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SECURITY OF SUPPLY IN THE NEW ZEALAND ELECTRICITY MARKET

Literature Review and Statement of Research Intent

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1: Background Information

1.1: Overview of Electricity Generation in New Zealand

The New Zealand electricity landscape is unique. As an isolated island nation, importing or exporting electricity is not an option. The country is therefore required to produce all of the electricity which it consumes.

New Zealand ranks fourth in the world in terms of the percentage of total electricity generated by renewable means [1]. In the 1950s and 1960s, the New Zealand government of the time invested large amounts of money in the construction of hydroelectric dams, which vastly increased the capacity of the hydro sector. Today, hydroelectricity accounts for approximately 62% of all electricity generation annually [2]. The remaining electricity demand is met by, in descending order of market share: geothermal, gas, wind, coal, biogas and solar energy [3].

The majority of water used to generate electricity is stored in seven lakes, of which six are in the South Island and one (Lake Taupo) is in the North Island. They are, in order of decreasing capacity: Pukaki, Manapouri, Hawea, Taupo, Tekapo, Benmore and Ohau. Other hydro plants are considered run-of-river, with negligible medium- to long-term storage capability – water either passes through the generator or is spilled. Most thermal and geothermal generation facilities are located in the North Island.

The New Zealand government has committed to at least 90% of electricity being produced by renewable sources by the year 2025, with a goal of 100% renewable energy “during a normal hydrological year” by 2035 [4]. This would involve placing many existing thermal generators into long-term storage, as well as potentially increasing the capacity of hydro, wind and/or geothermal generation facilities.

1.2: Huntly Power Station

One such thermal generation facility is the Huntly Power Station (‘Huntly’), located 95km south of Auckland and 32km north of Hamilton. It is owned and operated by Genesis Energy. Although the power station has six units, only four are currently operational. There are two 250 MW ‘Rankine’ steam turbine units in operation, which can use either coal or gas. The other two Rankine units were ‘mothballed’ (decommissioned) in 2013 and 2015 respectively. In 2004, the 50 MW ‘P40’ open-cycle gas turbine was commissioned, followed in 2007 by the more efficient 403 MW ‘E3P’ combined-cycle gas turbine.

Coal, which was previously sourced domestically and bought from Solid Energy, is now mostly imported from Indonesia. The gas comes from the Maui gas fields in Taranaki [5]. The majority of the electricity generated at Huntly typically undergoes transmission through the national grid to Auckland.

Despite conjecture from some commentators and press releases from Genesis Energy themselves, the future of Huntly remains unclear. In August 2015, Genesis announced that the remaining two Rankine units were to close by the end of 2018 [6]. However, a year later, the company backtracked on this decision in signing a 'swaption' contract with Meridian and "other [undisclosed] market participants" to keep the two Rankine units open as a contingency option through until 2022 [7].

In May 2012, the Waikato Regional Council granted a resource consent which effectively meant that the power station would be able to operate for another 25 years. Although this time horizon extends two years beyond the point at which the New Zealand government wishes to no longer use non-renewable energy generators, these thermal stations could continue to be used as 'peakers' to meet demand in dry hydrological years, if required.

1.3: Ensuring Security of Supply in the Future

The desire for electricity to be produced by renewable energy sources must be balanced against the need for the security of supply of electricity. The greatest factor affecting hydroelectricity generation is rainfall; during 'dry' years the reservoirs contain less water and therefore a lesser amount can be released through the turbines. There are other factors too, for example, on the 10th of April 2018, a large storm meant that natural gas could not be processed in Taranaki, which led to Huntly's coal-fired generators being 'ramped up' as a contingency plan was implemented [8]. Moreover, there are environmental regulations imposed, which restrict reservoirs from being lowered below a certain level. In general, hydro dams provides a 'base level' of electricity, with thermal resources being used to meet any additional demand as required.

The supply of electricity is naturally influenced by demand, and therefore during certain events when demand for electricity is unusually high, such as sustained cold temperatures, there must be enough electricity generated so as to not incur significant shortages. Although about 77% of New Zealand's population resides in the North Island, it accounts for approximately two thirds of New Zealand's electricity demand [9]. Demand is categorised as peak, off-peak or shoulder on a half-hourly basis.

Future security of supply in New Zealand is made more uncertain due to the questions surrounding the Tiwai Point Aluminium Smelter ('Tiwai Point'). Located near Bluff, the southernmost town in the country, the smelter is New Zealand's largest consumer of electricity, using 13% of all electricity annually. The power station at Manapouri effectively sends the entirety of its electricity to the smelter [10]. As Tiwai Point must constantly receive power in order to keep its alumina above a given temperature, its demand for electricity is consistent throughout the day – and year. Some have speculated that the closure of this facility for commercial reasons could lead to a large amount of cheap electricity being available on the market and vastly impact the New Zealand electricity landscape, subject to the expansion of the transmission network in Southland and Otago [11]. However, if the power station at Manapouri were to also close down, electricity prices would be likely to remain relatively stable.

1.4: New Zealand's Electricity Market

The New Zealand Electricity Market (NZEM) is governed by the Electricity Authority (EA), which replaced the Electricity Commission in 2010. One of the EA's key responsibilities is ensuring security of supply at a national level. The Electricity Authority has a narrower scope of work than the Commission did, focusing specifically on competition within the industry, reliability and efficiency [12].

The electricity sector was decentralised in the 1990s: Transpower was established in 1994 to oversee the transmission of electricity throughout the country, before the Electricity Corporation of New Zealand disbanded in 1999. This led to the formation of Contact Energy, Mighty River Power (now Mercury Energy), Meridian Energy and Genesis Energy, who, along with Trustpower, were the five largest generators and retailers of electricity in 2017 [13].

Today, the distribution of electricity is overseen by local organisations, under the jurisdiction of local councils, which typically operate as monopolies (such as Vector in Auckland, Orion in Christchurch and Wellington Electricity in the capital). Transpower, a state-owned organisation, remains responsible for the physical infrastructure necessary for transmission, as well as for the real-time operation of the national grid.

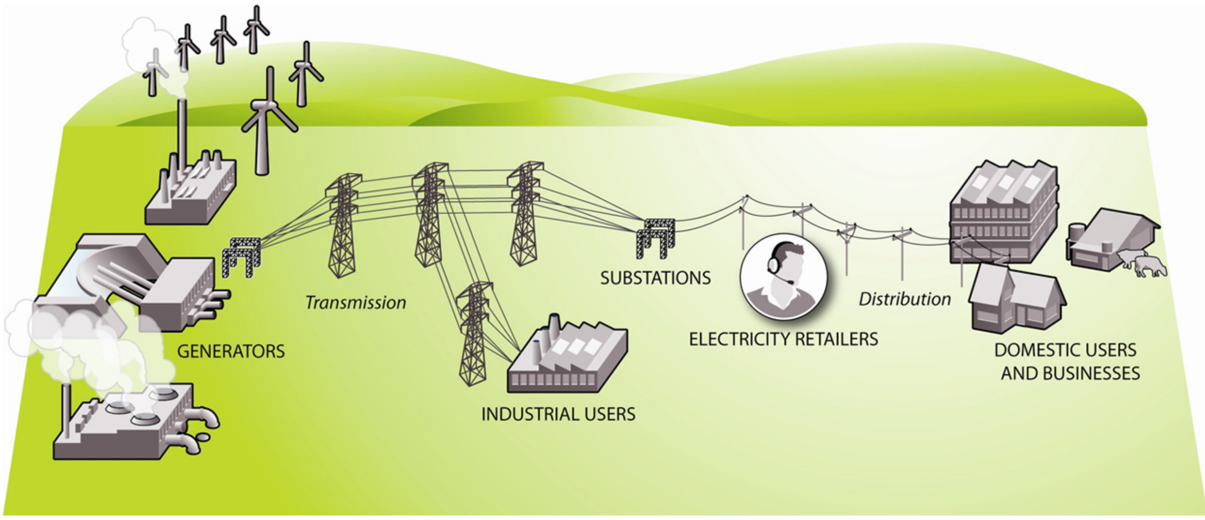

Figure 1: Schematic of New Zealand's Electricity Network. Source: MBIE

Contact, Genesis, Mercury, Meridian, and Trustpower produce and sell over 92% of New Zealand's electricity [14]. Because they act as both generators and retailers, they are commonly known as 'gentailers,' a term that will be used throughout the remainder of this report. Genesis, Mercury and Meridian were previously owned by the government. However, as part of the sale of state-owned assets programme which began in 2013, almost half of the shares in each of these gentailers are now held by private investors.

2: Statement of Research Intent

This project will investigate the future security of supply of electricity in New Zealand, in particular if Huntly Power Station were to close down its units. New Zealand's electricity supply is highly reliant on hydropower, and hence hydrological conditions affect not only the amount of electricity that is produced by hydro generators, but thermal generation too. In dry years, the marginal value of water increases, with thermal generators used to a greater extent so as to limit the risk of electricity shortages. However, thermal generators can be costly to maintain, therefore, it may not be worth keeping them operational if they are used infrequently.

Our project involves using and extending the JADE model in the programming language Julia. JADE, which stands for Just Another DOASA Environment, is a multistage stochastic model of the NZEM. DOASA itself is a hydro-thermal scheduling tool, which produces a policy of when and where to release water from reservoirs, as well as how much thermal electricity to produce, on a week-by-week basis. The price of electricity can also be extracted from the model.

The JADE model essentially runs a Stochastic Dual Dynamic Programme, which is necessitated by the fact that the amount of water in each reservoir is a continuous variable. This model sees the realisation of various stochastic hydrological inflows, which correspond to various reservoir levels.

The algorithm will be modified to produce an approximation of the terminal value of water function, in lieu of the arbitrary, fixed terminal function which is currently used. The accuracy of this approximation should improve with each iteration. My project partner, Shasa Foster, will extend the JADE model, by implementing an infinite horizon stochastic dual dynamic programme. In this way, the terminal value of water will be defined endogenously, thereby providing a more accurate representation. I will use this model to analyse different scenarios, in terms of the value of Huntly and additional renewable generation resources.

By analysing the operating surpluses of each gentailer, as a function of the price of electricity, the financial position of each gentailer can be computed under different scenarios. In effect, the respective operating surpluses of each gentailer will allow an estimate of the value that Huntly adds to the NZEM to be obtained. If shortages of electricity occur within acceptable levels without Huntly present in the model, then Huntly could shut down while still ensuring security of supply in the future.

Future energy options will also be considered. Additional geothermal and wind energy could be incorporated into the model to meet demand which would previously have been met by thermal generation. Differing levels of electricity contribution from each renewable generation source will be simulated, and the results of such comparisons visualised, in terms of the likelihood of shortages of electricity. Thus, we should be able to draw conclusions in terms of the value of Huntly's units, and how New Zealand will ensure the security of its electrical supply in the years to come.

3: Review of Existing Literature

In this section we review reports and manuals which describe concepts of relevance to this project. Pertinent ideas are noted, and results are summarised. In this way, we can explore approaches and models which may be of use.

3.1: *In Renewables We Trust: An Assessment of the Future Consequences of Changing the Electricity Generation Mix in New Zealand* – Master's Thesis by Martin Riva (2017)

Riva (2017) investigated various future energy scenarios with different mixes of generation technologies [15]. Both Tiwai Point, as New Zealand's single largest consumer of electricity, and Huntly, an important asset especially during dry years, are important for New Zealand's electricity landscape. Riva explored ten different scenarios as part of his thesis, which included different combinations of future possibilities, such as the decommissioning of Tiwai Point, closing down Huntly, and new renewable energy generation sources. Riva reasoned that if Tiwai Point were to shut down, "the market would be flooded with cheap electricity" and therefore there would no reason for Huntly to remain in operation.

This analysis was carried out using the Dynamic Outer Approximation Sampling Algorithm (DOASA). The DOASA model predicts the future price of energy, the value of lost load due to unmet demand, and the marginal value of water (see Section 3.7) under various hydrological scenarios. The Renewable Integration Model (RIM) was used to incorporate renewable generation methods other than hydropower, such as wind and geothermal energy, into the simulations.

DOASA partitions New Zealand into three nodes: the North Island, South Island and Haywards. The name Haywards is derived from the substation north of Wellington where electricity arrives from the South Island via the high-voltage direct current cable (HVDC). Aggregating all of the national electricity demand into three nodes will not capture all of the intricacies of electricity transmission, however this was deemed necessary in order to represent demand in an intuitive manner that would be computationally feasible.

Riva's analysis led to his conclusion that closing down Huntly would be justified, especially if the Tiwai Point smelter were also to close. Without Tiwai Point, enough electricity should be generated by existing means to meet demand even in a dry hydrological year, such as 2008. Riva theorised that if Tiwai Point were to close, then the price of electricity would decrease, which could drive up demand.

If Tiwai Point were to remain operational with Huntly closing down, new generation sources would be required, as the energy market is projected to grow by approximately 1.1% annually. In spite of this, Riva took an optimistic view. He described the potential for the geothermal sector to grow, the price of generating solar energy to decrease, and how marine energy could also be a viable option. These renewable energy sources would help to reduce New Zealand's carbon footprint in the energy sector.

3.2: *Value of Huntly's Coal-fired Power Station* – Part IV Project Report by Prashant Girdhar (2016)

Girdhar's 2016 report looked specifically at the value of the Huntly power station [16]. He discussed the speculation concerning Huntly (such as the various decisions to close certain units, some of which were later retracted) before using DOASA and Conditional Valuation at Risk (CVaR) optimisation techniques to, as Riva did, simulate different scenarios. Analysis of such scenarios revealed the usefulness of thermally-generated electricity and the impact its presence has on other generation technologies in terms of security of supply.

Risk was also a key part of Girdhar's research. There is risk on the part of generators, who must pay a nominal fee to customers when power conservation schemes are in place due to a lack of supply (usually when reservoirs are low, during a lean hydrological period). There is also the possibility that the gentailer will have to buy electricity off the grid at high prices. Interestingly, there is a further risk to hydropower generators if reservoirs are too full, leading to a lower marginal value for water and reduced profitability. Furthermore, coal and gas-fired generators face the risk of hydropower being relatively cheap with low overall demand, whereby it may not be profitable to operate these thermal generators.

Girdhar surveyed the five leading gentailers' generation mix, noting that, aside from Huntly, Genesis' electricity comes from a relatively small hydroelectricity network, and wind assets. It would thus have a much smaller market share (in terms of capacity) if Huntly were to close down.

Girdhar also described the notion of hydro risk curves, which are used by Transpower to determine appropriate reservoir levels (refer to Section 3.7). Risk curves see total controlled water storage levels plotted against time, with different curves corresponding to different risks of shortages. The nominal risk curve is typically higher in winter, when demand for electricity is greater and reservoirs are lower (due to the lack of snow melt), requiring a greater safety buffer and that a more conservative approach be taken.

Girdhar deduced that Huntly's Rankine units are a sunk cost, and that the risk of not being able to offset the cost of generating electricity at Huntly, especially considering the significant start-up costs, is large. However, some detail is provided in his report as to how swap options could be used to mitigate this risk. In the electricity sector, swaptions give buyers (typically hydro participants) the right, but not the obligation, to buy electricity (typically from thermal generators during dry years) at previously agreed upon prices.

His results show that Mercury, Meridian and Trustpower face the greatest risk if Huntly were to shut down entirely. These companies have the largest reliance on hydroelectricity for their generation. Moreover, removing Huntly from the market would lead to increased price volatility and higher risk curves, and hence a more conservative approach to managing reservoir levels, for all market participants. All five leading gentailers had decreased profit margins on average when Huntly was removed from the market in these simulations.

3.3: *Simulator for Electricity Related Investment* – Part IV Project Report by Salah Al-Chanati (2012)

Al-Chanati researched the use of contracts between gentailers to mitigate risk [17]. Gentailers use 'contracts for differences' to hedge against uncertainty in the future price of electricity. These futures contracts are often fixed price, fixed volume contracts and are traded on the Australian Securities Exchange (ASX). The specifications of these contracts are quite detailed and are based on two reference nodes in the New Zealand Electricity Market – Otahuhu and Benmore. Markov models were used in conjunction with simulations to predict future electricity prices (and hence the value of these contracts), given the current price of electricity.

Al-Chanati noted that the size of the Australian electricity contract market, where the volume of contracts traded outweighs the actual demand for electricity on a daily basis, far exceeds that of New Zealand. Hence there is potential for the New Zealand contract market to grow significantly. The trading of contracts is thought to have led to improved competition and fairer electricity prices for the consumer.

Al-Chanati also created a simulator where the inflation rate, number of contracts to buy/sell and other parameters could be chosen by the user. This simulator was tested using historical data. Discrepancies between the actual and predicted price of electricity revealed that, in the author's words, "Predicting contract prices three to six months in advance is extremely difficult." Having the most recent price datasets available was deemed critical for ensuring that these predictions would be as accurate as possible. Different risk portfolios were devised, based on whether the trader was averse or open to taking risks. In the simulations run, the risk-averse participant fared better on average.

3.4: *Stochastic Supply Chain Modelling in Julia* – Part IV Project by Jemma Simmonds (2017)

Simmonds' report looked at decisions to be made regarding Fonterra's milk supply: how much of each product should be made, and when these products should be sold [18]. Simmonds' analysis highlighted the effectiveness of Stochastic Dual Dynamic Programming, as the stochastic policy outperformed the deterministic one. In fact, the former led to an increase in profit for Fonterra of approximately $384 million, or 4.7%. The stochastic model could be adaptive, instead of making decisions well in advance.

After a linear programme had been formulated, a multistage Stochastic Dual Dynamic Programme was implemented and solved using backwards recursion. In this case, the random variable was the spot price of milk. Because the state space (the amount of each product to make) was continuous, Stochastic Dual Dynamic Programming needed to be used, where an approximation of the maximum expected value-to-go function provided an upper bound for the actual value-to-go function.

A forward and backward pass approach was used. The former sampled scenarios for given values of the random variable, being the price of each milk product. The backwards pass generated linear cuts which were used to improve the accuracy of the approximation of the value-to-go function, for each state and stage.

3.5: *Hedging Against Spot Price Uncertainty in New Zealand Electricity Markets* – Part IV Project Report by Thomas Moulder (2013)

Moulder undertook similar research to Al-Chanati but focused more specifically on predicting future spot prices as determined by reservoir levels [19]. Risk-averse models were devised in order to determine policies for purchasing future contracts, while hedging risk. The ASX futures market was again the focus of this research. Moulder's project aims were "To build a distribution for future electricity spot prices based on current water storage," alongside modelling optimal actions for both gentailers and speculators in the futures market.

Moulder began by examining the electricity spot market in New Zealand. He explained how offer curves consist of step functions, which correspond to a maximum of five different price/quantity levels or 'tranches.' Higher prices are charged when the quantity of electricity demanded is greater, due to the fact that additional, more expensive generation methods may be required. Transpower is responsible for ensuring that demand is satisfied, while minimising the cost of these offer stacks. Electricity is allocated using this method every half hour at 255 various nodes around the country. Future contracts can be a valuable means of hedging risk, as the price of electricity can vary significantly. Such contracts mature on a quarterly basis and use either Otahuhu or Benmore as the reference node.

The uncertainty which drives the utility of futures contracts comes from the ever-changing spot price of electricity. Moulder noted that, because most of the major players in the electricity market have both generation and retail arms, this itself is a means of hedging risk – high wholesale prices will benefit generation while hurting retailers financially. He deduced that most gentailers are somewhat risk averse, because they tend to have limited liquid capital.

Moulder also analysed the correlation between spot prices and reservoir storage levels, finding a broadly negative relationship – as reservoir levels increased, the spot price for electricity decreased, as expected. Quantile regression was used to generate spot price samples, and a cubic spline curve was fitted to model this relationship. In order to find an optimal portfolio, a bi-objective optimisation problem would typically be solved, which seeks to maximise profit while minimising risk. However, a single objective optimisation problem was desired with a unique optimal solution, in terms of the number of contracts to be bought or sold. Other risk measures were explored before Conditional Value at Risk (CVaR) was deemed the best means of representing risk aversion and applied to the electricity market.

Moulder warned that arbitrage opportunities exist under this two-island model. Contracts could be simultaneously bought at one island's node and sold at the other, leading to a net gain for the arbitrageur. He also recognised that future spot prices are affected by more than water storage levels (demand for electricity and availability of fossil fuels also have an impact, for instance) and acknowledged that his model does not impose an upper limit on the number of contracts that can be bought or sold at a given time. However, it is undeniable that the value of futures contracts is dependent on reservoir storage levels, and that these financial instruments can be beneficial for gentailers when it comes to hedging risk.

3.6: *EMI-DOASA* – Manual by Prof. Andy Philpott and Dr Geoffrey Pritchard (Version 22, 2017)

According to this report, produced alongside the DOASA software itself by Philpott and Pritchard, DOASA is "an optimisation methodology for hydro-thermal scheduling and water valuation" [20]. Hence, it provides a policy for the optimal amount of water to be released from each of New Zealand's seven largest reservoirs in a given week. This policy is determined for a multistage stochastic programme using Stochastic Dual Dynamic Programming (SDDP). In particular, a cost-to-go function is used to represent the financial cost of implementing an optimal policy from the given stage until an end-of-time horizon, given a certain level of water in each reservoir.

DOASA is only applicable to the New Zealand Electricity Market and is part of the Electricity Market Information (EMI) system overseen by the Electricity Authority.

The random inflows are responsible for the stochastic nature of this model. These inflows are taken from historical records. For the most part, stagewise independence between weeks has been assumed, which renders the algorithm simpler than it otherwise might have been. Due to this assumption, DOASA often underestimates the marginal value of water during dry years and may therefore produce an overly optimistic policy.

DOASA uses a complex mathematical model, with a large number of often inter-related variables. Stages are defined in terms of weeks. Demand is aggregated into blocks, corresponding to peak, off-peak and shoulder demand periods, and also to three locations: the upper half of the North Island (NI), Haywards in the lower North Island (HAY) and the South Island (SI). Load shedding is permitted, but at high cost. There is a value of lost load (VOLL) which varies, depending on whether only a small amount of demand is not met, or if a power outage results in none of the demand at a particular node being satisfied. This VOLL value is lower for the industrial sector, and higher for the commercial and residential sectors, as a constant supply of electricity is generally more critical for the latter types of customers.

DOASA considers hydro and thermal generation methods to be variable, and the other methods as fixed. Geothermal and wind is therefore embedded in the model; historical generation levels have been subtracted from historical demand at the relevant node. For thermal generators, the cost of operation is dependent on the heat rate of the generator and cost of the fuel used. For hydro generators, the generation output depends on the specific power (efficiency) of the hydro station.

After describing the mathematical model behind DOASA, the remainder of the document explains each of the input files in turn, only four of which should need to be modified by the user. Six files and four 'directories' are output by the algorithm, including 'Water Values.' The document also describes the two ways in which DOASA can be used: to generate a policy, and then to simulate the performance of this policy.

3.7: *Security of Supply Annual Assessment 2018* – Report by Transpower (2018)

Transpower produces an annual report on security of supply, which evaluates the current state of electricity generation in New Zealand and provides a ten-year assessment of the future of supply in the country [21]. Three scenarios were investigated in this particular report: the status quo, where thermal generation remains in use; the decommissioning of thermal power plants, with constant electrical demand; and a 'low carbon and electrification scenario' where only renewable energy is used, with an increased demand for electricity for transportation and industrial purposes (in lieu of fossil fuels). The third case corresponds with an aggregate demand increase of 2% annually, largely due to the increased prevalence of electric vehicles.

Under the first two scenarios outlined above, New Zealand would have enough electricity supplied by existing generation sources until at least 2023, at which point new generation options would need to be operational. However, under the low carbon/electrification conditions, new generation sources would be required from 2021. This analysis was carried out under the assumptions that the distribution network remains sufficient, that resource consents for already approved generation facilities remain valid, and that the impact of disruptive technologies (other than electrification of the transport fleet) is negligible.

Transpower's report used two measures to ensure that supply levels were within an acceptable threshold, so as to minimise the risk of shortages. These measures were referred to as the Winter Energy Margin (WEM), given by the ratio of aggregate supply over demand for the country; and the Winter Capacity Margin (WCM), calculated by adding the North Island's generation capacity and the amount of electricity transferred from the South Island, less North Island demand. Security of supply in the North Island, then, is affected by the capacity of the high-voltage DC inter-island cable. In the low carbon/electrification scenario, the nationwide energy margin was predicted to fall below the required WEM in 2026 and the North Island's capacity margin to dip below the necessary WCM in 2024. However, without the Tiwai Point smelter, the WEM and WCM would be satisfied until at least 2028.

The North Island is currently more sensitive to security of supply issues than the South Island, and thus decommissioning thermal power stations such as Huntly would render the supply of electricity for the upper half of the North Island even less secure. Hence, it could be valuable to carry out security of supply analysis at a more localised level than simply considering the total supply and demand of electricity nationally.

3.8: Relevance of Literature

This project will extend the DOASA model outlined in Section 3.6. DOASA, and JADE in turn, use concepts of SDDP similar to those described by Simmonds (3.4). Girdhar's analysis lays the foundation for analysing operating surplus distributions by gentailer (3.2). Moreover, the work carried out by Girdhar and Moulder (3.5) is considered when analysing risk for market participants. I will draw on Riva's conclusion (3.1) that geothermal and wind energy provide the most feasible renewable energy options when examining security of supply in the future. The reports by Al-Chanati and Transpower (3.3, 3.7) provide some background and context.

4: References

[1] J. E. Martin. (2010). “Hydroelectricity – Hydro, 19th and early 20th centuries.” *Te Ara – The Encyclopedia of New Zealand* [online]. Available: https://teara.govt.nz/en/hydroelectricity/page-2 [Accessed 26 April 2018].

[2] “Energy in New Zealand 2017.” *Ministry of Business, Innovation & Employment.* Available: http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/publications/energy-in-new-zealand [Accessed 27 April 2018].

[3] “Snapshot of Energy in 2016.” *Ministry of Business, Innovation & Employment.* Available: http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/publications/energy-in-new-zealand/documents-images/snapshot-of-energy-in-2016.pdf [Accessed 27 April 2018].

[4] B. Stickler. (2017). “New Zealand to Switch to Fully Renewable Energy by 2035.” *Blue and Green Tomorrow.* Available: https://blueandgreentomorrow.com/energy/new-zealand-to-switch-to-fully-renewable-energy-by-2035/ [Accessed 9 May 2018].

[5] “Acquisition of Maui Pipeline.” *Firstgas*. Available: http://firstgas.co.nz/media-release/acquisition-maui-pipeline/ [Accessed 27 April 2018].

[6] G. Bradley. (2015). “Coal No Longer King at Huntly Power Station.” *The New Zealand Herald* [online]. Available: https://www.nzherald.co.nz/business/news/article.cfm?c_id=3&objectid=11492939 [Accessed 16 August 2018].

[7] “Genesis Extends Life of Huntly Station to 2022.” *The New Zealand Herald* [online]. Available: https://www.nzherald.co.nz/business/news/article.cfm?c_id=3&objectid=11630125 [Accessed 16 August 2018].

[8] G. Evans. (2018). “Huntly ramps Up as Storm Halts Gas Processing.” *Energy News* [online]. Available: http://www.energynews.co.nz/news-story/gas-fired-generation/37238/huntly-ramps-storm-halts-gas-processing/ [Accessed 10 April 2018].

[9] “Subnational Population Estimates: At 30 June 2017 (Provisional).” *Statistics New Zealand.* Available: http://nzdotstat.stats.govt.nz/wbos/Index.aspx?DataSetCode=TABLECODE7541 [Accessed 27 April 2018].

[10] A. Bennett. (2007). “Meridian Boss Hails Deal with Smelter.” *The New Zealand Herald* [online]. Available: *https://www.nzherald.co.nz/business/news/article.cfm?c_id=3&objectid=10467340* [Accessed 28 April 2018].

[11] A. Woolf. (2016). “Tiwai Point Aluminium Smelter has ‘Reassuring Start’ to 2016 as New Zealand Dollar and Alumina Prices Fall.” *Stuff* [online]. Available: https://www.stuff.co.nz/business/76144276/tiwai-point-aluminium-smelter-has-reassuring-start-to-2016-as-new-zealand-dollar-and-alumina-prices-fall [Accessed 28 April 2018].

[12] “About Us.” *Electricity Authority.* Available: https://www.ea.govt.nz/about-us/ [Accessed 26 April 2018].

[13] “Electricity Generation.” *Ministry of Business, Innovation & Employment.* Available: http://www.mbie.govt.nz/info-services/sectors-industries/energy/electricity-market/electricity-industry/electricity-generation [Accessed 27 April 2018].

[14] “Energy in New Zealand 2017.” *Energy and Building Trends with Evidence, Monitoring and Governance, and Ministry of Business, Innovation & Employment.* Available: http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/publications/energy-in-new-zealand/documents-images/energy-in-nz-2017.pdf [Accessed 27 April 2018].

[15] M. Riva. (2017). “In Renewables We Trust: An Assessment of the Future Consequences of Changing the Electricity Generation Mix in New Zealand.” Master’s Thesis. University of Auckland.

[16] P. Girdhar. (2016). “Value of Huntly’s Coal-fired Power Station.” Part IV Project Report. University of Auckland.

[17] S. Al-Chanati. (2012). “Simulator for Electricity Related Investment.” Part IV Project Report. University of Auckland.

[18] J. Simmonds. (2017). “Stochastic Supply Chain Modelling in Julia.” Part IV Project Report. University of Auckland.

[19] T. Moulder. (2013). “Hedging Against Spot Price Uncertainty in New Zealand Electricity Markets.” Part IV Project Report. University of Auckland.

[20] A. Philpott and G. Pritchard. (2017). “EMI-DOASA.” *Stochastic Optimisation Limited.* Technical Report. Version 22.

[21] B. Tucker. (2018). “Security of Supply Annual Assessment 2018.” *Transpower.* Available: https://www.transpower.co.nz/sites/default/files/bulk-upload/documents/SoS%20Annual%20Assessment%202018%20.pdf [Accessed 23 March 2018].