowledge my project partner, Shasa, for working tirelessly, becoming a Julia expert, and coming back from Outer Mongolia in one piece (albeit on crutches).

Mum, thank you for giving me an appreciation for the mighty Waikato, home of the indefatigable Huntly Power Station. To Dad, for teaching me how to pronounce *Benmore* in a true Scottish manner. Thank you both for your unwavering support and compassion.

Finally, I would like to thank my friends and peers, for their camaraderie and sense of fun throughout the year.

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1 Introduction

This report discusses the security of supply of electricity in New Zealand in the next two decades. Security of supply refers to enough electricity being generated in New Zealand to satisfy demand, particularly in a dry year when there is less water available to produce electricity through hydro generation. We commence by explaining the reasons for carrying out this project and then expand on the structure of the remainder of this report.

1.1 Motivation

A large proportion of energy in New Zealand is currently generated by renewable means. Hydro, geothermal and wind energy sources currently account for approximately 82% of New Zealand's electricity needs [1]. However, one of the first announcements from the newly formed New Zealand Government in 2017 was that 100% of New Zealand's energy should be generated by renewable sources by 2035, under normal hydrological conditions [2].

Security of supply typically becomes an issue in dry years, when rainfall is low. This announcement means that New Zealand's 'thermal' stations, which typically use coal or gas as their source of energy, would only be able to be used in exceptional circumstances, that is, when electricity shortages are otherwise imminent.

Huntly Power Station, hereafter referred to as Huntly, accounts for about half of New Zealand's thermal generation capacity. Various announcements have been made regarding the future of Huntly's six units, which would suggest that the power station's future is unclear. This project considers security of supply of electricity if Huntly's two remaining coal-fired units were to shut down, as well as in the case in which the power station shuts down all six of its units.

The New Zealand Electricity Market is currently dominated by five companies which both generate and sell electricity. Because they act as both generators and retailers, they are commonly known as 'gentailers,' a term which will be used throughout the remainder of this report. This project will investigate which gentailers would benefit (and which would be worse off) if Huntly's two existing coal-fired units were to shut down.

Further motivation for this project is described in the associated Literature Review and Statement of Research Intent; please refer to [3].

1.2 Project Aim and Scope

The primary goal of this project is to generate policies and run simulations under various scenarios. Using output from the corresponding simulations, we then analyse the outcomes for each of New Zealand's five largest gentailers and look at future renewable energy options.

The two key questions that this project addresses are:
i) How secure is the supply of electricity in New Zealand currently, and
ii) How could New Zealand ensure a secure supply of electricity in the future, given a preference for renewable energy?

1.3 Report Structure

The remainder of the report continues as follows:

Section 2 provides a brief background to the New Zealand Electricity Market. We detail the differences between New Zealand's five largest electricity companies, and how security of supply is currently assessed. A short discussion of Huntly is also included.

Section 3 explains the mathematical algorithm of Stochastic Dual Dynamic Programming, and the software which implements this algorithm to generate a hydro-thermal scheduling policy. We also describe some of the assumptions within our model.

In Section 4, developments made to the existing software package and the new infinite horizon dynamic program are described. We then explain, at a high level, how our simulations are carried out.

Section 5 presents some analysis of the impact of Huntly Power Station. We plot reservoir levels over the course of historical years' inflows with different numbers of units able to produce electricity at Huntly. We then explain how output is aggregated in order to produce estimates of operating surpluses for each gentailer, under the different scenarios, and present the results of such calculations.

Section 6 introduces a further five scenarios, in which geothermal and/or wind sources are added into the model. We present the methods used to calculate electricity generation by source and carbon emissions for each scenario. The effectiveness of new renewable energy sources, and that of a carbon tax, are also discussed.

Finally, Section 7 describes future work which could be carried out, while Section 8 summarises the findings contained in this report and the project as a whole.

2 The New Zealand Electricity Market

The New Zealand Electricity Market, or *NZEM* for short, is a unique and intricate industry. This section of the report provides some context of the overall structure of the market; in particular, hydroelectric generation, Huntly Power Station, and the five largest gentailers. More background is provided in the accompanying Literature Review and Statement of Research Intent [3].

2.1 Overview of the Market

The NZEM can be broken down into four processes: generation, transmission, distribution, and retail. Transmission and distribution of electricity are typically monopolies, which are overseen by Transpower and various regional distribution companies respectively. Because the key issue at the centre of this project is security of supply, the generation arm is naturally of greatest importance in this report. However, the leading five gentailers also have retail arms; therefore, some analysis of the retail sector is required.

2.2 Hydroelectricity in New Zealand

The Bullendale Power Plant, in Central Otago, commissioned to provide power to the nearby gold mine in 1885, is the first example of a hydroelectric power plant in New Zealand [4]. Since then, a large number of power stations have been developed around the country, such that total hydro capacity today is in excess of 5000 MW [5]. Hydroelectric schemes rely on gravity to drive water downwards through turbines while converting kinetic energy into electricity.

New Zealand has seven lakes which are large enough to be able to store water over a period of weeks. They are, in order of decreasing capacity: Pukaki, Manapouri, Hawea, Taupo, Tekapo, Benmore, and Ohau. These reservoirs feed into some of New Zealand's largest hydro dams, such as Manapouri, Benmore, and Clyde. Smaller schemes, with minimal storage capabilities, are often considered 'run-of-river.'

There are strict regulations which govern the operating range of these lakes. Due to operational and environmental reasons, the water level of each lake cannot drop below a certain minimum, relative to some reference datum. Furthermore, an overflowing lake could impact on the neighbouring environment and communities, and as such, excess water must be spilled if the water level becomes too high.

The generation output of these hydroelectric power plant is highly dependent on the level of water present upstream. This water is often referred to as 'inflows' and includes both rainfall and snow melt. In dry years, inflows are typically less, which leads to lower lake levels. As a result, the nominal value of water and thus the price of electricity tends to increase. Managing the remaining water effectively is essential in order to ensure that there are not large electricity shortages throughout New Zealand.

2.3 Market Participants

In New Zealand, there are five companies which dominate both the generation and retail electricity sectors. Contact Energy (hereafter known as 'Contact'), Genesis Energy ('Genesis'), Mercury Energy ('Mercury'), Meridian Energy ('Meridian') and Trustpower together produce more than 95% of New Zealand's electricity, and sell more than 91% of all of New Zealand's electricity to consumers [1]. Because of their dominance, our analysis considers these five companies only. There are multiple barriers to entry into the NZEM which means that this five-company oligopoly is unlikely to change in the near future [6].

Because these gentailers are vertically integrated, they can hedge risk. Gentailers face different risks based on their respective asset mixes, which are detailed in Table 2.1 below.

Table 2.1: Gentailer by Generation Assets

Gentailer	**Hydro**	**Geothermal**	**Wind**	**Coal**	**Gas**	**Diesel**
Contact	✓	✓			✓	✓
Genesis	✓		✓	✓	✓	
Mercury	✓	✓				
Meridian	✓		✓			
Trustpower	✓		✓			

A gentailer with a large proportion of hydro assets would have a preference for high inflows, as this allows for greater hydroelectric generation. However, an equilibrium exists; if there is too much water in the upstream lakes, then some water may need to be 'spilled.' In this case, the value of water decreases, and with it the price of electricity.

The greatest risk for the likes of Genesis, which owns a relatively large proportion of New Zealand's thermal assets, is that there are large amounts of water in the nation's reservoirs, thereby decreasing the value of water. So long as each hydroelectric dam is not required to operate at its capacity (i.e. demand is not too large), thermal stations will not be able to produce electricity while making a profit, thereby earning no revenue while still incurring fixed costs.

To mitigate this risk, contracts called swap options (swaptions) are often traded between gentailers. For example, from 2019 until 2022, hydro-dependent Meridian will have 100 MW of thermal generation available courtesy of Genesis, with an additional 50 MW available between April and October each year [7]. This agreement decreases the risk associated with low reservoir levels in dry years. However, value of this contract is not publicly available.

Each gentailer tends to have a large share of its customers in similar regions of New Zealand as its generation assets. In this way, there is less risk of large discrepancies in the price of electricity in different regions adversely affecting the gentailer. For example, if Meridian, which owns many of the hydroelectric dams in the South Island, received a low price for its electricity due to an abundance of water in the South Island, while having to buy electricity off the grid at high prices (perhaps due to high demand) for many customers in the North Island, then it would likely suffer a financial loss. Having its customer base close to its generation assets provides the gentailer with a form of insurance against high transmission costs and large price differentials.

2.4 Huntly Power Station

Huntly Power Station is a thermal plant owned by Genesis Energy and was commissioned in 1983. It has six units, four of which are currently operational. Each unit runs on either coal or gas, but there is potential for the coal-fired units to transition to gas. Table 2.2 below shows the six units' capacities and fuel types.

Table 2.2: Units at Huntly Power Station

Unit Name	Status	Unit Type	Capacity (MW)	Fuel Type
E3P	Operational	Combined-cycle	403	Gas
Rankine 1	Operational	Steam Turbine	250	Coal
Rankine 2	Operational	Steam Turbine	250	Coal
Rankine 3	Mothballed in 2012	Steam Turbine	250	Coal
Rankine 4	Mothballed in 2015	Steam Turbine	250	Coal
Peaker	Operational	Open-cycle	50	Gas

As seen above, two of Huntly's Rankine units have recently been mothballed. Effectively, they have been placed into long-term storage; there is the potential for them to be used in the future, however the lack of maintenance applied to these units would mean that it would take a number of months before they could return to service.

As is typical for a thermal plant, Huntly generates most of its electricity when demand is high and available supply from hydroelectricity is relatively low. A large share of the electricity generated at Huntly is typically used to meet Auckland's demand needs.

Recently, Genesis has made several press releases regarding the future of its units at Huntly, in particular its coal-fired Rankine units. The two operational Rankine units are slated for decommissioning in the year 2022, as agreed upon in the swaption contract with Meridian [7].

2.5 Demand

New Zealand's annual electricity consumption is nearly 40,000 MWh [8]. Electricity demand is typically categorised in one of three ways: industrial, commercial, or residential. Each of these sectors is approximately the same size. Industrial consumers can generally buy electricity directly off the wholesale market, whereas businesses and households buy their electricity from the retail market, through a retailer, which could be one of the five gentailers described in Section 2.3.

Demand in New Zealand is naturally concentrated in the country's largest cities. In general, demand is proportional to the region's population. However, Southland consumes a large quantity of electricity for its size, due to the presence of the Tiwai Point Aluminium Smelter. The smelter consumes around 14% of New Zealand's total electricity demand annually, and requires a constant stream of electricity, which is in the order of 570 MW [6]. In essence, Manapouri Power Station and the Tiwai Point smelter have their own sub-network, whereby all of the smelter's demand is satisfied by the Manapouri Power Station's steady supply of electricity.

Monitoring demand is carried out by Transpower. During dry years, energy-saving campaigns are promoted by the Government, in conjunction with Transpower, in order to reduce demand and thereby reduce consumption of water from reservoirs. To encourage the responsible management of reservoir levels, retailers are required to pay a nominal fee to their customers during weeks when energy-saving campaigns are in place [9].

2.6 Hydro Risk Curves

Transpower plots hydro risk curves in order to graphically portray the likelihood of electricity shortages. New Zealand's reliance on hydroelectricity means that low reservoir levels are strongly correlated with high risk of shortages. Controlled storage (the net energy stored in New Zealand's largest reservoirs) is tracked, alongside levels at which a given risk of shortage would exist.

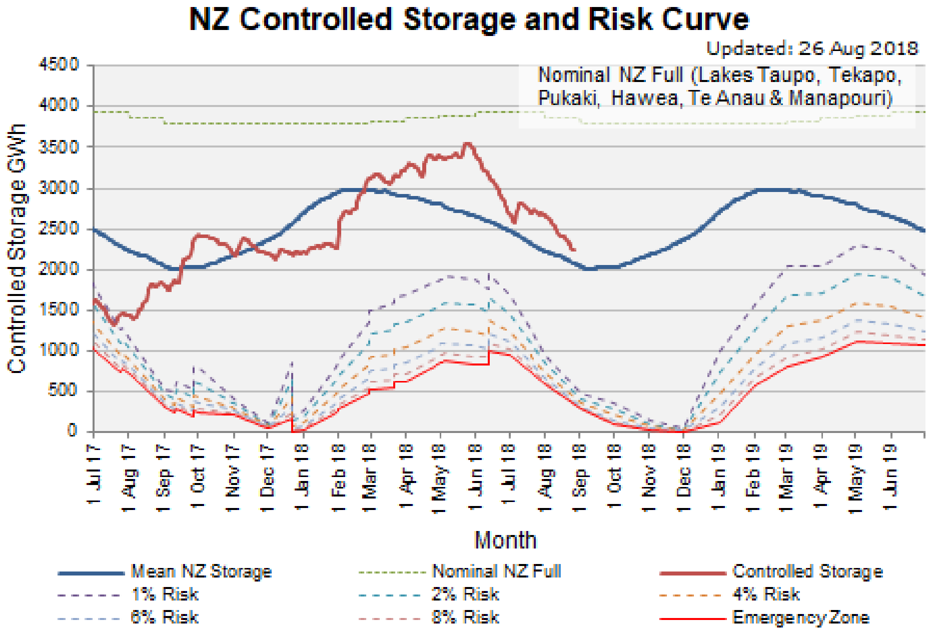


Figure 2.1: 2018 New Zealand Hydro Risk Curves. The red line is the actual storage in New Zealand's largest reservoirs. The blue line is the historical mean net storage level. The dashed lines show the risk curves, and the bright red line at the bottom is the water level below which New Zealand faces critical risk of water (and electricity) shortages. Source: Transpower [10].

In winter, the controlled storage level required is typically higher than in summer, for two reasons: demand is greater (due to fewer daylight hours and increased need for heating) and inflows are usually lower due to a lack of snow melt. Because of New Zealand's heavy reliance on hydroelectricity, increased water storage reduces the risk of supply being unable to meet demand.

Hydro risk curves provide an effective way of evaluating security of supply. The larger the gap between the risk curves and the actual controlled storage trajectory, the more secure the supply of electricity is.

3 Modelling

This section pertains to the Stochastic Dual Dynamic Programming approach used to generate optimal policies in terms of the amount of water to release from reservoirs and the amount of energy to produce at thermal stations, given information about the nature of the NZEM as a whole.

3.1 Dynamic Programming

Dynamic Programming is an approach used in mathematical programming and operations research to solve problems which can be broken into a sequence of smaller, similar sub-problems. These sub-problems, or *stages*, are solved to optimality in a recursive manner. In this way, an optimal set of *actions* can be obtained over the entire time horizon for the problem as a whole.

In each stage, a *state* is observed. Based on this information, the dynamic program determines the optimal action for the given stage.

At each stage, a dynamic program seeks to minimise the cost (or equivalently maximise the value) in that stage. In this case, we seek to minimise the cost of thermal generation and load shedding due to unmet demand. The future cost in all forthcoming stages, given a particular current state, is termed the *cost-to-go* and is given by:

$$V_n(x_n) = \min_{a_n \in A_n} \{c_n(x_n, a_n) + V_{n+1}(f(x_n, a_n))\}. \tag{3.1}$$

Here n is the index of the current stage, x_n is the current state, and $V_n(x_n)$ the minimum cost-to-go incurred from stage n onwards when in state x_n. We denote the cost of the present stage, given some state x_n and action to take a_n, with c_n; $f(x_n, a_n)$ represents the transition function between stages n and $n+1$, given state x_n and action a_n.

In our case, the stages, n are the weeks of the year, the states x_n, are the water levels of each of the major reservoirs, and the action a_n to take in a given week represents the amount of water to be released from each reservoir and the amount of electricity to be generated at each thermal station. The cost, c_n is the physical cost of the fuel at the thermal stations and the cost of lost load if demand is not met. The transition function $f(x_n, a_n)$ is governed by weekly inflows into reservoirs, as well as station outages; if a station (be it hydro or thermal) is scheduled to undergo maintenance in the following week, it will not be possible to transition to a state in which this given station produces electricity. $V_{n+1}(f(x_n, a_n))$ is the future cost-to-go, that is, the minimum cost from stage $n + 1$ to the final stage N, and in this case captures the end-of-horizon marginal value of water.

Such a dynamic program can be solved using backward recursion. Given the end-of-horizon marginal value of water for the system (see the associated Literature Review [3]), we can step backwards through each sub-problem and determine the optimal set of actions for each stage.

3.2 Stochastic Dynamic Programming

Stochastic Dynamic Programming (SDP) uses the same principles as a deterministic dynamic program, but includes some uncertainty [11]. In particular, the specific uncertainty in our SDP derives from the random sampling of inflows into our reservoirs. If this uncertainty is captured by a random variable in a given week ω_n, then our dynamic program can be written as:

$$V_n(x_n, \omega_n) = \min_{a_n \in A_n} \{c_n(x_n, a_n, \omega_n) + \sum_{\omega_{n+1} \in \Omega_{n+1}} \Pr(\omega_{n+1}|\omega_n) V_{n+1}(f(x_n, a_n, \omega_n), \omega_{n+1})\}. \tag{3.2}$$

The realisation of the random variable, ω_n, is known at the start of stage n. However, the random variable at stage $n + 1$ can take on any value in the set Ω_{n+1}. If there is stagewise dependence, then the probability of this random variable attaining such a value is given by the conditional probability $\Pr(\omega_{n+1}|\omega_n)$. In the stagewise independent case, the probability of attaining ω_{n+1} in the next stage is simply $\Pr(\omega_{n+1})$.

We can define $\mathcal{V}_{n+1}(x_{n+1})$ to be the *expected* future cost-to-go from stage $n + 1$ until the final stage, given a stage n and state x_n, prior to the realisation of the random variable ω_{n+1}. $\mathcal{V}_{n+1}(x_{n+1})$ incorporates the costs of fuel and shortage in each of these stages, as well as the end-of-horizon marginal value of water. Then, with stagewise independence:

$$\mathcal{V}_{n+1}(x_{n+1}) = \sum_{\omega_{n+1} \in \Omega_{n+1}} \Pr(\omega_{n+1}) V_{n+1}(f(x_n, a_n, \omega_n), \omega_{n+1}) \tag{3.3}$$

$$V_n(x_n, \omega_n) = \min_{a_n \in A_n} \{c_n(x_n, a_n, \omega_n) + \mathcal{V}_{n+1}(x_{n+1})\}. \tag{3.4}$$

This stochastic dynamic programming approach is an improvement on the dynamic program presented in Section 3.1 as it allows us to capture the uncertainty of inflows into reservoirs.

3.3 Stochastic Dual Dynamic Programming

Stochastic Dynamic Programming is typically used for systems which can exist in a countable number of discrete states. However, the water level of each reservoir is a continuous variable, and to discretise our state space would be computationally impractical. For this reason, a Stochastic Dual Dynamic Programming approach is employed [12].

Stochastic Dual Dynamic Programming (SDDP) sees the future cost-to-go function approximated by multiple linear functions. The pointwise maximum of these functions at a given value of x_n defines a lower bound on $\mathcal{V}_n(x_n)$. These functions are often referred to as *cuts*. In other words, dominating cuts form the outer surface of a convex function which provides a lower bound for the expected cost-to-go.

In each iteration of the Stochastic Dual Dynamic Program, a forward and a backward pass is carried out. The forward pass begins at the first stage and sees a realisation of the random variable ω_n for each stage n. An optimal action is taken for each stage which minimises the sum of the stage cost (fuel cost and lost load) and the cost-to go, given a current state x_n and realisation of the random variable ω_n. The backward pass determines a new cut to be added to the problem for every stage except for the last. The greater the number of cuts, the more accurate the approximation of the future cost-to-go should be.

3.4 Julia and SDDP.jl

The code used to carry out the SDDP algorithm has been implemented in the Julia coding language, which was first developed by Jeff Bezanson, Alan Edelman, Stefan Karpinski, and Viral Shah at the Massachusetts Institute of Technology in 2009. It is one of the few programming languages which is both high-level and fast [13].

The SDDP.jl package has primarily been developed by Oscar Dowson, a recent PhD student at the University of Auckland [14]. It implements the general SDDP algorithm in an efficient way and can be used to solve a variety of real-world applications, including hydro-thermal scheduling, agriculture, and asset management. SDDP.jl provides the functionality to be able to use, build, and simulate a model that uses Stochastic Dual Dynamic Programming.

3.5 JADE and DOASA

In particular, this project uses and extends the JADE.jl package in Julia, in conjunction with the SDDP.jl package. JADE stands for Just Another DOASA Environment. In turn, DOASA itself is an acronym for the 'Dynamic Outer Approximation Sampling Algorithm.' The DOASA algorithm was first developed in C++ by Andy Philpott, Ziming Guan, and Geoffrey Pritchard from the University of Auckland in 2007 [15]. JADE is the product of DOASA having been translated into Julia.

JADE uses Julia's inbuilt 'Julia for Mathematical Optimization' (JuMP) framework. JuMP is used to solve the individual sub-problems, in conjunction with Gurobi, which is a high-speed commercial optimisation tool used to solve linear programs. Each sub-problem is solved rapidly, but the size of the sub-problems increases as the number of cuts increases, which means that generating a policy can take a number of hours.

DOASA uses Stochastic Dual Dynamic Programming to carry out hydro-thermal scheduling and water valuation for the New Zealand Electricity Market. It seeks to minimise the expected cost of meeting electricity demand. Other implementations of hydro-thermal scheduling using SDDP, such as that implemented in Brazil [12], sample fixed inflow sequences. DOASA, however, randomly samples inflows at each iteration from historical sequences, which ensures that the algorithm 'almost surely' converges [16].

3.6 Assumptions Implicit in the JADE Model

In a model which encompasses the entire New Zealand Electricity Market, some assumptions are both inevitable and necessary. Assumptions within JADE include:

Location Demand is aggregated into three location nodes throughout New Zealand: North Island (NI), Haywards (HAY, which encompasses the lower North Island) and SI (South Island). Line capacities limit the amount of electricity which is allowed to flow between the nodes modelled in JADE, based on the capability of the transmission networks between regions of New Zealand.

Load Blocks Each half-hour throughout the day is denoted by one of three load blocks: 'peak,' 'off-peak,' and 'shoulder,' depending on how high demand is during that period. It is assumed that each of the nodes has a correlated level of demand in a given half-hour, such that all three nodes have the same load block type. Transmission line losses are also assumed to be zero.

Time A calendar year is assumed to contain 52 weeks, and decisions are made on a weekly basis. The amount of water to release from a given reservoir may differ by load block, but within each load block, it is constant over the week. Moreover, inflows are realised on a weekly basis. The model does not provide a means for recourse decisions to be made on a daily basis.

Unmet Demand In the JADE model, load shedding is allowed, but at high cost. This cost, termed the *value of lost load* (VOLL) depends on the sector (industrial, commercial or residential). For example, the VOLL for the residential sector in the North Island is \$10,000/MWh when the amount of reduction in load is between 10% and 100% of demand.

Hydro Flows The model also allows for some of the flow constraints along hydro arcs to be violated. For example, if inflows are sufficiently low, then the flow of water down a river can be less than the permitted lower bound, with an associated flow penalty cost applied. Likewise, a cost is incurred if the maximum allowed flow is exceeded, for example during a flood.

Stagewise Independence of Inflows In reality, one week's inflows should have an impact on those of the following week, due to seasonal and weather effects, for example. This stagewise independence assumption is partially overcome by a Dependent Inflow Adjustment, which sees a set number of user-specified weeks' inflows correlated so as to imitate stagewise dependent inflows [15].

Fixed Generation Some generation is deemed to be controllable, while other generation sources have fixed output. The controllable generation comes from the larger hydro stations and all of the thermal stations. In the model, there are five smaller hydro stations which have fixed generation outputs. Furthermore, historical amounts of electricity generated by geothermal and wind energy are subtracted from the demand for each node, load block and week.

Fuel Costs Each thermal plant has a heat rate (measured in GJ/MWh), which can be multiplied by the fuel cost (\$/GJ) to give the marginal cost of producing electricity at that plant, in a given week. However, this relies on the assumption that fuel can be purchased as required. In actuality, contracts exist between fuel suppliers and thermal plant owners, and the price of fuel increases when shortages occur. This is not presently modelled within JADE.

4 Implementation

This section of the report outlines the implementation of the algorithms and software required to address the project's key questions. Developments made to the JADE.jl and SDDP.jl packages are discussed, and an overview of the resulting simulations is also provided.

4.1 The Marginal Value of Water

The end-of-horizon marginal value of water is a function of the potential energy (in GWh) stored in New Zealand's seven largest reservoirs. Dynamic programs with backwards recursion require a terminating function. Without an end-of-horizon marginal value of water function, JADE, through generating a policy for a single year in isolation, would have no incentive to retain any water at the end of the year.

Because we are solving linear programs, the marginal value of water is given by a step function, whereby a certain amount of energy remaining in the reservoir at the end of the year corresponds to a fixed marginal value of water, in \$/MWh. For a range of energy values greater than this point, the marginal value of water is less. The step function shows the marginal value of water decreasing as the net amount of energy increases, as seen in Figure 4.1, since more water corresponds to a lower risk of shortages. In other words, an additional GWh of water storage is less valuable when all reservoirs are close to being full, than when reservoirs are low and electricity shortages are imminent.

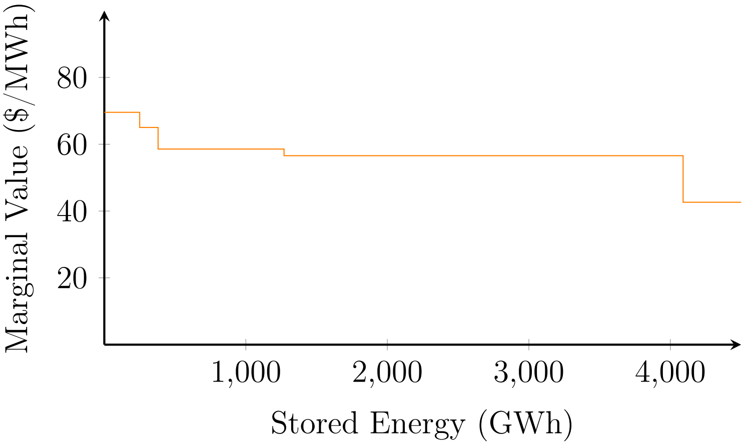


Figure 4.1: End-of-Horizon Marginal Value of Water Graph. The NZEM in current setup (four units available at Huntly)

JADE currently uses predefined *exogeneous* data to represent the end-of-horizon marginal value of water. This is defined in one of the JADE input files. In the first part of this project, we implement an *endogeneous* terminal marginal value of water function.

When all seven major reservoirs are close to capacity (approximately 4400 GWh), the marginal value of water tends towards about \$42/MWh, which corresponds to the marginal cost of electricity generation using coal at Huntly.

4.2 Determining the Marginal Value of Water Function

Initially, a two year model was used. The reservoir levels in the 52^{nd} week (at the end of the first year) can act as a proxy for the reservoir levels at the end of the model (in the 104^{th} week). In this way, although the reservoir levels at the beginning of the first year are fixed, reservoir levels at the start of the second year form a distribution, which is largely dictated by the end-of-horizon marginal water value function.

Hence, the end-of-horizon marginal value of water function in the 104^{th} week can be represented by *cuts* (as defined in Section 3.3) from week 52.

In order to estimate the new marginal value of water function, a simple Linear Program (LP) is solved. This LP finds the dominating cuts which define the outer surface of our end-of-horizon marginal value of water function. It takes the form:

$$\begin{array}{rrcll} \min & \theta & & & \\ \text{s/t} & \vec{\beta}_i^T \mathbf{x} + \alpha_i & \leq & \theta & \forall i \in \{1, 2, ..., K\} \\ & x, \theta & \geq & 0. & \end{array} \tag{4.1}$$

Here, our $\vec{\beta}_i$ values are the gradients of the cuts generated. Cuts are produced for each iteration $i \leq K$ of the SDDP algorithm. The x-axis represents the net amount of energy stored in the form of water, in GWh, and is a vector of the same length as the vector $\vec{\beta}_i$. α_i represents the y-intercept for the i^{th} cut, in \$/MWh.

The slope of each dominating cut defines the marginal value of water, and provides a lower bound on the expected future cost-to-go function over a particular set of water storage levels, as seen in Figure 4.2 below. A new CSV file is created, with each row containing a stored energy value and the corresponding marginal value of water, which is valid up until that energy level.

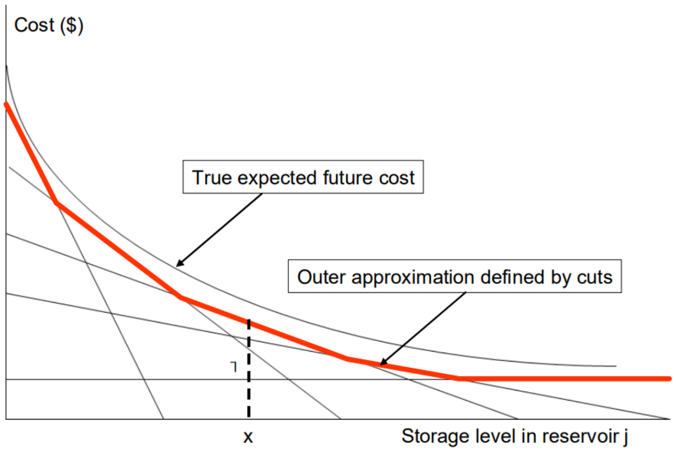


Figure 4.2: Linear Cuts Used to Define Marginal Value of Water Function

Cuts are generated for a fixed number of iterations, which is sufficiently large such that the marginal value of water function converges. Hence, our Stochastic Dual Dynamic Program uses *value iteration*; the stopping criterion is when the marginal value of water ceases to change between iterations (as opposed to when the policy converges).

4.3 The Infinite Horizon Model

Although useful as an initial model, the approach described in Section 4.2 is flawed in that the initial water level of each of the reservoirs is fixed (refer to the Figure 4.3). Furthermore, this single-threaded approach, whereby cuts are generated one at a time, means that each policy takes upwards of 18 hours to generate.

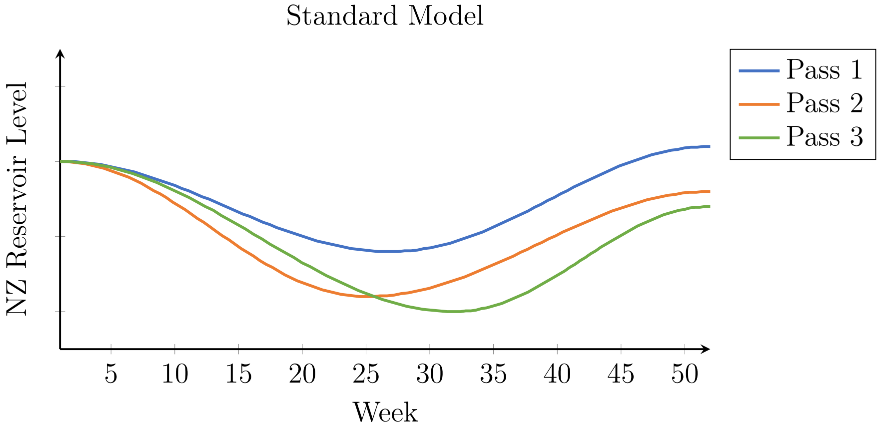


Figure 4.3: Schematic of Net Reservoir Levels for Standard Model

A more theoretically complex, but ultimately more computationally efficient model, involves using an infinite horizon approach. Instead of generating a policy over two years, the policy is generated for a single year, with cuts used to define a lower bound on the marginal value of water. An average cost model is used, which sees the new future cost-to-go for the $N+1^{\text{th}}$ stage being equal to the future cost-to-go for the first stage, less δ, the expected cost of all stages 1 through N. Here N is the total number of stages in the model, 52. The water level for a reservoir at the end of an iteration 'wraps around' and is equal to that at the beginning of the next iteration (year), as seen in Figure 4.4. In this way, the marginal value of water function is defined *endogenously*.

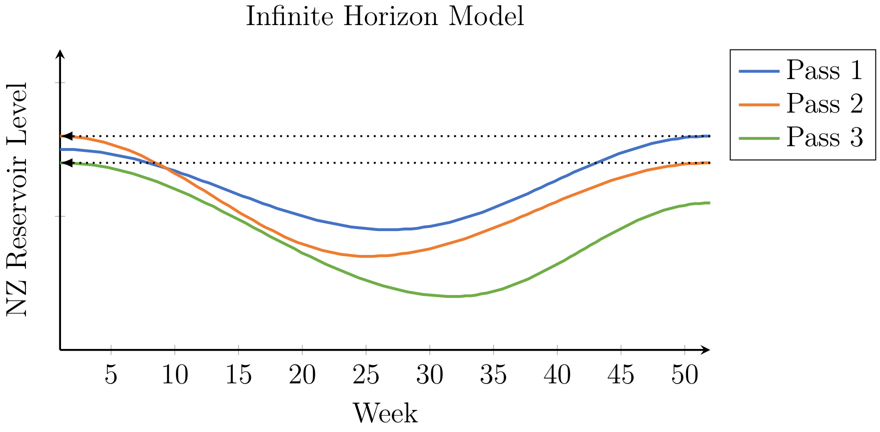


Figure 4.4: Schematic of Net Reservoir Levels for Infinite Horizon Model

This approach is thus more realistic than previous implementations of JADE. Further work by Shasa Foster [17] ensures the convergence of the model and use of a cut selection heuristic decreases the runtime significantly to approximately half an hour. The infinite horizon model therefore provides an excellent means of simulating the NZEM under various scenarios.

4.4 Simulations

Now, the end-of-horizon marginal value of water function is able to dynamically change each iteration. Moreover, the model allows the end-of-horizon marginal value of water function to change for each setup of the NZEM. Thus, simulations can be carried out in an effective way; previously, as a fixed end-of-horizon terminal value does not reflect the different needs in terms of managing water and thermal assets depending on the generation mix. Comparing mixes involves running the JADE model with some inputs modified for each run. Of particular note are the following input files: **station_outages.csv**, **demand.csv**, and **run.csv**.

The **station_outages.csv** file can be modified to represent different units being available. This can be implemented by imposing station outages equal to the capacities of the relevant units, so that no electricity is produced by these units throughout the desired year. In particular, this method can be used to shut down various units at Huntly.

The **demand.csv** file is then used to 'embed' additional generation into the model. Instead of adding stations, an estimate of additional output is subtracted from demand at the relevant node. In this way, scenarios are constructed and simulated with additional types of renewable energy (such as geothermal and wind) made available.

The **run.csv** file contains a set of inputs, which pertain to the exact parameters used when building the model of the NZEM. The number of weeks and year to build the model for as well as simulation type are all specified here. Our final model uses 52 weeks and 2008 demand values.

Historical sequences of inflows are used to simulate the performance of the generated policy. Simulations are carried out over 20 years' historical inflow sequences, between 1994 and 2013 inclusive.

The results of these simulations can be used produce a series of what are colloquially known as 'spaghetti graphs,' where the aggregate water levels across each of the seven major reservoirs are plotted over the course of 52 weeks. The water level of each reservoir reflects the nature of the policy at a high level – how much water to release, and when.

The simulations also produce a series of data files, such as the generation of each plant, the electricity price at each node, the amount of water spilled from each reservoir, the stored energy in each reservoir, the amount of lost load, and the total cost of the system.

5 The Role of Huntly Power Station

In order to investigate Huntly's significance to the NZEM in terms of security of supply, a series of simulations are carried out. This section shows how the outcomes of these simulations can be analysed and presents the ensuing results.

5.1 Financial and Physical Outcomes for Gentailers

Using the output of of a run using the JADE model, several metrics can be calculated by the method described below, with the following nomenclature:

Indices

$i \in \{\text{Offpeak}, \text{Peak}, \text{Shoulder}\}$	Load Blocks
$j \in \{1, 2, ..., 52\}$	Weeks
$k \in \{\text{NI}, \text{HAY}, \text{SI}\}$	Nodes
$l \in \{\text{Industrial}, \text{Commercial}, \text{Residential}\}$	Sectors
$m \in \text{Coal}, \text{Diesel}, \text{Gas}, \text{Water}\}$	Fuel
$n \in \{\text{Arapuni}, \text{Aratiatia}, ..., \text{Stratford}\}$	Stations

JADE Outputs

q_{ij}	Quantity of power produced (MWh) by a station during a given load block and week
γ_{m_n}	Mass of CO_2 equivalence (kg) emitted by a given fuel at a given station per MWh electricity produced
π_{ijk}	Price of electricity (\$/MWh) during a given load block and week at a node. This is equal to the dual of the Supply + Lost Load = Demand constraint
c_{jm}	Cost of fuel (\$/GJ) for a given week and fuel type
h_n	Heat rate (GJ/MWh) for a given station
p_{kl}	Proportion of demand met by a retailer (unitless) at each node and sector
d_{ijk}	Demand (MWh) in a given load block, week and node
λ_l	Cost of electricity (\$/MWh). Industrial customers are charged the wholesale price. Residential/commercial customers are charged retail prices

Total Electricity Generation
The total amount of electricity (in MWh) generated by each station n is given by:

$$\text{Generation} = \sum_{i \in \text{LoadBlocks}} \sum_{j \in \text{Weeks}} q_{ij} \tag{5.1}$$

Carbon Emissions
The carbon emissions for each station can be calculated by:

$$\text{Carbon Emissions} = \gamma_{m_n} \sum_{i \in \text{LoadBlocks}} \sum_{j \in \text{Weeks}} q_{ij} \tag{5.2}$$

Note that as γ_{m_n} is zero for hydro stations, hydro stations produce no carbon emissions. We can then sum over all stations to produce a value representing the total carbon emissions (in terms of equivalent kilograms of carbon dioxide) for each scenario.

Rents
The rent for a given station is given by:

$$\text{Rent} = \sum_{i \in \text{LoadBlocks}} \sum_{j \in \text{Weeks}} q_{ij}[\pi_{ijk} - c_{jm}h_n] \tag{5.3}$$

The node k for energy prices π_{ijk} is determined by the location of the station. The cost of fuel (in \$/MWh)c_jm is dependent on the cost of fuel (\$/GJ) used by and the heat rate (GJ/MWh) of the station. The total rent for each gentailer is found by adding the rents of each of the individual stations that a gentailer owns (refer to Appendix I).

It should be noted that, as hydroelectric dams effectively pay nothing for their fuel (water), there is no marginal cost c_{jm} associated with their rent, and hence these hydro stations can only ever have positive rent values.

Retail Income
The amount of money made by the retail arm of each gentailer is given by:

$$\text{Retail Income} = \sum_{i \in \text{LoadBlocks}} \sum_{j \in \text{Weeks}} \sum_{k \in \text{Node}} \sum_{l \in \text{Sectors}} p_{kl}d_{ijk}[\lambda_l - \pi_{ijk}] \tag{5.4}$$

Data from the Electricity Authority [18] has been used to find market share by gentailer at each node. The 'Lost Load' file within JADE provided a breakdown of market share by sector [16]. Hence, the p_{kl} variable incorporates both of these market share proportions.

Operating Surpluses
Finally, operating surpluses are calculated by adding the rents (marginal generation profits) and the retail incomes for each gentailer.

$$\text{Operating Surplus} = \text{Rent} + \text{Retail Income} \tag{5.5}$$

This allows for comparisons of financial standing by gentailer between scenarios.

5.2 Simulations of Various Configurations of Huntly

Three scenarios are used to represent the progressive shutdown of Huntly Power Station. Scenarios 1-3 are:

1. Four units at Huntly (two gas, two coal)
2. Two gas units at Huntly (all four coal units mothballed)
3. No units at Huntly

5.3 Reservoir Levels for Selected Scenarios

Here we present the reservoir levels for a given policy constructed for each scenario, over 20 years of simulated data. Each year corresponds to a line on the graphs below. In addition, we highlight the simulated reservoir levels with inflows from 2012 and 2013, given fixed reservoir levels at the start of the year, whereby each reservoir commences the year at half its maximum capacity level. This allows us to compare and contrast a relatively dry year (2012) against a wet year (2013).

The wrap-around nature of the infinite horizon Model (see Section 4.3) means that the storage level at the end of one year corresponds to that at the beginning of the next year. Hence, the distributions of reservoir levels at the start and end of the year (weeks 1 and 52 respectively) should match.

Figure 5.1a shows that for Scenario 1, storage trajectories are somewhat flat over the course of the year. Water is used up over the winter, as shown by the decreasing slope of each of the trajectories, in order to meet the higher demand in this part of the year. Reservoir levels then increase towards the end of the year, due to snow melt, decreasing demand, and the need to build up reservoir levels in preparation for the following year. In the drier year (2012), reservoir levels are lower in general than in 2013 (Figure 5.1b).

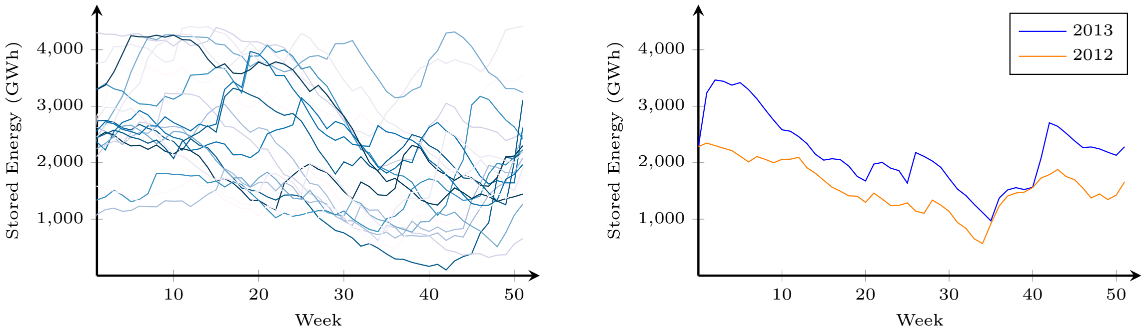
In Figure 5.1c we see a more pronounced wave-shaped curve than for Scenario 1. This indicates that a more forward-thinking approach to managing water is required. Reservoir levels start high in the first three months of the year, in anticipation of the water level dropping during the winter. As with Scenario 1, Figure 5.1d shows that the wetter year (2013) fares better than the drier one (2012).

Figure 5.1e presents a graph similar to that of Scenario 2 (Figure 5.1c). The concept of reservoirs being close to full at the start of some years is further reinforced, with some reservoirs spilling electricity so to maintain high reservoir levels, in case the year turns out to be a dry one. Our simulation shows that shortages would have occurred in 2001 (a particularly dry year) if Huntly was not available. Figure 5.1f shows that reservoir levels would have also been very low in 2012.

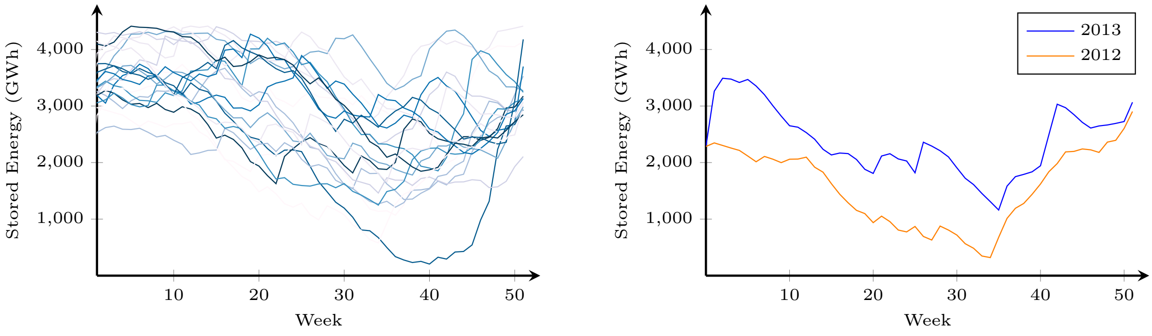
Without Huntly, reservoir levels would decrease significantly throughout the winter and then rise over the last three months of the year in anticipation of a dry following year, except in years where it is not possible to do so. Such a setup would negatively impact New Zealand, as the low reservoir levels in winter increase the risk of shortages. It is therefore unlikely that Huntly in its entirety would be removed from the NZEM, unless other changes were effected, such as a significant decrease in demand or the addition of a large supply of renewable energy.

Finally, Figure 5.2 shows the reservoir levels at the beginning of the year (Week 1), for 1000 Monte Carlo simulations. The inflow sequence for the year is a randomly selected year between 1994 and 2013, such that the year selected was neither the previously selected year, nor the year before that. This effectively is a Tabu list of length two. In this way, the same year's inflows cannot be selected several times in sequence, which could potentially model the persistence of a multi-year drought.

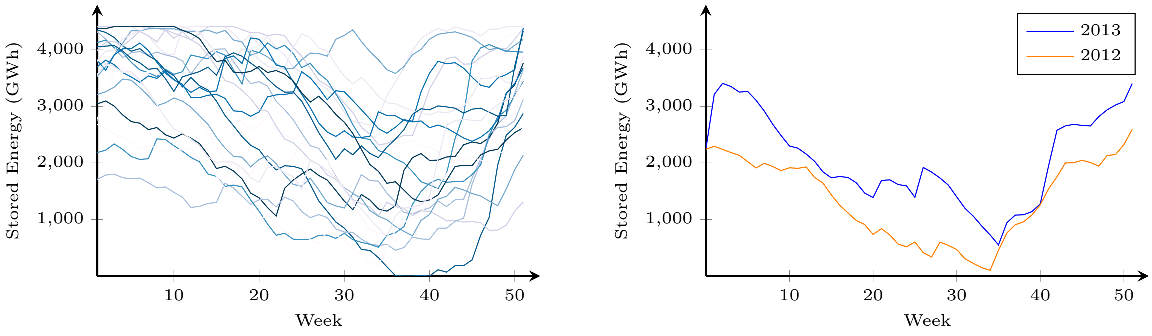
The graphs in Figure 5.2 underscore the notion that reservoir levels need to be higher when Huntly's coal units are removed (Scenarios 2 and 3), in case of a dry year. Interestingly, water levels are lower on average in Scenario 3 compared with Scenario 2, because water is more valuable without any generation at Huntly. It is better to use water, even if reservoir levels are low, than to face shortages of electricity.



(a) Scenario 1 (b) Scenario 1

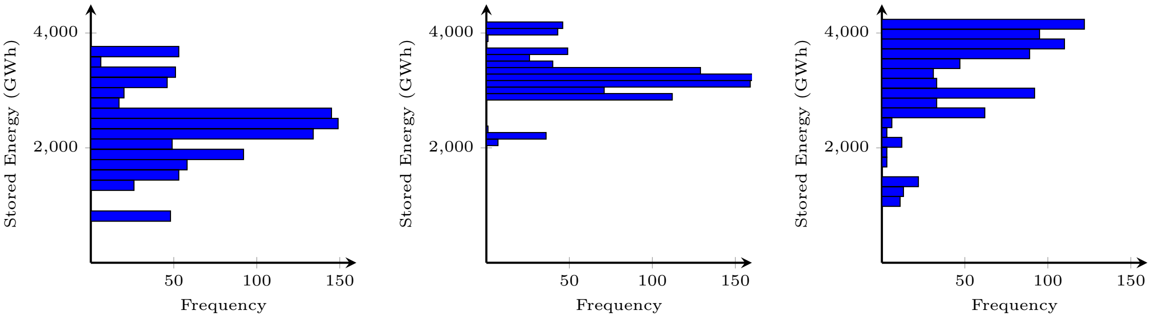


(c) Scenario 2 (d) Scenario 2



(e) Scenario 3 (f) Scenario 3

Figure 5.1: Net Reservoir Levels over Historical Years. The graphs on the left show inflow trajectories for 1994-2013. The graphs on the right portray the difference in behaviour for a wet year (2013) and a dry year (2012)



(a) Scenario 1 (b) Scenario 2 (c) Scenario 3

Figure 5.2: Distribution of Week 1 Net Reservoir Levels (1000 Monte Carlo Simulations)

5.4 Financial Outcomes for Scenarios 1 and 2

It is difficult to predict how future changes to the NZEM would affect each market participant; for example, if Huntly completely closing down would lead to a re-distribution of hydro assets. Hence, in Figure 5.3 we focus on Scenarios 1 and 2, in particular how removing the coal-fired Rankine units would impact the operating surpluses of each gentailer, with all other factors held equal. The removal of coal as early as 2022 is the next major change likely to impact the NZEM, hence it makes sense to focus on the most immediate, likely scenarios when carrying out financial analysis.

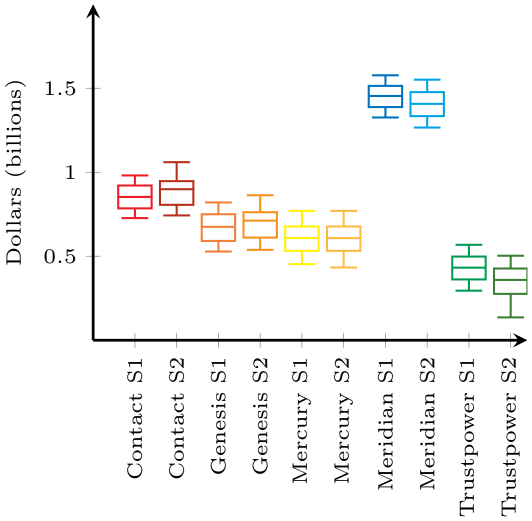


Figure 5.3: Distribution of Operating Surpluses by Gentailer for Scenarios 1 and 2

Figure 5.3 shows that Contact and Genesis, which own a large share of the existing thermal stations, would benefit from the closure of the two Rankine units. As net thermal generation is greater in Scenario 2 than Scenario 1, this result is as expected. However, this analysis does not incorporate the swaption contract in place between Genesis and Meridian (as discussed in Section 2.3), under which Genesis benefits from keeping the two Rankine units operational. Incorporating the value of this swaption into our financial forecasts would increase Genesis' operating surpluses and decrease those of Meridian in Scenario 1. Our results show that this swaption contract prevents Genesis from shutting down its Rankine units (which would increase their operating surpluses, and hence be favourable from a commercial perspective).

Meridian and Trustpower are negatively impacted by the removal of the Rankine units, for two reasons. A more conservative approach to managing water means that less electricity is produced by hydro stations, with some reservoirs spilling water to maintain high reservoir levels. This hampers gentailers with a large proportion of hydro assets (such as Meridian, and to a lesser extent, Trustpower). Furthermore, an increased electricity price π in dry years means that gentailers such as Trustpower, that have a larger retail market share than generation market share, are forced to buy electricity off the grid at high prices and therefore have lower operating surpluses.

The electricity prices π for each scenario are presented in Appendix II.

6 Future Renewable Energy Options

Given that the NZEM would likely face shortages in some years without Huntly, the pertinent question of how to ensure security of supply in the future must be asked. With this in mind, we investigate the viability of additional geothermal and wind energy, and simulate the NZEM with these additional renewable resources. A brief analysis of a carbon tax and a 100% renewable future is also provided.

6.1 Adding Renewable Energy into the JADE Model

In order to make up any deficit of unmet demand, new generation assets could be acquired so as to limit potential shortages in the future, particularly as New Zealand transitions towards a 100% renewable energy future.

The Electricity Authority maintains a register of proposed generation plant with a minimum capacity of 5MW (refer to Appendix III). As a result, solar units are not noted on this register. Currently there are diesel, gas, geothermal, hydro, marine and wind assets which have either been consented or are under consideration. Naturally, a 100% renewable goal (at least in a normal hydrological year) means that diesel and gas options are excluded from our analysis. There is a lot of uncertainty about the viability of marine energy [19] in the Kaipara Harbour, and assessing the environmental impact of introducing a new hydro plant is outside the scope of this report. Hence, the generation types of interest are geothermal and wind energy.

Geothermal Energy

We first consider additional geothermal assets. The four consented geothermal fields have a combined capacity of 358 MW and could all be commissioned by 2021. All proposed geothermal generation facilities are in the upper North Island. Only the largest of the four proposed geothermal plant would be owned by one of the ‘big five’ gentailers.

Wind Energy

Of the proposed wind plant, 11 are located in the North Island, and four in the South Island. If Huntly were to close down, it would make sense from a ‘socially optimum’ perspective to build new wind assets in the North Island in the first instance; closing Huntly would lead to a decrease in supply available in the North Island. Consented capacity is about 2530 MW, and about 80% of this capacity would be under the ownership of the largest five gentailers.

Increasing the Proportion of Available Renewable Energy

We capture the addition of geothermal and wind plant into the NZEM by an *embedded* demand approach. In the JADE model, electricity output from existing geothermal and wind sources are subtracted from demand at the relevant node. We use the same approach to embed additional geothermal and wind sources into the **demand.csv** input file.

However, predicting which facilities will actually be built is difficult, due to the market-based investment structure of the NZEM, where each gentailer has its own agenda. Instead, we consider the proportion of consented investments (in MW) made available, by using scaling factor, τ. This approach assumes that the HVDC Inter-Island cable is not a limiting factor, and that demand is approximately constant throughout each load block.

Increasing the Proportion of Available Renewable Energy

To calculate the new demand values, it is necessary to first consider the maximum amount of new generation that will be satisfied by geothermal and wind means respectively, for a given scenario.

Variables

ΔG	Change (increase) of geothermal electricity supply available (MWh)
τ_G	A value between 0 and 1 representing the proportion of consented geothermal assets to be built
G_{Max}	Maximum amount of electricity (MWh) satisfied by new geothermal assets (all consented stations added to model)
ΔW	Change (increase) of wind electricity supply available (MWh)
τ_W	A value between 0 and 1 representing the proportion of consented wind assets to be built
W_{Max}	Maximum amount of electricity (MWh) satisfied by new wind assets (all consented stations added to model)
$\hat{d}_{ijk}$	Updated electricity demand (MWh) with new geothermal and wind stations added into the model, for a given load block, week and node
d_{ijk}	Existing electricity demand (MWh) before geothermal and wind stations are added into the model, for a given load block, week and node

Hence the increase in geothermal and wind energy from the additional renewable sources is given by:

$$\Delta G = \tau_G \times G_{Max} \tag{6.1}$$

$$\Delta W = \tau_W \times W_{Max} \tag{6.2}$$

If only the geothermal assets are made available, then τ_W is zero, and vice versa for wind. In all five of our additional renewable scenarios, τ_G or τ_W is set to be the maximum value of 1 depending on whether geothermal or wind is added into the model. Where both geothermal and wind energy are added, $\tau_G = \tau_W = 1$. In saying this, the method described above does allow for different levels of geothermal and wind energy to be embedded in the model. The new demand at each node is given, for geothermal and wind energy respectively, by:

$$\hat{d}_{ijk} = d_{ijk} - \Delta G - \Delta W \tag{6.3}$$

Once the increased supply of renewable energy has been embedded in the demand file, we can run more simulations. Because it is near impossible to predict which plant will be built, it does not make sense to carry out extensive financial analysis. Instead, the results of our future renewable energy options are concentrated on the total generation mix and carbon emissions, for each scenario. If the lost load is negligible, then the new generation mix should be sufficient, supposing that actual demand does not change significantly in the future.

6.2 Simulations with Additional Renewable Energy

Five further Scenarios have been constructed. In Scenarios 4-7, all four Rankine units are non-operational. In Scenario 7, the thermal fuel costs are increased to represent a \$100/tonne carbon tax on carbon emissions from thermal stations. The final scenario simulates a '100% renewable' NZEM, with all thermal stations (including Huntly) shut down.

Thus, Scenarios 4-8 are:

4. Two gas units at Huntly + All consented geothermal
5. Two gas units at Huntly + All consented wind
6. Two gas units at Huntly + All consented geothermal + All consented wind
7. Two gas units at Huntly + All consented geothermal + All consented wind + Carbon tax
8. No thermal units + All consented geothermal + All consented wind

The storage trajectories for Scenarios 4, 5, 6, 7 and 8 are presented in Appendix IV.

6.3 The Electricity Mix for Each Scenario

The graph below (Figure 6.1) shows the amount of electricity produced by each generation source, for each of our eight scenarios. The electricity generation is per year, averaged over the 20 years of hydro inflows for which simulations were carried out, for each scenario.

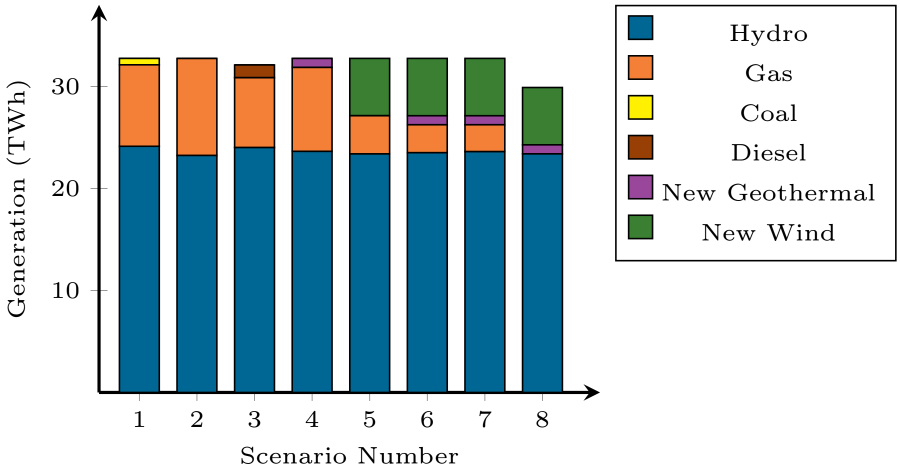


Figure 6.1: Generation Mix for an Average Year by Scenario

Even accounting for the loss of the two coal-fired Rankine units, we see an increase in the total thermal generation between Scenarios 1 and 2. This can be explained by examining the respective plots of reservoir levels in Section 5.3. In Scenario 2, there is less thermal capacity in the NZEM, and thus a more conservative approach to managing reservoir levels is taken. Hence, thermal stations are used even before this becomes a necessity, to avoid potential shortages in later weeks (if, for example, a dry spell were to occur and reservoirs were to drop to critically low levels).

Diesel at Whirinaki is only used when strictly necessary, in Scenario 3. The decrease in total electricity generation over the year for Scenarios 3 and 8 comes at the expense of the large lost loads during these years.

Figure 6.1 also shows that the capacity of consented wind far exceeds that of consented geothermal energy, and as a result, thermal production levels are much lower for Scenario 5 compared with Scenario 4. Note that only additional, new geothermal and wind energy sources are captured in Figure 6.1, as existing plant have already been embedded into the demand file.

A final observation is that the generation mix is virtually unchanged between Scenarios 6 and 7. This tells us that the imposition of a \$100/tonne carbon tax after Huntly's two Rankine units are shut down would have a negligible impact on the NZEM - thermal stations would continue to be used as required.

6.4 Carbon Emissions for Each Scenario

For each of the 20 historical years simulated for each scenario, the resulting carbon emissions for each year are calculated. The corresponding distributions are shown in Figure 6.2 below. The term 'carbon emissions' refers to the total mass of CO_2 equivalents emitted by the NZEM as a whole over a given year.

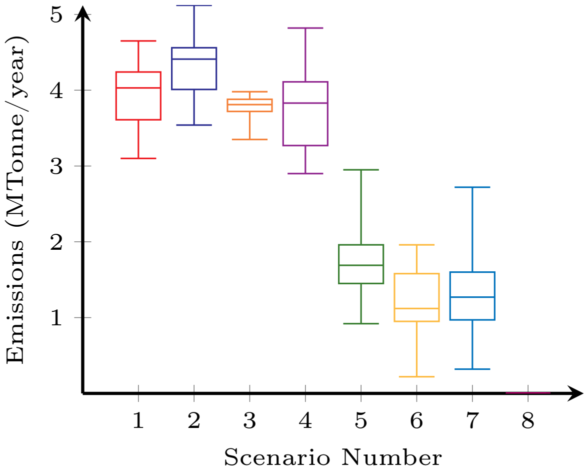


Figure 6.2: Distribution of Carbon Emissions by Scenario

A key result from this graph is that carbon emissions actually increase when the two Rankine units are shut down, in Scenario 2. This can be explained by the remaining thermal stations being used to a greater extent, even though there is less thermal capacity in the NZEM. This hypothesis is supported by Figure 6.1. Without the Rankine units, a more conservative approach is employed, whereby the remaining thermal stations produce more electricity earlier in the year as a contingency. This means that the market is less likely to become stuck in a position where very low reservoir levels and reduced thermal capacity means that shortages are inevitable.

Statistical analysis was carried out, using a paired sample t-test with common random numbers to compare the differences in carbon emissions between Scenarios 1 and 2. The mean difference in emissions between Scenario 1 and 2 was 0.37 MTonne/year. Our associated 95% confidence interval revealed that we could expect Scenario 2 to produce between 0.09 and 0.65 MTonne/year more carbon emissions than Scenario 1, and our p-value of 0.0126 means that this result is statistically significant.

7 Future Work

Coal Stockpile A coal stockpile, where coal can be bought by Genesis in advance at (hopefully) cheaper prices and stored for later use, could also be incorporated into the model. This may lead to fuel cost savings for Genesis and affect its policy of when to use Huntly. However, such a modelling approach may be at odds with a 100% renewable energy future. This analysis would likely only be relevant in the short-term, especially if Huntly transitions from using coal to gas in its Rankine units.

Future Hydro Assets Incorporating new hydroelectric dams (of which 11 have currently been approved at the consent stage) into the JADE model would require several modifications to be made. Hydro arcs may need to be added or modified to reflect the flow of water between rivers and reservoirs. The new assets would need a prescribed specific power. Moreover, each dam would need a set of inflows. This could involve using historical data (if it were available), or otherwise simulating inflows by adapting a known set of inflows from a similar water source. The latter process is likely to lead to some inaccuracy, unless the sampled inflows are from a location close to that of the new hypothetical station, with upstream rivers having a similar flow rate.

Simulating the Closure of the Tiwai Point Aluminium Smelter Recall from Section 2.5 that the aluminium smelter at Tiwai Point uses about 14% of New Zealand's electricity each day. Further work could investigate the impact of the smelter closing down, as was mooted in 2015 [20]. This may involve splitting the South Island node into two, to model the transmission around New Zealand of the electricity generated at Manapouri Power Station which was previously used at the smelter. It remains to be seen what the impact of the decommissioning of the smelter would be on the price of electricity in the South Island; for example, Meridian may not consider it economical to keep the Manapouri Power Station operational if the smelter were to close.

Capacity Markets One way of ensuring security of supply is with a capacity market, such as that currently in use in the United Kingdom. A capacity market sees market participants being paid a fixed rate for the electricity capacity (in MW) that they provide to the market. They are then required to meet this capacity when called upon by the National Grid [21] This approach leads to fixed income for generators, as well as encouraging investment in reliable sources of electricity. Some analysis could be carried out as to how such a market would affect security of supply in New Zealand, and how this might affect each of the five leading gentailers, given their different combinations of assets.

Modelling the Effect of a Changing Carbon Tax In Section 6.3, the impact of a \$100/tonne carbon tax was discussed. In the future, raising this carbon tax could be further analysed to find the point at which this carbon tax meaningfully impacts the amount of thermal generation. One proposed method would be to use regression analysis, whereby the wholesale price of electricity could be simulated against the carbon tax. This analysis would show the effect of a changing carbon tax, *ceteris paribus*.

8 Conclusion

This project has addressed security of supply in the New Zealand Electricity Market (NZEM). The motivation for this project came about when the New Zealand Government announced that electricity is to be produced by renewable means only, during a normal hydrological year, from 2035 onwards. Through generating policies for various scenarios and then simulating these policies over historical inflows, the viability of each scenario could be analysed.

The work carried out by Shasa Foster allowed these results to be obtained. His developments to the SDDP.jl and JADE.jl packages made it possible to more accurately model the NZEM. The model ensured that reservoir levels at the end of a given year correspond to reservoir levels at the start of the following year, through implementing a dynamic end-of-horizon marginal value of water function. Moreover, the use of parallel computing and cut selection heuristics decreased the runtime for generating policies significantly. This meant that more scenarios could be analysed within the fixed timeframe of this project.

A key finding of this project was that there is a low likelihood of electricity shortages with the status quo generation mix. Reservoir levels drop by a greater amount over the course of the year when the two coal-fired Rankine units at Huntly Power Station are removed from the model. However, closing down these two Rankine units would lead to greater net thermal generation per year and an increase in carbon emissions for the NZEM as a whole, as a more conservative approach to reservoir level management is required.

Of the five leading gentailers, Contact and Genesis would be set to benefit financially from the closure of the two Rankine units, with increased operating surpluses, while Meridian and Trustpower would be negatively impacted.

The best-suited energy types to replace thermal (coal, diesel and gas) energy in the NZEM appear to be geothermal and wind energy. Several geothermal fields and wind farms have already been consented and, if all approved assets were to be built, these renewable energy sources would have a meaningful impact on New Zealand's generation mix. Thermal generation would decrease significantly, and with it, annual carbon emissions from the electricity sector. However, if all thermal energy sources were to be shut down, significant electricity shortages would occur, even with the additional geothermal and wind assets.

Simulations also revealed that the imposition of a \$100/tonne carbon tax would have a negligible impact on the NZEM as a whole. Further research could be carried out to determine a suitable carbon tax which would influence the behaviour of market participants sufficiently so as to reduce carbon emissions.

In conclusion, New Zealand has the potential to increase its proportion of electricity generated by renewable means, simultaneously decreasing its carbon footprint. This would further enhance the nation's standing as a world leader in terms of renewable energy. In addition, our results demonstrate the importance of robust, impartial modelling frameworks when analysing the security of supply of electricity in New Zealand.

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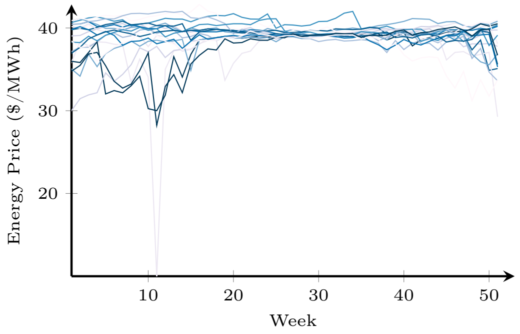
Appendices

Appendix I: Hydro and Thermal Stations in New Zealand

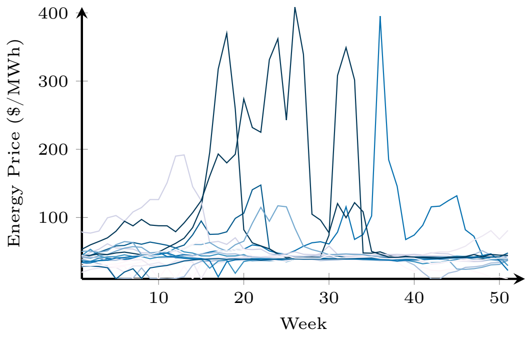
As Used in Our Model, Not All Are Currently Operational

Name	**Type**	**Owner**	**Location**	**Fuel Type**	**Heat Rate (GJ/MWh)**
Arapuni	Hydro	Mercury	NI	Water	-
Aratiatia	Hydro	Mercury	NI	Water	-
Atiamuri	Hydro	Mercury	NI	Water	-
Karapiro	Hydro	Mercury	NI	Water	-
Maraetai	Hydro	Mercury	NI	Water	-
Ohakuri	Hydro	Mercury	NI	Water	-
Waipapa	Hydro	Mercury	NI	Water	-
Whakamaru	Hydro	Mercury	NI	Water	-
Aviemore	Hydro	Meridian	SI	Water	-
Benmore	Hydro	Meridian	SI	Water	-
Ohau A	Hydro	Meridian	SI	Water	-
Ohau B	Hydro	Meridian	SI	Water	-
Ohau C	Hydro	Meridian	SI	Water	-
Tekapo A	Hydro	Genesis	SI	Water	-
Tekapo B	Hydro	Genesis	SI	Water	-
Waitaki	Hydro	Meridian	SI	Water	-
Clyde	Hydro	Contact	SI	Water	-
Roxburgh	Hydro	Contact	SI	Water	-
Manapouri	Hydro	Meridian	SI	Water	-
Cobb	Hydro	Trustpower	NI	Water	-
Coleridge	Hydro	Trustpower	NI	Water	-
Mangahao	Hydro	Todd	NI	Water	-
Matahina	Hydro	Trustpower	NI	Water	-
Rangipo	Hydro	Genesis	NI	Water	-
Tokaanu	Hydro	Genesis	NI	Water	-
Waikaremoana	Hydro	Genesis	NI	Water	-
Stratford	Thermal	Contact	NI	Gas	7.3
Huntly E3P	Thermal	Genesis	NI	Gas	6.8
Huntly Rankine 1	Thermal	Genesis	NI	Coal	10.5
Huntly Rankine 2	Thermal	Genesis	NI	Coal	10.5
Huntly Rankine 3	Thermal	Genesis	NI	Coal	10.5
Huntly Rankine 4	Thermal	Genesis	NI	Coal	10.5
Huntly Peaker	Thermal	Genesis	NI	Gas	15
NewPlymouth G1	Thermal	Contact	NI	Gas	11
NewPlymouth G2	Thermal	Contact	NI	Gas	11
NewPlymouth G3	Thermal	Contact	NI	Gas	11
Otahuhu B	Thermal	Contact	NI	Gas	7.05
Whirinaki	Thermal	Contact	NI	Diesel	11
Stratford Peakers	Thermal	Contact	NI	Gas	9.5

Appendix II: Electricity Prices for Each Scenario



(a) Scenario 1



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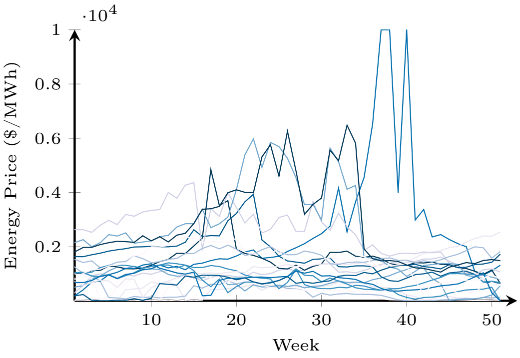

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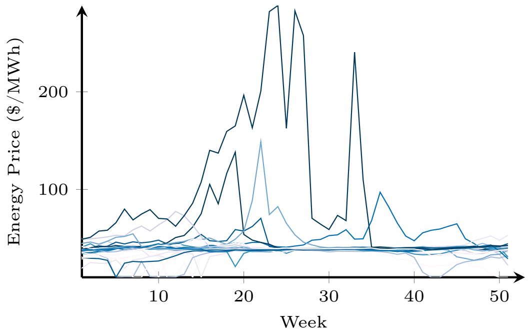

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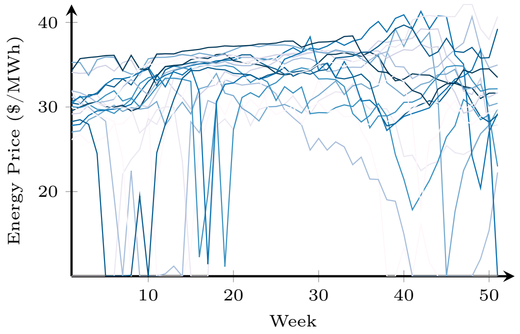

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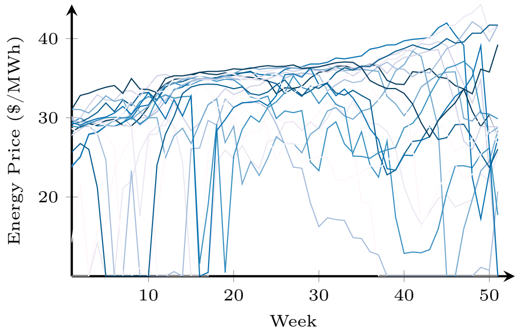

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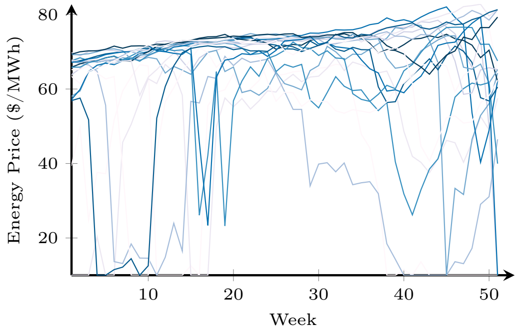

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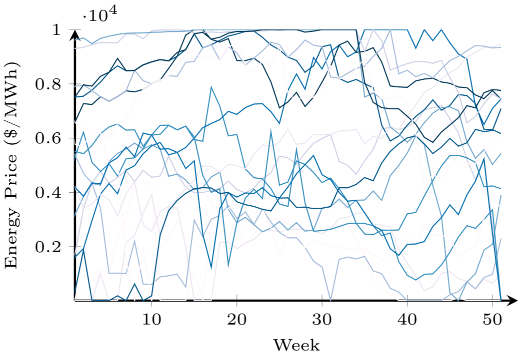


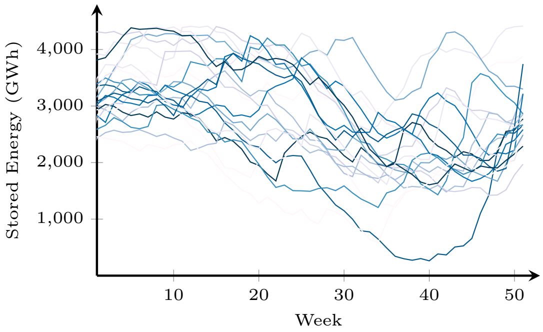
(h) Scenario 8

Appendix III: Proposed New Generation Facilities

Proposed Plant as at July 2018

Generation Type	**Region**	**Location**	**Owned by**	**Capacity (MW)**	**Earliest Commission Date**	**Status**
Diesel	Canterbury	Belfast	Orion	11.5	2019-2020	Consented
Diesel	Canterbury	Bromley	Orion	11.5	2019-2020	Consented
Gas	Taranaki	Junction Road	Nova Energy	100	2020	Consented
Gas	Waikato	Waikato Power Plant	Nova Energy	360	2021-2022	Consented
Geothermal	Waikato	Waikato Power Plant	Nova Energy	360	2021-2022	Consented
Geothermal	Bay of Plenty	Te Ahi O Maui	Eastland Group	20	2018	Under Construction
Geothermal	Waikato	Tauhara II	Contact Energy	250	2020	Consented
Geothermal	Northland	Ngawha Expansion	Top Energy	53	2021	Consented
Geothermal	Bay of Plenty	Rotoma	Rotoma	35	2019-2020	Applied for Consent
Hydro	Otago	Upper Fraser	Pioneer Generation	6.5	2019	Consented
Hydro	Canterbury	Balmoral Hydro	Meridian Energy	15	2019-2020	Applied for Consent
Hydro	Canterbury	Lake Pukaki	Meridian Energy	35	2019-2020	Consented
Hydro	Canterbury	North Bank Tunnel	Meridian Energy	240	2019-2020	Applied for Consent
Hydro	Canterbury	Rakaia River	Ashburton Water Trust	16	2019-2020	Consented
Hydro	Hawkes Bay	Ruataniwha Plains	Hawkes Bay Inv Co	6.5	2019-2020	Consent Under Appeal
Hydro	Marlborough	Wairau	Trustpower	70.5	2019-2020	Consented
Hydro	Otago	Hawea Control Gate Retrofit	Contact Energy	17	2019-2020	Consented
Hydro	West Coast	Arnold (Dobson)	Trustpower	46	2019-2020	Consented
Hydro	West Coast	Stockton Mine	Solid Energy	35	2019-2020	Consented
Hydro	West Coast	Stockton Plateau	Hydro Developments Ltd.	25	2019-2020	Consented
Marine	Northland	Kaipara Harbour Pilot	Crest Energy	200	2019-2020	Consented
Wind	Auckland	Awhitu	Trustpower	18	2019-2020	Consented
Wind	Canterbury	Hurunui	Meridian Energ	y 76	2019-2020	Consented
Wind	Canterbury	Mt Cass	MainPower	69	2019-2020	Consented
Wind	Hawkes Bay	Maungaharuru	Meridian Energy	270	2019-2020	Consented
Wind	Manawatu	Central Wind (Moawhango)	Meridian Energy	125	2019-2020	Consented
Wind	Manawatu	Turitea	Mighty River Power	303	2019-2020	Consented
Wind	Otago	Mahinerangi Stage 2	Trustpower	164	2019-2020	Consented
Wind	Southland	Kaiwera Downs	Trustpower	240	2019-2020	Consented
Wind	Taranaki	Waverley	Trustpower	135	2019-2020	Consented
Wind	Waikato	Taharoa	Taharoa	54	2019-2020	Consented
Wind	Waikato	Taumatatorara	Ventus	44	2019-2020	Consented
Wind	Wellington	Castle Hill	Genesis Energy	860	2019-2020	Consented
Wind	Wellington	Long Gully	Windflow Technologies	12.5	2019-2020	Consented
Wind	Wellington	Puketoi	Mighty River Power	159	2019-2020	Consented
Wind	Bay Of Plenty	Kaimai	Ventus	100	2020-2021	Applied for Consent

Appendix IV: Reservoir Levels for Scenarios 4, 5, 6, 7 and 8



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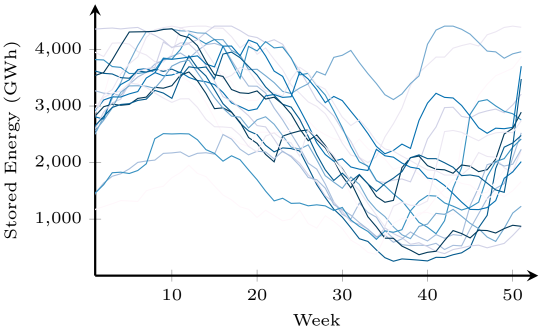

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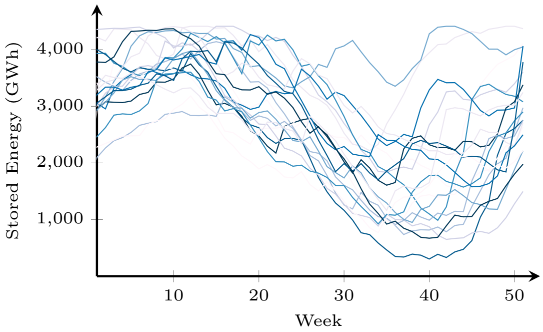

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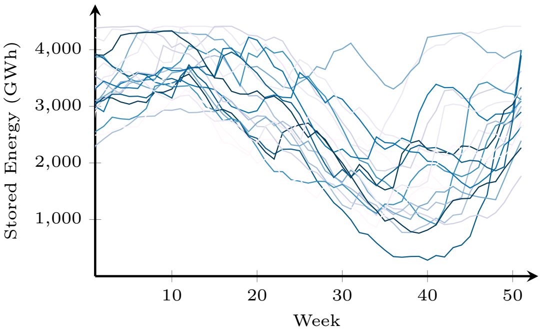

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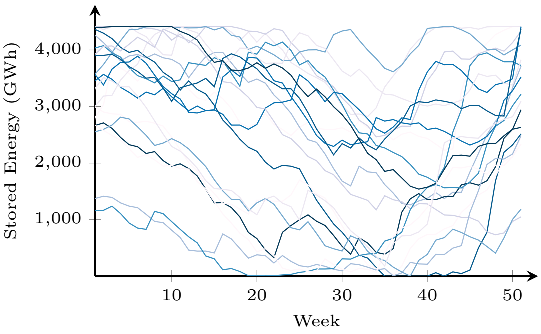

(e) Scenario 8