CHALMERS

Green Electricity in New Zealand

An Island Power System Based on Hydro and Wind Power

Master's Thesis within the Sustainable energy system programme

OLA ELFBERG

Department of Energy and Environment
Division of Energy Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2014

MASTER'S THESIS

Green Electricity in New Zealand

An Island Power System Based on Hydro and Wind Power

Master's Thesis within the *Sustainable energy system* programme

OLA ELFBERG

SUPERVISOR

Lina Reichenberg

EXAMINER

Filip Johnsson

Department of Energy and Environment
Division of Energy Technology
CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2014

Green electricity in New Zealand
An Island Power System Based on Hydro and Wind Power
Master's Thesis within the *Sustainable energy system* programme
OLA ELFBERG

Department of Energy and Environment
Division of Energy Technology
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Chalmers Reproservice
Göteborg, Sweden 2014

Green electricity in New Zealand
An Island Power System Based on Hydro and Wind Power
Master's Thesis in the *Sustainable energy system* programme
OLA ELFBERG
Department of Energy and Environment
Division of Energy Technology
Chalmers University of Technology

ABSTRACT

Due to the location of New Zealand in the middle of an ocean it is an island system with no possibilities to import or export electricity. The balance must therefore always be kept with the local generation. In this thesis, the potential for having an electricity generation from only renewable is evaluated for New Zealand. The current electricity supply system already consists of close to 60% hydro power and slightly more than 10% geothermal power. In order to achieve an electricity supply system fully based on renewable energy sources, it is assumed that that the wind power shares is increased from the current 5% up to 30%. This new power mix will more or less erase the need for fossil fuel in the electricity system. The country consists of two islands with a narrow strait between them. The North Island has the main electric load while the South Island has most of the hydro resources. This thesis evaluates the quota or allocation of the future wind power between these two islands and the capacity of the HVDC link that connects the islands. To evaluate this simulation was performed were the increased wind power generation was balanced with the south island hydro power. It is concluded that the most of the new wind power should be located close to the load in order to minimize the needed capacity of inter-island HVDC link. By placing 83% of the new wind power on the North Island, the system will minimize the need of thermal back-up for peak demand and curtail of wind power in low demand. Results of the analysis also indicate that the hydro storage levels will have an increased difference of stored energy between winter and summer due to the changes of electricity demand and inflow. This implies a significantly increase risk of draining the hydro assets during a dry year.

Key words: Wind Power, Renewable energy, Island system

Grön Elkraft i Nya Zeeland
Ett ö-kraftsystem baserat på vatten- och vind kraft
Examensarbete inom mastersprogrammet *Sustainable energy system*
OLA ELFBERG
Institutionen för Energi och Miljö
Avdelningen för Energiteknik
Chalmers tekniska högskola

SAMMANFATTNING

Pågrund av Nya Zeelands placering mitt i havet så är det ett isolerat ö-system utan några möjligheter för import eller export av elkraft. Balansen mellan produktion och förbrukningen av el måste därför alltid vara perfekt balanserad inom systemet. I denna uppsats undersöks möjligheten för Nya Zeeland att tillgodose all kraftproduktion från förnyelsebara källor. I nuläget står vattenkraften för nästan 60 % av produktionen och geotermiskaproduktionen för cirka 10 %. För att uppnå ett helt förnyelsebart system så antas att vindkraften ska byggas ut från de nuvarande drygt 5 % till 30 %. Denna nya produktionsmix skulle då radera behovet av fossilkraftproduktion. Systemet består av två större öar som skiljs av ett smalt sund. På den norra ön finns större delen av kraftkonsumtionen medans den södra ön har största tillgångarna på vattenkraft. Denna studie undersöker hur vindkraften ska fördelas mellan öarna och vilken överföringskapacitet HVDC-kabeln mellan öarna bör designs för. Detta undersöks genom en simulering där vindkraften ökas och vattenkraften på södra ön balanserar produktionen. Det framkom att större delen av vindkraften ska placeras på den norra ön, nära lasten för att minimera storleken på HVDC-kabeln. Genom att placera 83 % av vindkraften på den norr ön, så minimeras behovet av uppbackning från gasturbiner under toppar i efterfrågan och behovet att spilla vindkraft vid för hög produktion. Det framkom också att vattenmagasinens nivåer fick större variationen med lägre nivåer under vinter med högre efterfrågan och begränsat inflöde. Detta innebär en förhöjd risk att vattenmagasinen tömt under ett år med låg nederbörd.

Nyckelord: Vindkraft, förnyelsebarkraftproduktion, Förnyelsebar energi, ö-kraftsystem, ö-system

CONTENT

Preface

In this study a model of the New Zealand power system has been simulated were wind power replaced power generation from fossil combustion. This was done to estimate the possibilities of achieving a green electricity system in New Zealand. The work was performed between October 2012 and June 2013 at Chalmers University and Auckland University of Technology.

This thesis work has been carried out by Ola Elfberg as researcher, Lina Reichenberg as supervisor and Filip Johnsson as examiner at the Department of Energy and Environment,

Division of Energy Technology, Chalmers University of Technology. The work was partly been performed at and Auckland University of Technology under supervision of David Nutt, Institution of Engineering and Technology, AUT.

Göteborg February 2014

Ola Elfberg

Notations

NZ	*New Zealand*
NI	*North Island*
SI	*South Island*
TSO	*Transmission system operator*
HVDC	*High voltage direct current*
CCGT	*Combined cycle gas turbine*
OCG	*Open cycle gas turbine*
WN	*Majority of new wind on North Island*
WS	*Majority of new wind on South Island*
All NI	*All new wind power is installed on the North Island*
NZD	*New Zealand Dollar*
Ln	*Net load for the total time*
Ln_t	*Net load at time t*
$Demand_t$	*Demand at time t*
$Windpower_t$	*Wind generation at time t*
$Goethermalpower_t$	*Geothermal generation at time t*
T	*Total time for simulation, 8760h*
η	*Efficiency of hydro power station, m3/s/MW*
masl	*Meter above sea level*
$alfa$	*Quota for allocation of simulate wind power*
NIMBY	*Not in my back yard*

1 Introduction

New Zealand (NZ) is an isolated island in the south western Pacific Ocean. It has an area of 268 700 km^2 and a population of 4.5 million inhabitants. The country has good assets of domestic renewable energy sources such as hydro- wind- and geothermal power. However, in its current electricity generation system there is a large share of fossil combustion for power generation. Close to a fourth of the electricity is produced from fossil fuels resulting in 4.8 million tons of CO_2 for 2011 (New Zealand Energy 2012). As the environmental demands of reducing CO_2 emission are getting stronger and new ways to meet the energy need without fossil fuels are necessary. The role of renewable sources, and wind power in specific, is therefore likely to increase. This raises the question whether a country with good access to hydro power, geothermal energy and high wind resources really need electric power from fossil fuels? The aim of this study is to evaluate the possibilities for New Zealand (NZ) to have a 100% green power generation. This system would then only rely on the renewable sources hydro wind and geothermal power. Due to technical and political limitations, the possibilities to significantly expand the generation from hydro power and geothermal power are low, while there are already planned and consented wind farms with capacity of close to 3.5GW (List of power stations in New Zealand 2013). This work therefore studies the impact on the power system if wind power would be expanded to replace the generation of fossil based thermal power in today's electricity supply system.

1.1 Island power systems

A so-called island power system has no electric connection to other systems, which means that it must be self-sufficient in electricity generation as it lack the back-up function of trading with other systems. Trading can in many systems be crucial for the security of supply and often minimizes the need for reserve power. Several studies have been made on different island power systems with a purpose similar to this thesis, namely how renewable energy sources could be integrated in the system.

Kaldellis and Kavadias (2001) investigate a power system with high wind power share on small islands, in their case a couple of Greek islands. They also study how wind power and pumped hydro storage may be operated together, as their proposed systems used pumped hydro storage when the wind power generation was exceeding electricity demand(Kaldellis and Kavadias 2001). The proposed systems in their study used a pumped hydro storage while the wind power was producing more than the demand.

(Miller, Manz et al. 2011) studied the Hawaiian island system and conclude that it is possible to have a 25% share of the energy from wind and solar power with some modifications of the current generation that mainly uses thermal power plants. They also emphasis island system must be precisely balanced as there is not an option to import or export power to neighbour power systems. This means that an island system must be able to cope with every possible scenario while a non-island system might manage without covering the extremes themselves.

Mason, Page et al. (2010) compared different cases of wind and geothermal combinations in order to replace the fossil combustion for electricity generation. Their study regarded NZ as a combine system with no congestions. The main challenge was, according to this study, the limited hydro storage, causing hydro shortage and spill in several cases. They also concluded a short term capacity deficit that varied from 361 MW to 1167 MW(Mason, Page et al. 2010).

1.2 Aim and scope

The main aim of this study is to see if it is possible to have an electricity system were 30% of the electric energy is supplied from wind power. This thesis work is a case study of the requirements necessary to achieve a level of 30% of the total annual electric energy generation from wind power in New Zealand. Alternatively finding the limitations on why this goal would be unsuitable. How can the more flexible hydro schemes on the South Island cope with these changes in generation demands? The aim is to see limitation factors for a power system with high wind power penetration. Will the placement of the wind farms close to load or to generation affect the power system? What transfer capacity between two islands is the most suitable? How will this interisland HVDC link capacity change for the different cases of wind power allocation? This case study will compare the allocation of new wind power o find a preferred quot. In specific the Options of allocating the wind power close to the load on the NI or allocating it close to the variable hydro power on the SI will be investigated. The different allocation cases will be compared in the aspects of difference in cost for inter-island HVDC capacity, need of back-up power and CO_2 emissions.

2 New Zealand Power System

2.1 Demand of Electricity

New Zealand (NZ) consists of two major islands, the North Island (NI) and the South Island (SI). The islands are of resembling geographic size, but the majority of the population and the industry are located on the NI where also most of the major cities, for example Auckland Wellington and Hamilton, are situated. In 2011, the North Island electricity consumption stood for 63% of the country's total electricity demand, with the Auckland area as the biggest concentration of demand (Ministry of Business 2012). The South Island is more rural and with less industry. However there is one single aluminium smelter on the south end of the island that alone stands for 15% of the total national demand (Smith, Beatty et al. 2012). In Figure 2.1 the geographical location of the electricity demand is presented. The figure clearly shows that the main load is on the NI. The loads on the SI are in general small except for Christchurch on the mid east coast which is the only major city on the SI and an aluminium smelter on the south tip of the island.

Figure 2.1 Annual electricity demand in New Zealand given by location and size for 2011. Sorce Electric Authority, Electricity market performance, 2010-2011 in review

The New Zealand power demand is 40 TWh per year and has a peak demand of 7.5 GW during winter and a minimum demand of 2.6 GW during summer. The NZ power system is special in many ways to other countries. Not only is it an island system but it also have access to a lot of hydro power, geothermal heat, domestic gas generation and good wind recourses. Figure 2.2 presents the daily changes in demand during an average power demand for a spring month.

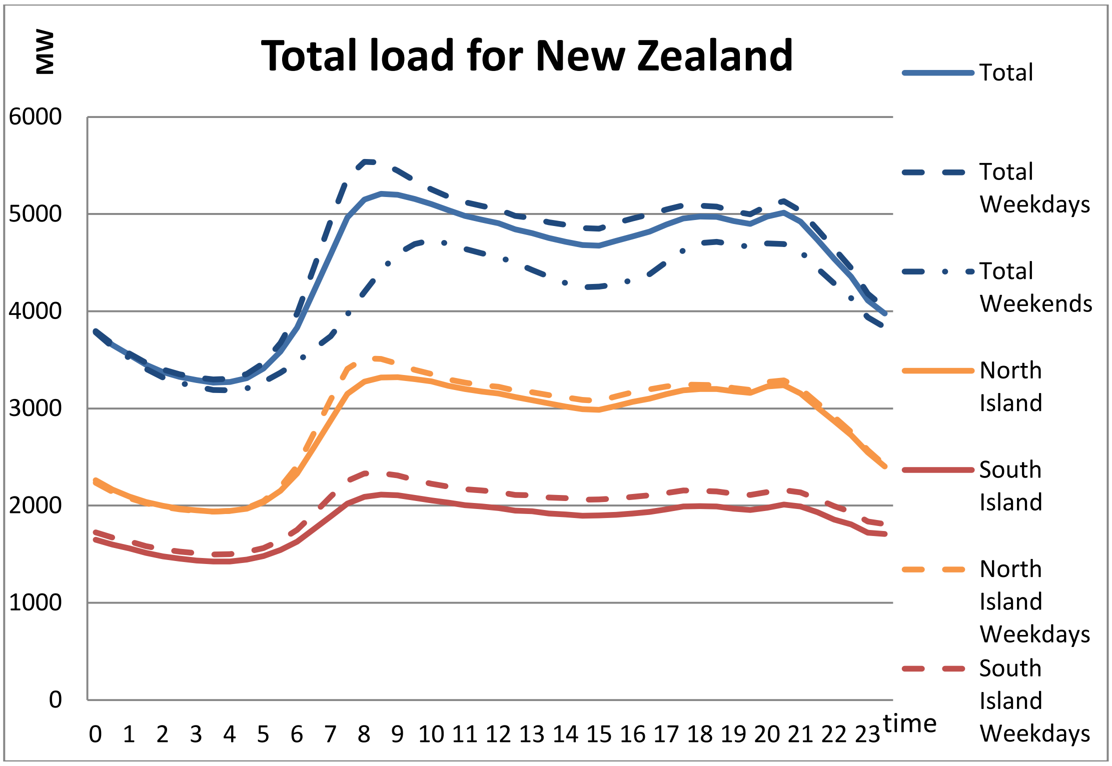

Figure 2.2 Average daily power demand for period 2012.10.08-2012.11.07 for NZ. The peak demand on a regular day occurs at 9 am right after the lowest demand early in the morning. There is also a smaller peak later in the evening.

For the power system the absolute peak load is important because that there must be enough capacity ready to meet the demand at this instant to keep the system stable. Table 1.1 shows the highest demand during the same period as the figure above but with a 5 minutes resolution instead of a 30 minute resolution. The peaks of demand presented in the Table 2.1 are higher than corresponding values in the Figure 2.2 due to the higher time resolution. Noteworthy is that the highest demand during the period reached 5830MW which is close to 300MW more than the average peak according to data from the TSO (Zone load Graphs, 2012.08.10).

Table 2.1 Maximum power demand for period 2012.10.08-2012.11.07 for NZ and dived upon the North Island (NI) and South Island (SI) with 5 minutes resolution. This shows that the actual peak is higher than what the graph with 03min average implies. Data from TSO (Zone load Graphs, 2012.08.10).

NZ TOTAL	NZ TOTAL	NI TOTAL	NI TOTAL	SI TOTAL	SI TOTAL
5830.3 MW	980.16 Mvar	3883.3 MW	678.37 Mvar	2001.5 MW	331.96 Mvar

2.2 Power Generation

The current generation of electricity is a mixture of hydro power, as the main source, and geothermal, gas coal and wind power as other significant parts. Figure 2. shows the contribution of the different primary energy sources for electricity in New Zealand in 2011 (Ministry of Business 2012). However, due to annual variation in precipitation the hydro power generation varies, and therefore the exact mixture of electricity generation changes from year to year. In average, hydro power represents 56% and fossil based power about 28% of the generation (Smith, Beatty et al. 2012)

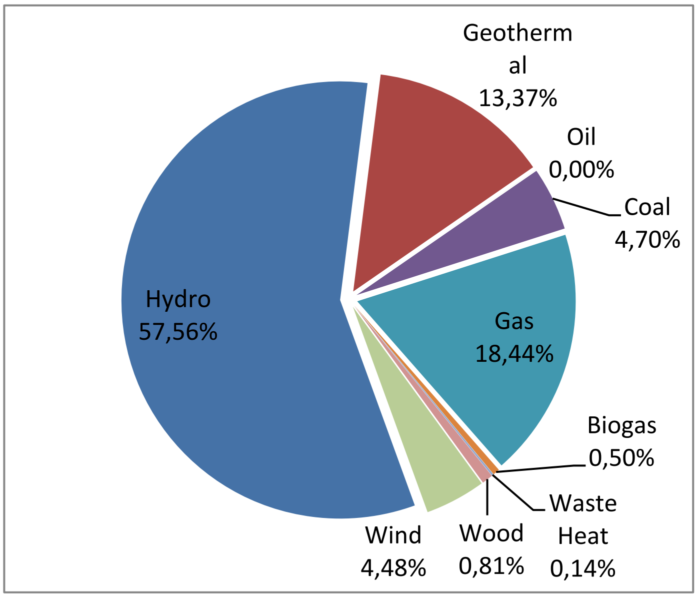

Figure 2.3 Specific generation mix for electricity generation for 2011

2.3 Hydro power

As mentioned above, hydro power is NZs most important power. The hydro power generation is considered CO_2 emissions free, and is associated with low cost. Moreover it is a flexible power source that is the generation can easily be adjusted to meet the demand without any major efficiency effects. This makes it a good frequency keeper for the total power system, as some hydro power turbines can start up fast and reach full power within just 6 seconds. The total capacity of the hydro power turbines are in general over dimensioned compared to the average output. This means that for a shorter time the hydro power can deliver power to meet a significant load increase. However there are some limitations to the hydro powers flexible use, first the hydro power can only operate it there is an inflow of water to the station. This can however be controlled by dams storing water and controlling the flow. But the operation of these storages must also adapt to regulations on the flow in the rivers and the levels in the storage dams. Most of the hydro storage is in lakes that are also used for recreational purposes and therefore the water level must be kept within certain levels, which limits the storage capacity. Compared to Scandinavian hydro storages the NZ storage potential is small. Sweden has a hydro storage potential of 33 675 GWh, which corresponds to almost half of the annual hydro power generation in Sweden. NZ has only 3 800 GWh of storage potential, equivalent to 1/6 of the total annual generation. This storage is only enough to cover the demand for a few weeks and many of the hydro power stations has no storage capacity at all. The main hydro storages are located in the SI while the NI only has a storage capacity of 600 GWh. This makes the hydro power generation sensitive to the inflow changes and dry periods. The average output hydro power effect can vary with 1 GW between different years during the same season, depending on whether if it is a dry or wet year. This variation in capacity output is equivalent to the maximum capacity of the Huntly power station which is the largest coal power plant that in NZ. Variation in hydro power generation between years is an impotent factor for how the power system is operated in New Zealand. Figure 2.4 shows the annual hydro power generation in New Zealand between the years 2000 and 2011. The variation is significant with are standard deviation is 1.4TWh for the last 11 years. The variations in power generation depend on the different hydro inflows that vary from year to year. 2001 and 2008 were dry years were generation was lower than normal. To avoid a shortage of hydro power and thereby risk a black out in the power system, the TSO uses a so-called hydro risk curve to see what levels of storage that must be kept. The method includes inflow statistics from 1931 to calculate different scenarios.

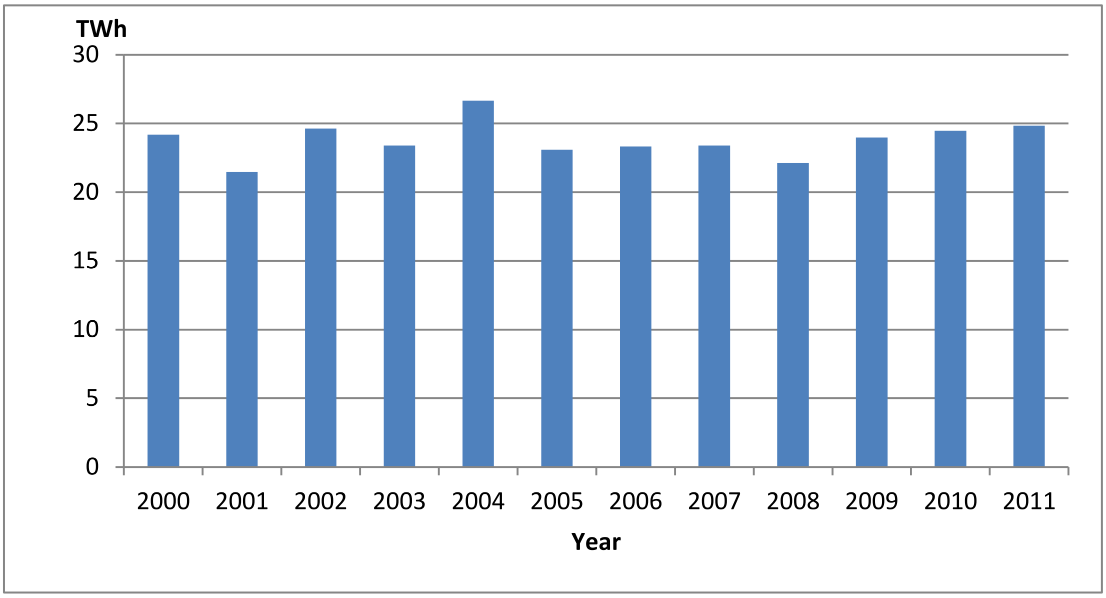

Figure 2.4 Annual hydro power generation in New Zealand for the years 2000 to 2011. The difference in generation output between years mainly depends on weather and precipitation. Source: (Ministry of Business 2012)

2.3.1 Hydro Schemes

Hydro dams and power stations are often linked together on a serial along on river. This means that the down river stations are dependent on the flows from the upstream stations. Therefore the planning of the generation is done together for the whole set of power stations, creating one mutual hydro scheme.

On the North Island there are two major lakes that are used for hydro storage and hydro power generation, Lake Taupo and Lake Waikaremoana. These two lakes supply the hydro schemes Waikato and Waikaremoana which produce about 30% of the country’s hydro power.

2.3.1.1 South Island Hydro Schemes

The remaining 70% of the hydro power is produced on the South Island which is more mountainous and have a higher share of precipitation. The South Island is also more rural and the lake levels are allowed to vary more.

Waikato hydro scheme

The Waikato hydro scheme is run by Mighty River Power Ltd and uses Lake Taupo as hydro storage. From the lake, water follows the Waikato River and passes through nine different hydro power stations on its way to the ocean. Lake Taupo is located in the centre of the North Island and is an extremely deep lake, and could, theoretically, have a much large storage capacity than of today. Due to resource consents the storage capacity is currently limited to 862.40 million m^3 as the lake level is only allowed to vary 1.4 m between 355.85 and 357.25 masl. This storage capacity corresponds to possible energy storage of 583 GWh.

The Waikaremoana scheme

The Waikaremoana scheme is operated by Genesisi Energy. The water follows the Waikarataheke River and passes through three hydro power stations. The stations are Kaitawa with a capacity of 36 MW and an efficiency of 0.994 m^3/s/MW. The Tuai with a capacity of 60MW and an efficiency of 0.630 m^3/s/MW. The final station is Piripaua with a capacity of 42MW and an efficiency of 1.062 m^3/s/MW.

Lake Waikaremoana has only a tenth of the area of Lake Taupo, but with a higher elevation and larger allowed span for lake level variation it still has a storage of 157.16 million m^3 corresponding to a storage of 154GWh.

The Waikati scheme

The hydro schemes of the lakes Ohau, Tekapo, and Benmore are combined in a cluster and also supplies stations further down streams. The whole scheme is called the Waikati hydro scheme.

The Ohau hydro scheme is operated by Meridian Energy. Lake Ohau supplies the scheme and the three power stations Ohau A, Ohau B and Ohau C, after that it ends up in Lake Benmore. Lake Ohau is mainly operated as a run of river capacity and has no controlled storage potential. The hydro inflow is instead controlled further up in Lake Tepako and Lake Pukaki.

The Lake Tepako scheme is also operated by Meridian Energy. At the lake outlet, the power station Tepako A with a capacity of 25 MW is located. Then the water follows through a man-made tunnel down to Tepako B with the much larger capacity of 160 MW at the inlet of Lake Pukaki. From Lake Pukaki the water continues to Lake Ohau and there joins the Ohau scheme. The storage capacity of Lake Tepako is 704.8 million m^3 which corresponds to 810 GWh if this water would be used to produce electricity at all downstream power stations. Lake Pukaki is a dam used for storage between Tepako and Ohau. The storage potential is 2335.92 million m^3 which corresponds to 810 GWh.

The Clutha hydro scheme

Lake Wanaka is the fourth biggest lake on the South Island and supplies the Clutha River and Lake Dunstan, as well as the power stations of Clyde and Roxburgh. Lake Wanaka is natural lake with no ability to control the hydro flow or to be used as energy storage capacity. Lake Hawea is another lake that supplies the Clutha River and in contrary to Lake Wanaka can regulate the flow and has a storage capacity of 11039.0 million m^3 which corresponds to 288GWh. This storage is based on the normal operation levels where the lake level is allowed to vary up to six meters. But it is possible to produce more as the Electronic Commission can approve an additional level reduction of two meters. Lake Wakatipu is, like Lake Wanaka, an uncontrolled lake that feeds Lake Dunsten. Lake Dunsten then feeds the Clutha River that passes Clude- and Roxburgh power stations. The Clyde power station has a capacity of 432MW and an efficiency of 1.93 m^3/s/MW and Roxburgh power station a capacity of 320 MW and a efficiency of 2.54 m^3/s/MW

Manapouri Scheme

The Waiau power scheme has only has one hydro power station, the Manapouri power station. This is the largest hydro station in NZ with a total capacity of 850 MW. The power station is built underground, 200 meters below Lake Manapouri, where water from the lake is led through a tunnel to the power station and thereafter continues through a tailrace tunnel to the ocean. Lake Manapouri has a storage capacity of 359.49 million m^3 which corresponds to 152GWh.

Lake Manapouri is supplied by the Waiau River which starts at Lake Te Anu's outflow. Lake Te Anu has a storage capacity of 467 million m^3 which corresponds to 152GWh.

The information for the power schemes is base on Knight (2009) and Sherly (2010).

2.3.2 Hydro storage capacity

Figure 2.5 Waitaki power station after a rainy period. The station is smaller than the up streams stations and cannot use the energy in the high flow for power generation. On the right in the picture one can see that water is instead spilled past the station without being used.

The current hydro storage is limited and mainly consists of a few main lakes on the South Island that are consented to vary for hydro operation. Table 2.2 presents the storage potentials in these and are calculated based on the assumption that all of the water is producing power in the downstream hydro power stations. This is however not possible to achieve in the smaller power stations when the flow exceeds the stations capacity. Figure 2.5 shows a situation where there is a major spill of water at the Waitaki power station due to high hydro inflow. This high flow is in turn due to a period of high rainfall and the controllable hydro storage in this scheme is only two of the three feeding lakes. The Waitiki station is one of the smaller power stations in the Wiataki power scheme and has, for example, less than a fifth of the capacity of the upstream Benmore power station.

Table 2.2 South Island hydro storage potential are the hydro storages with a large storage capacity that can be used between seasons. In addition to this, there are several smaller dams with limited capacity for inter-day storage

Lake	**Max storage [Mm3]**	**Conversion Efficiency** GWh/ (Mm^3)	**Calculated Energy Storage GWh**
Te Tekapo	704.8	1.1494594	**810**
Pukaki	2335.92	0.7288245	**1702**
Hawea	1139	0.2532876	**288**
Te Anau	647.68	0.4253871	**276**
Manapouri	359.49	0.4253871	**153**
TOT South Island	**5186.89**		**3230**

2.3.3 Coal and gas fired power stations

Close a forth of the electricity in NZ is produced with Gas or Coal. Due to the concentration of electric demand and limited hydro resources the fossil fuel power plants are located on the NI. In Figure 2.6 the location of the coal and gas power plants correspond well to the load location in Figure 2.1 (National Infrasturcture Unit 2011).

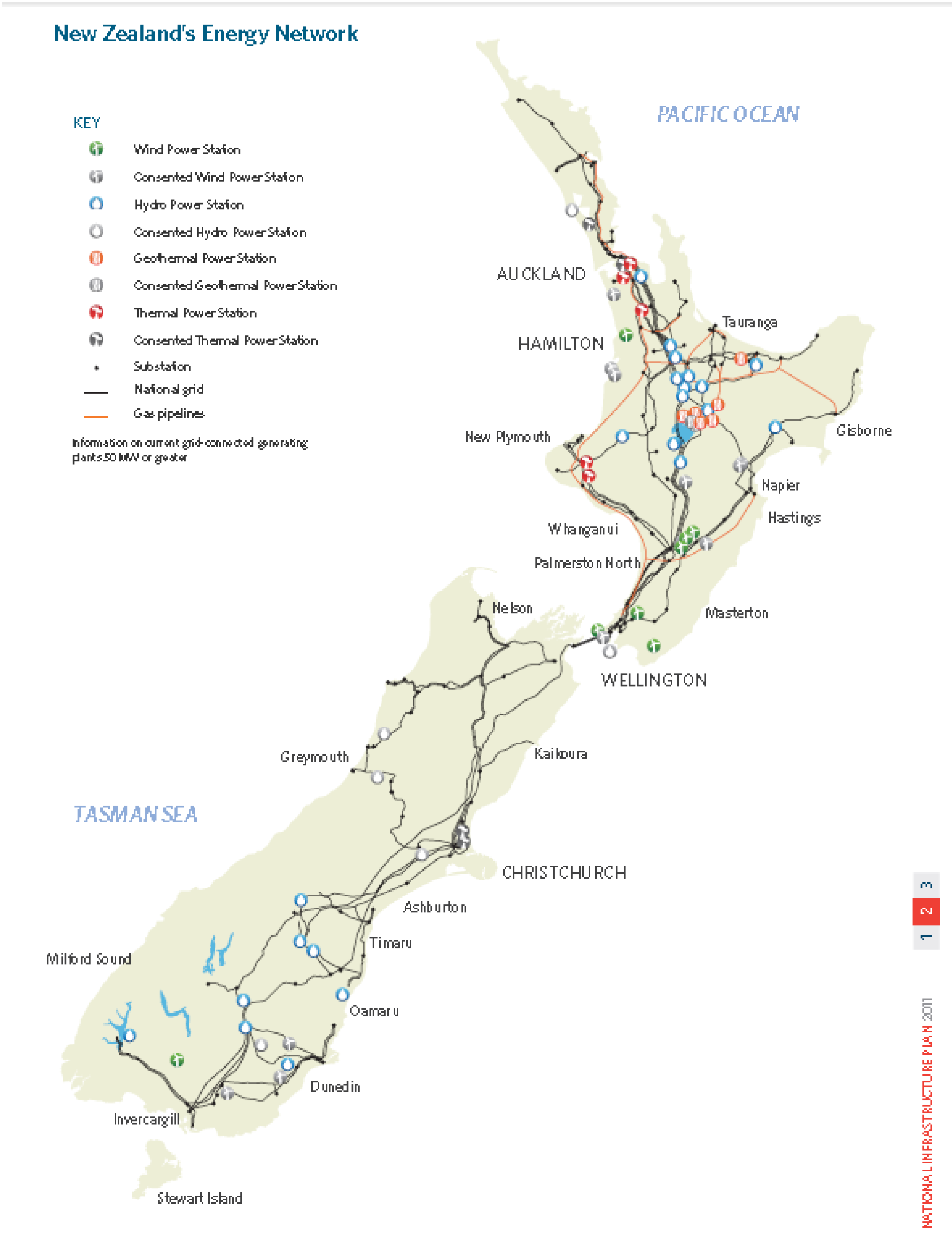

Figure 2.6 Location of power stations, were thermal power generation is allocated on the NI source: National Infrastructure Unit 2011

Coal

Coal fired power plants are used to support base load in the NZ power system. Most coal fired plants are cogeneration industrial plants (Genesis Energy 2012). However, the largest share of the coal-based electricity, 80%, is produced by is the power only plant Huntly Power Station, operated by Genesis energy. The station has six different units that either use coal or gas. Unit 1-4 are four identical boiler and turbine units that can burn coal or gas, while unit 5 and 6 are gas turbines. Unit 1-4 were fully commissioned in 1985 and has a capacity of 250 MW each. The units usually use coal as fuel and supply a significant amount of the total electricity generation(Genesis Energy 2012). Due to age and low growth in demand Genesis plans to decommission the plant in a few years' time.

Gas power

NZ has a domestic generation of natural gas and half of the gas generation is used to generate electricity. The gas is used for base and peak loads and also fuels cogeneration, combined cycles and gas turbines. Currently there is 884 MW installed in CCGT and 257 MW in OCGT. The CCGT power is often the marginal technology in the electricity market and some plants have trouble with losses during non-peak hours (Gray 2012) . The company Contact Energy is for example evaluating the possibility to redesign a 380 MW CCGT to an open cycle and use it for peak hour only (Energy NZ 2010). The opens cycles faster start and stop flexibility makes is more suitable for peak hour usage but reduces the general efficiency.

2.3.4 Geothermal power

With its position at the south west end of where the Australian and Pacific tectonic plates collide also known as the "Pacific Ring of Fire" the NI has a lot of volcanic activity. Geothermal heat is used to produce power and also some direct thermal usage. Geothermal power contributed with 5 770 GWh of the produced electricity in 2011 (Eletricity Authority 2012).

2.4 Power Transmissions system

In New Zealand, power generation and loads are in different part of the national system, with more power generation on the SI and a higher share of demand in the NI. This implies that the system is heavily dependent on the national electricity grid to transfer power from the south to the north. The transmission system consists of 220kV lines which is the core of the system and connects the larger power plant and the main loads. But it also includes supplementary 110kV and 66kV transmission lines in the more remote areas with limited loads.

There exists a HVDC link that connects the two islands. This link is vital for the power system and makes it possible to take advantage of the large hydro assets in the south. The HVDC line starts at Benmore hydro station on the South Island and connects to the North Island system at Haywards outside Wellington (the HVDC link is marked in purple in Figure 2.7). This gives it a total length of 570km and of this 40 km are subsea cable under the Cook straight. This link recently had a major upgrade with a new pole (Energy NZ 2010) that will give the link a total capacity of 1200MW in a first stage and then plans to reach 1400MW in 2017 (Tordesillas 2009). This upgrade will decommission the first pole built in 1962 which is since 2007 only used as back-up. Before 2007 it was only possible to transfer power from the SI to the NI, but with the performed upgrades the HVDC link can transfer in both directions [REF]. On an annual basis there is a net energy transfer from south to north as power from the hydro stations on the SI is transferred through the HVDC link to the NI to supply populous areas such as Auckland. However, during some dry years, mostly during summer the flow might go in the opposite way. Another recent upgrade of the HVDC connection makes it possible to have a common frequency keeping for the two islands instead of upholding one on each island. Therefore, the power system only needs one slack bus for both islands.

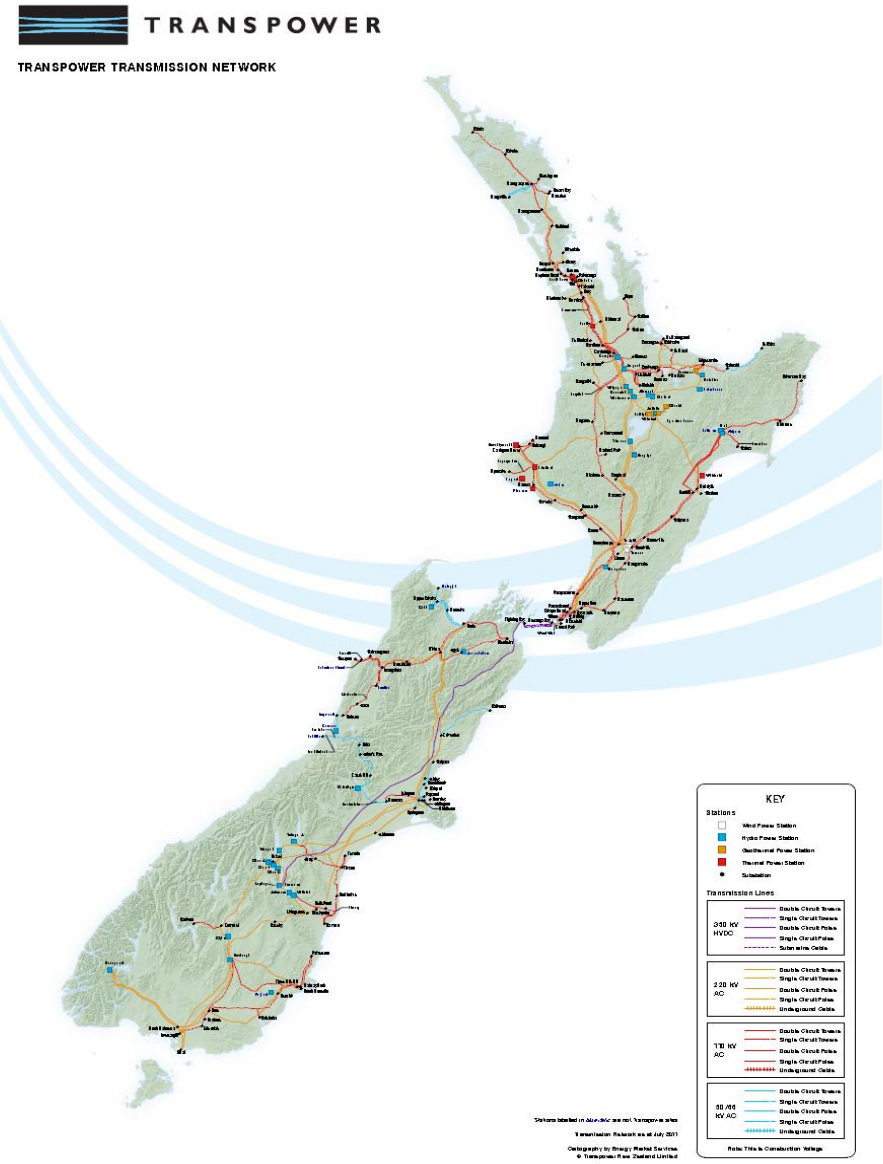

Figure 2.7 Map of the New Zealand power transmission system. The HVDC link that combines the island can be seen in purple. Source: Transpower website

2.5 New Zealand’s Electricity market

The electricity market in New Zealand is governed by the Electricity Authority, previously called Electricity Commission. Their assignment is to promote competition, reliability of supply and efficiency of the electrical industry. The NZ electrical market is a local marginal price system (based on the nodal marginal price system) which gives an independent price at each node in the system, determined by the merit order from the bids. The market is offer-based and the bids on generation and demand are made at a specific node for every half hour trading period (Anicell 2007). The bids then go to a Scheduling, Pricing and Dispatch model at the Transmission system operator (TSO). Based on the results from this model power generation is then scheduled for the next day against the expected load by the system operator. However, the bids can be revised up until 2 hours before the trading period starts. The TSO in New Zealand is the state owned Transpower and they are also responsible for the electricity supply. Transpower manages the different bids and schedules the generation. They also determine the needed reserve capacity for every trading period and control the frequency keeping. The different generators can also set bid for reserve capacity that can be in standby for the TSO to use if needed. To secure that renewable energy from wind power is used when possible, the wind power price is regulated to be set at either 0 or 0.01 $/MWh. The final nodal price differs between nodes and there may be a significant variations of the price in different parts of the power system (Elctricity Authority 2011).

2.6 Climate Impact on Wind and Hydro Power

New Zealand is located south of the equator which means that the coldest period is during July, while the temperature peaks around January and February. There is a small difference in temperature between the seasons that gives a significant increase in power demand during winter with more need of heating.

2.6.1 El Niño and La Niña

El Niño and La Niña are weather oscillations in the south Pacific. During normal conditions, the trade wind across the Pacific Ocean blows to the west, pushing hot surface water along with it. Cold sea water from the deep ocean rises up along the South American coast, giving the west Pacific a cold and dry climate while the east Pacific, with warmer water, gets more rainfall. The strength of this trade wind varies between years. During a period with increased winds the effect amplify, this phenomenon and are called La Niña while during weaker winds a conditions called El Niño with drought in Indonesia, Australia and flooding in Peru occurs.

The effects of these weather phenomena for NZ are rather limited, but changes in wind directions and precipitation can be significant. During an El Niño period, westerly winds tend to dominate giving the east coast less rain. The El Niña conditions tend to bring more north westerly winds, which brings more rain on the north eastern parts of the country while the southern and south western parts of the SI usually receives less precipitation (Wratt, Basher et al.). The temperature is in generally lower during El Nina which give more precipitation in the form of snow instead of rain. The increased amount of snow and lower temperatures delays the spring's melting season and delays the refill of the hydro storages (McGowan and Sturman 1996).

2.6.2 Wind resources

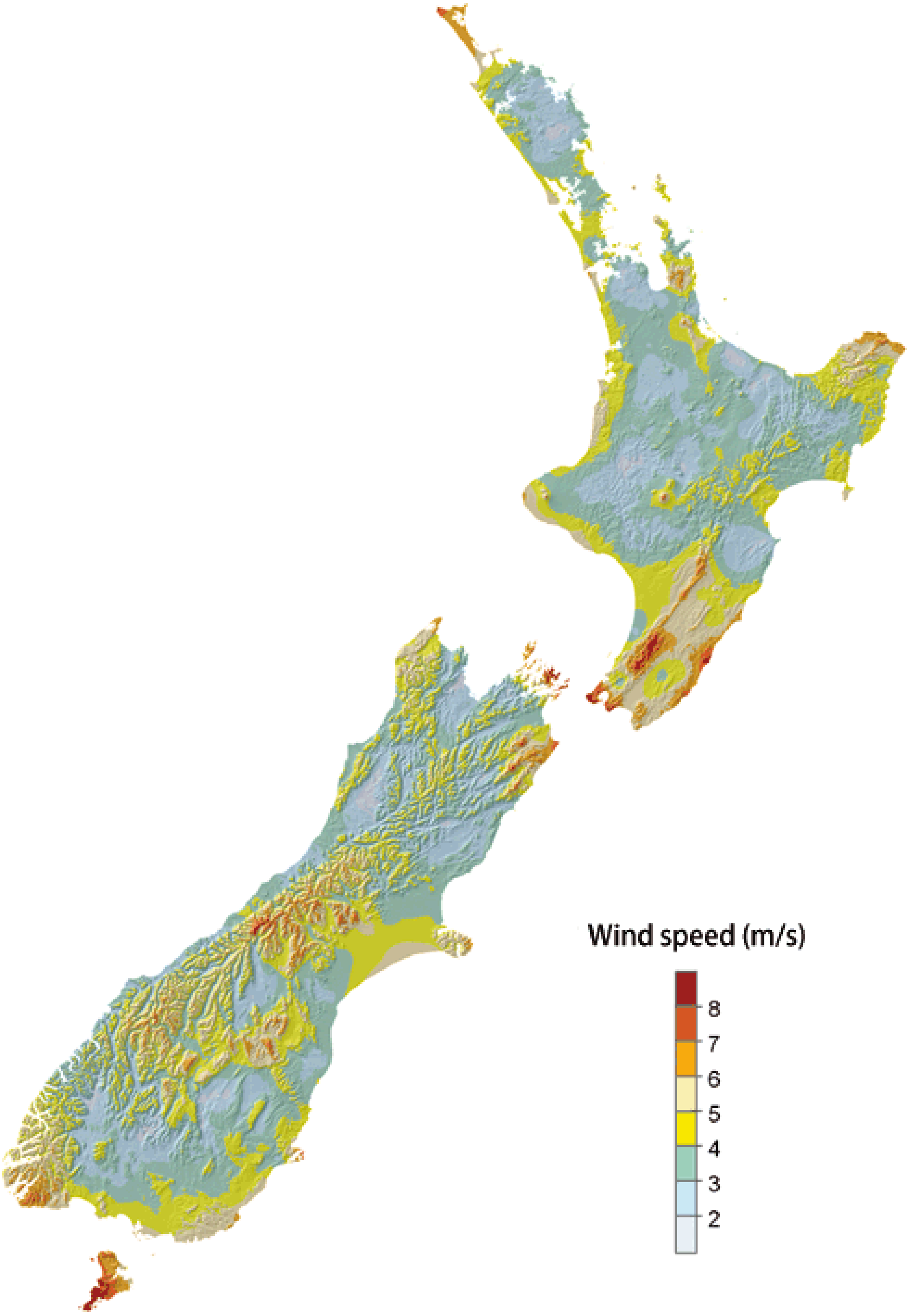

Figure 2.8 Annual mean wind speed map. The highest mean wind speeds can be found on the south of the NI, the wind speed accelerate and peaks at the mountain ridges. SOURCE: NIWA website

NZ is known for good wind resource due to the location surrounded by oceans. There are also some additional geographical effects that make some sites even more beneficial for wind power. Figure 2.8 shows a map with mean wind speed over NZ. As expected the high wind speed areas are along the coast and over high elevation. The dominant wind direction is westerly or north westerly where the land mass acts as an obstacle between the pacific oceans and the Tasmanian Sea. This forces the air through the Cook straight (separating the North and South Islands) which creates high local wind speeds. On the south part of the NI, aligned mountain ranges yield the wind an increased speed locally. As indicated in Figure 2.8, sites close to the mountain ranges on the lower central NI experience some of the highest mean wind speeds in the country marked in deep red.

There are some seasonal wind patterns with more westerly winds during winter and spring, while weaker wind are expected in summer and autumn. Climate research has indicated that as the global mean temperature increases, the westerly winds are expected to become stronger and more frequent in the future (Tait 2012).

2.7 Development of Wind Power

Wind power has been growing and will soon play a significant role in the NZ power supply system. Today there is 662 MW if wind power installed. But there are plans for 3500 MW more to be installed and most of these stations already have been granted consents to be built List of power stations in New Zealand (2013). However, the economic recession that NZ has experienced since 2008 has decreased the demand for electricity, resulting in that very few of the planned wind power farms has so far been constructed. Most companies are instead waiting for electricity demand to increase before implementing their plans (The Treasury 2010). This economic situation has resulted in that very few of the planned wind farms have been built. The companies are instead waiting for demand to grow.

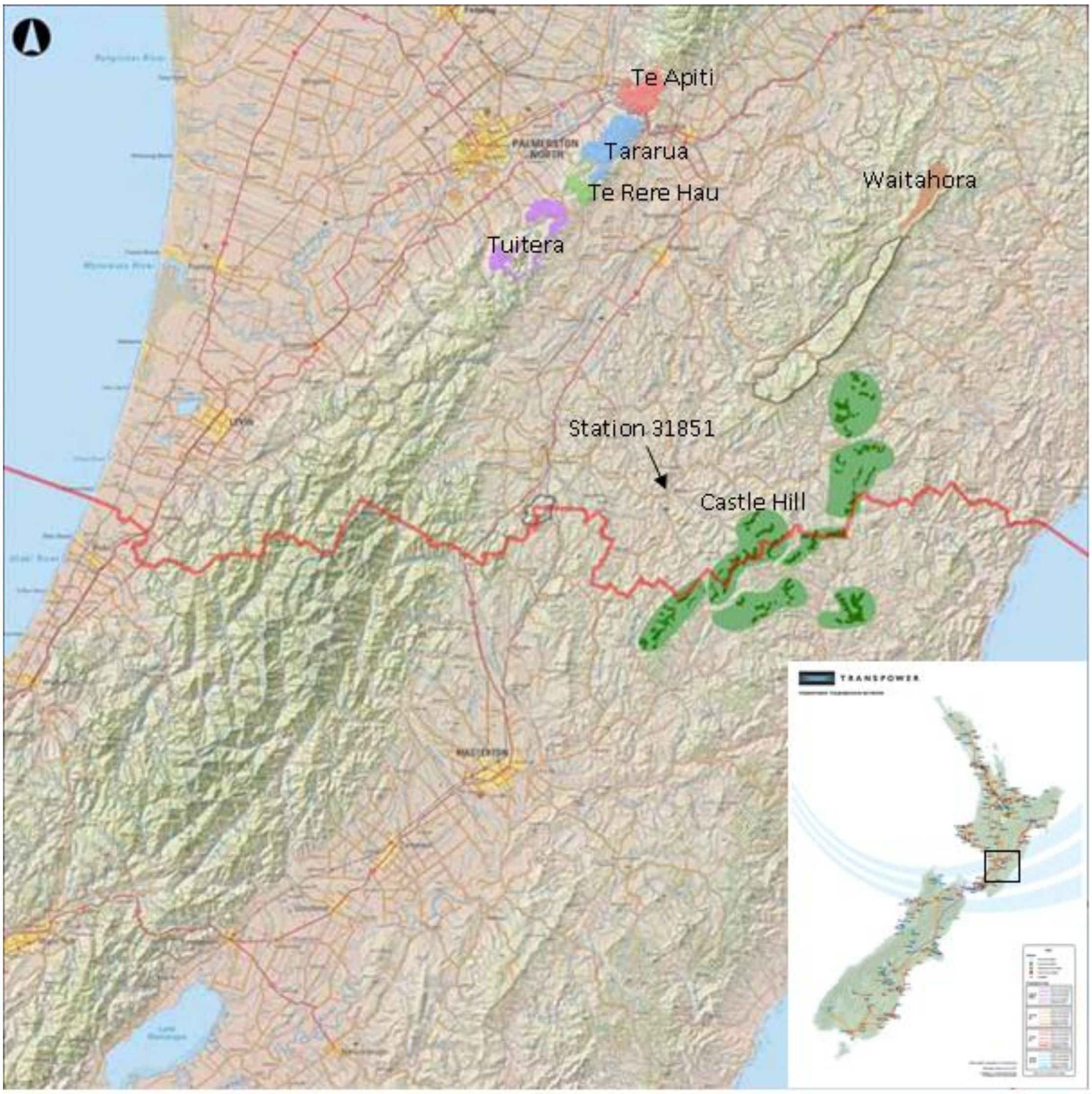

Figure 2.9 Map of the central part of the North Island with the wind farms Ta Apiti, TeRere Hau and Tuitera and the planned wind farms Waitahora and Castle Hill

All current wind power in New Zealand is onshore wind and is mainly located on the NI, with a high concentration around Palmerston North on the lower NI. The wind conditions, the ridges and the short distance to the grid make this spot interesting. In the map presented in Figure 2.9 the wind farms Te Apiti, Tararua and Te Rere Haut are marked, the other indicated locations are intended spots for new wind farms.

These are the main wind farm operating in NZ during 2013.

- Te Apiti is operated by Meridian Energy and has a capacity of 91 MW and was constructed in 2005.
- Tararua is operated by Trust Power and was built in three stages; 1999, 2004 and 2007 and has now a total capacity of 161MW.
- Te Rere Hau was also built in stages (2006, 2009 and 2011) and was finished in July 2011 and is now at a total capacity of 48.5MW.
- Te Uku, with a maximal capacity of 64MW is located in the middle of the NI west coast. Te Uku wind farm is located close to the larger demand centre of

the north. The turbines are placed on the ridges along the west coast, where the wind usually comes in from the ocean. The wind farm started to produce power in late 2010 but got fully operational by February 2011. The capacity factor is 39%. But according to Meridian Energy themselves, they still consider this a “B status” wind site, compared to Meridian Energy’s other wind farms (Scott 2012).

- Close to Wellington is the wind farm West Wind operated by Meridian Energy. It has a capacity of 143MW and was built in 2009. This wind farm is located west of Wellington, at the Cook Straight. This creates high wind conditions that allow the wind farm a high power output. This wind farm has thereby the best capacity factor (44%) of all wind farms in the whole country.
- White Hill has a capacity of 58 MW and was finished in 2007. It is located on the SI and is the only wind farm from the SI that has generation data available.

Figure 2.10 presents the wind power output as a fraction of capacity for the generation of 2011 (Eletricity Authority 2012).The larger wind farms that have been analysed are. Te Uku, Te Apiti, Te Rere Hau, West Wind, White Hill and Tararua. They have a joint capacity of 565.5MW and an average capacity factor of 36.5%. This value is calculated over the full year and does not consider the limitations in generation during building of Te Uku and Te Rere Hau. This means that the actual utilisation is even higher and indicates at the excellent wind power potential that NZ has. In many other parts of the world a capacity factor of only 20-30% are considered suitable for wind power generation. The analysed wind farms in NZ has intermittency for the analysed accumulated generation from these producers has a maximum variation of 129 MW between to 30 min periods during 2011 according to the data from(Eletricity Authority 2012) .

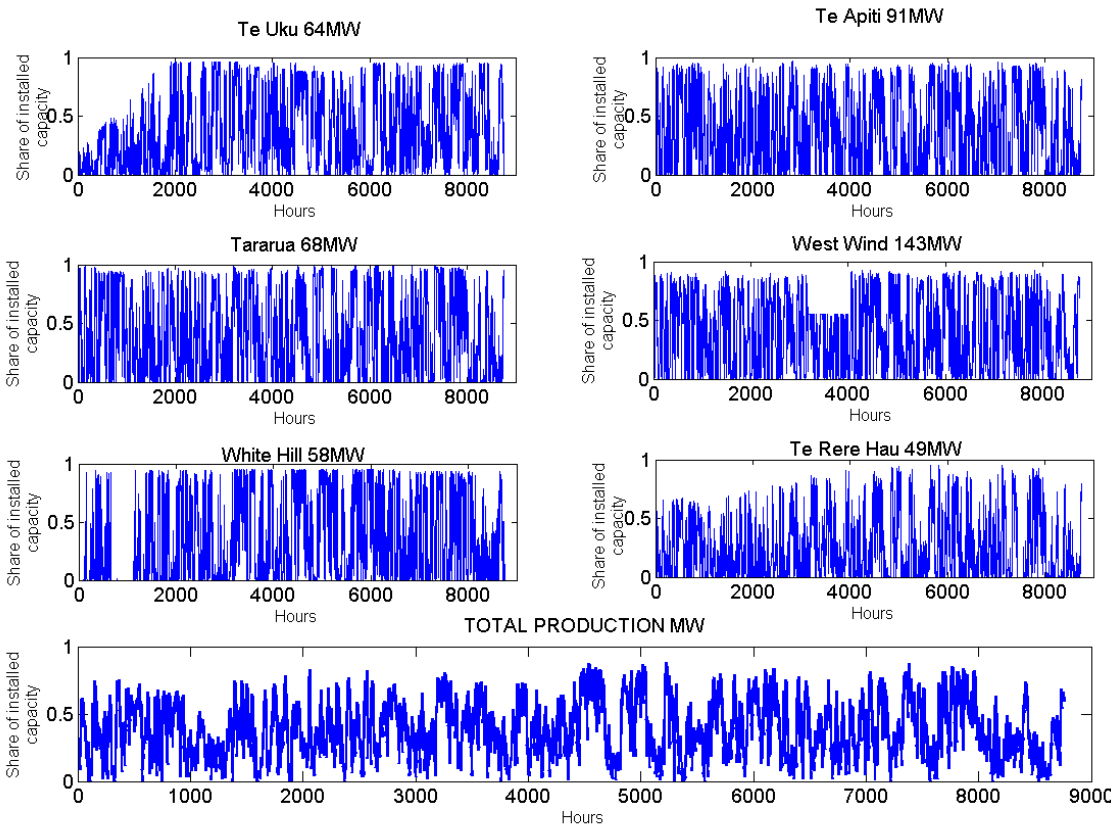

Figure 2.10 Actual wind power output as a share of the installed capacity over the year 2011 for the six main wind farms. The lower panel show their combined annual wind power generation. Graphs are based on data from (Electricity Authority 2012).

3 Method

This work has been performed as a case study on the options of placing new wind power on the north or south island. The HVDC link that connects the islands must be dimensioned to support the new generation. A new capacity of the link was therefore one variable that has been evaluated to match the new power system. A Matlab model was created to calculate a new hydro generation, adapted to balance the wind power. In Figure 3.1 a schematic of how the model will simulate the new power generation. This work evaluates how the major power schemes on the SI can support wind power generation. As the limited hydro power on the NI has more regulations on flow rates and a limited storage capacity it is not used for the back-up of wind power. Neither the small scale hydro producers on the SI without any major storage capacity are used for back up. This station and the geothermal power generation are instead set to be as the historical generation data. The need of generation is at first covered by the wind and geothermal power and the NI hydro power then, for the remaining part the NI uses the SI hydro to balance the load. This gives a net demand to cover the SI hydro power. The inter-island HVDC link also limits the amount of electricity that can be transferred between the islands. To estimate the potential and options to have a system with 30% of the annual energy of generated power from wind power this Case study compares 3 cases of allocation. The capacity of the HVDC link is also evaluated for the full capacity, contra a capacity to only cover the capacity maximum for 95% of the hours. If the non-variable generation exceeds the demand the energy cannot be used. In reality the extra wind power will be curtailed to keep the balance. In this study the need of curtailment is compared between the cases.

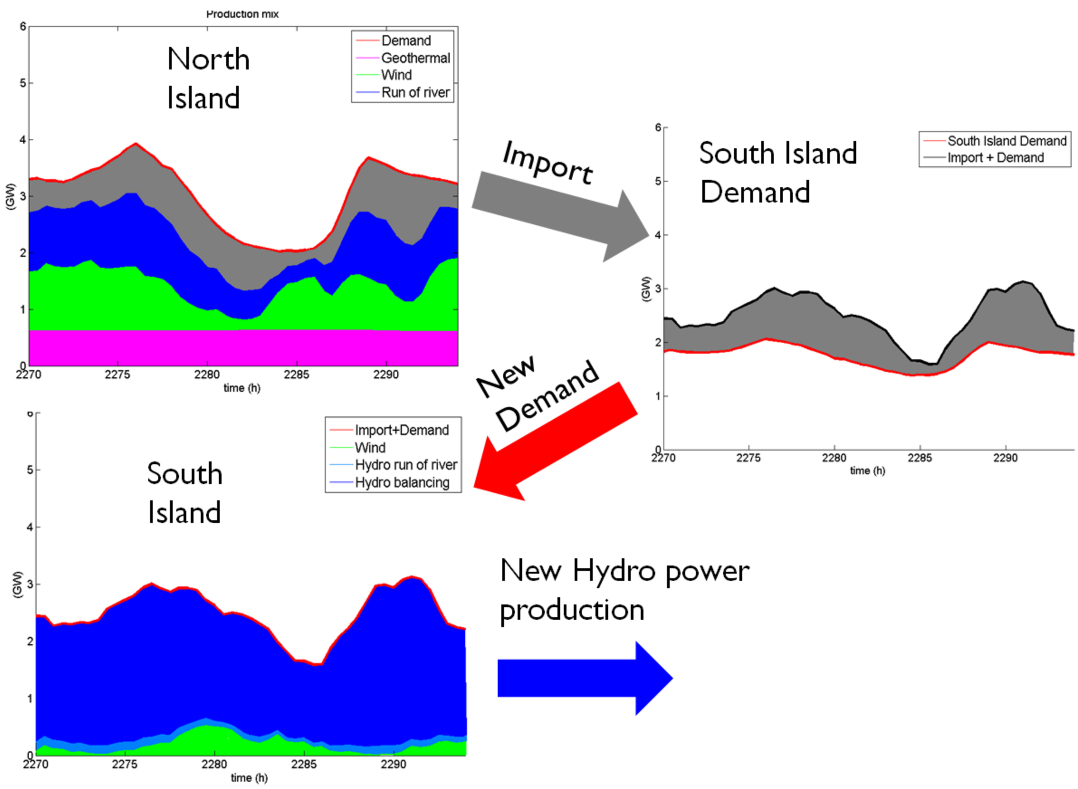

Figure 3.1 Description of the general steps of the model with an example for 24h. The two islands (the North Island and the South Island) are divided into two different systems. The difference between the NI demand of

electricity and generation of electricity will be compensated for by changes in the SI system where the generation is adjusted to meet the import need to the NI.

Below are the sources for power generation, used for power generation in the study. The sources each has different characteristic that affects the power system. Wind and Geothermal power cannot be controlled and historical generation data are used as input in the model. The hydro power can with some limitations be regulated. The part with run of river will be used as input while the regulated part of the hydro power will be an output.

- Wind intermittent
- Geothermal base load
- Hydro adjustable + storage (+ weather dependent)

3.1 Data

The Simulations of the power system has been done using power generation data for 2011. The data source for the generation is the Centralised Dataset from the Electric Authority which supplies data on power generation, reserve offers, demand and hydrology. For data of power generation the data is supplied for almost all power stations, except a few with very low capacity or new stations, wind farms with installed capacity under 10MW are not represented. The data is supplied in kW as the half hour mean for each station. Data on lake levels is on a day resolution and exists for the period 01.011990-30.06.2010.

Data for power generation in energy for whole year statistics is supplied in the Energy dataset from Ministry of Economic Development 2012

3.1.1 Wind Power Data

To predict the output from planned wind farms the first aim was to use wind data from NIWA weather stations and estimate the generation based on this data. The method was tried on some of the existing wind farms and compared to the actual generation. Due to poor correlation between the estimations and the actual generation the decision was made to use historical generation data from 2011from the current wind farms instead. This means that the variation in power generation is limited to the generation from on a few sites. In a situation where several sites exist, the combined generation can be expected to have a smoother characteristic.

The wind farms Te Uku and Te Rere Hau was not fully operational at the start of 2011 and was running on reduced capacity. The capacity was scaled up as more wind turbines was installed at the site. In February, the Te Uku wind farm was fully operational while the Te Rere Hau wind farm was finished first in July. The wind farms White Hill also had a stand still for the most time during January and February in the beginning of 2011. To compensate for this reduced capacity, generation data for 2012 for the same time of the year was used for these occasions. Wind power generation for the NI is based on the station Te Apiti, Tararua, Te Rere Hau, Te Uku, and West Wind. While the SI only had the wind farm White Hill that was operating and reported the generation.

3.1.2 Limitations

-The Centralised dataset does not include the smaller wind farms with an installed capacity under 10MW which limit the estimations to generation data to a few major farms. Furthermore is there no data for generation from the wind farm Mahinerangi (36 MW)

-The wind data for estimation of generation at planned wind farms are limited to the NIWA existing station with wind data for 2010 and 2011.

3.2 Model

This model simulates how the hydro power on the SI will be able to support the demand on the NI with the increased amount of intermittent wind power and no fossil combustion for power generation. The hydro power on the SI will change the generation depending both on the current demand and current power generation from wind farms.

A model for simulation the simplified power system with each island regarded as a subsystem with no transferring limitations was made in MatLab. The model separates the two islands into different sub systems. Each of this systems must meet the individually demand but import and export between the two systems is possible.

The model is based on the following data.

Fixed input from dataset:

$Demand_{NI}$	Demand for NI
$Run\ of\ river_{NI}$	Run of river hydro power for NI
$Wind_{NI}$	Wind power for NI
Geo_{NI}	Generation Geothermal power NI
$Demand_{SI}$	Demand for SI
$Run\ of\ river_{SI}$	Run of river hydro power for SI
$Hydro\ river_{SI}$	Controlled hydro power for SI
$Wind_{SI}$	Wind power for SI
$Storage_{SI}$	Hydro storage SI

Varied in the model and are different between cases:

$Wind\ New_{NI}$	New win power on the NI
$Wind\ New_{SI}$	New win power on the SI

Output

$Hydro\_New_{SI}$	New controlled Hydro generation on SI
$Hydro\ storage\_New_{SI}$	New controlled Hydro storage levels
Curtailment	The power curtail

$HVDC\ load$	New Load on the HVDC cable
$Back\ up\ Capacity$	Need of gas turbine Capacity
$Back\ up\ Energy$	Need of gas turbine Energy

For the NI the system has a set demand and generation. The power generation from geothermal, run of river hydro power, existing wind power and the new wind power is then retracted from that the set demand. The difference between the NI demand and generation must then be supported by adjusting the power generation from the SI system. This adjustment will occur either as a need of power import or of power export depending on the NI generation balance. I equation (1) the remaining demand is named import and will be added to the SI Demand seen to the right in Figure 3.1.

$$Import(t) = Demand_{NI}(t) \dots$$
$$\dots - Run\ of\ river_{NI}\ (t) - Wind_{NI}(t) - Wind\ New_{NI}(t) - Geo_{NI}(t) \qquad (1)$$

The need of support from the SI generation will then be added or subtracted to the demands on the SI. One should note that this need can either be positive which increase the demand or negative which will decrease the generation demand on the SI. The SI will have set producing from run of river hydro power, existing wind power and new wind power based on historical generation data. Then the remaining load will be covered by the variable hydro generation calculated in equation (2). This is the requested hydro generation and will later be adjusted due to limitations in generation and transfer capacity.

$$Hydro_{Req_{SI}}(t) = Demand_{SI}(t) + Import(t) \dots$$
$$\dots - Run\ of\ river_{SI}(t) - Wind_{SI}(t) - Wind\ New_{SI}(t) \qquad (2)$$

The SI controlled generation must be within the capacity limitations and the Requested Hydro generation is adjusted to these limitations done in equation (3). If the set power generation exceeds the demand then the additional power will be curtailed, as the power cannot be stored equation (4). If the set generation on the other hand is lower than electricity demand, the variable hydro power will adjust the generation with the generation limitations to meet the demand. As the controlled hydropower would not be able to balance the system at all times there will be some need of thermal back-up generation to keep the system from failing, equation (5). This back-up power need in capacity and energy will be one output of the model. Since the major load is placed on the NI and to minimize the capacity on the HVDC link the back-up power is assumed to be produced on the NI. Therefore the back-up power will be reduced from the original Import that symbolises the inter island traffic.

$$Hydro_{New_{SI}} = Hydro_{Req_{SI}}(t) \qquad (3)$$

$$when \begin{cases} Hydro_{Req_{SI}}(t) \geq Cap_{max} \ \rightarrow \ Hydro_{New_{SI}}(t) = Cap_{max} \\ Hydro_{Req_{SI}}(t) \leq Cap_{min} \ \rightarrow \ Hydro_{New_{SI}}(t) = Cap_{min} \end{cases}$$

$$Curtailment = -Hydro_{Req_{SI}}(t)^{-} \quad (4)$$

$$were\ Hydro_{Req_{SI}}(t)^{-}\ is\ the\ Hydro_{Req_{SI}}(t) \leq 0$$

$$back\ up\ load = Hydro_{Req_{SI}}(t) - Hydro_{New_{SI}}(t) + Curtail \quad (5)$$

To estimate the power transfer between the island imports from the NI will be the simulated load in the HVDC link. This is used to estimate the maximum dimension for dimensioning and compare the direction and power in every period. To limit the prize of the HVDC link an alternative size of the HVDC link that is dimensioned for the 95% percentile of the HVDC load is also used as an alternative capacity, implying that the link is only dimensioned for 95% of the cases. This would the not let all the needed electricity to be transferred between the islands. This eliminated peak will have to be compensated by increase the back-up power, and decrease the hydro generation, creating an alternative output of these variables (Restricted). This option will compare the option on investing in transfer capacity contra back-up power. This limitation will be compensated with an increased demand of back-up power while at the same time the variable hydro power will have the corresponding decrease.

The new hydro generation that this model creates will then be compared to historical generation given a change in generation. This change is used to simulate how the hydro storage levels would react to this hydro generation with storing water when the simulated generation is less than the historical and draining storage when simulated generation is higher. The new demands on hydro generation will change the hydro storage levels in the lakes. The storage change is calculated for each day and added to the historical data, equation (6). The new storage will investigate how the storage levels will change and confirm that shortage does not occur. If the storage levels drops the system will be at a risk of shortage.

$$New\ Storage(d) = Storage(d) + \sum_{t=1+\frac{T}{D}d}^{\frac{T}{D}*d} \left(Hydro_{SI}(t) - Hydro_{New_{SI}}(t)\right) \quad (6)$$

$$Where\ T\ is\ the\ number\ of\ 30 miutes\ peroides\ in\ a\ year$$

$$and\ D\ is\ the\ number\ of\ days\ in\ a\ year$$

3.3 Cases

The characteristics of the power system will be strongly affected by the allocation of the new wind power. The area with a high rate of wind power will have a high power generation during windy periods and a low power generation during low wind periods. Figure 3.2 presents two simplified power system, one system where all new wind power is allocated to the NI (left panel) and one system where all new wind power is allocated to the SI (right panel). In the case where all new wind power is allocated to the NI a surplus of power on the NI will occur during windy condition and this excessive power can be exported to cover the power demand on the SI. In Figure 3.2 the red lines indicate the flow of power in a windy situation. If the wind power instead has a low generation there will be a deficit on the NI and the hydro power stations on the SI will increase their generation and transfer power north (indicated by the blue lines in Figure 3.2). Where here in this case WN, the HVDC link will be used both for transferring wind power south and hydro power north depending on electricity demands and wind conditions. If all wind power is instead allocated on the SI, the power flow will always go from the SI to the NI, while the source of this power can vary from wind to hydro.

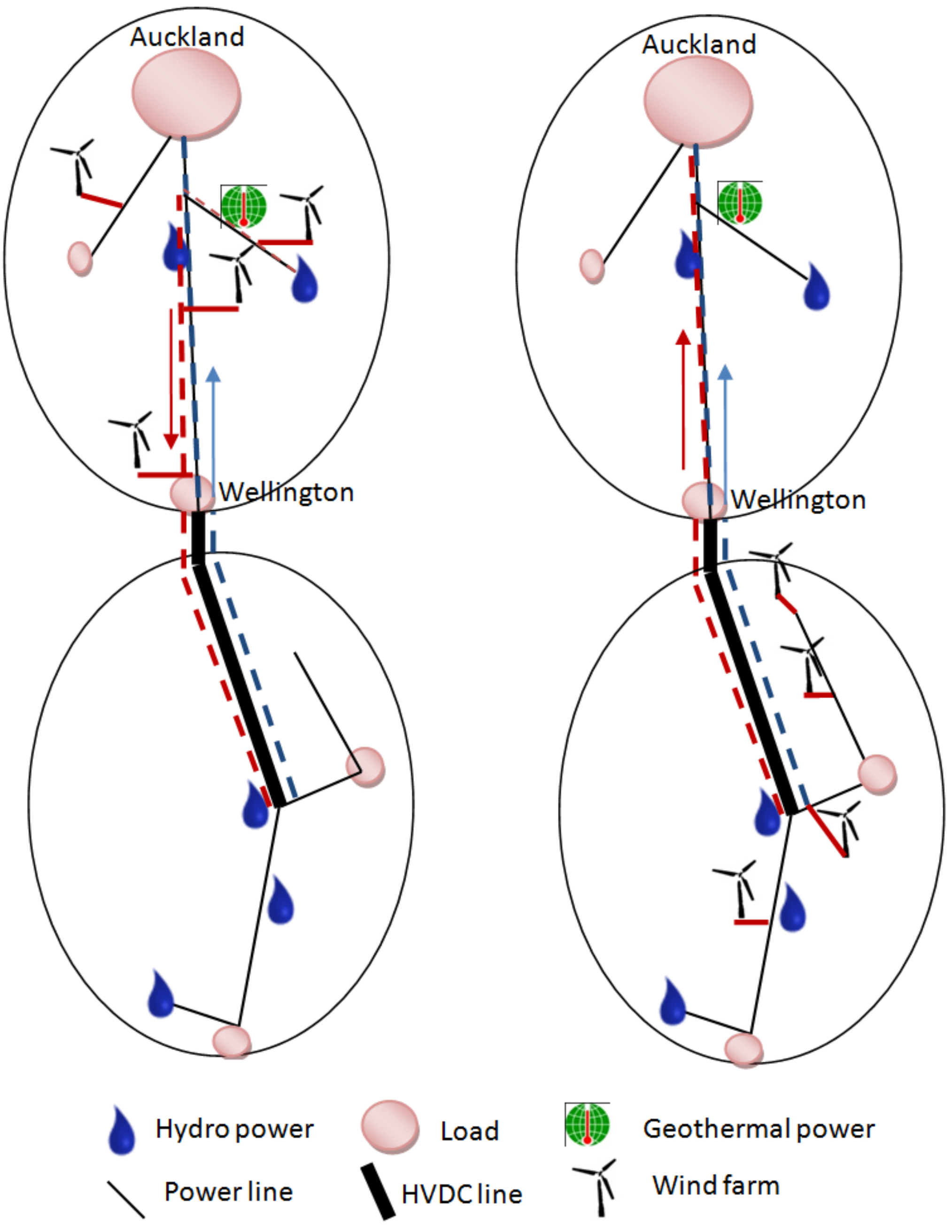

Figure 3.2 Simplification of the simulated power systems. To the left the situation when there is a lot of wind farms on the NI. The red lines are the direction of power in high wind conditions and the blue in low wind when hydro power is producing more power. To the right is the allocation with wind farms on the SI. Here power flow has the same direction regardless of the wind output.

For comparing different allocation of new wind power, three different cases were created with different proportions of the new wind power generation on the different islands. The new capacity needed for achieve the condition of contributing 30% of the electric energy from wind power was calculated from the average capacity factor for both islands in 2011. This capacity was then separated between the two islands according to the specific cases described in section 3.3.1. To determine the exact quota for allocation of the new wind power between the two islands, the optimum load coverage was calculated to create the first case called Wind North. The optimum quota was set in order to find the best coverage of the load with the new wind power. The fixed amount of power produced by geothermal power and existing wind power was first reduced from the demand to not benefit wind power that implies curtailment. Thereby only the actual deployed wind power will contribute to the load coverage.

$$Ln_t = Demand_t - Windpower_t - Geothermalpower_t - Run\ of\ River\ power_t$$

$$Ln = \sum_{t \in T} {Ln_t}^{+} \qquad (2)$$

$$were\ {Ln_t}^{+} is\ the\ net\ load\ \geq 0$$

The minimum Net load (Ln) gives the lowest energy need from the hydro and back-up generation. The Net load is the remaining energy need after the set power generation has been taken into account.

3.3.1 Case definitions

Case	**Definition**
WN	**Wind North.** The optimal load coverage resulted in 83% of the wind power allocated to the NI. This is the case where wind power is placed close to the load.
WS	**Wind South**. Is the case with an inverted proportion of wind power allocation between the islands compared to the Case WN, i.e. with 17% on the NI. This case, with a majority of the wind power on the SI, is the case where the wind power is allocated close to the balancing hydro power (situated on the SI).
ALL NI	**All Wind on the North Island**. As the NI is the main load an intuitive guess is that it is optimal to place all the simulated wind power there, with exception to the already existing wind power currently located in the SI. With generation and load in the same place the need for HVDC-capacity should thereby be minimized

3.4 Calculation of cost

The calculations of cost calculations do not consider the total cost of the cases. It instead aims to compare the differential in price for the different cases for investment cost of the HVDC cable, the investment cost of the gas turbines and fuel for the gas turbines. The final cost of the cases, are the sum of the variables above.

Equivalent annual cost (EAC) for investment was calculated with the equation (7).

$$EAC = {NPV}/{A_{t,r}} = {NPV}\Big/{\frac{1-\frac{1}{(1+r)^t}}{r}} \qquad (7)$$

$where\ t = yea\ ,\ r = capital\ cost,\ NPV = Net\ pressent\ value\ (investment)$

Assumptions for calculations

- 0.8 exchange rate between NZD and $(US)
- Capital cost of 8%
- Life span for HVDC line 40 years
- Life span for Gas turbines 25
- Gas turbines efficiency 35%
- Gas turbines investment cost of 871 $US/KW installed power or a gas urine in ha 100MW range according to (Parsons Brinckerhoff New Zealand Ltd 2008)
- Gas price are estimated to double from price at 2011 levels to 25668 $/GWh according to (Ministry of Business 2012)

Cost estimate of the HVDC link

Siemens is now involved in a major project to up rate the existing HVDC from 700MW to 1400MW by 2017. The whole project is expected to cost US$489 million (Tordesillas 2009). This specific cost in US$/MW will be used for investment calculations. These estimates should cover investment in converter stations, switchyards and the actual cable. The price is an early estimate of the project and cannot be fully reliable, nevertheless, it’s an approximation of this specific line and definitive the best available one.

4 Results

The three allocation cases will here be compared for both a full and restricted HVDC capacity. The Case with the lowest cost is NW Restricted. This case covers most of the demand and minimizes the need of reserve power, which gives the lowest emissions. But to minimize the emissions, which is the same as to minimize the reserve energy, the WN with unrestricted inter island transfer is the preferred case. This is the case that best covers the load and minimizes the back-up capacity.

4.1 Cost estimates

Table 4.2**Fel! Hittar inte referenskälla.** reviews the economic results for the different wind power allocation cases in this work. The result indicates that the least expensive alternative would be the strategy to allocate 82% of the new wind power on the NI and having the HVDC capacity limited to 1553 MW. The second cheapest alternative would be having all the new wind allocated on the NI, which due to a higher generation from wind power gives a significant reduction in need of reserve energy but would require a higher need of available HVDC capacity. In **Fel! Hittar inte referenskälla.** the cost for the analysed allocation cases are compared and the results indicate clearly that the case WS has higher cost for both HVDC cable and back-up power compared to the other cases. These results correlated well with the allocation of planned investments in reality. The economic calculations are based on estimations of future gas prices and investments assumptions, which are projections associated with uncertainly. A sensitivity analysis was therefore carried out to analyze the effect on results of the estimations on investments costs for the extension of the HVDC cable, investments cost for gas turbines and gas price. The specific results of this sensitivity analysis are further presented in Appendix I. In the sensitivity analysis, all specific costs were raised by 30% one by one to investigate the impact on the outcome. The results show that all cases all have the same ranking of the three cheapest alternatives and the same option as the most expensive alternative. The economic ranking between the cases analyzed, can therefore be considered reliable and robust.

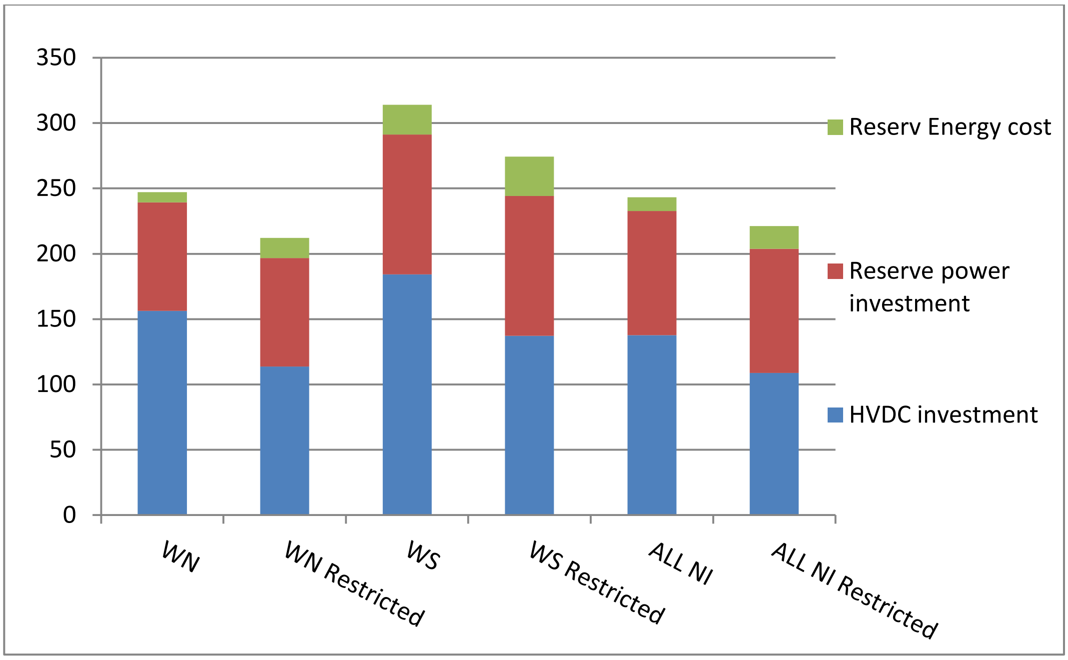

Figure 4.1 Comparison of the total cost for the cases WN, WN restricted, WS, WS restricted, ALL NI, ALL NI restricted. The total cost is split into investments for HVDC cable, investments cost for gas turbines and operations cost for reserve energy produced form gas turbines.

The option of designing the HVDC link for the full load in order to minimize the emissions will result in an unreasonably high cost, see bottom of **Fel! Hittar inte referenskälla.**. The price of reducing CO_2 emissions can therefore not from an economical view be considered a reasonable investment for emissions reduction.

Table 4.1 Annual cost estimate for the different cases. The bottom row estimates the resulting marginal cost of reducing CO2 emissions associated to the specific case compared to the reference case WN Restricted.

Million NZD	WN	WN Restricted	WS	WS Restricted	ALL NI	ALL NI Restricted
HVDC investment	156.2	113.7	184.2	137.2	137.6	108.7
Reserve power investment	83.1	83.1	106.9	106.9	95.0	95.0
Reserve Energy cost	7.8	15.4	22.7	30.1	10.7	17.5
Total Annual Cost	**247**	**212**	**314**	**274**	**243**	**221**
ton CO_2	28372	56200	82580	109300	38850	63263
NZD/ reduced ton CO2	**1252**	**0**	**- ***	**- ***	**1786**	**- ***

*These cases will have increased CO2 emissions and are therefore not relevant.

5 Case WN (Wind North)

This case is the result from modelling with 83% of the wind capacity is allocated on the North Island and 17% on the South Island. This case has the optimal quota to cover the load and therefore also minimise back-up power. As seen in Table 5.1 the back-up power is only half compared to the need in the WS case.

With 30% wind power in this set up, the wind power has an average capacity factor of 37.25 % and a total annual wind generation of 12 354 GWh. As seen in Figure 5.8 variations in wind power output can result in curtailment. This occurs during periods of low demand and high wind power generation resulting in an excess power generation. In this case the simulation gave an annual curtailment of 240.73 GWh, which is 1.95% of the total wind generation.

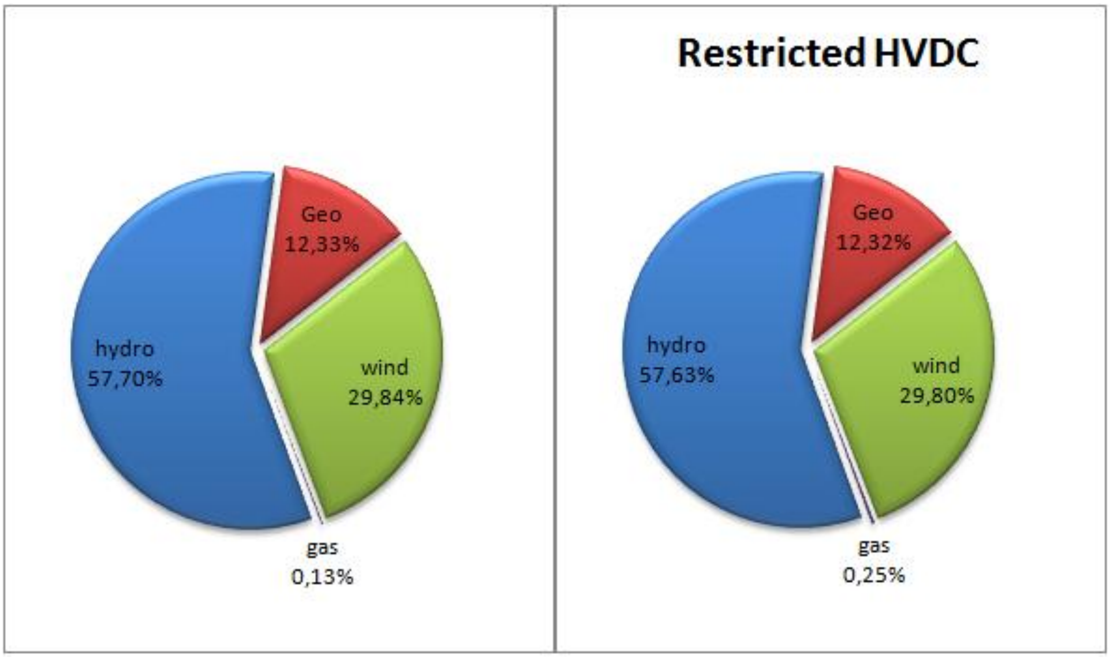

Figure 5.1 The power generation mix for the case WN. To the left are the results with no restrictions on the HVDC link. To the right is the result of a restricted HVDC capacity of 1553MW. With the restriction the power supplies from gas turbines are almost two times higher.

The Back-up power needed as calculated by the simulation is 53.25GWh which corresponds to 0.13% of the total energy. This back up power operates for 244.5 hours during the year (2.8% of the time). The capacity for the back-up must be 815 MW to meet the demand peaks. That means that the average utilisation factor for gas turbines that cover the peak demand is 0.75%. If assuming that the back-up power will be usage of open cycle gas turbines, the expected annual CO_2 emissions will be 28 372 ton.

With the restricted HVDC capacity the need for back-up energy increases by almost a factor two (105.5 GWh), which will cause emissions of 56 200 ton of CO_2. The back-up capacity needed is still unchanged but the operational time growths to 545.5 hours per year.

5.1 Case WS (Wind South)

This case is the invert of the WN case and this is the results from modelling with 17% of the wind capacity on the North Island and 83% on the South Island. In Figure 5.2 the energy mix for power generation shows a slight increase in hydro and gas power compared to case WN.

With 30% wind power in this set up the wind power has an average capacity factor of 36.61% and a total annual wind generation of 12 099 GWh. For the WS case the simulation gave an annual curtailment of 794.82 GWh, which corresponds to 6.57% of the total wind power generation.

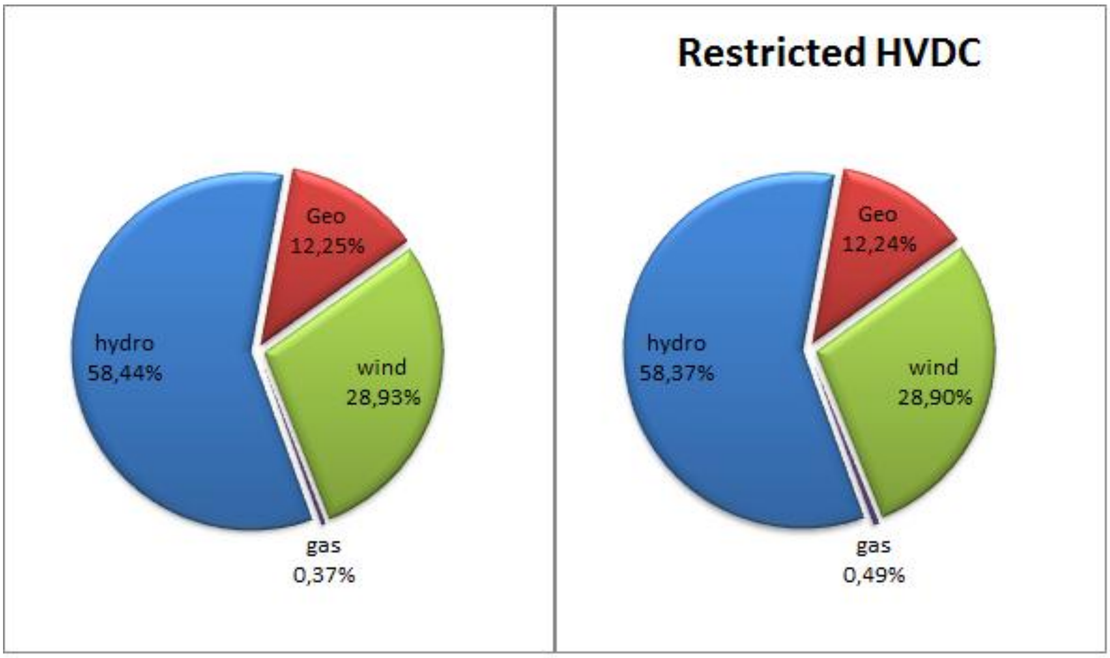

Figure 5.2 The power generation is supplied out of this mix for case WS. To the left are the results with no restrictions on the HVDC link. To the right are the results of Restricted HVDC capacity of 1874MW

In the case WS, the back-up power needed is estimated to 154.99 GWh, which corresponds to 0.37% of the total power demand. The back-up power will be run for 613 hours during the year (7.0% of the time). The capacity of the back-up must be

1048 MW to meet the demand peaks. That means that the average utilisation factor for the peakers is 1.9%. Assuming that back-up power will be open cycle gas turbines, the expected annual CO_2 emissions will be 82580 ton. It should however be noted that the fact that the data input from wind power on the SI derives from just one wind farm, makes the fluctuations more dramatic in the WS case. This case is the one where the most back-up energy is needed, while also demand the largest capacity of the HVDC cable.

With the restricted HVDC cable capacity for this case, the need for back-up power increases to a total need of 205.14GWh which will cause emissions of 109 300 ton of CO_2. The back-up capacity needed still the same as the unrestricted case while the operational time increases to 1026 hours a year.

5.2 Case All NI (All Wind North)

This case is results from modelling with all the new wind power allocated on the North Island. Due to the allocation close to the load, transferring capacity is minimized on the HVDC-link. For the case with unrestricted inter-island transfer, this case only requires an HVDC capacity of 1 879 MW, which is, as comparison, 12% less than WN case, while the case with a restricted capacity the capacity is only 4.5% lower. The lower cost, due to a smaller HVDC cable, is partly consumed by a higher cost of back-up power.

With 30% wind power in this set up the wind power has an average capacity factor of 37.32% and a total wind generation of 12 412 GWh for a year. The variations in wind power output results in curtailment during periods of low demand. In his case, the simulation gave an annual curtail of 348.8 GWh, which corresponds to 2.8% of the total wind generation. At point were the simulation gave the curtailment, the generation was 1.2 GW more than the current demand.

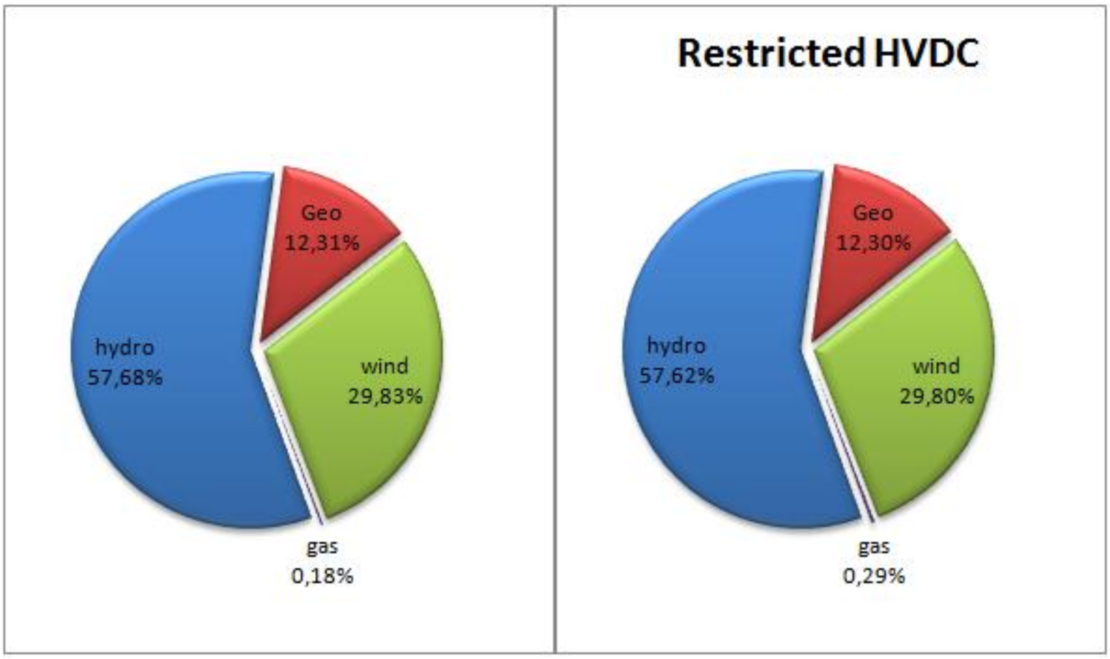

Figure 5.3 The power generation is supplied out of this mix for All NI case. To the left are the results with no restrictions on the HVDC link. To the right are the results of restricted HVDC capacity of 1484MW

In the case All NI, the back-up power needed is estimated to 73 GWh, which corresponds to 0.18% of the total power demand. The back-up power will be run for 307 hours during the year (3.5% of the time). The capacity of the back-up must be 931 MW to meet the demand peaks. That means that the average utilisation factor for the peakers is 0.89%. Assuming that back-up power will be open cycle gas turbines, the expected annual CO_2 emissions will be 38850 ton.

With the restricted HVDC cable capacity for this case, the need for back-up power increases to a total need of 119 GWh which will cause emissions of 63 263 ton of CO_2. The back-up capacity needed still the same as the unrestricted case while the operational time increases to 566 hours a year.

5.3 Comparison between cases

In this section comparisons of the three allocation cases are presented to give an understanding of their relative differences. Table 5.1 summarizes some of the most important results of generation, CO_2 emission and HVDC capacity.

Table 5.1 Generation mix for the different cases (GWh), percent of total power generation, emissions, needed HVDC capacity and cost for HVDC cable and back-up power.

Generation	WN GWh	WN Restricted HVDC GWh	WS GWh	WS Restricted HVDC GWh	ALL NI GWh	ALL NI Restricted HVDC GWh
WIND NI GWh	10327*	10327*	2092*	2092*	12228*	12228*
Wind SI GWh	2069	2069	10007	10007	184	184
Hydro SI GWh	16609	16609	17074	17074	16639	16639
Hydro NI GWh	7364	7364	7364	7364	7364	7364
Geothermal GWh	5124	5124	5124	5124	5124	5124
Reserve GWh	53	105	155	205	73	119
Total GWh	41546	41598	41815	41866	41612	41658
Generation mix						
Hydro	57.7%	57.6%	58.4%	58.37%	57.7%	57.6%
Geothermal	12.3%	12.3%	12.3%	12.24%	12.3%	12.3%
Wind	29.8%	29.8%	28.9%	28.90%	29.8%	29.8%
Gas Turbines	0.13%	0.25%	0.37%	0.49%	0.18%	0.29%
Emission CO2 (ton)**	**28372**	**56200**	**82580**	**109300**	**38850**	**63263**
HVDC capacity (MW)	**2 133**	**1 553**	**2 516**	**1 874**	**1 879**	**1 484**
Annual total Cost (Million NZD)	**247**	**212**	**314**	**274**	**243**	**221**

*Total energy generated without compensation for curtailment

** In 2011, emissions from electricity generation was 4 843 000 ton CO2-e.

5.3.1 HVDC

The characteristics of the load on the HVDC cable change significantly between the analysed cases, due to the geographical differences in power generation. With the WN case and All NI cases, the direction of power flow will change depending on wind conditions. During windy conditions, a surplus of power is created in the north, implying that power is exported to the SI. This will decrease the hydro power generation and there will be a south-going inter-island power transfer. In the opposite situations, with a low wind power generation in the north, the hydro power stations on the SI will increase their output to satisfy the NI demand and a transfer with a north direction occurs.

In comparison, the case WS, with wind power installed on the SI, the demand of the NI is almost always higher than the NI power generation, resulting in a continuous flow from the south to the north. The power transferred between the islands is in this case mainly dependent on the changes in demand and not generation. As seen in Figure 5.5 below the WS case have a more flat HVDC load curve compared to NW Figure 5.4. This case also has a higher capacity factor on the HVDC link.

In summary the load on the HVDC link are different for the scenarios. In the WN case the direction of the power depend on the wind output, while in the WS case the SI almost constantly supports the NI which gives a steady power transfer from south to north.

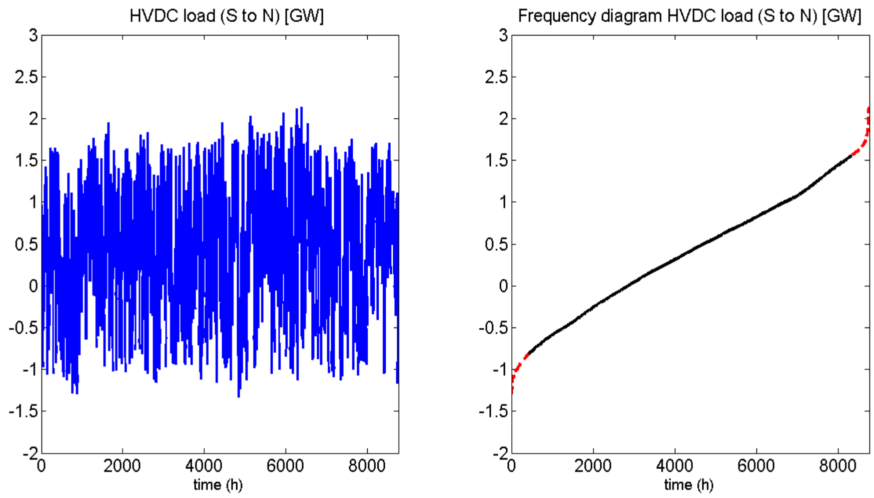

Figure 5.4 Load on the HVDC link in case WN. IN the frequency diagram to the right, the black line represents the restricted load and the red the full load.

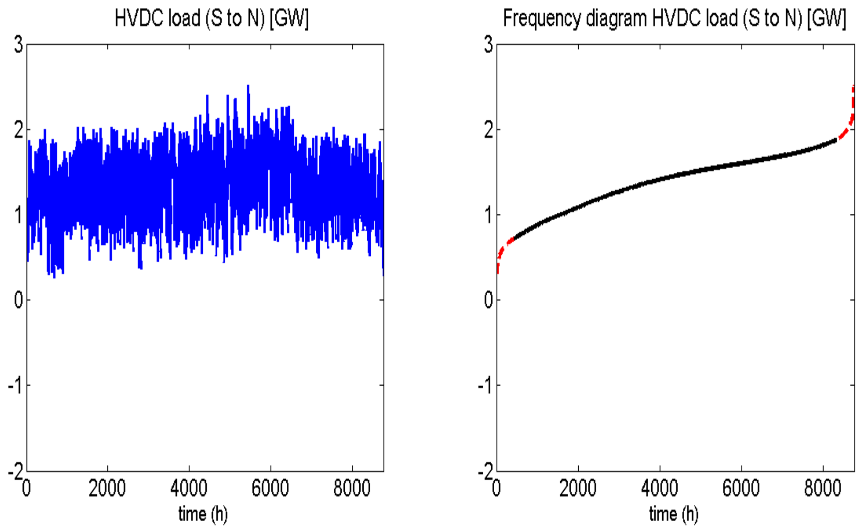

Figure 5.5 Load on the HVDC link in case WS. IN the frequency diagram to the right, the black line represents the restricted load and the red the full load.

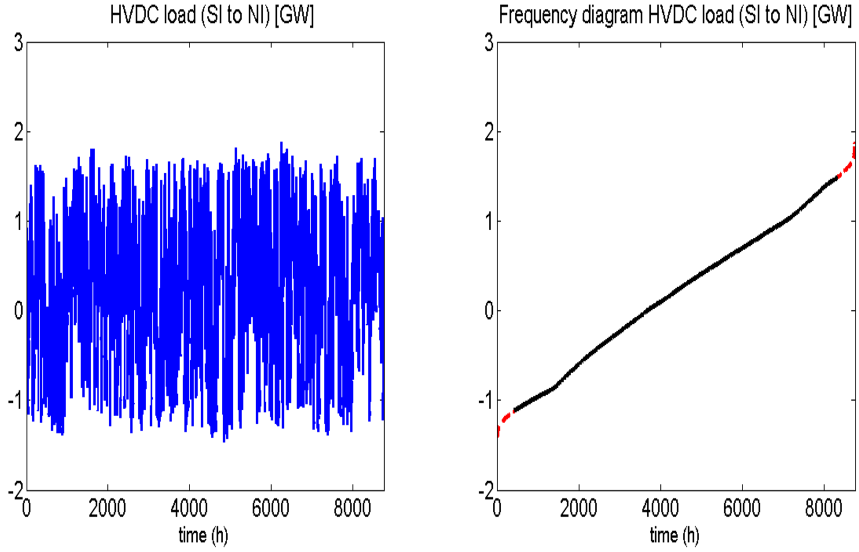

Figure 5.6 Load on the HVDC link in case All NI. IN the frequency diagram to the right, the black line represents the restricted load and the red the full load.

Table 5.2 lists the maximum loads on the HVDC link for each direction from the different cases. The maximum load of every case indicates the needed capacity on the cable for that specific case. Common for all three cases are that the highest load occurs for a north going power flow direction. This highest load case is the driven by a high load combined with low wind power in the NI, which results in major hydro generation on the SI. To design the cable capacity for this peak is not however the preferred choice, because of the few hours it is needed. In Figure 5.4-Figure 5.6 the frequency diagrams exponential growth in the last few hundred hour shows that very few extreme hours gives a significant increase of the peak load. For example, in case WN the peak capacity occurred during several extreme conditions with high wind in the south and low the north while high demand. In this case the peak occurs with almost maximum hydro generation and a 95% wind power output on the SI. This implies that the peak is a combination of both high demand and a wind peak which cannot be expected to often appear at the same exact time. Since such situations can’t be expected to overlap often and the system should therefore not be designed for that specific event.

Restricted HVDC capacity

For a more economical realistic design is was assumed that the HVDC link should only be dimensioned to cover the full load in 95% of the hours. With this restriction the size of the HVDC capacity can be significantly reduced, but the power system must have back-up power to compensate for the power that cannot be transferred. While only supports the peak of 95% of the hours only 72% of the capacity is needed and still 99.4% of the energy can be transferred. These criteria will be the restricted capacity of the HVDC-link for the different cases. An alternative source, such as gas turbines, can be used at these occasions. The total energy of the reserve power is roughly twice as high as with an unrestricted HVDC link for all cases, see results in Table 5.1.

The results in Table 5.2 show that the case WS demands both higher capacity of the HVDC link and more reserve power. The high HVDC load derives from the constant power flow to the NI where the power generation is low. The high need of reserve power can be connected with the modelling of the SI wind power, that act more rough due to that it is an upscale of only one station as also mentioned above in Section 3.1.1. The reserve power need is connected with low wind power output in the SI.

Table 5.2 Max capacity for HVDC link for the simulations in the different direction and cases

Case	Max SI to NI GW	Max NI to SI GW	Utilisation factor %
WN	2.1327	1.3357	32.63
WN Restricted HVDC	1.5530	0.8112	44.42
WS	2.5160	0 (*)	54.85
WS Restricted HVDC	1.8741	0 (*)	73.32
All NI	1.8791	1.4580	38.85
All NI Restricted HVDC	1.4838	1.114	48.85

* The power flow is only going from south to north and never in the opposite direction.

5.3.2 Generation mix

The power generation and demand is found in Figure 5.7. The wind power variations give at several times generation that exceeds the demand. This occurs even during the increased demand in winter, due to an increase in wind strength during this period. However generation that exceeds the demand is slightly more common during the lower demand months. In Figure 5.8 presents the same curves but limited to 500 hours (approximately 3 weeks). Here is possible to see the limitations of the system. When the demand (red line) is higher than the combined generation of geothermal power, wind power, and hydro power (blue line), the system must have some back-up power to keep the balance. The opposite situations of a generation higher than the demand can be seen in situations of high wind power which will result in curtailment.

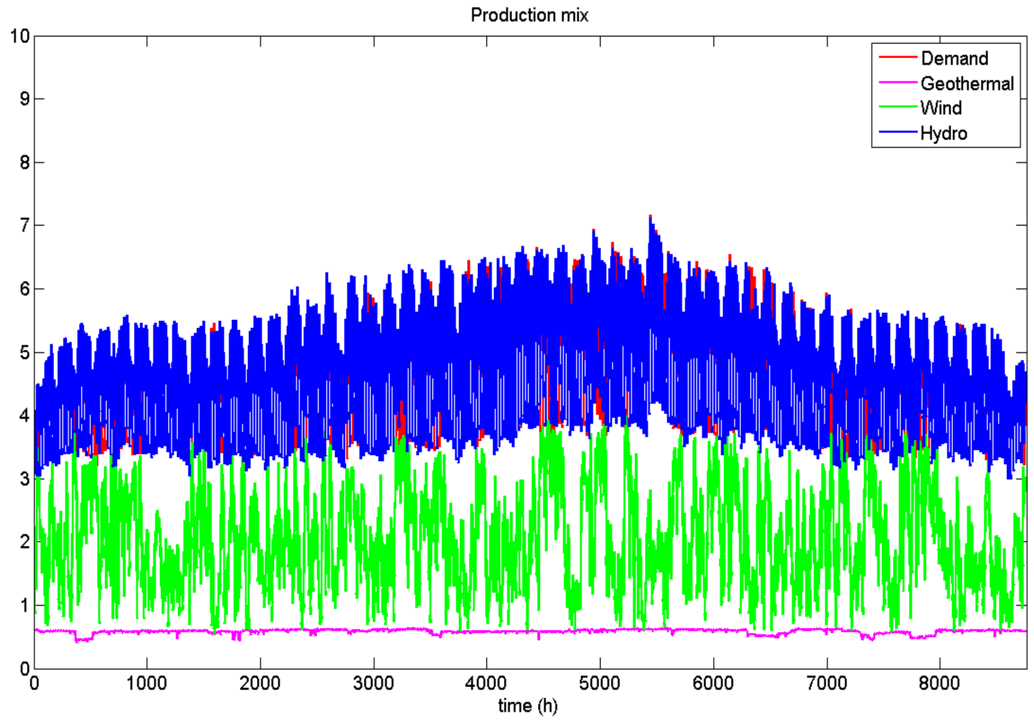

Figure 5.7 Generation mix Wind North. The difference between the combined generation (blue) an the demand indicates when the generation from geothermal wind and hydro are not able to fully balance the system

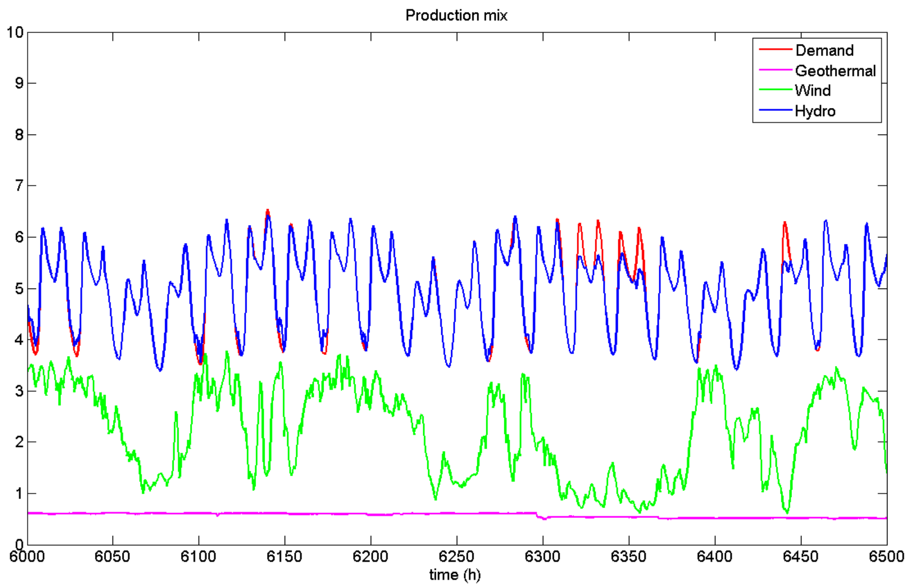

Figure 5.8 Generation mix and demand from modelled case WN hour 6000-6500. It's possible to view the shortage in high demand combined with low wind at peaks around hour 3400. At hour 6030 the generation is instead higher than the demand and curtails is necessary

In the case WS there is more variation in the wind power generation, which gives both more back-up power and curtailment. This tendency can be seen in Figure 5.9 as less correlations between demand and generation compared to Figure 5.7.

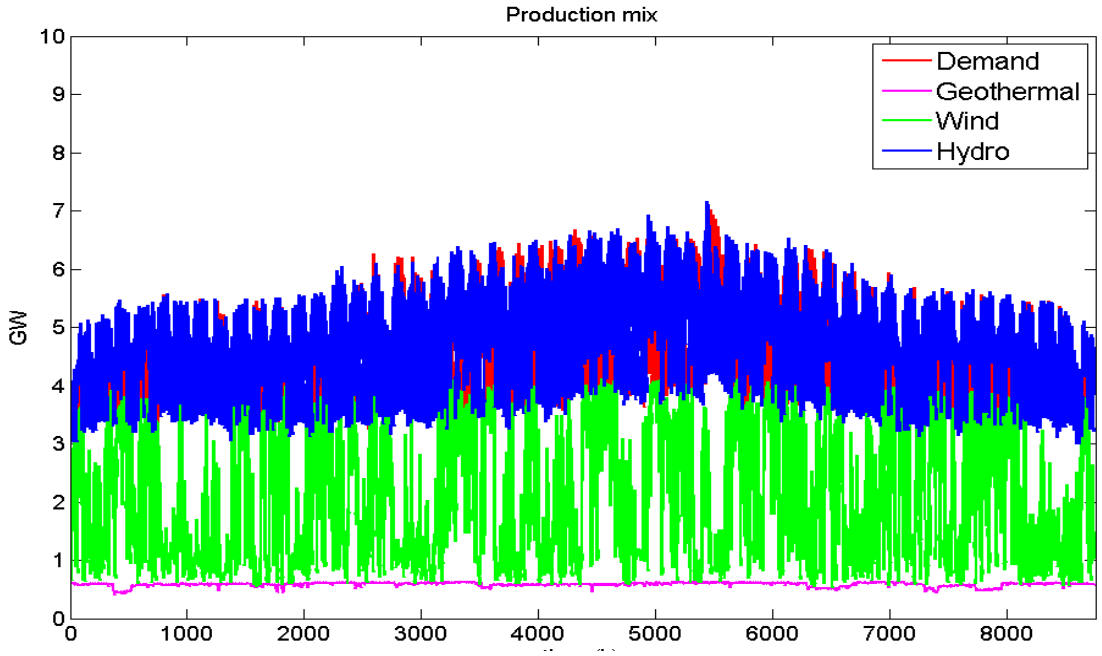

Figure 5.9 Generation mix Wind South. The difference between the combined generation (blue) and the demand indicates when the generation from geothermal wind and hydro are not able to fully balance the system

In Figure 5.10 the more fluctuating changes in the wind generation for case WS can be seen.

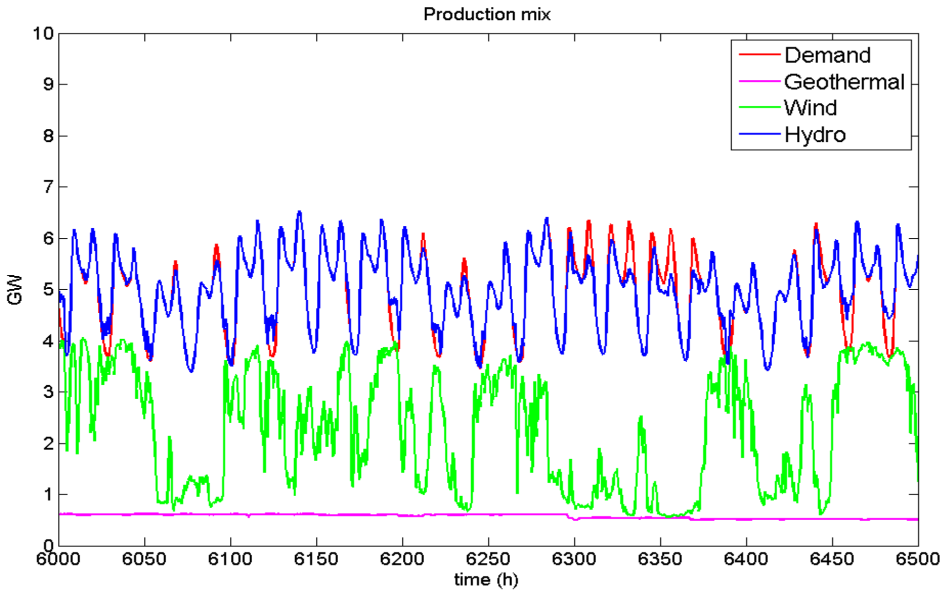

Figure 5.10 Generation mix and demand from modelled case Wind South hour 6000-6500. It is possible to view the shortage in high demand combined with low wind at peaks around hour 3400. At hour 6030 the generation is instead higher than the demand and curtailment is necessary

All Wind North case has results really close to the WN case

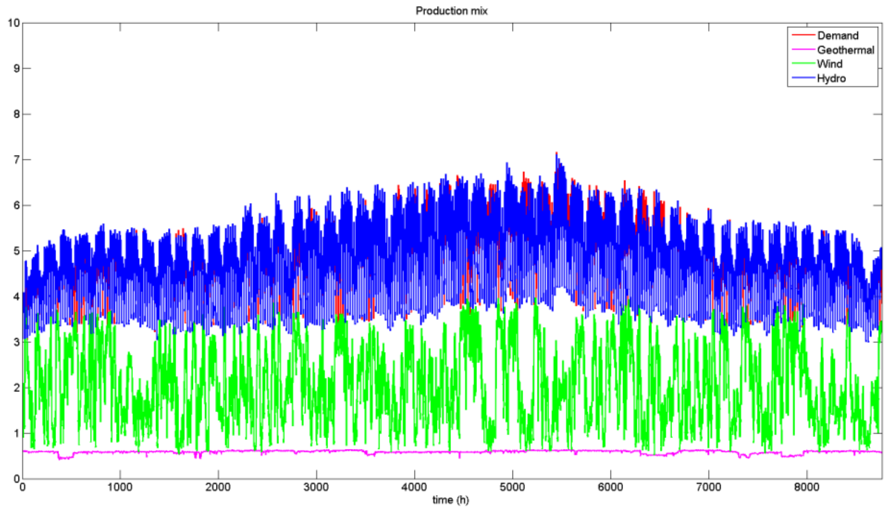

Figure 5.11 Generation mix All NI. The difference between the combined generation (blue) an the demand indicates when the generation from geothermal wind and hydro are not able to fully balance the system

5.3.3 Back-up Generation

Due to limitations of the hydro capacity and the Restricted HVDC link capacity there will be situations when the system will be in need of back-up power. As can be seen in Figure 5.8, the need of back up occurs for only a few hours at the time and not a continuous need. Therefore the most feasible back-up generation should come from a fast start-up generation source. In this model the back-up power is assumed to be supplied from gas turbines. More specific open cycle gas turbine specification are therefore used for calculations of emissions and cost for the back-up power. In Figure

5.12- Figure 5.14, the back-up power for the different cases with the restricted HVDC capacity is shown. The results clearly show that the back-up need occurs mainly during the winter, which corresponds to the demand peaks.

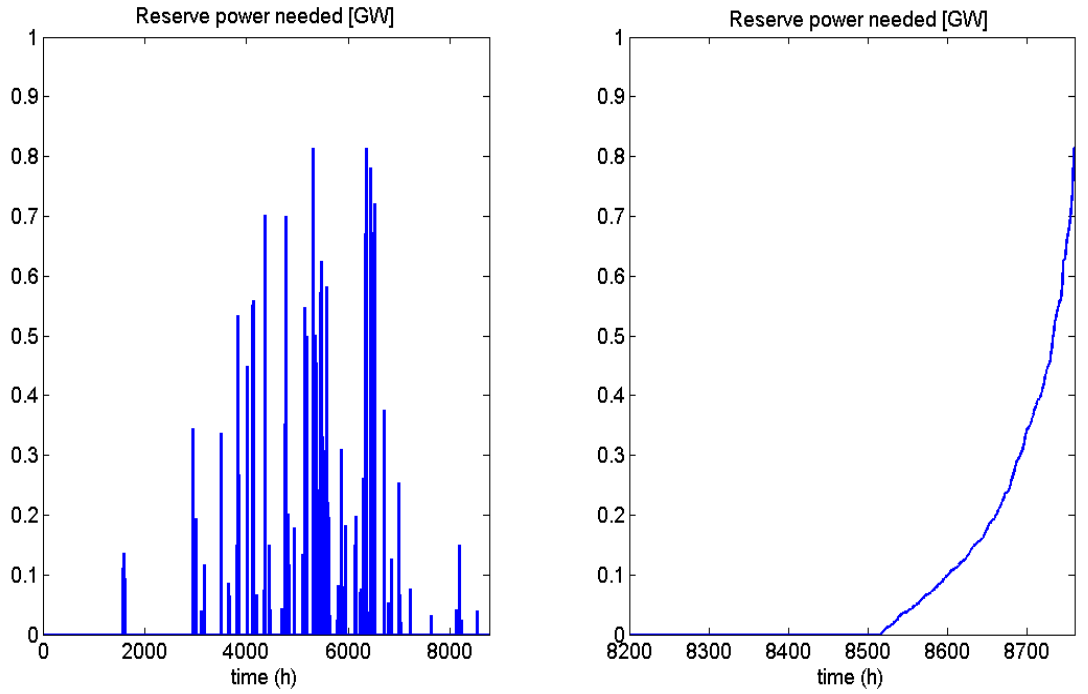

Figure 5.12 To the left is the back-up power from the simulation in case WN where the hydro power generation cannot supply sufficient power to satisfy the demand. To the right is a frequency diagram of the same data.

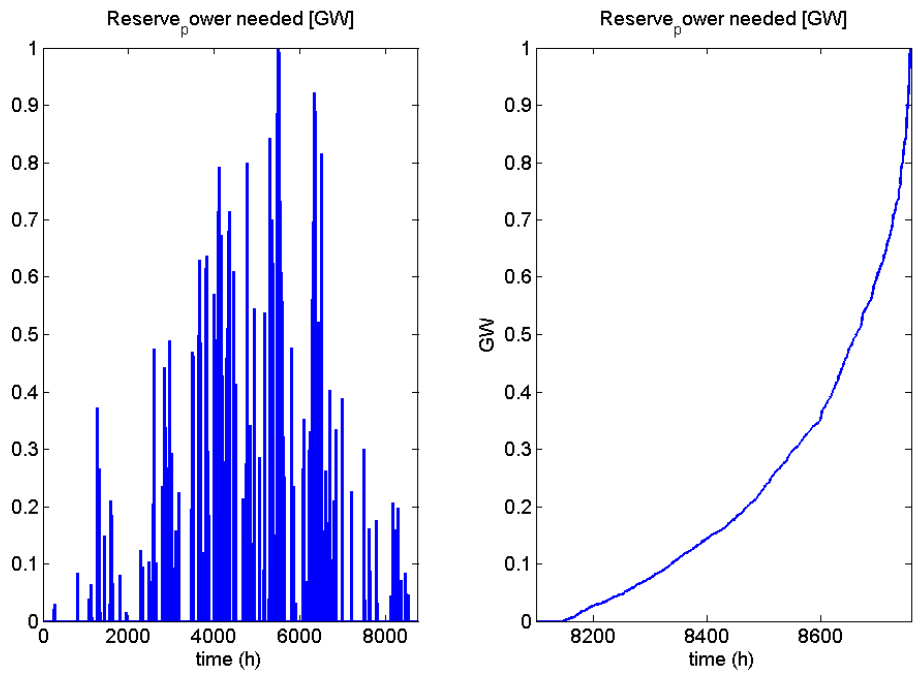

Figure 5.13 To the left is the back-up power from the simulation in case WS where the hydro power generation cannot supply sufficient power to satisfy the demand. To the right is a frequency diagram of the same data.

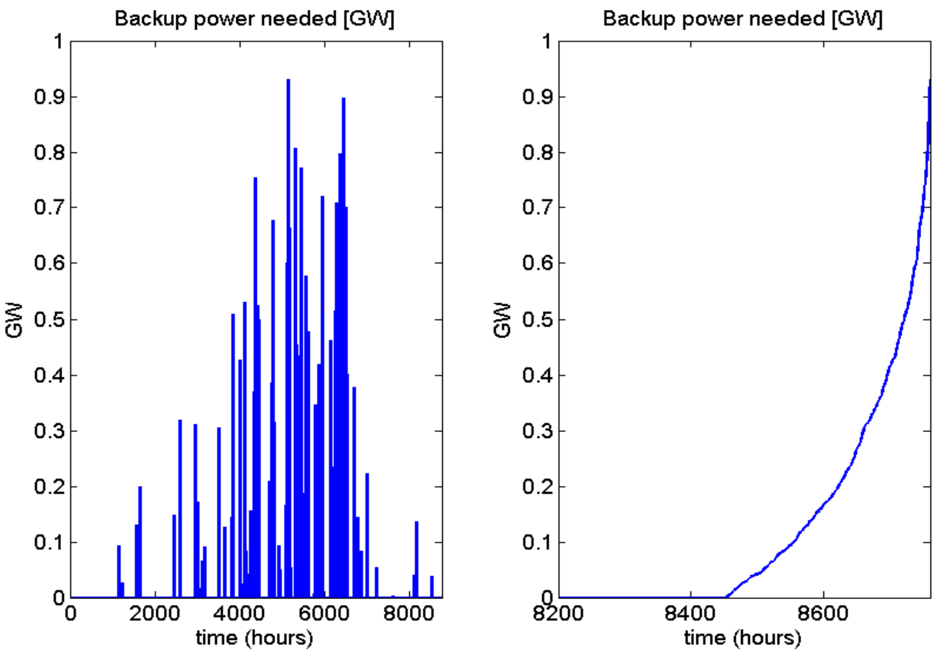

Figure 5.14 To the left is the back-up power from the simulation in case All NI where the hydro power generation cannot supply sufficient power to satisfy the demand. To the right is a frequency diagram of the same data.

The produced electricity from the back-up power is directly connected to the emissions. In Figure 5.15, emissions from back-up power (assuming open cycle gas turbines for generation) are presented.

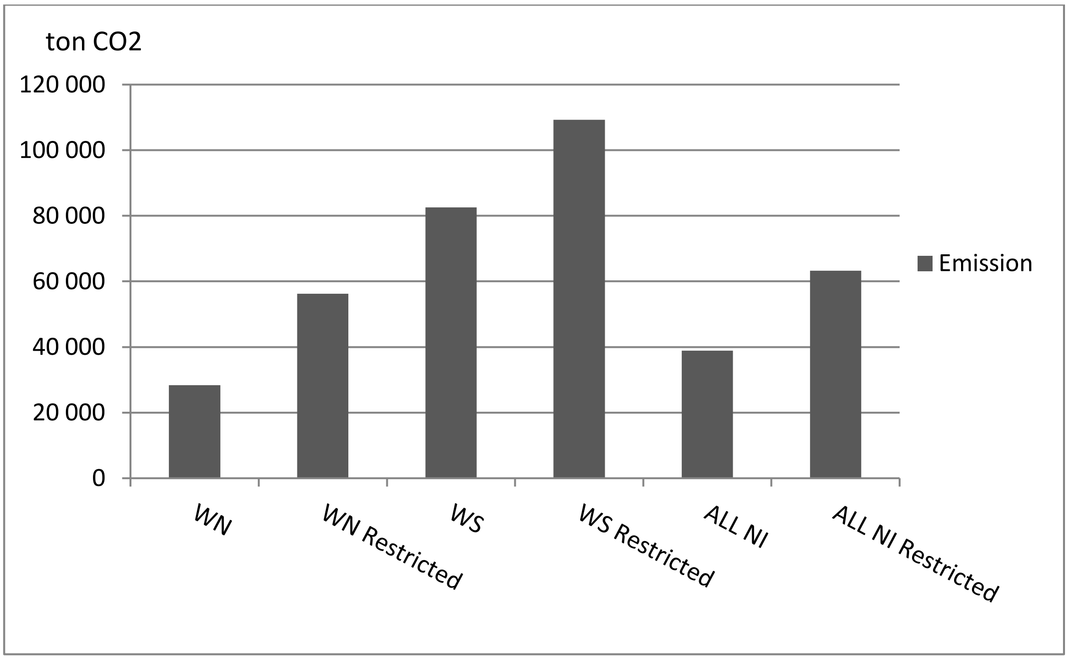

Figure 5.15 Annual CO2 emissions deriving from use of back-up power generation for the different cases

A summary of the back-up energy need can be found in Table 3.4.

Table 5.3 Resulting back-up power and resulting emissions.

	Electricity GWh	Max capacity MW	Utilisation factor %	Duration h	Amount ton CO_2
WN	53.25	815	0.75	244.5	28 372
WS	155	1048	1.69	613	82 580
All NI	73	931	0.89	307	38 850
HVDC Restricted					
WN HVDC Restricted	105.5	815	1.48	545.5	56 200
WS HVDC Restricted	205.1	1048	2.24	1026	109 300
All NI HVDC Restricted	119	931	1.46	566	63 263

5.3.4 Curtailment

Limitations of hydro generation capacity and storage opportunities combined with high wind output in low demand periods results in a few situations with a surplus of power. In the model, this will show as curtailment of wind power, while in reality water spilling at the power stations can be another option. The amount of electricity curtailed can be seen in Table 5.4. The energy curtailed is here compared to the total simulated wind power. As the curtailment occurs during low demand situation it is not affected by the restriction of the HVDC link and is same regardless of HVDC capacity option.

Table 5.4 Curtail of power due regulating constrains. The curtailment is not affected by the restriction of the HVDC link. The curtailed energy is compared to the total wind.

	Energy GWh	Max effect GW	Duration h	Part of total wind generation %
WN	240.73	1.21	734.5	1.95
WS	794.82	1.48	1521	6.57
All NI	348.8	1.24	900.5	2.81

5.3.5 New Grid invest

The new generation from the simulation will demand investment in the power grid to secure that the increased power from the hydro in the SI can reach the load on the NI. The cases will have some specific need but they will all have one thing in common. That is that when the wind is not producing the hydro generation in the south must be able to transfer an increased power supply to the north. This means an upgrade of the of the HVDC link and of the alternative current grid capacity between Wellington and Auckland. The HVDC link has been evaluated in Chapter 3.4.2 but this present section aims to answer how the transmission grid will be affected. Different transmission needs can be separated into two sub groups.

a) Connect the wind farm to the existing grid.
b) Transmission of AC on NI between Wellington and Auckland.

Figure 5.16 presents a simplified transmission system for the NZ included the required changes for the two scenarios WN and WS. The red lines in the figure symbolize a case with high load and high wind and blue lines the load from hydro power at low wind output.

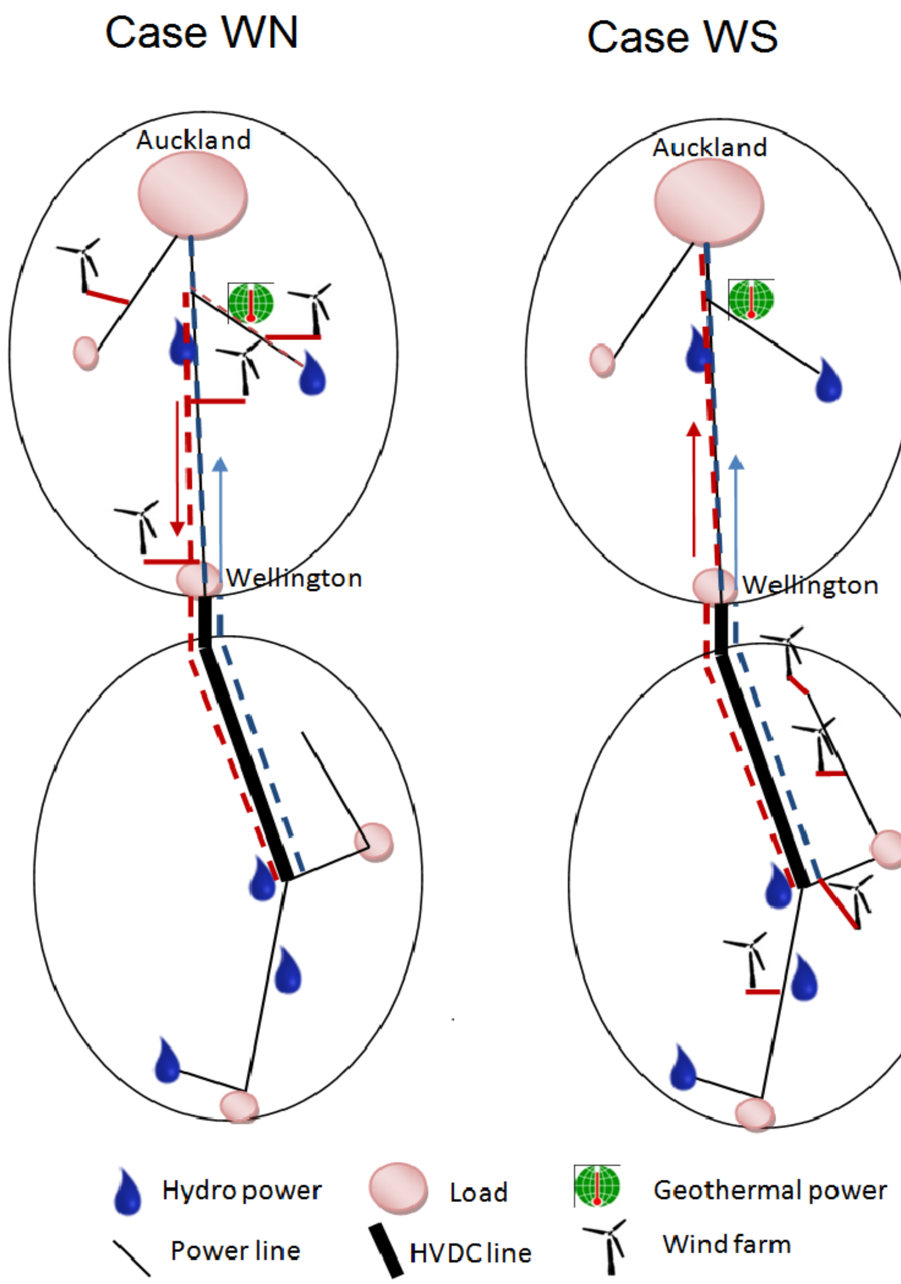

Figure 5.16 A simplified power system overview for two different wind power allocation cases. To the left is the case with wind on the NI and to the right wind on the SI. The red lines represent the flow of power during a high wind situations and the blue is the flow in a low wind condition.

a) Connect the wind farm to the existing grid

The investment in power lines to connect the wind farm to the grid is a significant part of the investment cost. It is estimated that it may be up to 10% of the total cost for a wind farm (Scott 2012). Thus, clearly the need for transmission investments influences the location of the wind farm site. The actual cost is mainly depending on the specific length from the farm to the grid for every wind farm. As the installed capacity is the same in all analyzed cases (the WS and the WN case), the cost can be assumed to be similar in all cases. The upgrade of the distribution grid is hard to estimate, but with wind farms with capacity of several hundred MWs the upgrades of some sort are likely to be built (Association 2012).

b) Transmission in the AC-grid on the North Island

In this study the main power flow focus has been on the HVDC cable and not on the regular AC transmission system. However with an increased load on the HVDC cable a corresponding upgrade on the transmission system is needed. The main loads are located on the northern part of the NI. This means that the increased power from the SI must be transferred across the whole NI as well as over the HVDC link. This will result in a significant grid investment requirement. A simplification of the extreme situation for a quick comparison on the scale of upgrade was done by calculate the maximum power flow going in and out of Wellington where the HVDC cable connect on the NI. The area of Wellington was assumed to consume 500 MW. For Case WN with restricted HVDC capacity the maximum north going HVDC load was 1.55 GW. This gives 1.05 GW to be transferred further north on the NI. For the opposite situation with power going south on the HVDC cable, the maximum was 0.81 GW. When the local power demand in Wellington is added, 1.31 GW must be supplied from the power grid north of Wellington. A large share of this power will be supplied from the wind farms close to Wellington, which will decrease the need of grid investments. This will thus be the design criteria for the case WN. For the case WS, the AC transmission grid must have the capacity to transmit the load on the HVDC cable except for the power consumed in the Wellington region. This results in a maximum capacity of 1.87GW and 1.2 GW for the unrestricted and the Restricted HVDC design cases respectively. These two cases WN and WS give rather similar load on the grid, but in different directions.

5.4 Effects on hydro storage

The hydro power generation is in this modelling study the only source capable of adjusting the output to meet the seasonal demand change. This results in low power generation during summer and larger power generations, to meet the increased demand, during winter. Therefore the storage levels will experience higher differences between summer and winter compare to the current variation, as seen in Figure 5.17 the below.

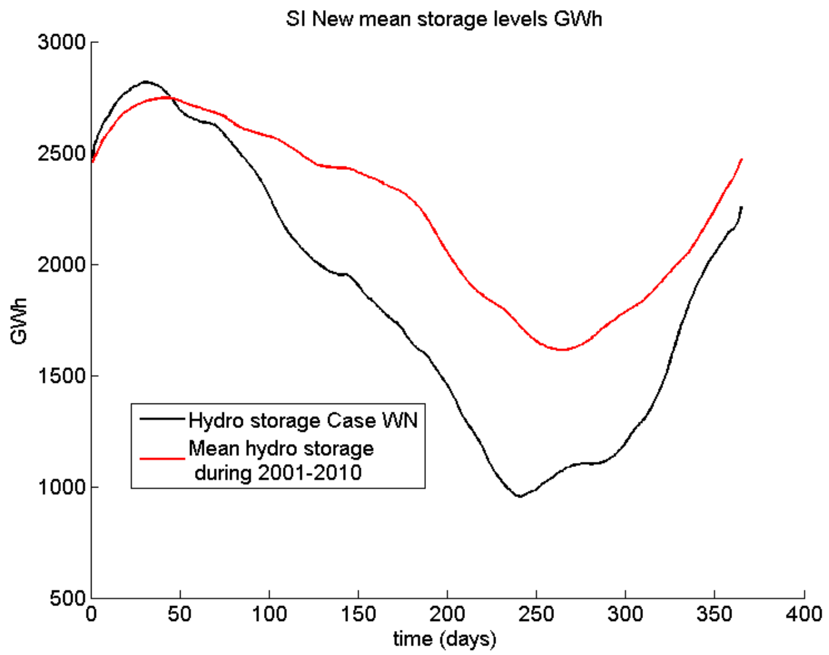

Figure 5.17 Mean hydro storage form historical data and simulated with the new system.

The results of the characteristic changes in hydro storages with decreased minimum levels during winter will increase the risk for shortage of hydro power than today's system. For year with low hydro inflow the total generation can be up to 2 TWh less than a normal year. This means that thermal generation must compensate for this shortage of hydro power. The ability to store the hydro energy between years is limited, since the storages normally are close to full at the start of the year as a result of the high inflow and reduced demand during spring and summer

To investigate for the system's sensitivity to changes in the hydro inflow the model was repeated 10 times using historical hydro level and inflows from 2001 to 2010. The storage was adjusted with the new hydro power generation that balanced the wind power. The new storage levels can be seen in Figure 5.18. At several times the hydro storage was not capable of supplying the requested demand as the storage became empty. For example, the levels reaches zero in the middle on the winter. For the adjusted storage for 2008 in Figure 5.18 the storage starts at a slightly lower level that normal that combined with a low inflow lowers the storage levels and results in a shortage of water in the hydro storages. The stored water is not enough to compensate for the new generation and the hydro storage levels drops to zero and a shortage of power occurs, when there is no hydro power available. Therefore, power must be contributed from another source, such as thermal generation. At the end of the year the water inflow increases and the storage levels reaches a high final level. Similar situations occurred for 3 out of 10 investigated year. This means, that this system is not stable and capable to cope with low hydro year without risking a shortage of power.

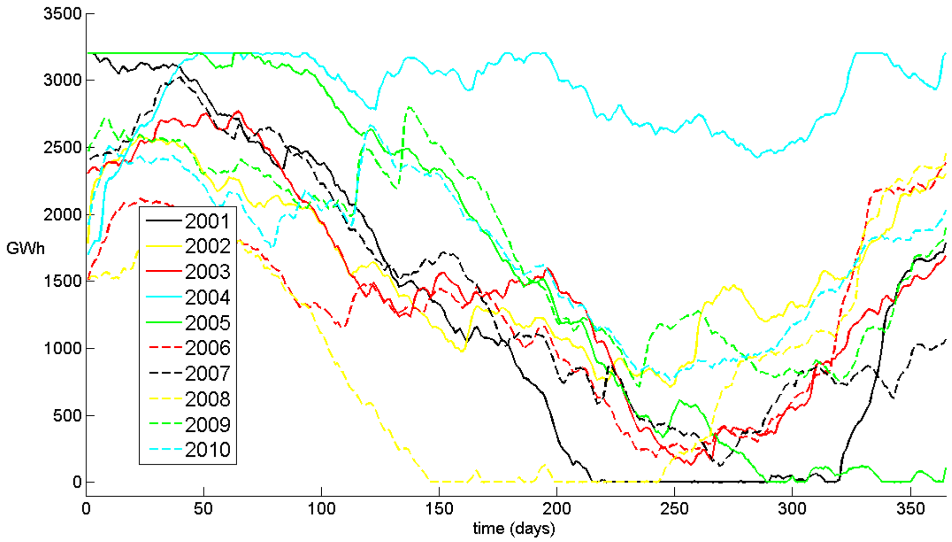

Figure 5.18 Simulated hydro storage for 10 years of hydro inflow with the simulated case WN and restricted HVDC capacity. With the increase of hydro generation, due to increased demand during winter, the storage levels drop to zero on several occasions during these years.

6 Discussion

6.1 Can this System Become a Reality?

The results indicate that, for a normal year, New Zealand can have all of its power generation from renewable sources. However, the suggested and simulated system is pushing the limits. Even though this study shows that a green power system can be realized the chance of this to be reality depends on politics, general opinion and the decisions of the main actors in the power sector. The hydro producers cannot be expected to like a significant change of the system, such as the investigated case, because this will imply a significant change for the hydro generation where they have to manage and adjust the generation to a greater extent. As the wind power in the system is, by marketing rules, set to be the first used energy source, the hydro power will be forced to adjust their generation depending on the wind power. This will of course be an effort from the hydro producer’s side compared to the more even and well planned generation they have now. However, there are some markets effects that could give the hydro power an extra profit for this generation changes by producing more during peak price hours. With a significant amount of wind generation, an increased variance in spot price can be expected (Woo, Horowitz et al. 2011). Due to an anti-correlation between the wind generation and the power price, the hydro power producers earn more than the average price on their generation.

In situations with high wind power the power price will drop due the high supply and no need of any expensive generation. At this time the hydro power generation will be limited. In the opposite situation, with low output from the wind power the limited supply will make the price rise. Here the hydro power has a high generation at a high price. This is the classic economic supply and demand model for price setting were the amount of power available controls the market. These same effects can have a negative impact for the income from the wind farms. In situations with a wind generation that has strong impact on the spot price, the wind producers will get less than average pay for their electricity generation. This can reduce the interest of further investments in wind power, also known as the suicide of wind power (Hvelplund 2013).

6.2 The Importance of Allocation

In this specific case for NZ this study has not indicated any advantages with allocating wind power far away from the load. This is partly due to that there was no improvement in capacity factor, but an increased investment need for the HVDC link. However, these results are not general and cannot be used for other systems. In a case where the allocation of wind power far from the load instead gives an increased capacity factor the results may be the opposite. If the capacity factor instead is higher, less installed capacity is needed to give the same output. If that were the case, the difference in investment cost for the wind farms and extra transferring capacity can be compared to find the optimal for that specific system. Another thing that should be taken into consideration is the public acceptance for building wind farms in areas with a densely population. The NIMBY problem can interfere for the possibilities of building the generation close to the load.

Since this cost are essential to the investments in new wind farms is clearly influence the location to minimize the distance on the existing grid. The grid is better developed on the NI where also the larger population will make it harder to get consenting for new wind farms. On the SI the consenting process should be easier as it has more rural areas, and therefore more possible locations. While a lot of the locations are far from the grid, there should still be several sites closer to the transmission system. Therefore general cost for connecting the wind farms to the existing grid can be considered equal. Therefore the cost of connecting the farms to the grid will not influence the choice of allocation. NZ are in general considered rural on both islands, it can therefore be assumed that it is possible to find suitable location for new wind development on NI and SI.

6.3 Need of increased HVCD capacity

The HVDC capacity needed for the different cases analyzed in this work varies, but common for all cases is that a major upgrade of the HVDC capacity is needed. This is a result of the reduced generation capacity on the NI when the thermal generation from fossil fuels is removed. The power for peak periods must then instead come from SI hydro power. Due to the intermittent character of the wind power, the system must have a capacity to transfer power to cover the peak load. There are of course other options that could be investigated, such as energy storages on the NI. This option would act as a load shifting and smoothening of the demand. In such a system the same amount of energy can be transferred but spread over a larger period of time. Therefore the HVDC cable can have a reduced capacity.

6.4 Wind data Reliability

The use of historical data for predicting the wind power can have had a significant effect on the simulations. In this work the wind generation has been scaled up based on historical wind power generation for each island. As the historical generation is based on just a few sites the scale up method gives sharp fluctuations. However, in a real case where new wind power capacity is allocated more outspread, the generation might change slightly. Smoothening effect may adjust the results as a more spread out allocation of the wind power can have a smoother combined output. In the model, case WN is the case with the capacity distribution most similar to the six historical sites and closest to the current installed capacity. This case resulted in the smallest need of back up energy, which could be a result of a slight smoothening effect. The load coverage is connected to the curtailment and back-up energy and decreases when they grow. These results can be interpreted as that bigger spread of the wind power gives the highest coverage of the load. To evaluate the significance of these phenomena, a correlation study of the power generation from the wind farms was compared to see how much the wind varies across the country. The results show (as also presented in Table 1 and 2 in Appendix II) that the correlation for the wind power generation and the smoothened data on the SI (White Hill) is low compared to the wind power generation from the NI. This reasons of course with that the correlation should be lower than between the NI wind farm due to the longer distances. However, what is more noteworthy is the difference in correlation between the farms on the NI. The three wind farm near Palmerton North has, as expected, a large correlation, but both Te Uku and West wind had correlation that was only one tenth larger than the correlation between SI and NI. There were also the same correlation between West wind and Te Uku. This low correlation is an example of that wind power over a lager geographical distance can decrease the intermittency. The system could therefore draw some usage of these smoothening phenomena and in the reality have a slightly smoother behaviour than the model implies. However, the wind can be expected to have a very low minimum output, as a period of no wind still can strike the whole area when, for example, a high pressure centre over the country occurs. Figure 2.10 shows for example how the current wind power generation for both island combined often drops to very low levels. While the estimated wind generation on the NI is based on several sites with some difference in generation the estimation can be assumed to credible. The estimated wind output or the SI is limited to only one measure point and the generation can be expected to be behaving more violent than a spread out generation. In the case WN, the new SI wind generation is relatively small and this can therefore be neglected. But in the case WS with a lot of wind on the South Island, the estimated SI wind generation is to some extent degraded in this simulation. A more true estimation of the simulated wind would have increased the load coverage in this case which could have reduced the need of back-up power. The specific case was not however close to the others in the evaluations and this affect was not the reason it was not the preferred case. For example the need of a higher capacity on the HVDC link is not influenced by the fluctuation in the wind generation, but instead only on the generation balances on the NI.

6.5 Hydro shortage

The minimum storage levels occur during the end of winter and spring with high demand. The hydro storages fill up during the spring flood and peaks during late summer. In the study with only renewable power sources, the seasonal differences in demand must be handled by the storage capacity of the hydro storage. Therefore the difference in the storage levels will be more extreme than employed today, with higher average peaks and lower minimum levels. The system will then have a greater risk to empty the storage in case of a low inflow during winter, which may be the case of a La Niña. The system also risks filling up the storage over the maximum and be forced to spill energy. With an historical difference between hydro generation up to 2TWh and a limited hydro storage, other sources of energy are necessary. As this level simulation is done over a 10 years’ period, a low hydro year gives a decreased level for the start of each following year. This decrease of the level can continue and cause a relatively normal year to drain the storage totally.

There are three problems with these simulations, causing the incremental draining.

- The first problem is that the simulations have different years for hydro generation and demand. The set hydro generation from run of river in the model has in the reality a small opportunity to adjust the generation from day to day. Therefore the generation does not match the demand curve as good as the data for the correct year. This result is more reserve power and curtailment.
- The second, and most important, reason is that the design year of 2011 had a relatively high hydro output and this was the year that the model was based and balanced for. To use approximately the same hydro power as the actual

year and get 30% of the energy from wind power, the geothermal power was reduced slightly to 90% of the original output. This was first not considered a problem and had only a small impact on the final storage level, if only one year at the time was considered. However, overtime this draining will have a severe impact, with slowly decreasing hydro storage levels.

- The third cause is that this simulation does not accept any storage over the maximum approved storage level and all that energy is lost. According to historical data, the actual levels exceed this limit with hundreds of megawatt hours every few years. As this energy is lost in the simulation, it will be a secondary failure with this energy missing in the storage level for the following years.

As seen in the results from the hydro generation in Figure 5.18, the system is sensitive to changes of the inflow, due to the limited storage capacity. The lake levels reach a minimum during the winter, when the demand is at its height, combined with a low inflow during the winter months. The case shown in the Figure 5.18 is not representative for how the system would react to a low hydro inflow. Instead alternative power would start to support the system to avoid a shortage and keep a minimum storage level in order to secure security of supply. The results only represent the amount of energy needed. To manage dry years like this, increased storage capacity would be the most desirable option, but highly unlikely due to the public resistance of destroying natural rivers and lakes. The remaining option would then be to have fossil capacity ready for usage in these conditions. As these are extreme situations, high spot prices can be expected and open cycle gas power could be run with profit over the most parts of the day.

The main part of the shortage problem with the system evaluated is the limitations in transferring energy from the summer to the winter months. The hydro storages are in addition to the impact of varying inflow the limiting factor for the system.

7 Conclusions and future work

This work has shown that a renewable power system with 30% of the energy from wind power is possible in New Zealand. This system, which is a combination of hydro, wind and geothermal power generation can during a year with normal precipitation support the power demand by adjusting the hydro power generation with the hydro storages on the SI.

The most cost efficient placement of the wind power will be place a majority of the wind power on the north island. This specific case was in the work named Case Wind North Restricted. This allocation was a result of optimizing the load coverage which was found to be 83% of the wind power on the north island. This allocation will cover the most possible demand and minimize the cost.

There will be some need for gas power during peak hours, in order to secure the supply. The energy demand from the gas turbines ends up to be 0.25% of the total energy generation for Case WN with restricted HVDC cable capacity. This small part of the generation is considered to be an acceptable fraction of fossil generation in this study.

Because of that the system consists of two islands the HVDC link that connects them should be designed according to the case WN with a restricted HVDC capacity. The capacity will be 1553 MW between the islands which will cover 99.4% of the energy transfer demand of the requested traffic from the system. This capacity is only 153MW higher than what the current plans or upgrading the link is at the time. The residual power that cannot be transferred from the SI is cheaper to supply with gas turbines placed on the NI. This will save 42.5 million NZD in investment costs a year compared to the option with a bigger cable, without increasing the investment cost in gas turbines and only double the gas output supply from 53 to 106 GWh. These results in a final savings of 34 million NZD in total compared to the unrestricted cable case, and the gas power is only 0.25% of the total generation in energy terms. The availability of these turbines will also create a security of supply to any other fails in the system as generation or transferring capacity.

Future work

The limitations to use wind power in the simulations to cover 30% of the demand creates big fluctuations in wind power generation that complicate managing of the system. One interesting alternative to evaluate would be to switch some of the wind power to solar power, which instead produces power during the day-time demand peaks.

A better estimation of future wind power output with more measuring points and with a higher resolution would improve the study significantly. This would also answer to how different allocations of the wind power can smooth the wind power output. The higher resolution will give a more true wind curve and the short term balance for the hydro power can be evaluated.

Other future work could be to investigate the potential of energy storage. In the best case as analysed in the present study, there was still 240 GWh of wind power that was curtailed and 106 GWh from gas turbines. Here is a potential to store wind power during low demand and sell during a demand peak, while getting rid of the gas fuelled power generation. With this significant wind power supply and higher price variations, discussed in Chapter 4.1, there can be a potential for profitable storage operation.

8 References

Anicell, G. (2007). Effect of unpredictability of wind
generation output on pre-dispatch
processes, Transpower.

Association, T. E. W. E. (2012). "Wind Energy. The Facts." Retrieved 14 June, 2013, from http://www.wind-energy-the-facts.org/en/part-3-economics-of-wind-power/chapter-1-cost-of-on-land-wind-power/cost-and-investment-structures/.

Elctricity Authority (2011). "Market." Retrieved 7 may 2013, from http://www.ea.govt.nz/footer-elements/faqs/market/.

Electricity Authority (2012). Anhui Electric Power Corporation (AEPC) Delegation 2012, Bruce smith, Ron Beatty, Tim Street.

Eletricity Authority (2012). Centralised Dataset, Eletric Authority.

Energy NZ (2010). "The third pole." Energy NZ **Vol.4**(No.5).

Genesis Energy (2012). "Huntly Power Station Plants." Retrieved 7 May 2013, from http://www.genesisenergy.co.nz/genesis/index.cfm?0E16177E-E313-418B-F397-3021BCE6E1EF.

Gray, J. (2012). Little growth in power demand - Contact Energy.

Hvelplund, F. (2013). Efficinet use of Elictricty with 50% Wind power. Chamers Energy conference, Gotherburg.

Kaldellis, J. K. and K. A. Kavadias (2001). "Optimal wind-hydro solution for Aegean Sea islands' electricity-demand fulfilment." Applied Energy **70**(4): 333-354.

Knight, J. (2009). Lake level History.

List of power stations in New Zealand (2013). 2013, from http://en.wikipedia.org/wiki/List_of_power_stations_in_New_Zealand.

Mason, I. G., et al. (2010). "A 100% renewable electricity generation system for New Zealand utilising hydro, wind, geothermal and biomass resources." Energy Policy **38**(8): 3973-3984.

McGowan, H. A. and A. P. Sturman (1996). "SHORT- AND MEDIUM-TERM TRENDS IN THE HYDROMETEOROLOGY OF THE CENTRAL SOUTHERN ALPS, NEW ZEALAND." International Journal of Climatology **16**(11): 1267-1279.

Miller, N., et al. (2011). Integrating high levels of wind in island systems: Lessons form Hawaii.

Ministry of Business, i. E. (2012). Ministry of Economic Development 2012.

National Infrasturcture Unit (2011). National Infrastructure Plan 2011, National Infrastructure Unit.

New Zealand Energy (2012). New Zealand Energy, Greenhouse Gas Emissions, Ministry of Business, Innovation & Employment.

Parsons Brinckerhoff New Zealand Ltd (2008). COST ESTIMATES FOR THERMAL PEAKING PLANT.

Scott, H. (2012). Interview with Hamish Scott, Site manager Te Uku wind farm.

Sherly, P. (2010). Lake Generation Potential History.

Smith, B., et al. (2012). Anhui Electric Power Corporation (AEPC) Delegation. E. Authority.

Tait, A. (2012). Interview with Andrew Tait Climate Researcher at NIWA, National Institute of Water adn Atmospheric Research.

The Treasury (2010). The Economy of New Zealand: Overview. T. Treasury.

Tordesillas, C. (2009). "Siemens to expand New Zealand HVDC link." Retrieved 7 may 20013, from http://asian-power.com/project/news/siemens-expand-new-zealand-hvdc-link.

Woo, C. K., et al. (2011). "The impact of wind generation on the electricity spot-market price level and variance: The Texas experience." Energy Policy **39**(7): 3939-3944.

Wratt, D., et al. El Niño and Climate Forecasting.

Appendix I Sensibility analysis of costs

Sensitivity analysis of economic results

Sensitivity aspect (million NZD)	WN	WN Restricted	WS	WS Restricted	ALL NI	ALL NI Restricted
30% increase HVDC investment	295	249	339	289	286	257
30% increase Reserve investment	273	240	314	279	274	253
30% increase Gas price	251	220	291	258	248	229

Appendix II Correlation between wind farms

Correlation analysis between the wind farms with half hour data as input:

	White hill (SI)	West wind (NI)	Tararua (NI)	Te Apiti (NI)	Te Rere Hau (NI)	Te Uku (NI)
White hill (SI)	1	0.0883	0.1482	0.1632	0.2135	0.0061
West wind (NI)	0.0883	1	0.2730	0.2730	0.3829	0.0530
Tararua (NI)	0.1482	0.3288	1	0.9434	0.9472	0.2912
Te Apiti (NI)	0.1632	0.2730	0.9434	1	0.8896	0.8616
Te Rere Hau (NI)	0.2135	0.3829	0.9472	0.8896	1	0.2135
Te Uku (NI)	0.0061	0.0530	0.2912	0.8616	0.2135	1

The same correlation but with a smoothened output over 400 samples:

Smoothed data with a factor 400 (Approximately 8 days)						
	White hill (SI)	**West wind (NI)**	**Tararua (NI)**	**Te Apiti (NI)**	**Te Rere Hau (NI)**	**Te Uku (NI)**
White Hill (SI)	1	0.1821	0.3841	0.4276	0.5744	0.1846
West Wind (NI)	0.1821	1	0.5221	0.4602	0.6225	0.1796
Tararua (NI)	0.3841	0.5221	1	0.9720	0.9723	0.5084
Te Apiti (NI)	0.4276	0.4602	0.9720	1	0.9171	0.9067
Te Rere Hau (NI)	0.5744	0.6225	0.9723	0.9171	1	0.5744
Te Uku (NI)	0.1846	0.1796	0.5084	0.9067	0.5744	1