The University of Auckland

Department of Engineering Science

Part IV Project

Literature Review and Statement of Research Intent

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1 Introduction

As a remote two-island nation, New Zealand must produce its own electricity with no ability to import additional power. New Zealand has a unique generation mix from hydro (62%), thermal (17%), geothermal (14%), wind generation (4%) and co-generation (2%) sources [1]. Most of the hydro generation occurs in the South Island, while thermal and geothermal generators are all in the North Island.

Over a year, geothermal, wind and co-generation generation have steady, predictable outputs. Conversely, hydro generation, which is dependent on lake levels is reduced when there is a drought. Lake levels are lower in the winter months due to precipitation being snow not rain while electricity usage is the highest due to heating and fewer daylight hours. Due to New Zealand's dependence on hydro assets for electricity generation, a drought poses the threat of a prolonged electricity shortage.

Thermal generation is reflexive to season and lake levels. During periods of low demand and high lake levels (typically January-March) thermal power stations run at partial capacity (some not at all), while in periods of high demand and low lake levels (typically June-August if in a drought) thermal stations may be at full capacity.

In New Zealand, five main generators produce 90% of all electricity. These generators are also all retailers; they sell the electricity directly to customers. This is known as vertical integration. Retailers are also known as 'power companies'. Retailers enter contracts with consumers to supply electricity at a fixed price. These companies are known as gentailers (generator-retailer).

New Zealand's Electricity Market (NZEM) is a wholesale market. The electricity spot price ($/MWh) is calculated every half-hour and varies with supply, demand and location. Generators offer to produce specified quantities of electricity in the future at a nominated price. The system operator (Transpower) ranks offers in terms of price and then selects the lowest-cost combination of generation options while ensuring reliable supply [2].

The spot market is highly volatile. Market participants can hedge against the volatility using ASX futures or with financial transmission rights that protect wholesale market participants from dramatic half-hourly variations in spot-market prices at one location versus another [2].

Gentailers have contracts with customers that guarantee supply of electricity. Gentailers do not have to satisfy the exact amount of their customer's demand; they can buy electricity from the wholesale market. For example in dry years, hydro-dominant gentailers may buy electricity of the wholesale market, but in wet years the same gentailers may sell their excess production back to the electricity market.

2 Motivation

Due to New Zealand's dependence on hydro generation, droughts increase risk to the security of supply (of electricity). In winter when electricity consumption is highest, inflows are low, and reservoirs usually hold only enough water for several weeks of full usage. This was demonstrated by in 2001 and 2008 when dry winters forced the New Zealand government to run power-saving campaigns.

In dry winters, thermal generation is 'ramped up' to meet demand. Due to the cheap hydroelectricity available in NZ, unless there is a drought, thermal generators typically operate at partial capacity.

The largest thermal plant in New Zealand in the Huntly power station located 95km south of Auckland and owned by Genesis Energy. Huntly has a total capacity of 1453 MW which is 35% of New Zealand's average demand. Huntly has several different generation units detailed in the table below.

Units operational	2x 250 MW Rankine steam turbine (can run on coal or gas) 1x 403 MW Combined cycle gas turbine 1x 50 MW Open cycle gas turbine
Unit decommissioned	2x 250 MW Rankine steam turbine (can run on coal or gas)

Table 1: Generation units at Huntly Power Station

Two Rankine units were decommissioned in 2012 and 2015, respectively, due to flat electricity demand, high maintenance costs, climate change initiatives and the high cost of thermal generation.

The New Zealand Emissions Trading Schemes (NZETS) is a climate change initiative that affects Huntly power station. The NZETS was the result of the 2008 Climate Change Response Amendment Act [3] and was introduced in 2010. The NZETS taxes companies for greenhouse gas emissions. As Huntly power station is the largest thermal plant in New Zealand, it has been most affected by this bill. It has been estimated the NZETS has caused increases in electricity prices by 5-10% since 2010 [4].

Assuming a normal hydrological year (no droughts), the government aims for 90% and 100% of electricity generation to come from renewable sources by 2025 and 2035, respectively. [3]. Renewable electricity generation targets threaten Huntly's long-term operation.

As Huntly's coal-fired units are expensive to run and are inflexible (cannot be switched on/off on a whim), there has also been uncertainty of the future of the remaining two coal-fired Rankine units. The Rankine units are usually only operated in dry-year conditions, but must be maintained even when not in use, giving Genesis Energy an irregular stream of income to keep the plants operational.

In 2015, Genesis stated the units would be shut down in 2018. However, in 2016 Genesis announced the units would now be operational until December 2022 [5]. This change of decision was due to a swaption contract signed between Genesis Energy and Meridian, valid from January 2018 to December 2022. The contract gives Meridian Energy the option of 100 MW of electricity supply to be available all year round, with an additional 50MW available from 1 April to 31 October [6]. This contract enabled insurance for Meridian Energy against a dry year, while giving Genesis the cash flow to keep the two Rankine 250 MW steam turbines operational.

Thermal generation such as Huntly provides security of supply in dry years. However, in most years, Huntly only runs at partial capacity, which led to the decommissioning of two of its coal units discussed previously. The uncertainty of the future of Huntly's thermal units causes major uncertainty in NZ's security of supply as without Huntly there is the risk other gentailers may not be able to meet demand when a dry year occurs.

Droughts are not the only factor affecting the security of supply. On April 10, 2018, storms in Taranaki meant that gas processing could not occur leading to increased Huntly generation as a contingency. [7]

There are other factors that threaten the security of supply. The Tiwai Point aluminium smelter (NZAS) is a cause of major uncertainty in the security of supply of electricity in New Zealand. The NZAS is the only aluminium smelter in New Zealand located at Tiwai Point, Southland. The smelter has constant electricity usage of 580-600 MW, which is equal to 13% of New Zealand's average electricity generation. There have been threats of closure from the smelter, resulting from the smelter suffering losses since 2013, due to the contributing factors of electricity prices in New Zealand and low aluminium prices [8].

If the HVDC Inter-Island link that transmits electricity between the North and South Islands was upgraded to export power from Otago, the closure of the NZAS would flood the market with electricity and lower electricity prices, hence the smelter's potential closure is affecting investment in new generators (Transpower, 2017). Furthermore, a clause in the contract of power supply between the NZAS and Meridian Energy states that the NZAS need only give 12 months of notice before closure [9]. However, recent rising prices of aluminium and a falling NZ dollar have resulted in increased confidence in the future of the NZAS [10].

To summarize the situation so far, the uncertainty of droughts, the future of Huntly, and the future of the Tiwai Smelter cause uncertainty in both future supply and demand in the NZEM and threaten the security of supply in the NZEM.

As we do not know if there will be a drought this year, this causes difficulty in the decision-making regarding the management of hydro dams/generators. Gentailers do not know what future inflows to their reservoirs will be, so they do not want to run the reservoirs empty as they then may not be able to meet their contracted demand. Simultaneously, a too conservative operation of hydro dams/generators results in more thermal generation (and possible spills of water) which is costly.

The marginal value of water in New Zealand's reservoirs is defined as the dollar value of having one more MWh of water available for hydro generation. The additional water provides value by reducing the amount of (expensive) thermal generation needed and/or reducing load shedding. This marginal value of water varies seasonally as well as with the amount of water in the reservoirs. An additional 1 MWh of hydro generation is more valuable when reservoirs are nearly empty versus when the reservoirs are full.

In the context of hydro-generation, water is a scarce resource and its use must be scheduled carefully. A hydro-thermal scheduling model can be used to help hydro-thermal schedule decision making. The Electricity Authority, an independent Crown entity responsible for the efficient operation of the New Zealand electricity market offers various tools to assist informed decision making in the electricity sector. The hydro-thermal scheduling modelling tool offered by the Electricity Authority is DOASA [11].

A description of DOASA from the EMI-DOASA manual, 2017, by A. Philpott and G. Pritchard follows.

DOASA is an implementation of the stochastic dual dynamic programming technique applied to the hydro-thermal scheduling problem in New Zealand's electricity market.

"The DOASA model can be used to formulate a policy of releasing water from reservoirs for electricity generation while satisfying demand over a fixed time horizon and minimising the expected fuel cost of thermal generation. But the model will not necessarily satisfy demand in all scenarios. Given an appropriate penalty cost, some load shedding may occur." [11]

The DOASA algorithm divides a year into 52 weekly stages. The stochasticity of the stages is the weekly reservoir inflows that are assumed to be stagewise independent. All other input data is deterministic.

A major assumption of DOASA is the terminal value of water. The terminal value of water is the cost-to-go function in the final stage of the (backwards recursion) dynamic program. More intuitively, the terminal value of water is the value of water in all reservoirs at the end of the year. Without a terminal value of water, DOASA would leave all reservoirs empty at the end of the year. To avoid this, an exogenous terminal value of water is an input to DOASA which is dependent on the amount of water stored.

Stored Energy (GWh)	Value ($/MWh)
1000	137.2
1500	85.0
2000	55.9
2500	33.7
3000	19.0

Table 2: Terminal water value of DOASA

The set value of the stored energy is staggered. The first 1000 GWh is worth $137/MWh. The next 500 GWh is worth $85/MWh [12]. This assumption of the value of stored energy at the end of time horizon is a significant flaw in the DOASA model.

DOASA can also be used to model changes to the electricity system, such as the scenario of the decommissioning of Huntly's coal-fired units, and the shutdown of the Tiwai Point aluminium smelter. When modelling changes to the NZEM, these changes will affect the terminal value of water. As the terminal value of water in DOASA is not calibrated to these different scenarios, corresponding results are also flawed.

3 Statement of Research Intent

This project aims to investigate the future security of supply of electricity in New Zealand. We will assess the performance of the NZEM with the decommissioning of Huntly's coal-fired Rankine units, determine which market participants are affected by the decommissioning and who should pay Genesis for the security of supply Huntly brings to the NZEM.

The following scenario's will be considered.

1. The performance of the NZEM in dry years without Huntly's Rankine units

2. The effects of adding additional geothermal and wind generation units to the NZEM

Given the size of the NZEM, modelling the different potential scenarios is worthwhile and valuable. However, the modelling results are only as useful as our model is accurate. In the section 2 (the motivation), the issue of DOASA's assumption of the exogenous terminal value of water were discussed.

This project will consider the previous scenarios using an extended version of JADE (Just Another DOASA Environment), which is the same mathematical model as DOASA but implemented in Julia vs C++. We will extend JADE to implement an endogenous terminal value of water that depends on the modelled scenario of the NZEM. Hence the terminal value of water will be an accurate representation of the NZEM, not an assumption of JADE/DOASA.

With the extended DOASA model we will run simulations of the different potential scenarios of the NZEM. From simulation results, we will be able to determine the value of Huntly in the NZEM and to which gentailers the value (or cost) accrues to. We will also be able to determine which renewable energy generation is the best alternatives to fill the void in supply if Huntly is decommissioned.

This project is a collaboration between Ben Fulton and Shasa Foster. I, Shasa Foster will be extending the JADE model to use an endogenous market derived terminal value of water. Ben Fulton will be carrying out simulations with the extended DOASA model, analyzing and interpreting the results.

4 Review of Existing Literature

This section reviews the literature relating to this project. As my role in this paired project is the extension of the JADE hydro-thermal scheduling model, this literature review is skewed to my part of the project.

4.1 Hydro-Thermal Scheduling Modelling

The DOASA model was built using the Stochastic Dual Dynamic Programming algorithm first presented by Pereira and Pinto in 1991 [13]. Pereira and Pinto presented the original methodology for solving multistage stochastic optimisation problems with a continuous state variable. The paper proved a series of piecewise linear functions could approximate the expected future cost-to-go function of stochastic dynamic problems with a continuous state. This approximation of the expected future cost to go avoids the "curse of dimensionality" associated with dynamic programs with many discrete states [13].

The piecewise linear functions representation of the expected future cost-to-go are obtained from the dual solution of the linear program sub-problem at each stage in the dynamic program. This paper produced two new algorithms, a Dual Dynamic Program algorithm (DDP) and a Stochastic Dual Dynamic Program (SDDP). SDDP aimed to optimise hydro-thermal scheduling in Brazil.

The first versions of the Dynamic Outer Approximation Sampling Algorithm (DOASA) were first published in 2008 [14]. The aim of DOASA, like SDDP, is hydro-thermal scheduling. The main difference between SDDP and DOASA is DOASA's random inflow sampling each iteration compared to the fixed inflow sample paths of SDDP. This difference improved the performance of DOASA.

The implementation of DOASA is in C++. DOASA can be used to form a policy for the thermal generation and hydro release for the New Zealand electricity system. This policy can test be simulated in DOASA using a Monte Carlo method.

DOASA divides a year into 52 weekly stages. The state of the system is the reservoir levels in the seven New Zealand lakes with meaningful inter-week storage (Taupo, Benmore, Pukaki, Tekapo, Ohau, Hawea, Manapouri).

DOASA defines the operating policy as follows, *"The operating policy for the system is defined implicitly by a cost-to-go function or Bellman function. This function represents the expected future cost of operating an optimal policy from the end of the current week till the end of the planning horizon if the system is in a given state, i.e. there is a certain amount of water stored in each reservoir. The optimal decision of what water to release and what thermal generation to dispatch is then determined by solving a single-stage optimization with known inflows that minimizes the sum of thermal generation and shortage cost in that week plus the expected cost to go from the levels of water in each reservoir that result at the end of the week."* [12].

Inflows are modelled by random variables in DOASA, as described by Pereira and Pinto (1991) [13] which makes the dual dynamic program stochastic. Inflows are assumed to be to stagewise independent and are sampled from a historical record dating back to 1970. In actuality, inflows are not stagewise independent so this assumption, while convenient leads DOASA to produce overly optimistic policies during a drought, hence underestimating the true marginal value of during these periods. DOASA provides an option to counter this through Dependent Flow Adjustment, which modifies inflows from the empirical distribution to bring about dependence, however, this option increases run-time significantly, resulting in a worse policy generated than with stagewise independence under the same time frame.

This paper also described the model of the New Zealand electricity system used in DOASA. DOASA models the demand for electricity in the NZEM by a three-node network (NI, HAY, SI). NI refers to the upper North Island, HAY refers to Hayward an electricity station north of Wellington, and SI refers to the South Island. The demand for electricity in New Zealand is aggregated to these three nodes.

Electricity demand varies over the day, and DOASA models the variation in demand at each of the three nodes by three demand "load blocks"; peak, off-peak and shoulder. The input data for DOASA is provided by CSV files. These CSV files characterize the New Zealand electricity system. DOASA reads in the data from these CSV files and constructs the dynamic program.

As mentioned in the Statement of Research Intent, the specific module we are extending is JADE.jl, the implementation of the DOASA model in Julia. We will also be modifying SDDP.jl, the implementation of the Stochastic Dual Dynamic Program algorithm in Julia. Both JADE.jl [15] and SDDP.jl [16] were produced by Dowson and Kapelevich in 2017. Using Julia comes at a performance time cost of 30% slower compared to the C++ DOASA implementation, however, this a small trade-off compared to the benefits of using a high-level language like Julia such as quicker development.

The SDDP algorithm presented by Pereira and Pinto in 1991 [13] did not consider stochastic objective coefficients. Downward et al. [17] extended the SDDP algorithm for the case of stagewise independent noise in the objective function and proved this extension still resulted in the convergence of the SDDP algorithm. The extension to SDDP was then implemented in SDDP.jl, the Stochastic Dual Dynamic Program used by JADE. An example of the use of this additional functionality in DOASA is modelling the price -related objective coefficients as stochastic processes.

4.2 Results from Hydro-Thermal Scheduling Modelling of the NZEM

The DOASA algorithm has been used to model the NZEM in multiple papers.

In 2017, Martin Riva's Master's thesis "In Renewables We Trust: an assessment of the future consequences of changing the electricity generation mix in New Zealand" [18] used the DOASA model for analyzing the future security of supply of electricity and wholesale electricity prices in New Zealand under different scenarios. Scenarios considered included permutations of the shutdown of the Tiwai point aluminium smelter, the decommissioning of Huntly power station and the introduction of additional sources of renewable energy. These are the scenarios we are interested in, however, we will be using the extended JADE/DOASA model.

Riva determined the shutdown of Huntly's coal units is justified if Tiwai is shut down, as the remaining generators will be capable of meeting demand. However, the cost of meeting demand is expected to be higher, particularly in dry years, as more expensive gas-fired stations with fill the role of Huntly's coal units.

Results from DOASA sole shutdown of Tiwai point smelter would flood the NZEM with cheap electricity. In contrast, the decommissioning of Huntly with the Tiwai Point smelter remaining requires a significant new electrical capacity to ensure the security of supply. If New Zealand was to pursue further renewable penetration, Riva's analysis revealed a mix of geothermal power stations and wind farms is desired. Placement of these power stations in the North Island is important due to the high demand but lower present supply.

While Riva's thesis used the DOASA model to investigate future scenarios at a higher level, in 2016, Prashant Girdhar provided an in-depth analysis on the value of the Huntly to the NZEM in his Honours Thesis "Value of Huntly's Coal-fired Power Station" [19].

Girdhar investigated the different scenarios of the NZEM with and without Huntly's coal-fired Rankine units using the DOASA model. He then determined the value of Huntly in profits and risk-adjusted profits to the major NZEM market participants: the gentailers Contact Energy, Genesis Energy, Mercury Energy, Meridian Energy, and Trustpower.

Huntly has four Rankine units, however only two are available to the market with the remaining two units currently decommissioned. Girdhar determined that if the remaining two Rankine units were to shut down, all gentailers would be worse off. Genesis Energy, the owner of Huntly as well as Contact Energy, have the highest profit when one or two Rankine units are available to the market. Mercury Energy, Meridian Energy, Trustpower have lower profits for every Rankine unit that is removed from the market.

Girdhar states an important finding was in only hydro-dominating firms (Mercury Energy, Meridian Energy, Trustpower) would be willing to pay for the availability of all four Rankine units. Also, every removal of a Rankine unit from the market increased the risk of an electricity shortage. Huntly's value to risk-averse market participants and for the security of supply was also mentioned in Transpower Security of Supply reports in 2016, 2017 and 2018 [20], [21] [22]. Girdhar concluded, "the future of Huntly depends on the ability of Genesis Energy to negotiate agreements with other participants based on their willingness to pay".

4.3 Results from other models of involving the NZEM

Other papers discussed financial models and derivatives relevant to the NZEM. These papers are less relevant to my part of the paired project.

In 2013 in his Honours Thesis, "Hedging Against Spot Price Uncertainty in New Zealand Electricity Markets", Thomas Moulder investigated the relationship between New Zealand hydro storage reservoirs and present and future electricity spot prices (Moulder, 2013). He developed a model for estimating a distribution of future electricity spot prices, based on spot price correlation with current water storage. He also found there was a stronger correlation between future electricity spot prices as the difference between the future expected and future observed reservoir levels. Next, Moulder created a model to assist market participants in the ASX futures market on the NZEM. The model helped risk-averse parties such as gentailers make contract purchases for hedging against spot price risk. The model used Conditional Value at Risk (CVaR) as the measure of risk.

In 2012, in his Honours Thesis "Simulator for Electricity Related Investment ", Salah Al-Chanati investigated the use of contracts in the NZEM. ASX futures contracts for the Otahuhu and Benmore NZEM nodes allow market participants to hedge against the volatility of the electricity spot market. "The futures contract is a fixed volume variable price (contracts for differences) financial instrument that enables parties to secure an average price now, for a 3-month period into the future, as reflected by the contract's expiry date" (Al-Chanati, 2012)." Al-Chanati used Bayes' rule and a hidden Markov model to predict the settlement prices of these contracts. He also produced a simulator to test his model and his buy/sell strategy.

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