2009

Nuclear Feasibility

For a New Zealand System

Auckland University of Technology
4th Year Project Report

Brent Wilson

10/15/2009

Table of Contents

1. Acknowledgements

I, Brent Wilson, would sincerely like to thank and acknowledge the following people for the help I received on this project, without it this project would not be.

To David Nutt, my industrial supervisor who has always been there to help me with any problems or queries I have had about certain aspects of this project and has gained valued information for this project from his contacts within industry. I greatly appreciate his help and could not have done this without him.

To the modeling team at the Electricity commission, Dr. Bruce Smith, Dr. Phil Bishop and Dr. Erwan Hemery, thank you for the initial project idea and continuous input. Extra gratitude goes to Dr. Phil Bishop for spending a lot of his time with me, showing me the ropes on how to use GEM.

Finally I would like to thank my partner and family for sticking by me through this project and giving me the support needed to finish with good results.

2. Executive Summary

The aim of this project was to assess the economic and engineering feasibility of nuclear power in a New Zealand setting. The types of nuclear power systems that are available are considered and assessed. Special modeling software (GEM) along with levelised cost analysis of electricity equations are used to analyze the technology under different scenarios.

The work carried out suggests that nuclear power would not be a feasible option for New Zealand in the short term, however if certain conditions are met some level of nuclear generation may be installed in the medium to long term future.

3. Introduction

Electricity has become one of modern society's greatest necessities after food, water and shelter. The economy depends on electricity so greatly that if power outages occur in central business hubs huge amounts of money will be lost hourly. An unforgettable example is of the 1998 Auckland power crisis which lasted 5 weeks. Businesses lost an estimated $60,000 per week. The power outage occurred due to low capacity transmission lines that were passed their life expectancy and subjected to an increased load demand **(Gutmann, 1998)**. Because of this and many other examples around the world, power system planning is of the utmost important in running a reliably efficient system.

Planning for the future can be achieved by analyzing how the system has run from past data, the state of the present system and then modelling different scenarios that have a probability of occurring in the future. By doing this a plan can be formed thirty plus years into the future and action can be taken to address reliability issues years before they occur.

This is currently being done at the Electricity Commission (EC) using an open source model created by the EC called the Generation Expansion Model (GEM). By using this modelling tool future generation capacity can be chosen under different potential scenarios. This tool is currently being used for Grid Planning Assumptions (GPA) and was used to create GPA for the 2008 Statement of Opportunities (SOO).

Most technologies have been included thus far into GEM as seen from the following list:

- Coal
- Cogeneration, coal-fired

- Coal, Integrated Gasification Combined Cycle (IGCC)
- Coal, IGCC with Carbon Capture and Storage (CCS)
- Lignite
- Lignite, IGCC
- Lignite, IGCC with CCS
- Combined cycle gas turbine
- Combined cycle gas turbine with CCS
- Cogeneration, gas-fired
- Open cycle gas turbine – gas
- Peaker, diesel-fired Open Cycle Gas Turbine (OCGT)
- Peaker, fast start gas-fired peaker
- Peaker, bio fuel-fired peaker
- Geothermal
- Cogeneration, biomass-fired
- Cogeneration, other
- Hydro, pumped storage
- Hydro, peaking
- Hydro, run of river
- Hydro, schedulable
- Hydro, distributed generation
- Wind
- Wind, distributed generation
- Wave
- Tidal

Nuclear power generation is one of the only technologies missing from this list. It seems to have been left out of the list due to New Zealand's present stance on nuclear energy. When planning a power network the future is being forecasted and there are many uncertainties. If technology gets better and nuclear power becomes safer who is to say that New Zealand will not change their view on nuclear power generation?

The discussion was made between myself and the modeling team at the EC and it was proposed that nuclear power should be investigated to see if it would be economically feasible and should therefore be included in GEM, in that regard. The project is not to analyze the merits and demerits of nuclear power and the political and social arguments behind it but to look at nuclear power in New Zealand from an economic and engineering standpoint.

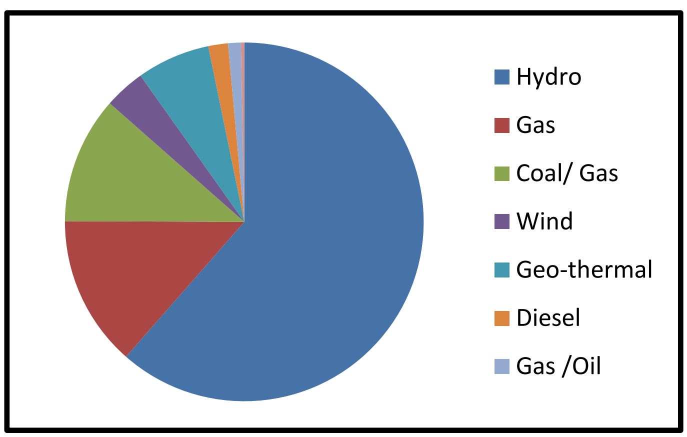


Figure 1 –2008 New Zealand Generation Capacity by Plant Type

The power generation in New Zealand is predominantly hydro generation at 61 percent followed by gas and coal at 13.6 and 11.4 percent respectively. The generation capacity by plant type in 2008 can be seen in figure 1. This brings about a strange system where prices and generation availability, depend highly on the rain in a given year. Due to this unpredictability of how much generation will be available from hydro in any given year, the base load is supplied by hydro, coal, gas and geothermal plants with other hydro supplying upper base load and some peak load.

New Zealand's generation scheme is very different from most countries worldwide because New Zealand is a small Island nation. If load demand is above the amount of generation available, the system operator cannot buy electricity from another country to supply this demand. The capacity must be found from within the system and this is why reserves are a very important factor of the New Zealand system. The type of reserves available are spinning reserves, where a plant is producing electricity but not operating at its full capacity so that if needed, more energy can be put into the system to generate at, or near, its level of capacity. The second type of reserve is an offline reserve; this is where capacity is available to be put into the system but depending on the type of plant, it will take a certain time before it can be injected, e.g. a few minutes for a hydro station to a few hours for a thermal station.

Another peculiarity of the New Zealand system is that it has two islands that are connected together via a high voltage direct current (HVDC) link. The HVDC link has a capacity of 1040 MW and operates at voltages of 270kV and 350kV **(Transpower, 2009)**. The majority of the load is in the upper North Island and a large lump of generating capacity is situated at the bottom of the South Island seen in figure 2. This forces the electricity to travel long distances which produce large losses resulting in inefficiency of the system and an increased burden to the HVDC link. This increased stress on the cables can cause problems especially if one link goes down, such as in April 2008 **(Fitzpatrick, 2008)** as the capacity of the link is halved. It should be noted that in a dry year the electricity will flow from north to south and again can reach near capacity of the link.

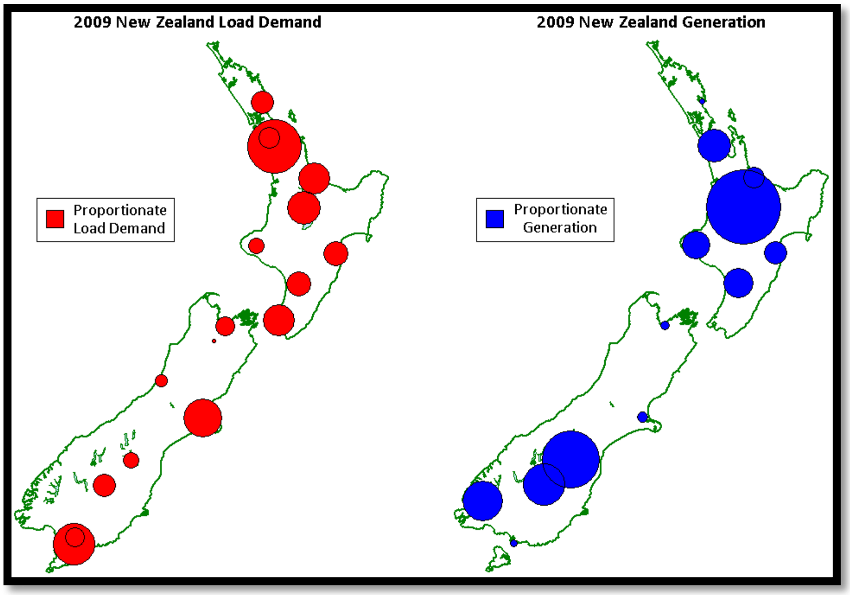


Figure 2 – 2009 New Zealand Load Demand and Generation

As the population of New Zealand increases, the load demand increases along with it. There are many options that can be taken to meet this rising load demand, from demand side management to an increase in generation capacity. One thing is for sure, the base load generation must be increased one way or another. Because of New Zealand's political viewpoint on nuclear technology it has not been seen as an option in base load generation and other technologies such as coal and gas have been the perferred choices. However with the increasing publicization of global warming, carbon emissions are being scrutinized and targets are being set. The target that has been set in New Zealand is ten to twenty percent below 1990 levels by 2020 **(Chan, 2009)**. This means alternatives will have to be looked at and although the political and social views may not change in the near future, nuclear should at least be considered to determine whether or not it could be economically and engineeringingly feasible.

The methods to determine whether nuclear is feasible in New Zealand are:

- Compare the Levelised Cost of Electricity (LCOE) for the three base load technologies, nuclear, coal and gas by using a model based on the 2003 MIT nuclear study.
- Use GEM under all different scenarios with different cost variables to determine whether or not the nuclear plants would ever be built, if not what are the conditions needed to build a nuclear plant.
- Look into the current technologies that are available for nuclear reactors, what stage they are at and if the size is feasible for New Zealand's power system.

4. Options

There are many different paths that New Zealand could take to supply the increasing load demand. These paths depend on assumptions made on certain events that could happen in the future. GEM uses five different scenarios to model what would likely happen under these assumptions. These assumptions and likely results are described below.

4.1 Sustainable Path

A path of sustainable electrical development and a focus on emissions reduction are assumed. Major thermal plants are closed and replaced with renewable sources with thermal peakers as backup for security. Electric vehicle use is rapid after 2020. **(Commission, 2008)**

4.2 South Island Surplus

Renewable development proceeds at a slightly more moderate pace. Gas-fired stations stay in operation until 2030. Units at Huntly are shifted into a reserve role and eventually decommissioned. Wind and hydro increase considerably especially in south island, relatively little geothermal is used. Thermal peakers are again used as security. **(Commission, 2008)**

4.3 Medium Renewables

This is a middle of the road scenario. Renewable technology is developed in both islands with north island geo playing an important role. Coal fired units at Huntly transition through dry-year reserve to total closure. Thermal peakers and a CCGT supplement renewable development. **(Commission, 2008)**

4.4 Demand Side Participation

This scenario is driven by a desire from consumers to become more fully involved with the part they play in the system. Electric vehicle uptake is high. New coal and lignite-fired plants are constructed after 2020 and geothermal resources are developed. Little new hydro can be consented and some schemes have to reduce their outputs due to water rights. Huntly stays open until 2030. Electricity emissions rise but transport emissions decrease. **(Commission, 2008)**

4.5 High Gas Discovery

Major new indigenous gas discoveries keep gas low to 2030 and beyond. Some existing thermal stations are replaced by new more efficient gas-fired plants. New CCGT's and gas-fired peakers are built to meet the country's power needs, the most cost effective renewable are also developed. Demand side remains relatively uninvolved. **(Commission, 2008)**

The major work being done on GPA in New Zealand is done by the EC, Transpower and the key generators. The EC works closely with Transpower and the key generators to gain important information on how the grid is running and what is being planned. The modeling software used to aid in the GPA's, GEM, has helped greatly in displaying what plants would be best to build under different scenarios.

5. Planning Methods

There are several different methods that can be used to evaluate the economic competitiveness of different generation options. These economic analyses methods are as follows:

- Levelised annual cost method
- Cumulative Present Worth Method
- Pro forma analysis **(Black, 1996)**

5.1 Levelised Annual Cost Method

The real levelised cost of electricity is the price, at present value, that would cover the costs incurred by the plant during its operational period. The costs that are incurred are all operating expenses, project debt, taxes and a return to equity investors **(MIT, 2003)**. This allows for different technologies with different operating parameters, costs and lifetimes to be compared and ranked on their levelised cost **(Short, Packey, & Holt, 1995)**.

The main disadvantage of this method is of the uncertainty of future prices, such as fuel and inflation. If a technology has a high capital cost but low operating costs, it may result in a lower levelised cost and look more favorable than other options however if conditions change, e.g. fuel prices increase heavily, and the option is no longer viable the large capital cost is still incurred and must be repaid **(Black, 1996)**. The advantages of this method are that it is heavily used in industry and is easy to implement. The disadvantages can be overcome by inserting sensitivities for situations that may arise and comparing the results under different scenarios.

Other calculations similar to the levelised annual cost method are the total present worth method and the capital equivalent cost method; these will not be investigated further as the levelised annual cost is the preferred method of this type **(Black, 1996)**.

5.2 Cumulative Present worth Method

In the cumulative present worth method, annual present value costs are added and calculated on a year-by-year basis throughout the evaluation period. Although similar to the total cost method, alternatives can be evaluated throughout the lifetime. The additional information from this method can determine at what year one plans accumulated present value costs become cheaper than another. This is a benefit when dealing with uncertainties as timelines can be analyzed and projected uncertainties can be overlaid to help in the comparison **(Black, 1996)**.

5.3 Pro forma Analysis

A pro forma analysis is carried out by non regulated businesses that evaluate an investment based on the investments financial returns. This analysis will generate future financial cash flows and balances over a projected timeline. A pro forma will use detailed input data to obtain a detailed level of output. Typical pro forma analysis input for a generating plant includes the following: **(Black, 1996)**

- General operating parameters such as capacity, capacity factor, construction, operating, on an off peak periods, fuel specifications;
- Plant capital costs
- Financing assumptions
- Sales and revenue data
- Expense data for fuel and operating and maintenance items
- Other cash flow parameters such as depreciation and income tax assumptions.

5.4 Generation Expansion Model (GEM)

The other resource, to determine if or under what circumstances nuclear power could be feasible in New Zealand, is GEM.

GEM is the Electricity Commission's generation expansion model. It was produced in 2006 to aid in the development of generation expansion paths under different scenarios, which is a central aspect of the grid planning assumptions and was also used for the 2008 SOO **(Commission, Generation Expansion Model, 2009)**.

GEM is used under different scenarios to see what type of technology would be best to build under the scenarios conditions. There are five different scenarios that are used by the model with the variable name MDSx and are Sustainable path (MDS1), South Island Surplus (MDS2), Medium Renewables (MDS3), Demand Side Participation (MDS4), High Gas Discovery (MDS5).

GEM uses three main programs to run, excel is used for the input data, GAMS which stands for General Algebraic Modeling System is used for the coding, calculations, reading of inputs and organizing of outputs and all of the output graphs are produced with the use of matlab and matlab component runtime scripts. The input data that gem uses is provided in an excel document that contains many different arrays on a number of sheets. The most important sheets that are edited most in respect to this project are the following,

Generation: This includes all current and future generation schemes with info such as technology, generating capacity, typical generation per year, earliest decommissioning year depending on chosen scenario, capacity, operating and maintenance costs, overnight costs, transmission costs and fuel delivery costs.

Technology and fuel: This specifies the typical cost of each fuel, emissions, capacity factor and carbon taxes.

The flow diagram for GEM can be found in Appendix C and the main sections are explained below.

GEMmodel.gms: Contains all the GAMS declarations of symbols, the sets, parameters, variables and equations. The algebraic formulation of GEMs objective function and constraints are specified in this file.

GEMBase.gms: It imports the data from an excel input file and converts it into useable code for use with the model.

GEMexec.gms: This is what solves the model and collects the output for each GEM solution. So depending on how GEM is configured to run, quick and dirty or slow and accurate each level of iteration is captured, stored in separate files then once it is finished these separate files will be merged into one and this is the data that will be used by GEMreports.gms

GEMreports.gms: Creates the text file reports of output data.

GEMplots.gms: Used to initiate the matlab scripts to create plots using appropriate data.

RunGEM.gms: Central controlling program for GEM, which runs all these other files and contains the settings that can be changed by users of GEM. Such as how accurately you want the program to run, how long it can take before it is cut off if the certain percentage is not being met type of solver etc.

(Bishop, 2009)

5.5 Recent Studies on Nuclear Costs

Other notable reports that have conducted nuclear economic studies have been; the 2003, Michigan Institute of Technology, The Future of Nuclear Power with a 2009 update; The 2004, University of Chicago, The Economic Future of Nuclear Power and; the 2004 Canadian Energy Research Institute, Levelised Unit Electricity Cost Comparison of Alternative Technologies for Base Load Generation in Ontario.

5.5.1 MIT

The MIT study uses a model that incorporates a little of all three methods. The outcome is shown in a levelised annual cost method and this is what is used to compare the different technologies. The way the model is setup, through spreadsheets, allows a cumulative present worth method to be achieved if needed and the level of detailed input matches the pro forma analysis.

5.5.2 University of Chicago

The LCOE calculation used by the University of Chicago is identical to that of MIT. Extra sensitivities have been included in the study, such as different capital costs, different loan guarantees, different accelerated depreciation allowances, investment tax credits and production tax credits.

5.5.3 Canadian Energy Research Institute

This report again uses a similar calculation that is now called levelised energy unit cost (LUEC). It is again almost identical to the MIT calculation and uses similar inputs.

From these three studies it can be seen that there is a standard model to use when comparing different technologies to determine which will be the most economic. The MIT model has an excel spreadsheet along with the calculation formulas found in the report that can be analyzed and modified. This is transformed into a matlab script to perform the LCOE calculations for this project and the code created can be found in Appendix C.

6. Nuclear Research

6.1 Technology

When describing reactor technology two things are needed to be known. The type of technology the reactor uses and the generation of the technology. The generation being either one to three for existing plants, three for new builds and four for future designs.

Generation one reactors were the first power reactors to be built in the 1950’s and 60’s. Most of these reactors have come to the end of their lifetime and have been decommissioned.

Generation two reactors are the majority of the reactors found around the world built in the 1970’s, 80’s and 90’s. These are typically cooled by water and use enriched uranium fuel.

Generation three reactors are built off of the back of generation two reactors and have simplified and safer designs. These are the reactors that have been built recently in Japan, China and other countries.

Generation four reactors are newer designs that completely rework or improve technology so that construction and operation is cheaper and safer. These reactors will not be seen in commercial operation before 2020.

There is a large variety of technology for nuclear reactors. Because a reactor can be cooled and moderated many different ways, reactor manufacturer look for the cheapest and safest way using different methods so that they can take a large share of this lucrative market. This competition has brought about many different forms of technology, which are described below.

6.1.1 Pressurised Water Reactor (PWR)

A PWR is made up of three structures, the containment structure, the turbine and generator room and the cooling tower. The containment structure houses the reactor and steam generator. These are connected together via two, three or four cooling loops which pump water in a closed cycle, which is called the reactor coolant system. Water is heated to about 325^{o}C by the reactor while the reactor coolant system is kept to about 150 times atmospheric pressure so that the water does not boil **(WNA, 2009)**. It can be seen from this process that the water also acts as the primary moderator and if it were to turn to steam the fission reaction would slow down. This negative feedback is one such safety feature of the PWR. The secondary shutdown involves adding an element typically boron to the primary circuit.

The secondary circuit connects the steam generator to the turbine. The steam generator is under less pressure so water is allowed to boil, creating steam and spinning the turbine which in turn spins the generator producing electricity. Again this is a closed cycle where the steam is condensed by cooling water from the sea, river, lake or cooling tower and pumped back into the steam generator.

PWR fuel is delivered to the reactor in fuel bundles which consist of many cylindrical rods of Zircaloy tubes filled with enriched uranium pellets. These tubes are about one centimeter in diameter and the gaps between them are filled with helium gas so as to improve the conduction of heat from the fuel to the gaps. In a PWR core there are around 179-264 fuel rods per fuel bundle and about 121 to 193 fuel bundles about four metres in length this equates to around 80-100 tonnes of uranium **(WNA, Fuel Fabrication, 2009)**.

The PWR is the predominant reactor in the world today with a share of 60% of total reactors **(WNA, 2009)**. The typical size of a PWR is 1000MWe, 3000MWt and the main manufacturers of these reactors have been Babcock & Wilcox, Combustion Engineering, Framatome, Kraftwerk Uninon, Mitsubishi, Siemens and Westinghouse. Due to industry consolidation there are now only two main PWR manufacturers these being, Framatome-ANP and Westinghouse **(Tourist, 2005)**.

Westinghouse manufactures the AP1000, a 1000MWe reactor, which is primarily the front runner of large reactors being built or planned to be built at present. It is the reactor of choice in China with four being built at present and an envisioned one hundred total by 2020 **(Pfister, 2008)**. The United States have also filed twelve combined construction and operating licenses for the AP1000. This will therefore be used as one of the reactors for a case study as it will give accurate costs and figures.

6.1.2 Boiling Water Reactor (BWR)

The BWR is quite similar to the PWR. The main difference being that there is only one circuit where the water is at a lower pressure of about 75 times atmospheric pressure so that this water will boil at about 285^{o}C **(WNA, Nuclear Power Reactors, 2009)**. The reactor is designed so that 12-15% of the water in the top part of the system is steam and is extracted through the steam separator **(WNA, Nuclear Power Reactors, 2009)**.

This steam is then fed into the high pressure turbines and then the low pressure turbines which turn the generators producing electricity and the steam is then condensed , which is again cooled by the sea, river, lake or cooling tower , and fed back into the reactor in a closed cycle.

Because this is a single circuit system the turbines receive radioactive water. This means the turbines need to be encased in radiological protection; however cost is balanced by the fact that it is a simpler system. Although radioactivity enters the turbine, the turbine hall can be entered soon after reactors are shutdown because the majority of the radioactivity in the water is N-16 which has a seven second half-life **(WNA, Nuclear Power Reactors, 2009)**.

BWR fuel is similar to PWR fuel except the bundles have a thin tube which surrounds them. A typical plant will have a fuel assembly containing 90 to 100 fuel rods and 750 assemblies in a reactor core which equates to a possible total of 140 tonnes of uranium **(WNA, Nuclear Power Reactors, 2009)**.

The BWR is the second most common at 21% of the world's reactors **(WNA, Nuclear Power Reactors, 2009)**. The main manufacturers of this reactor are; General Electric, ASEA-Atom, Kraftwerk Union, Toshiba and Hitachi **(Tourist, Boiling Water Reactor, 2006)**. The latest BWR builds were done in Japan by Toshiba. An 825MW BWR was commissioned in 2002 at Onagawa and an 1100MW 2005 at Higashidori although these are more likely generation three technology and could be argued to be advanced BWR's (WNA, Reactor Database, 2009).

6.1.3 Pressurised Heavy Water Reactor 'Candu' (PHWR)

The PHWR was developed in the 1950's in Canada as the CANDU. The CANDU has a similar design to the PWR however it uses different fuel and cooling water.

The moderator is in a large tank called a calandria vessel, penetrated by hundreds of horizontal pressure tubes which create slots for the fuel. Due to this configuration the reactor can be refueled without shutting down by isolating certain pressure tubes **(WNA, Nuclear Power Reactors, 2009)**.

The cooling water used by CANDU reactors is called heavy water because it consists of two deuterium atoms, which is a non-radioactive isotope of hydrogen, and one oxygen atom. Special processing plants are needed to separate the heavy water from the light water which adds to the initial capital cost. But because the heavy water is a much more efficient moderator than light water natural uranium can be used as fuel which offsets the cost of the heavy water.

The fuel used by CANDU are pellets of uranium dioxide with natural uranium (0.7% U-235) opposed to the slightly enriched uranium (2-5% U-235) used in other plants. This means the fuel is cheaper and allows a higher lifetime capacity factor. However fuel burn up in a CANDU is only 6500 to 7000 MWD per metric ton of uranium (mtu) opposed to 33000 to 50000 MWD/MTU from PWR and BWR **(Tourist, CANDU and Heavy Water Moderated Reactors, 2003)**. The CANDU fuel configuration uses bundles of about half a meter in length and 30cm in diameter. A typical CANDU core will load 4500 bundles **(WNA, Fuel Fabrication, 2009)**.

The manufacturer of the CANDU reactor is Atomic Energy of Canada Limited (AECL). The CANDU reactor does offer a benefit in a smaller sized option, this being the CANDU 6 reactor. There are currently 11 CANDU 6 reactors, in five countries, in operation. The most recent commissioning has been in China at Qinshan where two CANDU 6 reactors were commissioned in 2002 and 2003 **(AECL, 2009)**.

The CANDU 6 reactor has now evolved into the Enhanced CANDU 6 (ECANDU 6), a generation three technologies, and will be used as a second case study due to its availability and smaller size.

6.1.4 Gas-Cooled Reactor (AGR & Magnox)

GCR's were one of the first reactor designs. They use a gas, usually carbon dioxide but can be helium, as a primary coolant and graphite as a moderator. The GCR's were primarily built in Great Britain and were known as Magnox because the fuel used consisted of natural uranium metal clad with a magnesium alloy called Magnox. All Magnox and GCR plants have been shutdown or are in the process of being shutdown.

The generation two design of the GCR was deemed the Advanced Gas Cooled Reactor (AGCR). Fourteen AGR's were commissioned in Great Britain between 1976 and 1989 **(WNA, Reactor Database, 2009)**.

This improved design, uses a fuel of uranium oxide pellets, enriched to 2.5 to 3.5 percent, in stainless steel tubes **(WNA, Nuclear Power Reactors, 2009)**. Because carbon dioxide is used as a coolant the reactor can reach a much higher temperature of 650^{o}C **(WNA, Nuclear Power Reactors, 2009)**. Which means the thermal efficiency is higher than PWR and BWR at 40% compared to 33-34% **(Tourist, Gas Cooled & Advanced Gas Cooled Reactors, 2009)**.

Other than the units built in Great Britain, there seems to be little progression of AGR technology and thus will not be investigated further.

6.1.5 Light Water Graphite Reactor (RBMK)

The Reaktor Bolshoy Moshchnosti Kanalniy (RBMK) is a Light Water Graphite Reactor (LWGR) designed in Russia. It is similar in design to a BWR where the cooling water is boiled in the reactor and a steam separator is used to feed steam to the turbines. The difference being it uses a large graphite block, as a moderator, which sits around the core with many vertical pressure tubes running through it. This allows for refueling without the need to shutdown the reactor, which is similar to the CANDU design.

The biggest flaw in this design is due to the graphite moderator. If excessive boiling occurs cooling and neutron absorption reduces without reducing the fission reaction allowing it to spiral out of control. This is what occurred at Chernobyl and is why these reactors have not been built anywhere outside of Russia.

However after Chernobyl the RBMK safety systems were thoroughly changed so that all operations were automatic with possibilities of manual override. This meant the reactor could never reach criticality and is why there are still sixteen reactors operating in Russia today, with only a few being planned to add capacity to existing sites **(WNA, Reactor Database, 2009)**. Due to the safety issues in design, the lack of builds outside of Russia and no new builds the RBMK technology will not be investigated further.

6.1.6 Fast Neutron Reactor (FNR)

The Fast Neutron Reactor (FNR) is the most radical design of current reactor technology. FBR's have been operating since the 1950's but only in small numbers due to the technical difficulties and cost.

There are two types of FNR's one is a Fast Breeder Reactor and the other is a Burner. The FBR is designed to produce more plutonium that it consumes and the burner consumes as much as it produces.

Natural uranium contains about 0.7% U-235 and 99.3% U-238. In the reactor the U-238 turns into isotopes of plutonium where two of these, Pu-239 and Pu-241 experience fission the same as U-235. Because FNR's breed this fuel it can utilize the uranium up to sixty times more efficiently than standard reactors. FNR's have no moderator and rely on fast neutrons to cause fission. This is why plutonium is generally used because uranium is more efficient with slow neutrons. There are 25% more neutrons per fission for plutonium than uranium so there is enough to maintain the chain reaction and convert U-238 into more Pu-239 **(WNA, Fast Neutron Reactors, 2009)**. The coolant used in an FNR is a liquid metal, generally sodium in large scale reactors but molten-lead has been used, because it does not act as a neutron moderator such as water.

Although FNR's have been built sparingly since the 1950's the design is still in research and development and can be considered a generation four technology. Due to the high costs and limited research and design this technology will not be investigated further.

6.2 Case Study Reactors for Economic Analysis

6.2.1 AP1000

The AP1000 is a two-loop PWR with passive safety systems and extensive plant simplifications that improve plant operation and maintenance, while reducing construction cost and schedule. It is manufactured by Westinghouse and is based on the standardized AP600 plant and received a design certification from the NRC in January 2006 **(USNRC, 2006)**.

The AP1000 uses modular construction techniques. The standard plant is comprised of 50 large and 250 small modules. The small modules are rail-shippable units approximately 12 feet high, 12 feet wide, and 80 feet long, with a weight 80 tons. These modules are constructed in parallel and independent of one another at a shipyard-like factory and later assembled onsite. This technique reduces construction costs and schedule. The simplified plant design, with its reduced building volumes and fewer components also contribute to a short construction schedule **(Westinghouse, AP1000 Technology Fact Sheet)**.

There have been eight AP1000's contracted so far, with four under construction in the Haiyang and Sanmen provinces of China. These reactors have scheduled commercial operation dates of 2013 to 2015. Four have been contracted in the USA with ten more units planned **(Powell)**.

6.2.2 Candu Reactor

The Candu reactor is a Canadian design manufactured by Atomic Energy of Canada Limited (AECL). It is a 700 MWe PHWR that was designed solely for electricity production. The first CANDU 6 plant went into operation in the early 1980's and has been followed by 34 plants based on the same design. There are currently eleven CANDU 6 reactors operating worldwide, these are shown in table 1 along with their commissioning dates. The CANDU 6 has had over 150 years operating experience and through this the designs have constantly improved through lessons learned.

Unit	Location	Date Commissioned	Lifetime Capacity Factor
Point Lepreau	Canada	01/02/1983	82.4 %
Wolsong 1	Korea	22/04/1983	85.8 %
Gentilly 2	Canada	01/10/1983	79.5 %
Embalse	Argentina	20/01/1984	85.3 %
Cernavoda 1	Romania	02/12/1996	87.5 %
Wolsong 2	Korea	01/07/1997	94.0 %
Wolsong 3	Korea	01/07/1998	95.1 %
Wolsong 4	Korea	01/10/1999	97.2 %
Qinshan 1	China	31/12/2002	87.7 %
Qinshan 2	China	24/07/2003	86.1 %
Cernavoda 2	Romania	05/10/2007	-

Table 1 – CANDU 6 Reactors World Wide

The CANDU 6 reactor contains a large stainless steel horizontal cylinder tank called the calandria. The calandria is sealed with end shields on both sides and is filled with a heavy water moderator at a low temperature and pressure. The calandria is located within a steel lined, water filled concrete vault **(Whitlock, 2009)**.

Inside the calandria are many sheets of metal that traverse the cylinder evenly spaced horizontally and vertically to form fuel channels. Control devices are situated between the rows and columns to measure fuel quality, flux and other useful information for computer simulations **(Whitlock, 2009)**.

This configuration of fuel channels allows the CANDU reactors to be refuelled on the go without the need for shutting the plant down. This technique allows the plants to have greater capacity factors because there is less shutdown time. The average capacity factor for plants in operation is 88%. However it is seen that the three latest plants built in Korea have an average capacity factor of 95% which is an extremely high figure and an impressive feat of the CANDU plants. It can also be seen that the older plants have a lower capacity factor. This is because they are at the point where they are being refurbished and so the plants have been shut down for long periods **(Whitlock, 2009)**.

There are 380 fuel channels in a CANDU 6 reactor and each channel can support 12 fuel bundles. The fuel bundles consist of 37 elements, arranged in circular rings and held together at each end by end plates **(Doria, 2001)**.

The type of fuel used by the CANDU 6 is typically natural-uranium although because of its makeup it could potentially use other varieties of fuel such as MOX, Plutonium and recovered uranium. This is unique to CANDU reactors and is attractive due to low fuel costs **(Whitlock, 2009)**.

The reason the CANDU reactors can use this fuel is due to the heavy water used as a moderator. Heavy water is the common name for Deuterium oxide (D20). Deuterium is a stable but rare isotope of hydrogen containing one neutron and one proton in its nucleus opposed to one proton for Hydrogen. The Deuterium makes the water 10% heavier than light water and is so called heavy water. The benefit of using heavy water over light water is that it has a moderating ratio of 80 times higher. The moderating ration is the ratio of how well it moderates neutrons and the macroscopic absorption cross-section **(Whitlock, 2009)**.

The process of enriching the moderator is very expensive and is why CANDU reactors have a slightly higher capital cost than other PWR reactors. The heavy water can represent 20% of the capital cost. But because the fuel is much cheaper, the costs tend to even out over a life-time.

The CANDU 6 plant that will be investigated to gain information on costs and operating figures will be Qinshan in China. All costs gathered will be converted to represent what they would in today's market.

6.2.2.1 Qinshan 1-2 China

The life-time of the two units installed is 40 years with an average annual design capacity factor of 85 percent. The 85 percent figure has been reached by a typical yearly capacity factor and a forced refurbish outage halfway through their life-times.

The construction time of Unit 1 was 54 months from the first concrete to full power, 43 days ahead of schedule and Unit 2 came in 112 days ahead of schedule. This shows that by following the CANDU construction and management plan the builds will be constructed on time meaning cost estimates will not be exceeded due to cost overruns because of time **(Coffin, 2008)**.

Unit 2 performed at a 99.68% capacity factor in 2007. Although average capacity factor this far is at 87% which could be due to unplanned outages in early stages **(Coffin, 2008)**.

6.3 Small Reactor Technology

If New Zealand is to seriously think about nuclear technology, then for it to be feasible the reactor size must be smaller than the 1000MW that is typical of reactor technology today. Because nuclear technology has huge capital costs which make them very expensive initially the thought to make them cheaper has always been one of economies of scale, i.e. the larger the plant the cheaper it will be due to similar sized plant locations, with only a slight increase in materials and resources, but with a large increase in output generation the overall cost is cheaper and you achieve an economy of scale.

However the thought process has changed recently to one of economies of modular construction. This has come about due to the limited number of countries that can afford and support nuclear technology. The upfront overnight cost is much smaller for a 250MW reactor compared to a 1000MW reactor and the economies of scale is balanced through production line construction of the modular plants.

There are many companies that are involved with small reactor designs as shown in table 2.

Plant Name	Size and Technology	Company and Location
B&W mPower	125 MWe PWR	Babcock & Wilcox, USA
BREST	300 MWe LMR	RDIPE, Russia
FUJI	100 MWe MSR	ITHMSO, Japan Russia USA
GT-MHR	280 MWe HTR	General Atomics-USA, Minatom-Russia
HTR-PM	105 MWe HTR	INET & Huaneng, China
IRIS-100	100 MWe PWR	Westinghouse, International
PBMR	165 MWe HTR	Eskom, South Africa

Table 2 – Small Reactor Technology by Company and Type

(WNA, Nuclear Power Reactors, 2009)

6.3.1 Fuji 200MWe MSR

The Fuji MSR is a simplified molten salt reactor which will be used in a closed 233U-Th fuel cycle. The plant life is set for thirty years with periodic fissile-fertile feeding from an internal reservoir. The design is based on previous MSR reactors at the Oak Ridge National Laboratory between 1950 and 1976. The principal stake holder is the International Throium Molten-Salt Institute (ITHMSI). The development of this program is currently at a stage of an early conceptual design with further R&D needed **(IAEA, 2007)**.

6.3.2 B&W mPower

B&W mPower plans to deploy a scalable, modular, passively safe, advanced light water reactor system. The plant can be scaled to provide between 125 MWe to 750 MWe and operates under five year fuel cycles. In the June 2009 B&W press release, **(Simmons, 2009)** B&W states the current progress of the mPower reactor;

- B&W has notified the Nuclear Regulatory Commission (NRC) of its intent to submit an application for design certification of the reactor in 2011.
- A group of future customers have been assembled to invest in this technology so that it makes regulatory requirements in North America, Europe and elsewhere.
- A letter of intent has been received from Tennessee Valley Authority (TVA) to begin the process of evaluating a potential lead site.

6.3.3 BREST

The BREST reactor is a Russian designed, 300 MWe lead-cooled fast reactor fuelled with uranium-plutonium mononitrate. Conceptual designs have been prepared and the associated design studies and analyses have been performed. Nikiet state the designers felt confident enough about the basic aspects of the plant to embark on a detailed design of a demonstration plant with on-site fuel cycle facilities at the Beloyarsk nuclear power plant (NPP) site **(Nikiet)**. In “Nucleonics Week” **(Kiev, 2005)** Valery Yazev, chairman of the parliament committee for energy, transportation and communications stated the BREST-300 project is “less optimistic” than another project the BN-800 and would not be realized before ten or fifteen years, after BN-800. The BN-800 its construction suspended and has only recently begun construction again **(INSP, 1999)**, **(Lisitsyn, 2009)**.

6.3.4 GT-MHR

THE GT-MHR from general atomics is a gas turbine-modular helium reactor. It uses a gas turbine instead of a steam turbine used in standard nuclear power plants to achieve much higher efficiency. It also has increased efficiency due to the helium moderator which allows the plant to run at much higher temperatures **(Atomics)**. No information about possible construction or testing could be found for this plant. However similar plants are seeing construction and testing in Russia, Japan, China and South Africa **(Atomics, History)**.

6.3.5 HTR-PM

The HTR-PM is a project being developed in China for a pebble-bed modular high-temperature gas-cooled reactor. It is similar to the GT-MHR design but uses fuel that is in the form of pebbles, this is explained further in the PBMR section. This project has come after the successful construction of HTR-10 a 10 MWth research reactor. This design has been developed by the Institute of Nuclear and New Energy Technology (INET) of Tsinghua University. The HTR-PM project will consist of two 250 MWth reactors coupled to one steam turbine-generator that will provide 210 MWe. The first HTR-PM demonstration plant will be supported by the Chinese government so that the operator obtains investment recovery. However the plant must demonstrate that it will not incur cost overruns and high performance is met so that it can compete with LWR plants in the future without government support. The cost estimate given for this plant is USD $2000/kWe very competitive with LWR plants. The target commissioning date is approximately 2013 and a date of around 2015 to determine whether or not the claims made are met **(Zhang, Wu, Wang, Xu, Li, & Dong, 2009)**.

6.3.6 IRIS-100

The International Reactor Innovative and Secure (IRIS) reactor design is being developed by an international team of 21 organizations from ten countries. The IRIS design is an advanced LWR with an increased emphasis on modularization and passive safety. The modular IRIS configuration allows gradual introduction of single modules or multiple modules at a single site or multiple sites **(Carelli & Petrovic,**

2004). This allows for compatibility with the smaller grid in New Zealand. The first commercial plant was expected around 2015 in 2006 as shown in table 3, the IRIS project schedule found from **(IRIS, 2006)**. It takes approximately three years to construct an IRIS plant so based on this information the earliest commissioning date would be 2018 when true economic competitiveness would be gauged.

Program started	October 1999
Assessed key technical and economic feasibility	End 2000
Preformed conceptual design, preliminary cost estimate	End 2001
Initiated NRC pre-application licensing for design certification	End 2002
Completed NSSS preliminary design	Mid 2005
Initiate necessary testing for NRC design certification	Spring 2006
Complete above testing	Mid 2008
Obtain Final Design approval from NRC	2012
Ready for deployment	About 2015

Table 3 – IRIS Project Schedule

6.3.7 PBMR

The Pebble Bed Modular Reactor (PBMR) is helium cooled, graphite moderated high temperature 165MWe reactor. The fuel is different in makeup than other nuclear reactors. It is enriched uranium dioxide coated with silicon carbide and pyrolytic carbon. The particles are encased in graphite to form a fuel sphere about the size of a billiard ball. The core of the reactor contains approximately 360,000 of these spheres **(PBMR)**. This technology is being developed by Pebble Bed Modular Reactor (Pty) Limited a South African company with an 800-member strong team based in Centurion near Pretoria **(PBMR, About Us)**. However as of September 2009, the planned demonstration plant has been indefinitely postponed due to lack of funding. At a press briefing in June, Portia Molefe, the director general of the government Department of Public Enterprises had confirmed 2018 as the target date for commissioning. However in the latest press release Jaco Kriek, CEO of PBMR said that the 2018 target date “will definitely move out” **(News, 2009)**.

6.4 Plant Location

Siting of a nuclear power plant is much the same as any other power plant however there is an increased emphasis on security, due to the higher risk of disaster if an accident were to happen.

When New Zealand was considering nuclear power in the 1960’s a location on the Kaiapara harbor was discussed due to its close proximity to water for cooling and Auckland, the biggest load centre in New Zealand. Four 250MW reactors were envisioned that would supply 80 percent of Auckland by 1990. This was abandoned by 1972 when the Maui gas fields were discovered **(WNA, Nuclear Energy Prospects in New Zealand, 2009)**.

To determine what location would be suitable for a nuclear power plant several criteria must be met. The criteria are subdivided into enabling, avoidance and exclusion criteria shown in table 4. It is subdivided into these regions so that some criteria can be softened if not enough locations are available or other criteria strengthened if too many locations are available **(Rodwell, 2002)**.

Enabling Criteria	**Availability of land.**
	Cost effective access to grid.
	Availability of cooling water supplies.
Avoidance Criteria	Coastal erosion.
	Flooding.
	Proximity to urban population centres.
	Areas of outstanding natural beauty.
	Environments protected from development.
Exclusion Criteria	Seismic activity / fault lines.
	Volcanic activity.
	Proximity to aircraft movements.
	Proximity to hazardous infrastructure.

Table 4 – Siting Criteria

Two locations have been chosen based on these criteria, one being Oyster Point in the Kaipara Harbour and the other at Marsden Point.

The Kaipara harbour has been chosen as one possible site due to the following reasons,

- It is close to Auckland the largest load centre in New Zealand, which means less loss in the system and less stress on the HVDC link.
- The transmission line run's close to the possible site so the cost of connecting it to the grid is not as expensive as in other places; however this cost is small with respect to the capital cost of a nuclear plant.
- The seismic activity seen from historic data is not significant; this can be found in Appendix A.
- The predominant winds are south easterly and north westerly which limits the spread of radiation leaks to town centres. This data can be found in Appendix A.
- It is close to a large body of water that can be used to cool the reactor.

Other criteria such as flooding, coastal erosion, volcanic activity and proximity to hazardous infrastructure still need to be collected but this data is something that is done when the site is being evaluated at a higher level.

Marsden Point has been chosen as a second possible site due to the following reasons,

- It has a decommissioned oil power plant located at the site. This allows for some reduced costs due to facilities already being at hand.

- A port is available at close proximity which means delivery of fuel is cheaper and safer.
- It is not as close to Auckland as the Kaipara harbour but is still relatively close.
- Seismic activity is not an issue as seen in Appendix A.
- It is close to a large body of water that can be used to cool the reactor.
- The predominant winds are again in a south easterly and north westerly direction which will miss areas of population if radiation leaks were to occur. This data can be found in Appendix A.

Again more criteria are needed to finalize the decision but this would be done at a higher level of evaluation.

6.5 Reactor Size

The size of the reactor is a very important topic in the engineering feasibility of nuclear power in New Zealand. New Zealand's generation capacity is very small, at approximately 9 GW, in comparison to other countries around the world as seen in figure xxx (EIA, 2009). Due to the small size of the New Zealand grid, it cannot support large individual generators. The largest individual generator in New Zealand that is not hydro is the 400MW combined cycle gas turbine (CCGT) at Huntly power station.

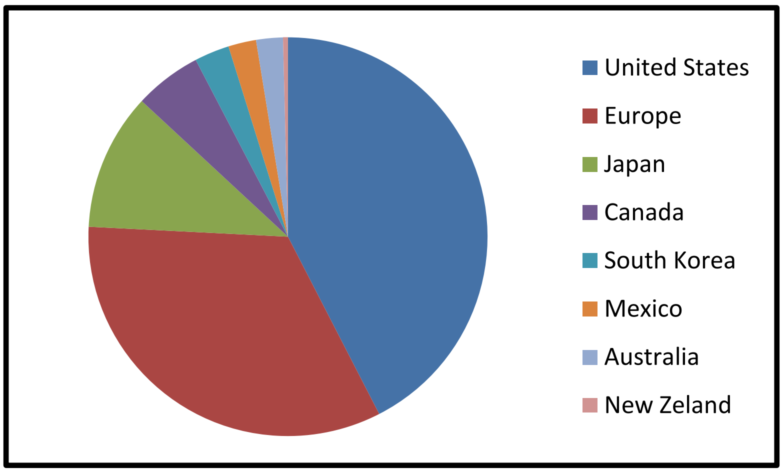


Figure 3 – 2009 Generation Capacity per Country

The size of a generator is limited by the amount of reserve that is available in the system. This reserve does not imply the amount of capacity that is not operating at any given point but the amount of capacity that could be added to the system instantly from spinning reserves or fast starting plants such as hydro. The way operators ensure there is enough reserves available and what could happen if there is not has been explained by Kiran Nanu, Generation Engineer at Contact Energy in correspondence to David Nutt, Senior Professor at AUT University, which is found in Appendix B and is summarized as follows;

New Zealand has a reserve market where reserve generation and load shedding is contracted by the market and generally the larger units will pay for the reserve. The system operator will ensure that they have enough reserve generation at any given time to cover the largest contingency effect such as Huntly

400MW CCGT tripping. Other stations around the country will be contracted so that they have enough unused capacity to cover this event. The speed at which the reserve picks up the loss of generation is also very important because if it is not covered in a short amount of time the frequency will not recover and load shedding will result. If any large generator finds the reserve costs are too high they may back off generation to lessen the amount of reserve that is need to be paid for.

This last statement is a big concern with respect to nuclear power. The average sized nuclear reactors worldwide are 1000MW and are usually built as twin reactors. This is two and a half times larger than New Zealand's biggest thermal unit. Most of these plants operate at base load, which is fine as it would match the 1000MW Huntly coal fired units, however the Huntly 1000MW is made up from four 250MW generators so that if one trips there is not a large loss to the system, compared to a 1000MW unit. The option to lessen generation is also not available with reactors in operation, as controlling nuclear fission is not as simple as letting less/more steam/water in, so high reserve prices would have to be paid continuously.

Based on these statements, reactors with smaller ratings would have to be found if nuclear power was to be incorporated into the New Zealand system.

6.6 Fuel

The fuel used by nuclear reactors will vary depending on the type of technology used. However the majority of reactors will use the U-235 isotope of uranium for its main fission reactions although Pu-239, U-233 and Th-232 can also be used in certain reactors.

The U-235 fission occurs by absorbing a slow neutron which renders the isotope unstable and towards nuclear fission which can yield 200 million times the energy of the neutron that began the reaction **(Physics)**. Fast neutrons cannot cause this reaction in standard reactors and therefore need to be slowed down (moderated) by some sort of moderator usually water or gas.

Natural uranium found in the earth's crust is composed of 0.72% U-235, 99.27% U-238 and a trace quantity 0.0055% U-234 **(Physics)**. This small amount of U-235 is generally, except in the case of PHWR, not enough to start a fission reaction and so the natural uranium must be enriched to about 4.5% depending on the reactors requirement.

Uranium must go through the process of mining, milling, conversion, enrichment and fuel fabrication. Each of these steps is described below;

6.6.1 Mining

Uranium is approximately 500 times more plentiful than gold and about as common as tin. It is found in many places such as sea water, rivers, four parts per million (ppm) in granite which makes up 60% of the earth's crust and can be as high as 100 ppm in some coal deposits (WNA, The Nuclear Fuel Cycle, 2009). Although there are a lot of places where uranium can be found there are limited places where uranium can be found in large enough quantities to make it economically viable to mine. The list of areas with known resources can be seen in table 5.

	Tones U	Percentage of World
Australia	1,243,000	23%
Kasakhastan	817,000	15%
Russia	546,000	10%
South Africa	435,000	8%
Canada	423,000	8%
USA	342,000	6%
Brazil	278,000	5%
Namibia	275,000	5%
Niger	274,000	5%
Ukraine	200,000	4%
Jordan	112,000	2%
Uzbekistan	111,000	2%
India	73,000	1%
China	68,000	1%
Mongolia	62,000	1%
Other	210,000	4%

Table 5 – 2007 Amount of Uranium per Country

Data obtained from **(OECD, 2007)**.

Large deposits of uranium that are economically feasible to mine are called ore. The most common mining technique is in situ leach (ISL) mining. This is where oxygenated groundwater is circulated through a very porous ore body to dissolve the uranium oxide and bring it to the surface. The uranium oxide is then recovered from the surface and sent to a conventional mill **(WNA, The Nuclear Fuel Cycle, 2009)**.

6.6.2 Milling

A uranium mill is a chemical plant designed to extract the uranium from ore. This is done with an acid solution typically sulfuric acid. This process extracts the uranium as well as impurities and the final product is called "yellow cake" U_3O_8 **(Diehl, 2004)**.

6.6.3 Conversion

To enrich uranium, the uranium must be in a gaseous form, conversion from yellow cake to uranium oxide is achieved through the conversion stage. This uranium oxide concentrate is the converted to uranium hexafluoride, which is a gas at relatively low temperatures **(WNA, The Nuclear Fuel Cycle, 2009)**.

6.6.4 Enrichment

The enrichment process separates gaseous uranium hexafluoride into two streams, one being enriched to the required level known as low-enriched uranium and the other is depleted of U-235 and is known as tails **(WNA, The Nuclear Fuel Cycle, 2009)**.

6.6.5 Waste

After the fuel has been depleted of useable isotopes to continue the nuclear fission reaction, the fuel must be removed and replaced with fresh fuel. The used fuel will be emitting radiation and heat so the fuel is unloaded into a storage pond immediately on site close to the reactor. The water is used to both shield the radiation and cool it down. The pools can contain the spent fuel from several months to several years. This fuel must be dealt with eventually and will depend on the countries policies when it will happen. The fuel must either be disposed of in some safe way or reprocessed to be used again. This is possible because used fuel contains 95% U-238 but also 1% non fissioned U-235 and 1% of plutonium **(WNA, The Nuclear Fuel Cycle, 2009)**.

6.6.6 Cost of Fuel

The cost of nuclear fuel for a typical LWR plant can be divided into the different processes; uranium, conversion, enrichment, fuel fabrication and back-end. The percentage for each is shown in figure 4.

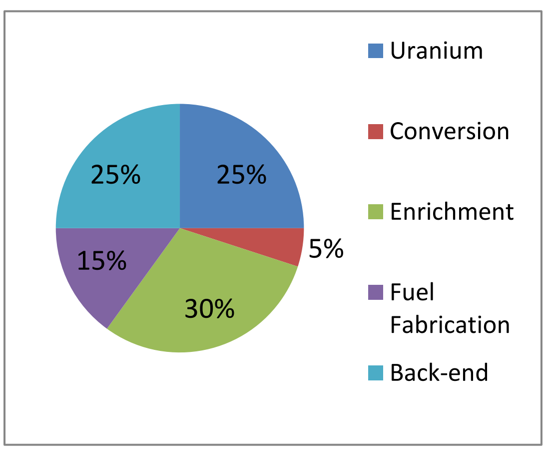


Figure 4 – Fuel Cost Breakdown

Data taken from **(OECD, Trends in the Nuclear Fuel Cycle, 2001)**

As with any commodity when there is a supply and demand, prices will change unpredictably over time. Appendix A shows the change in price for uranium, conversion and enriched fuel. From these graphs, the unpredictable nature of uranium prices can be seen which leads to a lot of uncertainty. The reason for the large price spike in 2007 is due to increased development in nuclear projects when the past fifteen years had seen little development due to events such as Chernobyl and Three Mile Island. This meant there had been little exploration for new ore fields and a fear of not meeting demand. Another reason according to David Miller, C.O.O. of Strathmore Minerals is that nuclear power plants had, until recently, been living off a huge uranium stockpile from the 1980's. That stockpile was created in anticipation of an onslaught of new U.S. nuclear plants that never eventuated **(Dubner, 2008)**.

6.6.7 Fuel Sensitivities

Nuclear reactors are not hit as hard with sudden price changes in uranium as a gas or coal fired plant would be with a sudden increase in the price of gas or coal. This is because the fuel stays in a reactor for a long period of time and is refueled when needed which can be as long as 18 months as in the case of the AP1000. This means the price of fuel can be monitored and stock piles can be made in times when prices are lower so that costs can be minimized.

7. Detailed Analysis

7.1 Levelised Cost of Electricity Calculation

The Levelised Cost of Electricity or Energy (LCOE) is a way of comparing the cost of different generation technologies with differing operating parameters. The differing parameters could be heat rate, plant life, and capacity factor and so on. This is helpful in planning generator build schedules as different technologies and plants can be compared under a standard calculation and the options with the lowest LCOE can be chosen. The LCOE is a constant price of electricity that would be needed over the lifetime of the generation technology to cover all operating expenses, debt, equity payments and taxes incurred.

The LCOE can be calculated by using discounted cash flow analysis, which is used in the method below. Revenues and expenses are projected over the lifetime of the technology and are discounted to satisfy debt investors and interest, in real dollars.

The LCOE model used is based on **(Du & Parsons)**. It must be noted that this is a US calculation and some tax breaks may not apply, however all inflation and tax rates have been modified to fit New Zealand's economy and results do not differ greatly from an alternative New Zealand model as described later in this section.

The matlab model used to calculate the LCOE for the different technologies and plants is described below. A legend of variables used in the LCOE calculation can be found in table 6.

LCOE	Levelised Cost of Electricity, \$/kWh	i_F	Real Fuel Escalation Rate	i_{OM}	Real O&M Escalation Rate
TOT_{CT}	Total Expense, \$	Y	Year	V_C	Variable O&M Costs, mills/kWh
R_T	Total Revenue, \$	B_y	Base Year, 2009	F_C	Fixed O&M Costs, \$/kW/year
C_{CT}	Total Construction Costs, \$	W_C	Waste Costs, \$/kWh	R_C	Refurbishment Cost, \$ million
A_D	Total Asset Depreciation, \$	CF	Capacity Factor	D_C	Decommissioning Cost, \$ million
IC_{CT}	Total Incremental Capital Costs, \$	C	Capacity, MW	I_{CC}	Incremental Capital Cost, \$/kW/year
D_{CT}	Total Decommissioning Costs, \$	Fl_C	Fuel Cost, \$/mmBtu	D_R	Depreciation Rate
R_{CT}	Total Refurbishment Costs, \$	H_R	Heat Rate, Btu/kWh	C_T	Total Construction Costs, \$ million
NF_{CT}	Total Non Fuel O&M Costs, \$	WACC	Weighted Average Cost of Capital	P_L	Plant Life
F_{CT}	Total Fuel Related Costs, \$	n	Period	O_C	Overnight Cost, \$/kW
i	Inflation Rate	T_R	Tax Rate	CP	Construction Percentage

Table 6 – LCOE Variables Legend

7.1.1 Capital Expenditure

The biggest cost of any power plant is the large capital investment. This hurdle must be overcome before electricity can be produced and the investment pays off. Because a generation plant will take two to five years to build, depending on the technology, the capital can be divided into each year of construction with an inflation factor included for each year following the initial year of construction. There are different ways to divide the amount that is paid each year such as a sinusoidal percentage or a straight line percentage, following the MIT calculation a sinusoidal percentage will be used. This makes sense as the biggest costs of construction will usually occur in the middle of construction. The formula used to calculate the total cost of construction for each year of the build is shown in equation 1. The annual capital expenditure during construction for a \$5323/kW nuclear power plant, with a 2.5% inflation factor can be seen in table 7.

$$C_{CT} = \sum_{n<0} \frac{1}{(1 + WACC)^n} \times \frac{C}{1 \times 10^3} \times O_c \times CP(n) \times (1 + i)^{y-By}$$

Equation 1 – Total Construction Cost

Period (n)	-5	-4	-3	-2	-1	Overnight Cost $/kWe	Total Cost $/kW
Year (y)	2010	2011	2012	2013	2014	2009	2009
Cost million	$349	$941	$1196	$989	$385	$5323/kW	$6698.5/kW

Table 7 – Annual Capital Expenditure during Construction

7.1.2 Asset Depreciation

Asset depreciation is defined as a portion of the cost that reflects the use of a fixed assed during an accounting period **(Day)**. Asset depreciation is valid for a power plant because it is a depreciable property. Meaning the property will decline in value while used (IRD). In the MIT calculations, Modified Accelerated Cost Recovery System, MACRS, guidelines were used to create a depreciation schedule over a 15 year asset life. For the following calculations the straight-line method will be used over the asset's entire lifetime.

The straight-line method is widely used and is simple to calculate. It is based on the principle that each accounting period of the asset's life should have an equal amount of depreciation **(Tutor2u)**. The formula for depreciation rate is shown in equation 2.

$$D_R = \frac{1}{P_L}$$

Equation 2 – Depreciation Rate

The depreciation rate is multiplied by the tax rate and the total cost of construction and then multiplied by the discount factor for the given year. This formula can be seen in equation 3.

$$A_D = \sum_{0}^{n} \frac{1}{(1 + WACC)^n} \times -T_r \times D_R(n) \times C_T$$

Equation 3 – Total Asset Depreciation

7.1.3 Revenue

The revenue obtained from a power plant is the amount of electricity produced and sold on the electricity market. The price is equivalent to the levelised cost of the plant **(MIT, 2003)**. This means that the base year cost of electricity is set at one dollar and is inflated each subsequent year to represent a real levelised cost. This price of electricity is then multiplied by the amount of electricity generated per annum to calculate the annual revenue. The formula for total revenue can be seen in equation 4.

$$R_T = \sum_{0}^{n} \frac{1}{(1+WACC)^n} \times \frac{C}{1 \times 10^6} \times CF \times 8760 \times (1+i)^{y-By}$$

Equation 4 – Total Revenue

7.1.4 Operating Costs

Operating costs occur throughout the power plants operational life time. These are in the form of incremental capital costs, refurbishment costs, decommissioning costs, operating and maintenance costs, fuel costs, waste fee's and carbon emission tax's. Incremental capital expenditures have been treated as operating expenses instead of additions to the depreciable asset because the simplification creates only a very small error **(MIT, 2003)**.

Decommissioning and refurbishment costs are onetime costs and have been added to the costs incurred at the end of the plants life time and in the middle respectively. These costs are inflated and the tax is deducted this is then multiplied by the discount factor. The formula for decommissioning, refurbishment and incremental costs can be seen in equation 5.

$$I_{CCT} = \sum_{0}^{n} \frac{1}{(1+WACC)^n} \times (1-T_R) \times \left(\frac{C}{1 \times 10^3} \times I_{CC} \times (1+i)^{y-By}\right)$$

$$D_{CT} = \sum_{0}^{n} \frac{1}{(1+WACC)^n} \times (1-T_R) \times (D_C \times (1+i)^{y-By})$$

$$R_{CT} = \sum_{0}^{n} \frac{1}{(1+WACC)^n} \times (1-T_R) \times (R_C \times (1+i)^{y-By})$$

Equation 5 – Total Incremental Capital Costs, Decommissioning Costs and Refurbishment Costs

The non fuel operating and maintenance costs consist of a variable and fixed cost which increases at a rate of inflation and in the MIT model a real escalation rate of one percent is included which has been followed in this model. The formula for non fuel operating and maintenance costs can be seen in equation 6.

The fixed O&M costs include operating labour, maintenance labour, maintenance materials, overheads, administration and support, distribution and marketing, research and development etc. The variable operating costs consist of the costs for operating supplies other than fuel costs e.g. water, chemicals and disposing of waste material **(Bejan, Tsatsaronis, & Moran, 1996)**

$$\boxed{\begin{aligned} NF_{CT} = \sum_{0}^{n} \frac{1}{(1+WACC)^n} \times (1-T_R) \times \left(\left(\frac{C}{1\times 10^3} \times F_C\right) + \left(\frac{C}{1\times 10^6} \times CF \times V_C \times 8760\right)\right) \\ \times \left((1+i) \times (1+i_{OM})\right)^{y-By} \end{aligned}}$$

Equation 6 – Total Non Fuel Operating & Maintenance Costs

The fuel cost is another important operating cost that changes at a real escalation rate. The fuel cost is discussed further below. The waste fee is also included in the fuel coast for nuclear power. The formula for this can be seen in equation 7.

$$\boxed{\begin{aligned} F_{CT} = \sum_{0}^{n} \frac{1}{(1+WACC)^n} \times (1-T_R) \\ \times \left(\left(\frac{C}{1\times 10^3} \times CF \times W_C \times 8760\right) + \left(\frac{C}{1\times 10^6} \times CF \times Fl_C \times H_R \times 8760\right)\right. \\ \left. \times \left((1+i) \times (1+i_F)\right)^{y-By}\right) \end{aligned}}$$

Equation 7 – Total Fuel Related Costs

The total costs are then the sum of the construction, post construction, incremental, decommissioning, refurbishment, non fuel O&M and fuel related costs. As seen in equation 8.

$$\boxed{Tot_{CT} = C_{CT} + A_D + I_{CT} + D_{CT} + R_{CT} + NF_{CT} + F_{CT}}$$

Equation 8 – Total Costs

The LCOE is then the total cost divided by the revenue. This can be seen in equation 9.

$$\boxed{LCOE = \frac{TOT_{CT}}{R_T}}$$

Equation 9 – Levelised Cost of Electricity

7.1.5 Input Variables

The input variables for the nuclear, AP1000 and CANDU6, coal and gas plants can be found in table 8. The values for the LCOE model and the GEM model are shown with conversion factors provided where applicable.

INPUT VARIABLES	AP1000	CANDU6	COAL	GAS
PLANT COSTS				
Overnight Cost, $/kW	4925.00	3447.53	1367.00	590.00
Overnight Cost + 15%, $/kW	5663.75	3964.66	0.00	0.00
Overnight Cost + 35%, $/kW	6648.75	4654.17	0.00	0.00
Overnight Cost Double, $/kW		6895.06	0.00	0.00
Year	2008	2003	2009	2009
Currency	US	CND	US	US
Overnight Cost (GEM) NZ$/kW	8826.10	5323.70	1367.00	590.00
Overnight Cost + 15% (GEM) NZ$/kW	10150.02	6122.26	0.00	0.00
Overnight Cost + 35% (GEM) NZ$/kW	11915.24	7187.00	0.00	0.00
Overnight Cost Double, (GEM) $/kW		10647.40	0.00	0.00
Incremental Capital Cost, $/kW/year	40.00	40.00	26.54	10.20
Year	2007	2007	2007	2007
Currency	US	US	US	US
Incremental Capital Cost (GEM) NZ$/kW	73.48	73.48	48.75	18.74
Fixed O&M Costs, $/kW/year	56.40	12.90	100.00	50.00
Fixed O&M Costs + 15%, $/kW/year	64.86	14.84	-	-
Fixed O&M Costs + 35%, $/kW/year	76.14	17.42	-	-
Fixed O&M Costs Double $/kW	-	25.80	-	-
Year	2007	2003	2009	2009
Currency	US	CND	NZ	NZ
Fixed O&M Costs (GEM), NZ$/kW	198.51	107.06	100.00	50.00
Fixed O&M Costs + 15% (GEM), NZ$/kW	214.05	110.05	-	-
Fixed O&M Costs + 35% (GEM), NZ$/kW	253.39	114.03	-	-
Fixed O&M Costs Double (GEM), NZ$/kW	-	126.98	-	-
Variable O&M Costs, mills/kWh	0.42	-	9.00	4.25
Year	2007	-	2009	2009
Currency	US	-	NZ	NZ
Variable O&M Costs (GEM), NZ$/MWh	0.77	-	9.00	4.25
Fuel Costs, $/mmBtu	0.67	1.10	5.80	6.33
Year	2007	2003	2009	2009
Currency	US	CND	NZ	NZ
Fuel Costs (GEM), NZ$/GJ	1.23	1.70	5.50	6.00

Waste Fee, $/kWh	0.001	-	-	-
Year	2007	-	-	-
Currency	US	-	-	-
Waste Fee (GEM), NZ$/kWh	0.001837	-	-	-
Decommissioning Cost, $ million	700.00	354.00	-	-
Year	2007	2003	-	-
Currency	US	CND	-	-
Decommissioning Cost (GEM), NZ$ million	1285.83	546.65	-	-
Refurbishment Cost, $ million	-	200.00	-	-
Year	-	2003	-	-
Currency	-	CND	-	-
Refurbishment Cost (GEM), NZ$ million	-	308.84	-	-
PLANT PROPERTIES				
Capacity, MW	1117.00	673.00	400.00	410.00
Capacity Factor	0.93	0.88	0.80	0.85
Heat Rate, Btu/kWh	9715.00	10366.00	8151.66	5829.38
Heat Rate (GEM), GJ/GWh	10249.33	10936.13	8600.00	6150.00
Plant Life, years	60.00	40.00	30.00	25.00
ECONOMIC VARIABLES				
Inflation Rate	0.03			
O&M Real Escalation	0.01			
Fuel Real Escalation	0.01			
Tax Rate	0.30			
WACC	0.08			
US to NZ Exchange Rate	1.75			
CND to NZ Exchange Rate	1.33			
CONVERSION FACTORS				
$/mmBtu to $/GJ	0.95			
Btu/kWh to GJ/GWh	1.06			

Table 8 – Variable Inputs

7.2 Input Variables Explained

7.2.1 Overnight Cost

Overnight cost is the cost of a construction project if no interest were incurred during construction, as if the project were completed "overnight" or the present value cost that would have to be paid as a lump sum up front to completely pay for a construction project.

7.2.1.1 AP1000

The initial overnight cost for the AP1000 nuclear power plant has been taken from the average proposed costs from Levy County 1 & 2, V.C. Summer 2 & 3 and Plant Vogtle at US $4,206/kW, US $3,787/kW and US $4,745/kW **(Du & Parsons)** respectively, giving an average of US $4,246/kW. However all three of these plants are twin builds, meaning two AP1000 reactors are being built, which decreases the cost per kW and a factor is needed to account for a single reactor build. The difference in a single reactor build and a twin reactor build is approximately 16%, bringing the total to $4925/kW in 2008 US $/kW.

This overnight cost cannot be justified in the New Zealand case because New Zealand has no experience in nuclear power. This means there are no skilled professionals that can begin this build in the required fields. This is an added cost which would have to be brought in from overseas or through new university courses in New Zealand, implemented well before construction begins.

Two factors have been used to include this cost. The first is an added cost of 15%, which states that because the technology is not a FOAK and has a modular construction schedule the 35% factor for FOAK (Chicago, 2004) technology should not be used and a more realistic value of 15% if New Zealand were a late adopter of the AP1000 technology **(Government, 2006)**. This increases the cost to $ 5,664 in 2008 US $/kW. The second factor is the use of a FOAK 35% increase. This factor is chosen because although the technology is not FOAK and there are no unforeseen costs, New Zealand does not have a large workforce compared to Australia, New Zealand has no nuclear research programs compared to Australia and New Zealand has no nuclear regulations and construction experience. This increases the cost to $ 6649 in 2008 US $/kW.

7.2.1.2 CANDU 6

The CANDU 6 initial overnight cost is $3448 in 2003 CND $/kW. This figure was found from the initial figure of CND $ 4 billion for the total construction cost of twin CANDU 6 reactors at the Qinshan power plant in China **(Coffin, 2008)** and **(Ayres, MacRae, & Stogran, 2004)**. This figure is then divided by the total capacity to get the cost per kW which equals $2,972/kW and is then multiplied by the 1.16 single unit factor to equal the total overnight cost shown in the variable table.

The CANDU 6 has similar cost increase factors as the AP1000 but also has an additional 100% increase. This 100% increase is due to the uncertainty in construction deadlines being met in countries outside of China and Korea, with CANDU technology. The main target in this accusation is the four-unit Darlington plant in Canada. The total cost estimate was said to be $7.46 billion when the plant was finished the final cost was $14.33 billion **(Robertson, 2004)**. This increase can be attributed to unfortunate events such as a 46 per cent increase in the CPI over three years, an unexpected rapid 20 per cent increase in interest rates, a six-month strike by electrical workers, and unexpected refurbishment costs **(CANDU)**. However these unforeseen events are all things that could happen during a New Zealand build and it is very unlikely that a New Zealand build would run the same course as a China build due to the different economies and size of labour force.

7.2.2 Incremental Capital Cost

The incremental capital cost for the AP1000 and CANDU6 has been taken as $40 in 2007 US $/kW/year, the coal incremental capital cost has been taken as $26.54 in 2007 US $/kW/year and the gas incremental capital cost has been taken as $10.20 in 2007 US $/kW/year. These figures have been taken from **(MIT, 2003)**.

7.2.3 Fixed O&M Costs

The fixed O&M costs for the AP1000 reactor is set at $56.40 in 2007 US $/kW/year. This figure has been taken from **(MIT, 2003)** for a standard 1000MW reactor. The fixed O&M costs for the CANDU 6 reactor is set at $12.90 in 2003 CND $/kW/year. This figure has been taken from **(Ayres, MacRae, & Stogran, 2004)**. At first a factor was included to increase the cost by the same factors as the overnight cost, however these costs are for services that are provided annually and may have a higher cost initially but will soon settle to the lower cost. With the increase factor the final cost only changes by 2 per cent and due to the previous reasoning it is not factored into the calculations.

7.2.3.1 GEM

As GEM does not have variables for incremental capital, refurbishment and decommissioning costs these costs are added to the fixed O&M costs.

7.2.4 Variable O&M Costs

The variable O&M cost for the AP1000 reactor is set at $0.00042 in 2007 US $/kWh. This figure has been taken from **(MIT, 2003)** for a standard 1000MW reactor. The variable O&M cost for the CANDU 6 reactor is has been given as zero by two sources. **(Ayres, MacRae, & Stogran, 2004)** and (RTDB, 1996). Another source has given $1.42/MWh **(OPA, 2005)**. The addition of the variable O&M cost sees an increase of 2.7 per cent to the LCOE. This cost will not be included because the majority of the other figures used for the CANDU 6 reactor are taken from sources that used zero as the variable O&M cost.

7.2.5 Fuel Costs

The fuel cost for the AP1000 is set at $0.67 in 2007 US $/mmBtu. This figure has been taken from **(Du & Parsons)**. The fuel cost for the CANDU 6 reactor is set at $1.10 in 2003 CND $/mmBtu. This figure was obtained from **(Ayres, MacRae, & Stogran, 2004)**. It should be noted that the CANDU 6 fuel costs should not be higher than the AP1000 because a PHWR does not need enriched fuel which leads to extra costs. The increase in cost is due to the extra waste fee included into the total cost of the CANDU 6 fuel whereas the AP1000 has a separate waste fee.

7.2.6 Waste Fee

The waste fee for the AP1000 is $0.001 in 2007 US $/kWh. This figure has been taken from **(MIT, 2003)** for a standard 1000MW reactor. The waste fee for the CANDU 6 reactor is zero because it is included in the fuel costs.

7.2.7 Decommissioning Cost

The decommissioning cost for the AP1000 is $700 million in 2007 US $. This figure has been taken from **(MIT, 2003)** for a standard 1000MW reactor. The decommissioning cost for the CANDU 6 is $354 million in 2003 CND $. This figure has been taken from **(Ayres, MacRae, & Stogran, 2004)**. Coal and gas plants do not have decommissioning costs because they do not pose ecological risks in the same way nuclear plants do.

7.2.8 Refurbishment Cost

The CANDU 6 reactor is the only plant that requires refurbishment costs. This is due to the heavy water that is used as the moderator and the degradation it causes on the fuel channels **(Whitlock, 2009)**. The refurbishment occurs halfway through the reactors life time so that the capacity factor can be kept at its original rate. The refurbishment cost is $ 200 million in 2003 CND $ and has been taken from **(Ayres, MacRae, & Stogran, 2004)**.

7.2.9 Capacity

The capacity for the AP1000 is 1,117 MWe and this figure has been obtained from the **(Westinghouse)**. The capacity for the CANDU 6 is 673 MWe and this figure has been obtained from **(Ayres, MacRae, & Stogran, 2004)**.

7.2.10 Capacity Factor

The capacity factor for the AP1000 is 93 percent. This figure has been obtained from **(Popp, 2008)**. Although this figure seems high, it can be justified as the average capacity from nuclear power in the US for 2007 was 91.8 percent **(EIA, Electric Power Industry 2007: Year in Review, 2007)**. The capacity factor for the CANDU 6 reactor is 88 percent. This figure has been obtained through averaging the lifetime capacity factors of ten CANDU 6 reactors in current operation **(AECL, 2009)**.

7.2.11 Heat Rate

The heat rate for the AP1000 reactor is 9715 Btu/kWh. This heat rate has been obtained from **(Westinghouse, Design Control Document- Steam and Power Conversion System - Turbine-Generator, 2007)**. The heat rate for the CANDU6 reactor is 10366 Btu/kWh. This heat rate has been obtained from the CANDU technical datasheet from **(UNENE)**.

7.2.12 Plant Life

The plant life for the AP1000 is sixty years and this figure has been obtained from **(Westinghouse, AP1000 Technology Fact Sheet)**. The plant life for the CANDU 6 is forty years and this figure has been obtained from the lifetime specified for the reactors built at Qinshan in China **(Coffin, 2008)**.

7.2.13 Inflation Rate

The inflation rate is set at 2.5 percent as per GEM.

7.2.14 O&M Real Escalation Rate

The O&M real escalation rate is set at 1 percent as per **(Du & Parsons)**.

7.2.15 Fuel Real Escalation Rate

The fuel real escalation rate is set to 0.5 percent as per **(Du & Parsons)**.

7.2.16 Tax Rate

The tax rate is set at 30 percent as per GEM.

7.2.17 Weighted Average Cost of Capital

The WACC is set at 8 percent as per GEM.

7.2.18 US to NZ Exchange Rate

The US to NZ exchange rate is set at 1.75. This exchange rate has been calculated by taking the average exchange rate over a ten year period from 1999 to 2009 can be found in Appendix A.

7.2.19 CND to NZ Exchange Rate

The CND to NZ exchange rate is set at 1.33. This exchange rate has been calculated by taking the average exchange rate over a ten year period from 1999 to 2009 as seen in Appendix A.

7.2.20 Conversion Factors

7.2.20.1 $/mmBtu to $/GJ

The conversion factor from $/mmBtu to $/GJ is 0.95 because,

$$1\ mmBTu = 1.06\ GJ, \frac{\$1}{mmBtu} = \frac{\$1}{1.06GJ} = 0.95$$

7.2.20.2 Btu/kWh to GJ/GWh

The conversion factor from Btu/kWh to GJ/GWh is 1.06 because,

$$1\ BTu = 1.06 \times 10^{-6}GJ, 1\ kWh = 1 \times 10^{-6}GWh, \frac{1\ Btu}{1\ kWh} = \frac{1.06 \times 10^{-6}GJ}{1 \times 10^{-6}GWh} = 1.06$$

7.2.21 Gas and Coal

All gas and coal values, apart from the incremental capitals costs, have been taken from the GEM input data spreadsheet. The coal plant that has been used is named, GCoal1G – Generic coal 1 Glenbrook and the gas plant that has been used is named, GGas1A – Generic Gas 1 Auckland.

8. Results

8.1 LCOE

By running the LCOE calculations and the GEM long range marginal cost (LRMC) calculations, similar results were obtained with a difference of less than one percent. These results can be seen in table 8, 9 and figure 5.

Reactor Type	AP1000		CANDU6	
Method of Calculation	LRMC	LCOE	LRMC	LCOE
Original Overnight Cost	$130/MWh	$0.1276/kWh	$94/MWh	$0.0954/kWh
Overnight Cost + 15%	$143/MWh	$0.1405/kWh	$103/MWh	$0.1047/kWh
Overnight Cost + 35%	$162/MWh	$0.1578/kWh	$116/MWh	$0.1171/kWh
Overnight Cost + 80%	-	-	-	$0.1321/kWh
Overnight Cost + 100%	-	-	$156/MWh	$0.1574/kWh

Table 9 – Nuclear LCOE Results

Technology	Coal		Gas	
Method of Calculation	LRMC	LCOE	LRMC	LCOE
Original Cost	$111/MWh	$0.118/kWh	$66/MWh	$0.683/kWh
$20 t/CO2	$127/MWh	$0.1336/kWh	$73/MWh	$0.0745/kWh
$40 t/CO2	$143/MWh	$0.149/kWh	$79/MWh	$0.0807/kWh
$60 t/CO2	$158/MWh	$0.1644/kWh	$86/MWh	$0.0869/kWh

Table 10 – Coal and Gas LCOE Results

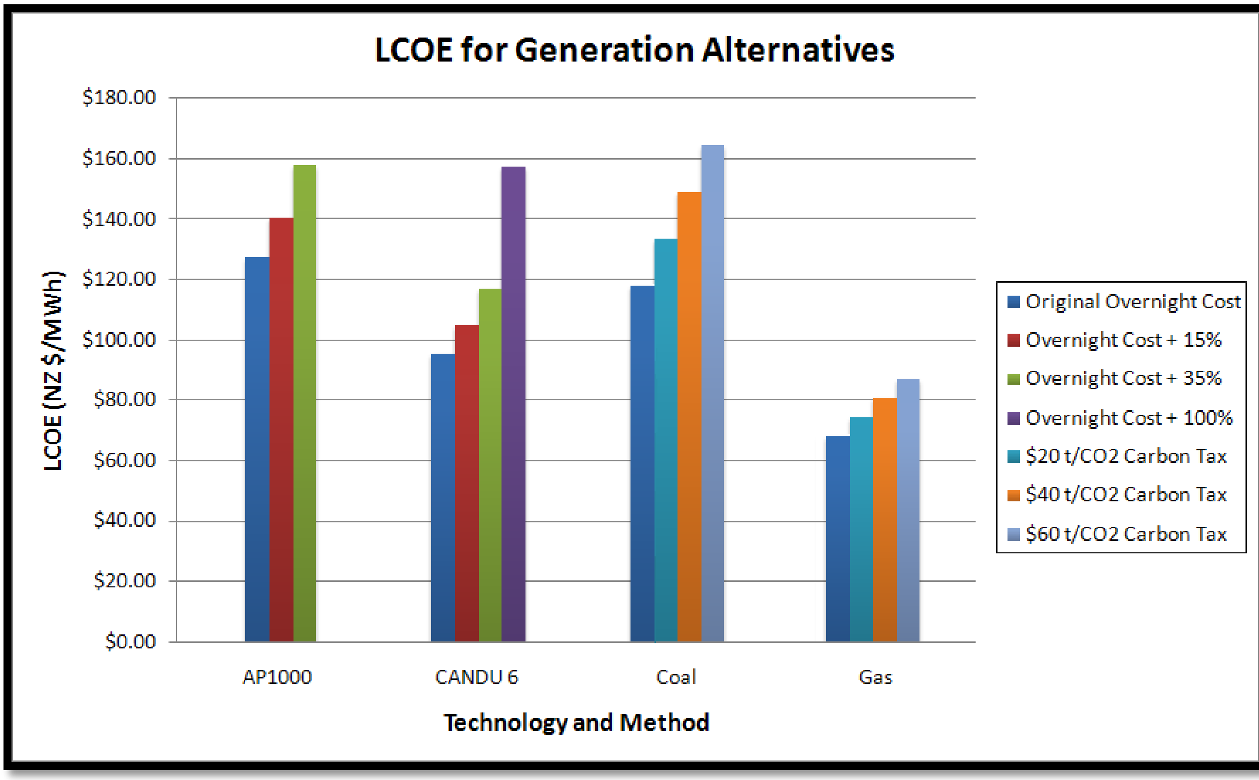


Figure 5 – LCOE for Generation Alternatives

8.2 GEM

By running GEM with the different input variables under all scenarios the following results were obtained:

AP1000, Low Overnight Cost, All Scenarios	
Scenario	Result
MDS 1	Not Built
MDS 2	Not Built
MDS 3	Not Built
MDS 4	Not Built
MDS 5	Not Built

CANDU 6, Low Overnight Cost, All Scenarios	
Scenario	Result
MDS 1	Built
MDS 2	Built
MDS 3	Built
MDS 4	Built
MDS 5	Not Built

CANDU 6, Overnight Cost + 15% , All Scenarios	
Scenario	Result
MDS 1	Built
MDS 2	Built
MDS 3	Built
MDS 4	Built
MDS 5	Not Built

CANDU 6, Overnight Cost + 35% , All Scenarios	
Scenario	Result
MDS 1	Built
MDS 2	Built
MDS 3	Not Built
MDS 4	Not Built
MDS 5	Not Built

CANDU 6, Overnight Cost + 80% , All Scenarios	
Scenario	Result
MDS 1	Built
MDS 2	Not Built
MDS 3	Not Built
MDS 4	Not Built
MDS 5	Not Built

CANDU 6, Overnight Cost + 100% , All Scenarios	
Scenario	Result
MDS 1	Built
MDS 2	Not Built
MDS 3	Not Built
MDS 4	Not Built
MDS 5	Not Built

8.3 Important Remarks from the Results

- It can be seen from the LCOE results that the gas price is much cheaper under all circumstances including carbon taxing. The reason for this is that the LCOE calculation does not take into account the increasing gas price under scenarios where there is no high gas discovery in New Zealand.
- It can be seen that if the LCOE for a 600MWe nuclear power plant is between $95/MWh and $105/MWh a plant will be built in GEM under all scenarios except for a high discovery of natural gas.
- It can be seen that if the LCOE for a 600MWe nuclear power plant is between $117/MWh and $132/MWh, plants will only be built under sustainable scenarios as carbon emissions are zero for a nuclear plant.
- It can be seen that the AP1000 plant is not built under any scenario at its lowest cost. This is due to the bigger cost to buy reserves than that of the smaller CANDU 6 reactor.
- At double the overnight costs and with an LCOE of $156/MWh the CANDU reactor is only built under a sustainable scenario.

8.4 Comparison of LCOE results with other Studies

The studies that are being used to compare the LCOE results with are;

- MIT, Update on the Cost of Nuclear Power, 2009 by Yangbo Du and John E. Parsons.
- University of Chicago, The Economic Future of Nuclear Power, 2004.
- CERI, Levelised Unit Electricity Cost Comparison of Alternate Technologies for Baseload Generation in Ontario, 2005 by Matt Ayres, Morgan Macrae and Melanie Stogran.
- Australian Government, Uranium Mining, Processing and Nuclear Energy – Opportunities for Australia? 2006.

8.4.1 MIT

The MIT results see nuclear at $0.154/kWh, coal at $0.114/kWh and gas at $0.12/kWh. The nuclear price matches very closely to the higher side of results found from the LCOE calculation. The coal and gas cannot be compared because these plants used in the MIT study are rated at 1000MW each **(Du & Parsons)**.

8.4.2 University of Chicago

The University of Chicago research has a lot of data gathered from many resources. The cost of nuclear ranges from $0.071/kWh to $0.164/kWh, the cost of coal ranges from $0.071/kWh to $0.147/kWh and the cost of gas ranges from $0.059/kWh to $0.131/kWh. This again fits the data found from the LCOE calculation **(Chicago, 2004)**.

8.4.3 CERI

The CERI results see a CANDU 6 LCOE range from $0.095/kWh to $0.133/kWh, coal fired range from $0.072/kWh to $0.089/kWh and gas range from $0.108 to $0.113/kWh. The CERI CANDU 6 LCOE matches what was found in this study. However most of the data for the CANDU 6 was found from the CERI report so there is no expectation for it to be different. The gas and coal prices are completely different though. In this study gas was much lower and coal was much higher. This is not an error, it just shows the difference in the prices and availability of resources in different countries **(Ayres, MacRae, & Stogran, 2004)**.

8.4.4 Australian Government

In this study calculations have not been made from data that has been obtained. Results from other studies such as the MIT and Chicago reports have been used with a 15% increase to represent that Australia has no nuclear power construction experience, nor regulatory infrastructure. The LCOE range for nuclear power is stated as $0.059/kWh to $0.104/kWh. This figure is a lot lower than the other three results and is hard to determine how the numbers were manipulated as there are no calculations available **(Government, 2006)**.

9. Conclusion

Based on the results found in this report, a CANDU 6 nuclear power plant could be economically feasible under certain conditions. These conditions are that no new gas fields are discovered, a carbon tax scenario takes place and the overnight costs do not escalate to more than 35 percent. However the size of the plant creates an issue when connecting it to the New Zealand grid. At 673 MWe the CANDU 6 reactor is more than one and a half times the size of the largest thermal generator connected to the grid. This causes a problem where enough spinning reserve must be on standby so that if for some reason the reactor trips offline, the loss of capacity will be replaced by the reserve immediately, or else load shedding could occur.

To overcome this size limitation the only other option for nuclear plants in New Zealand would be ones of small modular construction. However this technology is in its infancy with the first HTR-PM demonstration plant planned to be commissioned by 2013 and to then have it run for a few years to evaluate the economic competitiveness of it. Other small rector technology is even further behind than this.

From this study it can be seen that nuclear power would not be right for New Zealand in the short term not only because of political and social justifications but ones of technical feasibility. It is not to say that nuclear power should never be thought about for New Zealand in the future. If global warming becomes an increasingly important issue and large carbon reductions are needed, nuclear would be an option to replace thermal power plants at Huntly but only if modular reactors have become a well developed and economically competitive form of nuclear power.

As a result it is recommended that small modular reactors, especially the Chinese HTR-PM, should be monitored because one day this type of technology could be a feasible option for New Zealand.

10. References

AECL. (2009). *CANDU 6 Reactors*. Retrieved from AECL: http://www.aecl.ca/Reactors/CANDU6.htm

Atomics, G. (n.d.). *GT-MHR*. Retrieved from General Atomics Energy Group: http://gt-mhr.ga.com/

Atomics, G. (n.d.). *History*. Retrieved from General Atomics Energy Group: http://gt-mhr.ga.com/history.php

Ayres, M., MacRae, M., & Stogran, M. (2004). *Levelised Unit Electricity Cost Comparison of Alternate Technologies for Baseload Generation in Ontario.* Ontario: Canadian Energy Research Institute.

Bejan, A., Tsatsaronis, G., & Moran, M. (1996). *Thermal Design & Optimization.* New Jersey: John Wiley & Sons.

Bishop, P. (2009, July). *The Components of GEM*. Retrieved from Generation Expansion Model: https://gemmodel.pbworks.com/The+components+of+GEM

Black, V. (1996). *Power Plant Engineering.* New York: Springer.

CANDU. (n.d.). *Debunking Darlington*. Retrieved from CANDU: http://www.canducanada.ca/eng/darlington.html

Carelli, M. D., & Petrovic, B. (2004). Recent Developments of the IRIS Project of Interest for Latin America. Pittsburgh, United States of America: Westinghouse Electric.

Chan, Y. (2009, August 10). *New Zealand's "ambitious" emissions target fails to impress greens*. Retrieved from Business Green: http://www.businessgreen.com/business-green/news/2247553/zealand-sets-ambitious

Chicago, U. o. (2004). *The Economic Future of Nuclear Power.* Chicago: University of Chicago.

Coffin, D. (2008, October 24). *China Celebrates 5 Year Anniversary of CANDU Nuclear Power Plant*. Retrieved from AECL: http://www.aecl.ca/NewsRoom/News/Press-2008/081024.htm

Commission, E. (2008). *2008 Statement of Opportunities.*

Commission, E. (2009, September 16). *Generation Expansion Model*. Retrieved from Electricity Commission: http://www.electricitycommission.govt.nz/opdev/modelling/gem

Day, J. (n.d.). *Understanding Asset Depreciation.* Retrieved from The Sideroad: http://www.sideroad.com/Accounting/asset-depreciation.html

Diehl, P. (2004, August 15). *Uranium Mining and Milling Wastes: An Introduction.* Retrieved from WISE Uranium Project: http://www.wise-uranium.org/uwai.html

Doria, F. J. (2001, May 24). CANDU Safety #4: Thermalhydraulic Safety Characterisitcs of CANDU Reactors.

Du, & Parsons. (n.d.). Update Cost of Nuclear. Massechusetts, United States of America.

Dubner, S. J. (2008, March 24). *Why Did the Price of Uranium Skyrocket?* Retrieved from Freakonomics: http://freakonomics.blogs.nytimes.com/2008/03/24/why-did-the-price-of-uranium-skyrocket/

EIA. (2007). *Electric Power Industry 2007: Year in Review*. Retrieved from Energy Information Administration: http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html

EIA. (2009, May 27). *International Energy Outlook 2009*. Retrieved from Energy Information Administration: http://www.eia.doe.gov/oiaf/ieo/ieoecg.html

Fitzpatrick, A. (2008, April 28). *Outage of HVDC Link*. Retrieved from Transpower: https://transpower.co.nz/n2493,163.html

FXHistory. (2009). *FXHistory - Historical Currency Exchange Rates*. Retrieved from FXHistory: http://www.oanda.com/convert/fxhistory

Government, A. (2006). *Uranium Mining, Processing and Nuclear Energy - Opportunities for Australia?* The Couch.

Gutmann, P. (1998, May 24). *Aucklands Power Outage.* Retrieved from University of Auckland, Department of Computer Science: http://www.cs.auckland.ac.nz/~pgut001/misc/mercury.txt

IAEA. (2007). *Status of Small Reactor Designs Without On-Site Refuelling.* Austria: IAEA.

INSP. (1999, February 22). *Beloyarsk Nuclear Power Plant*. Retrieved from International Nuclear Safety: http://insp.pnl.gov/-profiles-beloyarsk-be.htm

IRD. (n.d.). *Repairs and Maintenance to the Tax Depreciation Rules*. Retrieved from Inland Revenue Department: http://taxpolicy.ird.govt.nz/publications/files/html/depreciationpaper/c2.html

IRIS. (2006, February). IRIS Project.

Kiev, A. B. (2005, April 21). *Russian Duma Calls for National Strategy Favoring Fast Reactors.* Retrieved from Our Energy World: http://www.ourenergyworld.com/russianbreeder.htm

Lisitsyn, P. (2009, February 09). *Visual Iran*. Retrieved from http://visualrian.com/images/item/443271

MIT. (2003). *The Future of Nuclear Power.*

NEA. (2000). *Reduction of Capital Costs of Nuclear Power Plants.* Paris: NEA.

News, W. N. (2009, September 11). *PBMR Postponed.* Retrieved from World Nuclear News: http://www.world-nuclear-news.org/NN-PBMR_postponed-1109092.html

Nikiet. (n.d.). *BREST.* Retrieved from Department of Marine Nuclear Power Systems and Innovative Designs: http://www.world-nuclear.org/info/inf98.html

OECD. (2001). *Trends in the Nuclear Fuel Cycle.* Paris: OECD.

OECD. (2007). *Uranium 2007: Resources, Production and Demand.*

OPA. (2005). *Supply Mix - Analysis Report.* OPA.

PBMR. (n.d.). *About Us*. Retrieved from PBMR: http://www.pbmr.co.za/index.asp?Content=167

PBMR. (n.d.). *How the PBMR Works*. Retrieved from PBMR: http://www.pbmr.co.za/index.asp?Content=223

Pfister, B. (2008, June 28). *China Wants 100 Westinghouse Reactors*. Retrieved from Pittsburgh Tribune Review: http://www.pittsburghlive.com/x/pittsburghtrib/s_575073.html

Physics, H. (n.d.). *Nuclear Fission*. Retrieved from Hyper Physics: http://hyperphysics.phy-astr.gsu.edu/HBASE/nucene/fission.html

Popp, D. (2008, December 10). AP1000 Safety Case Overview. Pittsburgh, United States of America.

Powell, D. (n.d.). Westinghouse AP1000 UK Equipment Supplier Launch. United Kingdom.

Robertson, J. (2004). *Can CANDU Estimates be Trusted?*

Rodwell, E. (2002). *Siting Guide: Site Selection and Evaluation Criteria for an Early Site Permit Application.*

RTDB. (1996). *CANDU 6 Reference Technology Data.* Retrieved from IAEA Refernce Technology Database: http://www.iaea.org/OurWork/ST/NE/Pess/RTDB/RTDB_Data/C_Level-VI-NU_061.htm

Short, W., Packey, D. J., & Holt, T. (1995). *A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies.* Colorado: National Renewable Energy Laboratory.

Simmons, J. (2009, June 10). B&W Introduces Scalable, Practical Nuclear Energy. Washington DC, United States of America.

Tourist, N. (2006, February 17). *Boiling Water Reactor*. Retrieved from The Virtual Nuclear Tourist: http://www.nucleartourist.com/type/bwr.htm

Tourist, N. (2003, April 12). *CANDU and Heavy Water Moderated Reactors*. Retrieved from The Virtual Nuclear Tourist: http://www.nucleartourist.com/type/candu.htm

Tourist, N. (2009, April 13). *Gas Cooled & Advanced Gas Cooled Reactors*. Retrieved from The Virtual Nuclear Tourist: http://www.nucleartourist.com/type/gcr.htm

Tourist, N. (2005, December 19). *Pressurized Water Reactor*. Retrieved from The Virtual Nuclear Tourist: http://www.nucleartourist.com/type/pwr.htm

Transpower. (2009). *HVDC*. Retrieved from Transpower - Grid New Zealand: http://www.gridnewzealand.co.nz/hvdc

Tutor2u. (n.d.). *Balance Sheet - Fixed Asset Depreciation*. Retrieved from Tutor2u: http://tutor2u.net/business/accounts/assets_fixedassets_depreciation.asp

UNENE. (n.d.). *Past Exams.* Retrieved from University Network of Excellence in Nuclear Engineering: www.unene.ca/un702-2009/qbank/20090402145241501.pdf

USNRC. (2006, January). *Issued Design Certifictation - Advance Passive 1000*. Retrieved from Nuclear Regulatory Commission: http://www.nrc.gov/reactors/new-reactors/design-cert/ap1000.html

Westinghouse. (n.d.). AP1000 Technology Fact Sheet.

Westinghouse. (2007). *Design Control Document- Steam and Power Conversion System - Turbine-Generator.*

Whitlock, J. (2009). *CANDU Technology*. Retrieved from The Canadian Nuclear FAQ: http://www.nuclearfaq.ca/cnf_sectionA.htm#a

WNA. (2009, October). *Fast Neutron Reactors*. Retrieved from World Nuclear Association: http://www.world-nuclear.org/info/inf98.html

WNA. (2009). *Fuel Fabrication.* Retrieved from World Nuclear Association: http://www.world-nuclear.org/how/fuelfabrication.html

WNA. (2009, April). *Nuclear Energy Prospects in New Zealand*. Retrieved from World Nuclear Association: http://www.world-nuclear.org/info/inf97.html

WNA. (2009, April). *Nuclear Power Reactors.* Retrieved from World Nuclear Association: http://www.world-nuclear.org/info/inf32.html

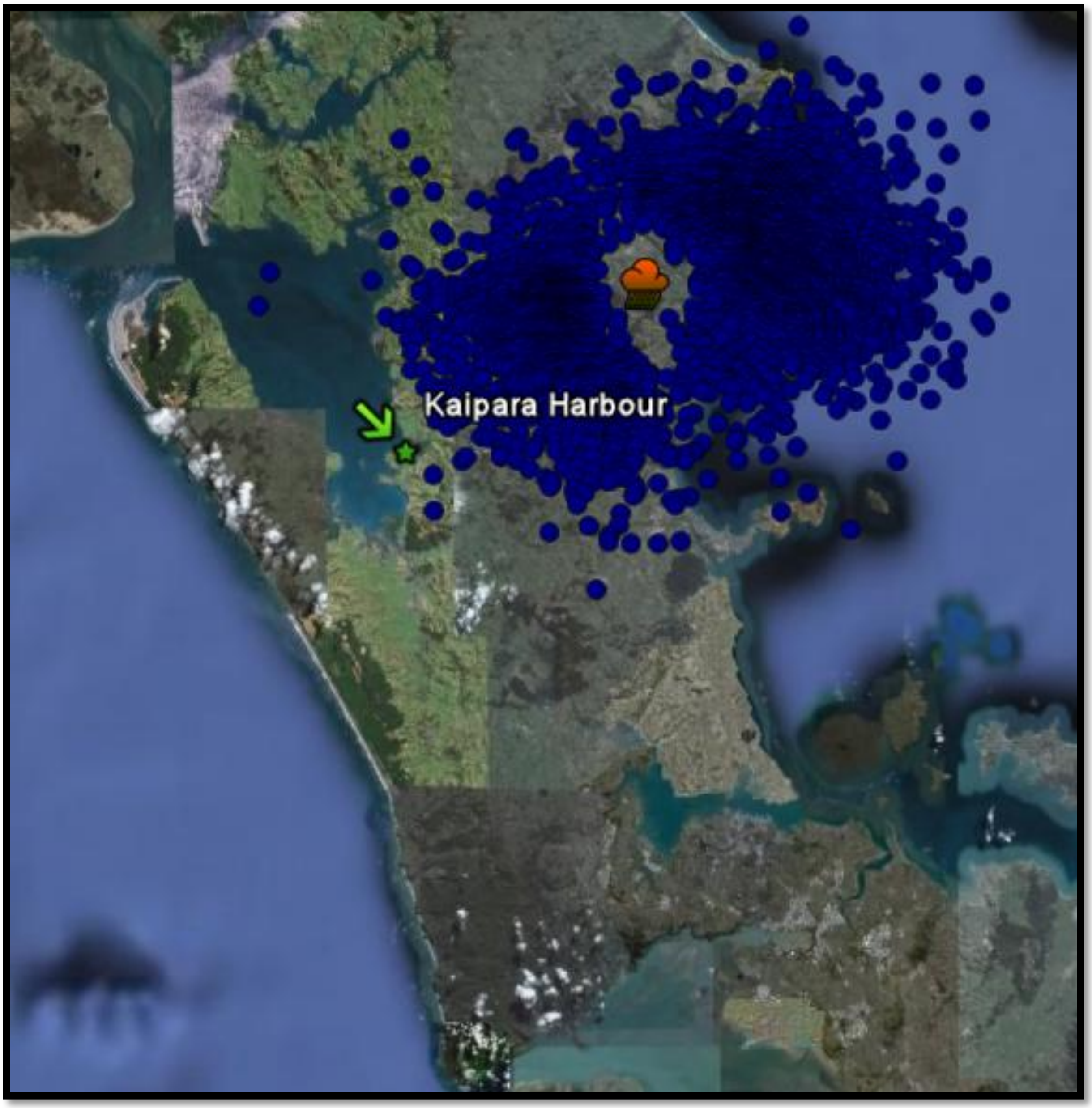
WNA. (2009). *Reactor Database*. Retrieved from World Nuclear Association: http://www.world-nuclear.org/rd/#1

WNA. (2009, January). *The Nuclear Fuel Cycle*. Retrieved from World Nuclear Association: http://www.world-nuclear.org/info/inf03.html

Zhang, Z., Wu, Z., Wang, D., Xu, Y., Li, F., & Dong, Y. (2009, February 27). Current Status and Technical Description of Chinese 2 x 250MWth HTR-PM Demonstration Plant. Beijing, Tsinghua, China.

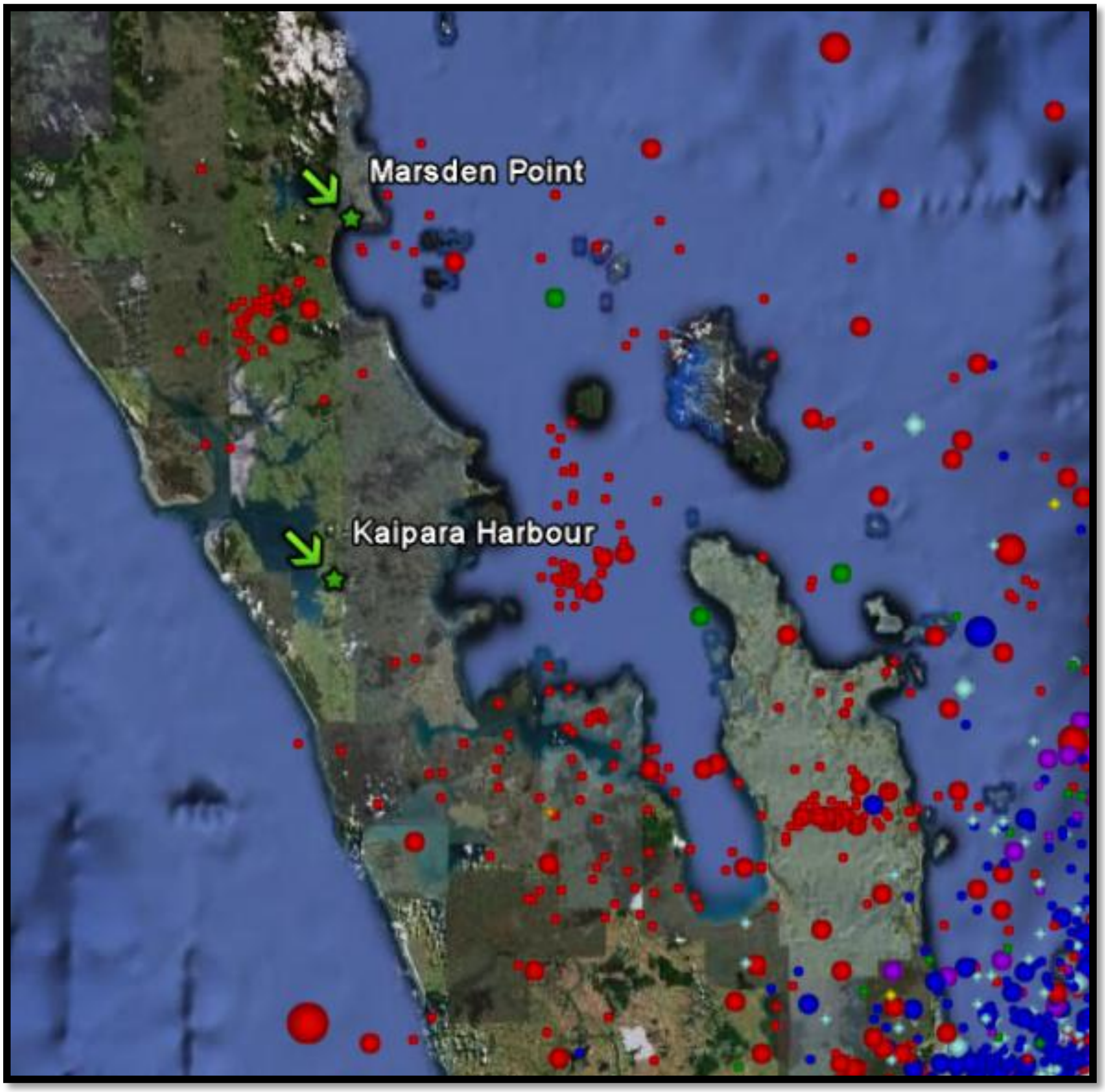
Appendix A

Wind Data



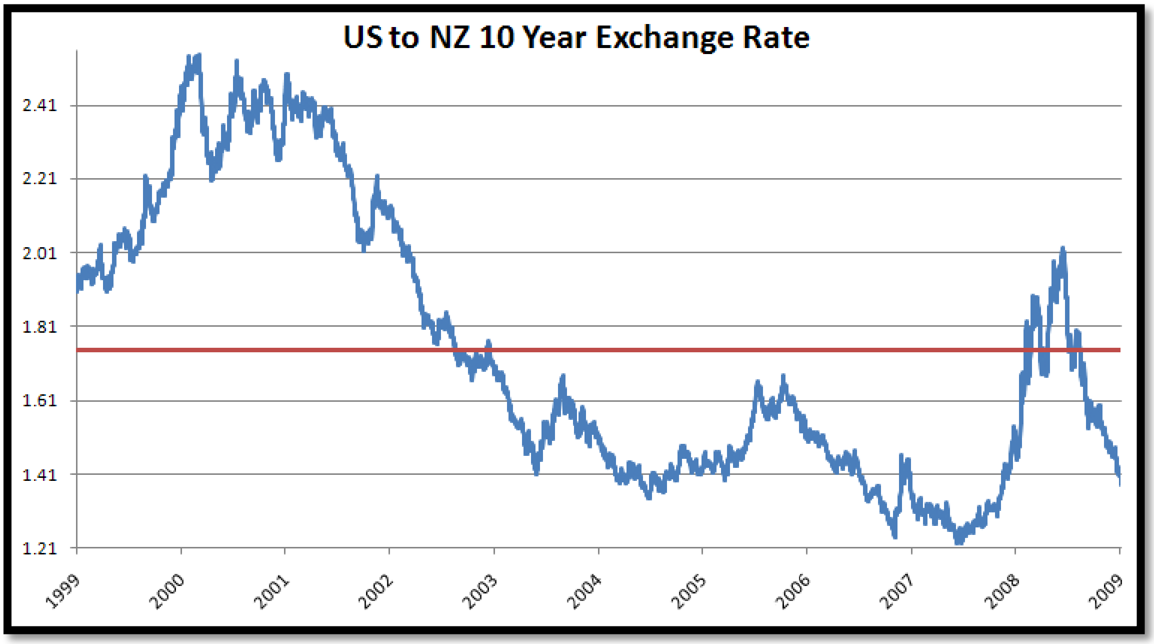
Each blue dot represents the average daily wind speed over a ten year period. It can be seen that the predominant wind directions are south west and north east. This data was obtained from http://cliflo.niwa.co.nz/.

Seismic Data



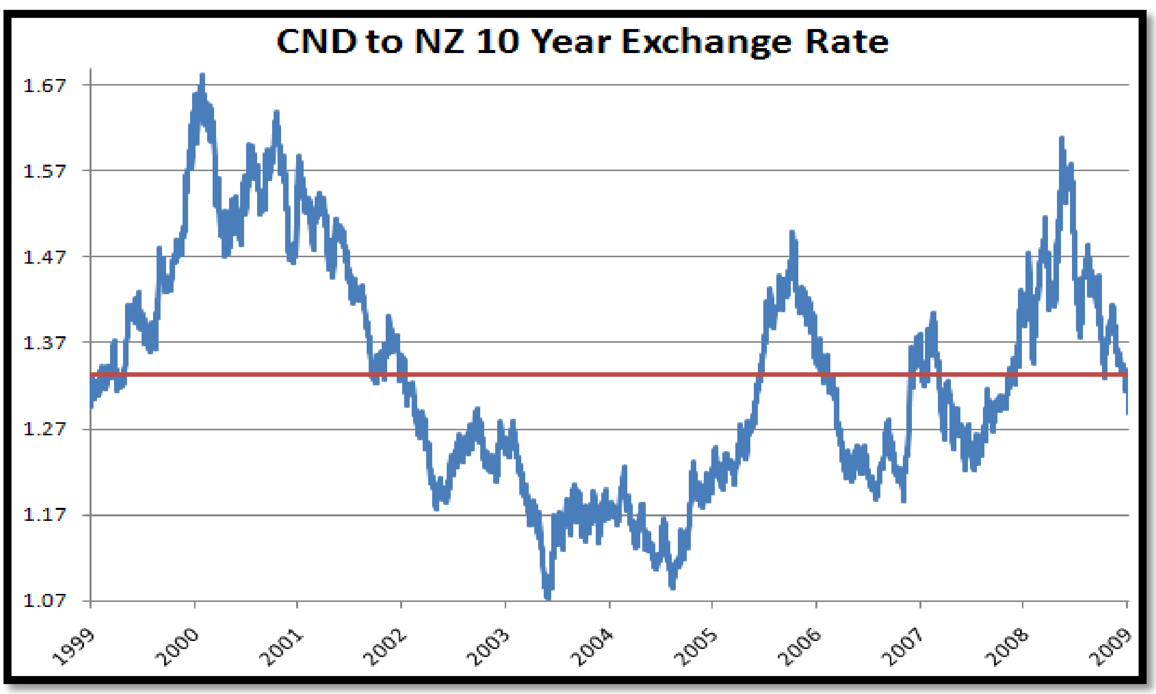
The two possible site locations are located on the map above. The dots on the map above represent historical seismic activity. Red represents seismic activity that has been close to the surface and the size of the dot represents the magnitude of the seismic activity. It can be seen that there is limited seismic activity near both of these locations. This information has been obtained from http://magma.geonet.org.nz/resources/quakesearch/.

US to NZD Interest Rate



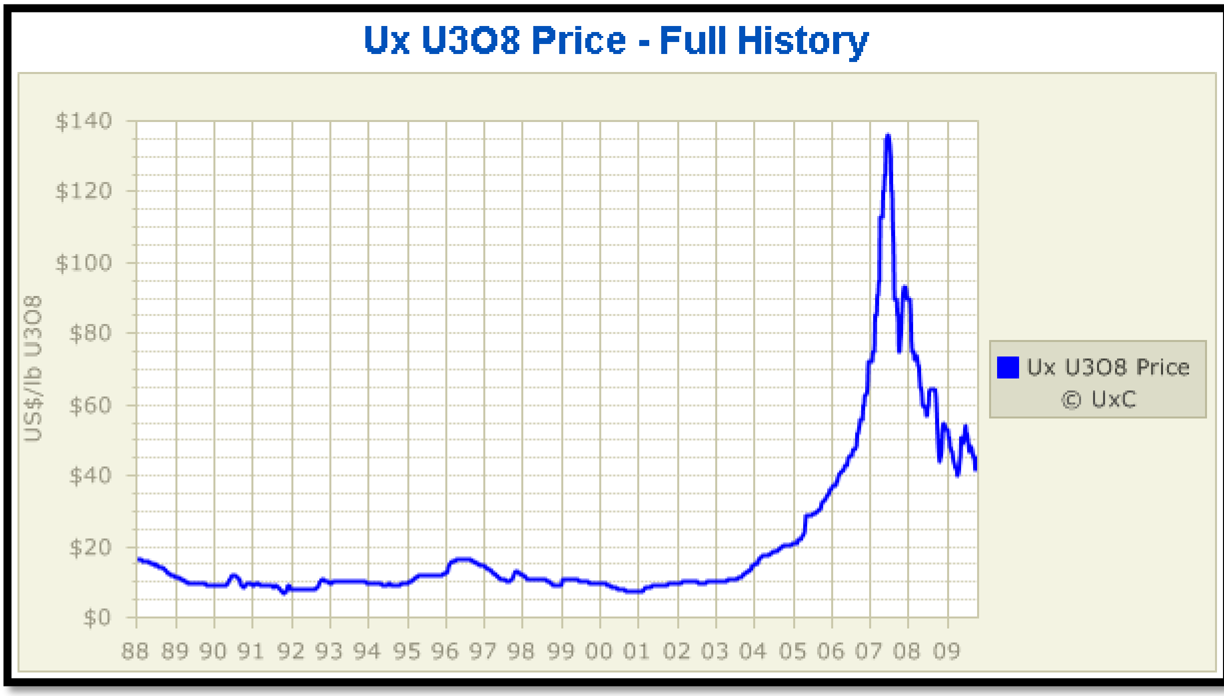
This information has been found from http://www.oanda.com/convert/fxhistory

CND to NZD Interest Rate



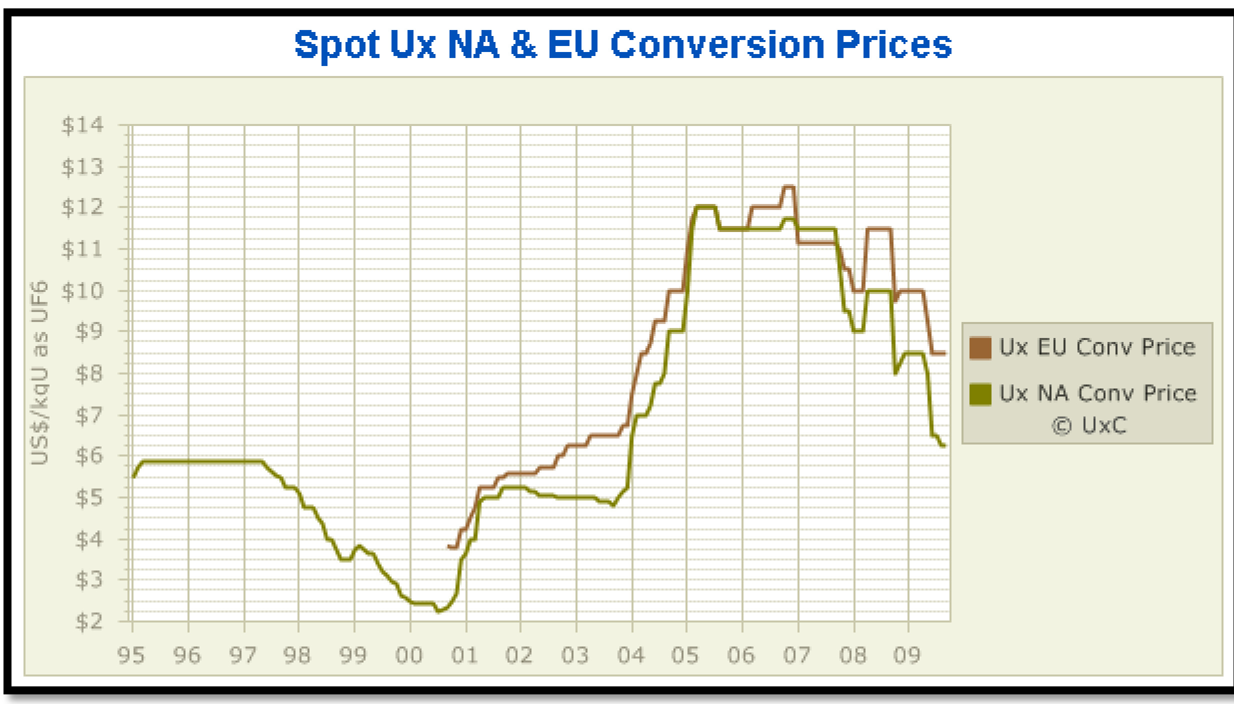
This information has been found from http://www.oanda.com/convert/fxhistory

Uranium Price Change



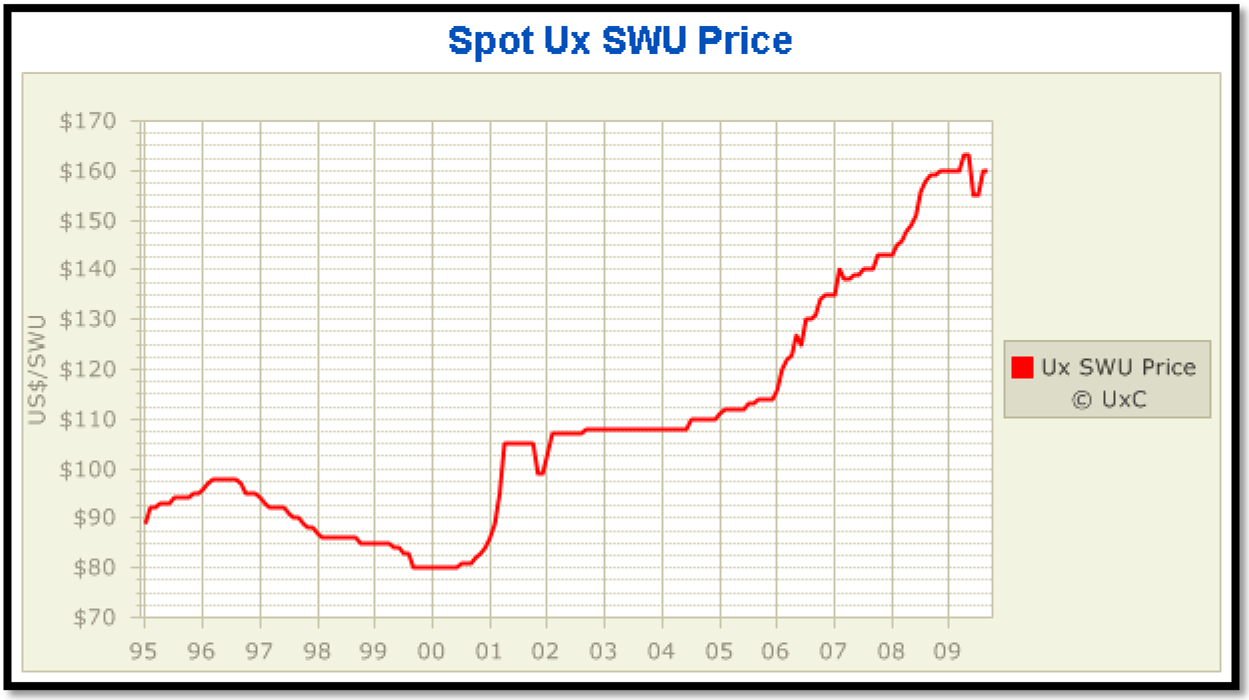
This information has been found from http://www.uxc.com/review/uxc_Prices.aspx

Conversion Price Change



This information has been found from http://www.uxc.com/review/uxc_Prices.aspx

Enrichment Price Change



This information has been found from http://www.uxc.com/review/uxc_Prices.aspx

Appendix B

Correspondence

Email correspondence, on Fri, 25 Sep 2009 at 17:19:42,

From: Kiran Nanu, Generation Engineer at Contact Energy.

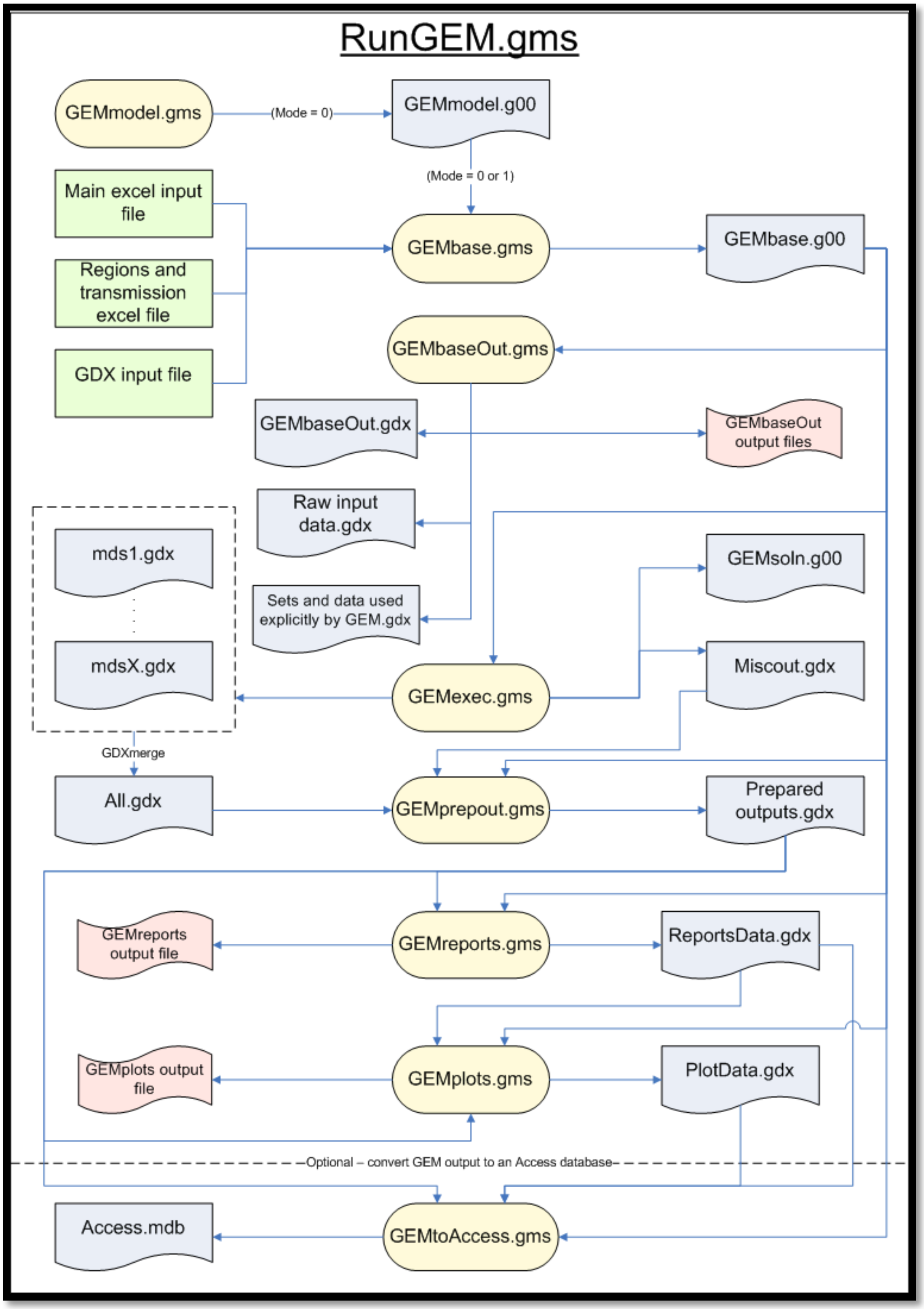
To: David Nutt, Programme Leader, Bachelor of Engineering, Auckland University of Technology.

David
There is no simple answer to this question as there are many factors which affect reserve generation such as grid constraints and the performance of the units providing backup. If one of the larger 350 - 400MW machines or DC link trips off the shortfall has to be made up by other generators or load reduction. There is a reserve market where reserve generation and load shedding is contracted by the market and generally the larger generating units pay for most of the reserve. Transpower will try to ensure that they have enough reserve generation to cover the largest contingency effect such as Otahuhu B tripping. Stations contracted for reserve will have enough spare generation available to cover the largest single event. So if an Otahuhu B trip at 380MW is the largest event there will be approximately 380MW reserve generation available, however grid constraints may prevent all the reserve generation from maintaining the pre-event levels. The speed at which the reserve generation picks up the load is also critical as the shortfall has to be made up immediately or the frequency will not recover and load shedding will result. If any large generator finds the reserve costs are too high they may back off generation to lessen the amount of reserve they have to pay for. Stand by generation such as at Whirinaki takes up to 10 minutes to start up so short term reserve is provided by generators operating at reduced capacity. The System Operator (Transpower) continuously models the reserve requirements to ensure there is enough reserve to meet the grid performance targets at any time. Performance standards define the number and size of under frequency events allowed on the grid per year.

Regards
Kiran Nanu
Generation Engineer, Gas Turbines

Appendix C

GEM Flow Diagram



Obtained from https://gemmodel.pbworks.com/The+components+of+GEM

Matlab Code

This is the generic code that was used to calculate the LCOE. There was one for each technology; the code for gas is shown as it has an extra section to calculate the cost of carbon taxing.

```
clc %Clear the way, coming through!
clear
%%Economic Inputs

OCi      = 590;       %Overnight Cost $/kW (INITIAL VALUE)
OC_YR    = 2009;      %Cost given in this year
OC_C     = 2;         %CURRENCY (1 = NZ, 2 = US, 3 = CAN)
ICCi     = 10.2;      %Incremental Capital Costs $/kW/year (INITIAL VALUE)
ICC_YR   = 2007;      %Cost given in this year
ICC_C    = 2;         %CURRENCY (1 = NZ, 2 = US, 3 = CAN)
FOMCi    = 50;        %Fixed O&M Costs $/kW/year (INITIAL VALUE)
FOMC_YR  = 2009;      %Cost given in this year
FOMC_C   = 1;         %CURRENCY (1 = NZ, 2 = US, 3 = CAN)
VOMCi    = 4.25;      %Variable O&M Costs $/kW/year (INITIAL VALUE)
VOMC_YR  = 2009;      %Cost given in this year
VOMC_C   = 1;         %CURRENCY (1 = NZ, 2 = US, 3 = CAN)
FCi      = 6.33034;   %Fuel Costs $/mmBtu (INITIAL VALUE)
FC_YR    = 2009;      %Cost given in this year
FC_C     = 1;         %CURRENCY (1 = NZ, 2 = US, 3 = CAN)
WFi      = 0;         %Waste Fee $/kWh (INITIAL VALUE)
WF_YR    = 2009;      %Cost given in this year
WF_C     = 1;         %CURRENCY (1 = NZ, 2 = US, 3 = CAN)
DCi      = 0;         %Decomissioning Cost $ million (INITIAL VALUE)
DC_YR    = 2009;      %Cost given in this year
DC_C     = 1;         %CURRENCY (1 = NZ, 2 = US, 3 = CAN)

IR       = 0.025;     %Inflation Rate
OMRE     = 0.01;      %O&M Real Escalation
FRE      = 0.005;     %Fuel Real Escalation
TR       = 0.3;       %Tax Rate
WACC     = 0.08;      %Weighted Average Cost of Capital

UER      =1.748392;   %US to NZ Exchange Rate
CER      =1.331565    %CANADA to NZ Exchange Rate

%%Plant Inputs

CAP      = 410;       %Capacity MW
CF       = 0.85;      %Capacity Factor
HR       = 5829.38;   %Heat Rate Btu/kWh
PL       = 25;        %Plant Life

%%Time Inputs
```

```
CT      = 2;        %Construction Time
BY      = 2009;     %Base Year
CY      = 2013;     %Construction Year
YR      = 8760;     %Hours in a year

PC      = [ 0.5,0.5,0,0,0];  %Percentage of Construction Total

%%Carbon Inputs

CP1     = 20;       %Carbon Price 1 $/tCO2
CP2     = 40;       %Carbon Price 2 $/tCO2
CP3     = 60;       %Carbon Price 3 $/tCO2

%%Calculations

%Carbon Price

CP1a = CP1*(53.1*HR/1e6)/1000; %Carbon price @ $20/tCO2
CP2a = CP2*(53.1*HR/1e6)/1000; %Carbon price @ $40/tCO2
CP3a = CP3*(53.1*HR/1e6)/1000; %Carbon price @ $60/tCO2

for i=1:PL
   DER(i) = 1/PL;    %Depreciation Rate Straight Line Method
end

%ECONOMIC INPUTS

if (OC_C == 1)
OC      = OCi*((1+IR)^(BY-OC_YR));
else if (OC_C == 2)
OC      = UER*OCi*((1+IR)^(BY-OC_YR));
else if (OC_C == 3)
OC      = CER*OCi*((1+IR)^(BY-OC_YR)); %Overnight Cost $/kW (BASE YEAR VALUE, NZD)
   end
   end
end
if (ICC_C == 1)
ICC     = ICCi*((1+IR)^(BY-ICC_YR));
else if (ICC_C == 2)
ICC     = UER*ICCi*((1+IR)^(BY-ICC_YR));
else if (ICC_C == 3)
ICC     = CER*ICCi*((1+IR)^(BY-ICC_YR)); %Incremental Capital Costs $/kW/year (BASE YEAR VALUE, NZD)
   end
   end
end
if (FOMC_C == 1)
FOMC      = FOMCi*((1+IR)^(BY-FOMC_YR));
```

```
else if (FOMC_C == 2)
FOMC     = UER*FOMCi*(((1+IR)*(1+OMRE))^(BY-FOMC_YR));
else if (FOMC_C == 3)
FOMC     = CER*FOMCi*(((1+IR)*(1+OMRE))^(BY-FOMC_YR)); %Fixed O&M Costs $/kW/year (BASE YEAR
VALUE, NZD)
   end
end
end
if (VOMC_C == 1)
VOMC      = VOMCi*((1+IR)^(BY-VOMC_YR));
else if (VOMC_C == 2)
VOMC     = UER*VOMCi*(((1+IR)*(1+OMRE))^(BY-VOMC_YR));
else if (VOMC_C == 3)
VOMC     = CER*VOMCi*(((1+IR)*(1+OMRE))^(BY-VOMC_YR)); %Variable O&M Costs $/kW/year (BASE
YEAR VALUE, NZD)
   end
end
end
if (FC_C == 1)
FC      = FCi*((1+IR)^(BY-FC_YR));
else if (FC_C == 2)
FC      = UER*FCi*(((1+IR)*(1+FRE))^(BY-FC_YR));
else if (FC_C == 3)
FC      = CER*FCi*(((1+IR)*(1+FRE))^(BY-FC_YR)); %Fuel Costs $/mmBtu (BASE YEAR VALUE, NZD)
   end
end
end
if (WF_C == 1)
WF      = WFi*((1+IR)^(BY-WF_YR));
else if (WF_C == 2)
WF      = UER*WFi*((1+IR)^(BY-WF_YR));
else if (WF_C == 3)
WF      = CER*WFi*((1+IR)^(BY-WF_YR)); %Waste Fee $/kWh (BASE YEAR VALUE, NZD)
   end
end
end
if (DC_C == 1)
DC      = DCi*((1+IR)^(BY-DC_YR));
else if (DC_C == 2)
DC      = UER*DCi*((1+IR)^(BY-DC_YR));
else if (DC_C == 3)
DC      = CER*DCi*((1+IR)^(BY-DC_YR)); %Decomissioning Cost $ million (BASE YEAR VALUE, NZD)
   end
end
end

TT     = PL+CT; %Total time from construction to decomission
```

```
%%Inflation Factor
for i = 1:TT
   IF(i)=(1+IR)^(CY+i-BY-1); % (1+Inflation Rate)^(year - base year)
end

%%O&M Escalation Factor
for i = 1:TT
   OMEF(i)=((1+IR)*(1+OMRE))^(CY+i-BY-1); %((1+Inflation Rate)*(1+O&M Inflation Rate))^(year - base
year)
end

%%Fuel Escalation Factor
for i = 1:TT
   FEF(i)=((1+IR)*(1+FRE))^(CY+i-BY-1); %((1+Inflation Rate)*(1+Fuel Inflation Rate))^(year - base year)
end

%%Discount Factor
for i = 1:TT
   DTF(i)=1/(1+WACC)^((CY+i-1)-(CY+CT-1)); %1/(1+WACC)^Period, Period is 0 once plant is
commissioned, negative before and positive after.
end

%%LCOE, Amount of energy produced per year
for i = 1:TT
   if (((CY+i-1)-(CY+CT-1)) > 0) % If the period is greater than 0 then calculate the LCOE.
      LCOE(i)= DTF(i)*IF(i)*CF*CAP*YR/1e6; % Discounted/inflated (Capacity Factor * Capacity * hours
per year)
      else if (((CY+i-1)-(CY+CT-1)) <= 0)
         LCOE(i) = 0;
      end
   end
end

%Right Side
RS = sum(LCOE)*(1-TR); %Total - Tax Rate

%%Construction Costs Net of Depreciation Tax Shields
for i = 1:TT
   if (((CY+i-1)-(CY+CT-1)) <= 0)
   CCN(i)=DTF(1,i)*CAP*OC*PC(1,i)*IF(1,i)/1000; %Calculate the cost of the year in construction
   CCNC(i)=CAP*OC*PC(1,i)*IF(1,i)/1000; %Cost while constructing
   j=i; %Set j to equal i so that length of the array can be found and when it is maxed, stop calculating
otherwise errors occur.
   else if (((CY+i-1)-(CY+CT-1)) > 0) && (length(DER) >= i-j) %Check the array has not been exceeded.
      CCN(i)=DTF(1,i)*-TR*DER(1,i-j)*sum(CCNC); %Cost after construction.
      else if (length(DER) < i-j)
         CCN(i)=0; %Fill in the rest of the array with 0's
      end
```

```
   end
   end
end

%%Incremental Capital Costs and Decomission Costs
for i = 1:TT
   if (((CY+i-1)-(CY+CT-1)) > 0) && (i<TT)
   ICCDC(i)=DTF(1,i)*(1-TR)*(CAP*ICC*IF(1,i)/1000); %Find this cost per year
      else if (i==TT)
      ICCDC(i)=DTF(1,i)*(1-TR)*(CAP*ICC*IF(1,i)/1000+DC*IF(1,i)); %Once it the plant has reached the end
of its lifetime the decommissioning cost is included
         else if (((CY+i-1)-(CY+CT-1)) <= 0)
               ICCDC(i)=0; %Fill in the construction period with 0's
         end
      end
   end
end

%%Non-Fuel O&M Costs
for i = 1:TT
   if (((CY+i-1)-(CY+CT-1)) > 0)
   NFOMC(i)=DTF(1,i)*(1-TR)*(CAP*FOMC/1000+(VOMC*CF*CAP*YR/1e6))*OMEF(1,i); %Find this cost
per year
      else if (((CY+i-1)-(CY+CT-1)) <= 0)
      NFOMC(i)=0; %Fill in the construction period with 0's
      end
   end
end

%%Fuel Costs & Waste Fee
for i = 1:TT
   if (((CY+i-1)-(CY+CT-1)) > 0)
   FCWF(i)=DTF(1,i)*(1-TR)*(((CF*CAP*YR*FC*HR)/1e9*FEF(1,i))+(WF*CF*CAP*YR/1000)); %Find this
cost per year
      else if (((CY+i-1)-(CY+CT-1)) <= 0)
      FCWF(i)=0; %Fill in the construction period with 0's
      end
   end
end

%%Net Cost
NC = CCN+ICCDC+NFOMC+FCWF; %Net Cost in array format

%%Price ($/MW)
PMW = sum(NC)/sum(RS); %Price per MW for the base year.

%%Price ($/kW)
GAS_PkW = PMW/1000 %Price per kW for the base year.
```

```
%%Price ($/kW) + Carbon tax of $20/tCO2
Gas_PkW_CO2_1 = GAS_PkW+CP1a
%%Price ($/kW) + Carbon tax of $40/tCO2
Gas_PkW_CO2_2 = GAS_PkW+CP2a
%%Price ($/kW) + Carbon tax of $60/tCO2
Gas_PkW_CO2_3 = GAS_PkW+CP3a
```