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**Nuclear Power in New Zealand:  
A Question of Economics?**

A thesis presented in partial fulfilment of the requirements for the  
degree of

**Master of Arts**

in

**Economics**

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**New Zealand.**

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## **Abstract**

The purpose of this research is to investigate whether there is sufficient economic justification of the omission of nuclear energy from the policy sphere in New Zealand. Technologically speaking nuclear is a reliable and clean source of electricity, but concerns surround its safety and cost competitiveness.

In order to reach a relevant conclusion, a range of literature, scientific reports, cost data, and other various institutional publications have been evaluated. Consideration is also made of the political treatment of nuclear technology, with the understanding that nuclear power needs to gain acceptance in the eyes of the public and policymakers, not just prove economically competitive.

The findings of the research are two-fold. First, nuclear power is potentially economically competitive – when carbon cost estimations are taken into account. In the absence of any adjustments for emissions, the outcome is less clear. Nevertheless, this is promising in the case of New Zealand, which has a carbon trading scheme and a strong focus on emissions costs in its energy outlook. Secondly, the safety risks of a modern nuclear energy are not nearly as drastic as public perception may hold. The oft-quoted examples of Chernobyl and Three Mile Island are – in the case of a modern reactor design – irrelevant and encouraging, respectively. However, the findings also point to on-going challenges facing nuclear energy, particularly that of long-term waste disposal.

The author asserts that, on balance, there is no justification for simply dismissing nuclear as an energy option. Further research and an integration of the technology into the evaluation of possible future electric generation mixes would be desirable, in order to reach a definitive conclusion about the possible role of nuclear generation in the NZ energy sector.



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## 1. Introduction

Within the New Zealand context, discussion on the topic of nuclear power is noticeably lacking. Academic literature on the topic is remarkably scarce, as is coverage in government publications. Hansard, a database of debates from Parliament, returns 38 results for “nuclear power” over the last decade, the majority of which are only brief mentions. The last major attention paid to the possibility of nuclear energy in New Zealand was the Royal Commission of Enquiry’s report entitled “Nuclear Power Generation in New Zealand”, which is dated April 1978. Present day discussion on nuclear affairs seems largely confined to the issue of nuclear-powered ships docking in NZ ports. Indeed, there is perhaps some irony in the situation, given that this is the country that was home to Ernest Rutherford, otherwise known as the father of nuclear physics (see Chapter 2). This state of affairs is a large part of the rationale for this research project. When public feelings over nuclear energy run so strongly, the absence of discussion is that much more surprising. From an academic perspective, a valuable purpose of research is examining areas that might otherwise have been neglected in order to yield useful conclusions.

Nuclear energy is a broad and relatively controversial topic, which is reflected in the fortunes of the industry. “A source of great hope in the 1950s, a focus of great fear in the 1980s, nuclear energy has never become a commonplace of everyday life.” (Nuclear Energy Agency, 1991). After entering in commercial operation during the late 1950s, the technology was adopted rapidly, with installed capacity quickly expanding. The 1970s and 80s saw spiralling costs driven by increased litigation, although the oil crises of 1973 and 1979 prompted countries with a significant reliance on oil for energy generation to move towards the nuclear option. The most notable example is France, for whom nuclear energy supplies about 75 percent of electricity generated – see Appendix A. The concurrent incidents at Three Mile Island and Chernobyl<sup>1</sup> fuelled a groundswell of public opinion against the technology, and such concerns, along with the stigma of association with the nuclear bomb, have damaged the public perception of the technology.

Nuclear power as an industry is composed of a variety of economic interrelationships. Quoting from an OECD report on the economic impact of nuclear power (Nuclear Energy Agency, 1992, pp. 51-52):

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<sup>1</sup> Refer to sections 4.3 and 4.4 for case studies on these two incidents.

*The nuclear industry comprises reactor designers and constructors, reactor component manufacturers, reactor operators, and the associated mining, conversion, fabrication, storage, reprocessing and waste management and disposal functions associated with the fuel cycle. The associated infrastructure includes education, research and development, and the planning, regulatory and inspection functions. In total these make a small but significant contribution to the economic activity of the OECD nations.*

Nuclear has held at least the promise of cheap, clean, and reliable energy, a combination not readily matched by alternative sources. This prompts the key question driving this research project: is the present policy attitude toward nuclear power (i.e., complete exclusion) justified by the historical experiences and current data on nuclear energy? The country faces the looming challenges of climate change and energy security, which it must reconcile with the desire to keep electricity prices as low as possible. Electricity itself is a vital commodity for maintaining and improving living standards, since it facilitates much of the production of goods and services that underpin Western society. Economics at its core is about production, consumption, and distribution, and economists as a whole are generally concerned about the efficient allocation of resources. In terms of economic policy analysis, the exclusion of any option with the potential to provide an efficient solution to the problem of scarce resources suggests weakness in the ability of the process to reach an optimal outcome.

Therefore, this thesis conducts an appraisal of a range of literature in order to evaluate whether there is sufficient economic and scientific evidence to dismiss the nuclear power option outright, or whether there are wider political motivations. In turn, the limitations of the research should be acknowledged. This thesis does not set out to draw definitive conclusions about the viability of nuclear power (in terms of costing and risk), nor to provide a conclusive answer as to how New Zealand's future energy requirements should be met: such a goal is beyond the scale and scope of this project. Rather, it aims to provide exploratory research, examining a range of primary and secondary sources to see whether or not sufficient justification for more constructive research exists.

## **1.1. Methodology**

This thesis is not a traditional quantitative analysis, but rather it has a mix of qualitative and quantitative components. In terms of the topic at hand, there is a large quantity of available data and reports that provide considerable insight into nuclear

power. These have been used as the basis for a systematic assessment in preference to estimating a model and interpreting the results, with the narrowed perspective and necessary assumptions that the latter requires. The intention is to evaluate and investigate a range of sources (subject to the size and time limitations of the project) to provide concise and useful conclusions in a New Zealand context, where it is not commonly applied. The thesis synthesises a range of existing conclusions from a range of sources to provide an analytical perspective as to whether domestic energy policy discussion might potentially be improved by bringing nuclear electricity generation to the table.

Thus the research is similar in nature to a systematic review, a methodology often used in healthcare. It begins with a defined question (is the present energy policy stance justified by an economic analysis of nuclear generation?) and searches a range of literature for relevant input. Both traditional and 'grey' literature is employed to this end, and the resulting material is filtered for eligibility. When examining the costs of nuclear reactor construction and operation, for example, data from the previous 5 – 10 years are the most relevant, while the use of older figures is largely restricted to providing insight into the historical experience of the nuclear industry. Once selected, material is weighed and (where appropriate) subjected to a critical appraisal in order to synthesise conclusions and contextualise them to the domestic context of the research question. It should be noted that the examination of the costs and benefits of nuclear electricity generation has been made solely in terms of quantifiable characteristics: no estimation has been made of intangible preferences for power generation methods (for example, the aesthetics of wind farms or hydro dams). However, in terms of the later examination of the political and public debate over nuclear energy,

This approach was necessitated by the broad-based nature of the research topic. Evaluating nuclear power in the New Zealand context requires the consideration of two major subtopics, cost and safety, for which there is no historical domestic experience. Consequently, a less traditional structure was selected in order to provide a more appropriate analysis. This is first and foremost an economics thesis, but it intends to be economics applied to investigating the prevalent perspectives and beliefs in the policy-making environment, because these are the realities that ultimately determine the allocation of scarce resources.

The ease of access provided by the internet has enabled the use of material from institutions such as the International Atomic Energy Agency (IAEA), Nuclear Energy Association (NEA), and World Nuclear Association (WNA) to be utilised, which has been invaluable in providing accurate and up-to-date information on the nuclear

industry. Use of the internet has also facilitated the exploration of very specific sources, such as safety reports from the United States Nuclear Regulatory Commission (NRC), information on international radiation levels, etc., that would have otherwise been very difficult to acquire. Iterative keyword searches on databases such as ScienceDirect have been a key approach in engaging resources from journals such as Energy Economics, while other online tools such as Google Scholar have been used to follow the links between different sources.

## **1.2. Chapter Structure**

In order to provide an answer to the question of whether the current policymaking attitudes towards nuclear power are justified, two key areas will be investigated. As a prerequisite, Chapter 2 begins with a short historical background to familiarise the reader with the basic history of the nuclear industry, then continues on to a discussion of the New Zealand electricity sector. This forms an understanding of the role nuclear might play, and the technologies it must necessarily compete. Chapter 3 provides the first of our key topics, an examination of the costs and benefits of nuclear reactors, using figures primarily sourced from the OECD (since these countries provide the most transparent and readily available data on their nuclear industries). The focus here is on comparing and contrasting nuclear power with competing technologies in economic terms: in short, its cost effectiveness. Chapter 4, the second key topic, investigates the – often polarising – safety issues associated with nuclear energy: both the well-publicised risks of serious incidents (such as ‘meltdowns’) and general issues of radiation, waste, occupational hazard. It is fair to say that these two chapters form the core of the thesis: cost and safety might be considered as the two sides of the nuclear coin, at least in terms of making policy decisions.

With the conclusions of the preceding two chapters in mind, Chapter 5 discusses the interrelationships between nuclear energy, public opinion, and political will. The purpose of this chapter is twofold. First, it seeks to broaden the perspective of the thesis and acknowledge the realities of politics, where rhetoric is often as important as debate or dialectic. Secondly, it also seeks to judge the public and political treatment of nuclear energy, by investigating how informed popular opinion and debate on the topic is. Taken as a whole, it attempts to provide insight into how the nature of New Zealand’s political paradigm influences the treatment (or lack thereof) of nuclear energy. Lastly, Chapter 6 provides a final conclusion, summarising the findings of the preceding chapters and considering possible directions for future research.





## **2. International Experience and Domestic Relevance**

This chapter takes the first step towards answering the key question. Sections 2.1 and 2.2 provide a short historical background to illustrate that nuclear itself is not a static technology, but is continually evolving and improving. Indeed, nuclear is a relatively young and exciting technology, and is experiencing much greater technological advances than most generation options. Even if this thesis were to conclude that nuclear is so untenable in the New Zealand context that it could be completely disregarded, how long that conclusion would remain valid is almost impossible to predict.

Section 2.3 is particularly vital to this project, discussing New Zealand's present and future electricity requirements and investigating how nuclear might play a role. This is a key step towards answering the question posed by this thesis, as it provides a context and the justification for the analyses of cost and safety that follow in Chapters 3 and 4, and establishes which technologies nuclear would specifically compete against.

### **2.1. Origins and Adoption of the Technology**

The sciences of atomic radiation, atomic change, and nuclear fission itself began in 1895, when Wilhelm Rontgen discovered radiation in a form commonly known today as x-rays. Perhaps most notably, in 1919 it was a New Zealander, Ernest Rutherford (who has since become known as the father of nuclear science), who first successfully split the atom (Craats, 2000, p. 27). Researchers continued to make advances over the succeeding years, but the most rapid developments occurred during the 1939-45 period, World War II, the era in which the nuclear bomb was developed.

In the wake of the war, focus shifted to more peaceable civil applications for nuclear technology. The first reactor to produce electricity in any amount, rather than just material for bombs, was started up in December of 1951, in Idaho, USA. Two years later, President Eisenhower introduced the Atoms for Peace program, which redirected research efforts and laid out the path for civil nuclear development in the USA. The then-Soviet Union also directed research towards energy needs, launching the world's first dedicated, nuclear-powered electricity generator in 1954, the AM-1, which produced five<sup>2</sup> MWe (and was used for research up until 2000). Shortly thereafter, in 1955, the first nuclear powered submarine (the USS Nautilus) became operational (World Nuclear Association, 2010b). In 1959, the Soviets completed the BR-5, which

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<sup>2</sup> To put this in perspective, in 2002 NZ would have required around 7,000 of these to meet domestic energy requirements.

was upgraded in 1973 and again in 1983 to become the BR-10, which is still used at present for research purposes (World Nuclear Association, 2010g).

Further US efforts led to the Pressurised Water Reactor (PWR), intended originally for naval (specifically submarine) usage. The PWR design utilised enriched (processed) uranium, and importantly, was cooled by ordinary water. This development gave rise in turn to the US Atomic Energy Commission building a demonstration 60 MWe reactor in Pennsylvania, which ran for five years from 1957. Given the relative US monopoly on enriched uranium, British development focused on different designs utilising different fuel sources, but eventually they too moved to the PWR model (World Nuclear Association, 2010g).

1960 saw the inception of the first fully commercial reactor, with Westinghouse building a 250 MWe PWR-type reactor in the US (which operated until 1992). Around the same time, an alternative design, the boiling water reactor (BWR) was also developed. By the end of the decade, both PWR and BWR reactors were being built to supply in excess of 1000 MWe. Like the British, Canada developed their own design using natural uranium as fuel, but they have resisted the move to PWR, continuing to refine their technology. France, one of the most successful countries in employing nuclear energy, settled on the predominant PWR design after brief experimentation with other options (World Nuclear Association, 2010g). Today, around 60 percent of global nuclear energy is PWR, and 21 percent is BWR, with the remaining 19 percent composed of a mix of reactor design variations (see Appendix B).

## **2.2. Decline in Public Support**

However, the period from the late 1970s through to around 2002 saw an overall deterioration in the nuclear power sector.

*“Few new reactors were ordered, the number coming on line from mid 1980s little more than matched retirements, though capacity increased by nearly one third and output increased 60% due to capacity plus improved load factors. The share of nuclear in world electricity from mid 1980s was fairly constant at 16-17%. Many reactor orders from the 1970s were cancelled. The uranium price dropped accordingly, and also because of an increase in secondary supplies. Oil companies which had entered the uranium field bailed out, and there was a consolidation of uranium producers.”* (World Nuclear Association, 2010g)

In large part, these declines stemmed from a major deterioration in public support for nuclear power. The origins of this shift can be traced to two notable events circa 1978. A fictional movie called *“The China Syndrome”* debuted, wherein a nuclear meltdown

took place. In the movie plot, the molten fuel ate down until it came into contact with groundwater,<sup>3</sup> creating a steam explosion that ruptured the plant's containment system. The film was released 12 days prior to the actual meltdown at Three Mile Island, which itself created a storm of controversy and media-fuelled public panic as a result of miscommunication between officials. Seven years later, the Chernobyl disaster occurred, an event with much more dire consequences than Three Mile Island, which further reinforced public distrust of nuclear energy. Public disapproval has since extended beyond the presence of reactors; a fact illustrated as recently as November 2010 by violent demonstrations in Germany over shipments of high-level waste (Brown, 2010).

The decline in support was certainly not limited to the US, either. Austria, Sweden, and Italy voted in referendums to phase out or limit nuclear energy, and public opposition in Ireland prevented a nuclear programme from developing there. New Zealand, of course, passed the Nuclear Free Zone, Disarmament, and Arms Control Act 1987, making all territorial sea, land and airspace of the nation into a nuclear-free zone (although, strictly speaking, NZ is not nuclear free: see section 5.2). The act remains a major part of New Zealand foreign policy today, especially in terms of relations with the US. However, the Act does not forbid land-based nuclear reactors from being built. Consequently, there are no legal obstacles to a nuclear power programme in the country (World Nuclear Association, 2010c).

### **2.2.1. Recent Developments**

The industry began to show signs of recovery in the late 1990s, when a 1350 MWe BWR was commissioned in Japan. Moving into the new century, the projected increases in electricity demand, the importance of energy security, and environmental concerns (specifically carbon emissions) have all led to a revival in interest in nuclear solutions.

In 2004, Finland ordered the construction of a new PWR reactor supplying around 1600 MWe. US President Obama announced US\$8 billion in loan guarantees for the construction of a nuclear plant, describing the move as a necessary step in light of carbon pollution issues (Associated Press, 2010). In East Asia, plans are even larger; China alone plans to increase nuclear power's share of total generating capacity from 1.9 percent to over 10 percent by 2020, and has more than one hundred large units proposed. Nuclear technology itself has experienced considerable potential in recent years. Along with continued improvement of burnup in standard nuclear reactors, some interest is also being shown towards breeder reactors, which produce additional

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<sup>3</sup> Hence the name: a hyperbolic reference to the fuel melting through to China.

fuel as they operate, and can run on natural uranium (not requiring an enrichment process) or thorium (four times more common than uranium) (Lide, 2004). India in particular has shown interest in the thermal breeder type using thorium, since the element is far more abundant within its geographic borders than uranium. The current Prime Minister, Manmohan Singh, has expressed a desire to see up to 470,000 MWe of generating capacity created by 2050, utilising the technology (Ramesh, 2009).

As of July 2010, there are 439 power reactors in operation, generating a combined total of 373 gigawatts, or about 16 percent of global requirements; 61 are under construction globally. Refer to Appendix A for a chart demonstrating the share of generation capacity accounted for by nuclear power in the various countries employing it. In addition, approximately 150 ships are powered by small nuclear reactors, with over 12,000 reactor years of marine operation having been accumulated. A focus on personnel training and design standardisation has resulted in an unmarred safety record for the US Navy. The then Soviet navy, conversely, experienced a number of major incidents, but by the 1970s a renewed dedication to safety saw a much-improved operating record result (World Nuclear Association, 2010b).

In terms of future prospects, the most interesting analyses are those from the Intergovernmental Panel on Climate Change (IPCC), which is strongly focused on mitigating the effects of greenhouse gas. Their 2007 reports include a range of factors, most notably:

1. Energy requirements calculated on the basis of improving international living standards, rather than simply maintaining current trends.
2. The threat of fossil fuel depletion.
3. A focus on the most economically optimal decisions in the long-run, rather than accepting restrictions of present political attitudes.

The IPCC analysis posits an important role for nuclear power in the long term, specifically as a tool for reducing fossil fuel consumption. Whether public and political attitudes can or will evolve to allow for this remains to be seen (Moore). A more traditional analysis from the International Atomic Energy Agency (IAEA) shows steady growth for the industry, with electricity generated from nuclear sources increasing by about 70 percent from 2002 to 2030. However, the overall growth of electricity generation is expected to exceed that figure, resulting in nuclear power's share declining (International Atomic Energy Agency).

### **2.3. Nuclear Energy and the Electricity Market**

New Zealand's energy market is split into components by legislation, namely the Electricity Industry Reform Act 1998 and the Electricity Amendment Act 2001. The most notable feature of the legislation is the separation of generation and distribution. There are five primary generation companies at present, three of whom are state-owned enterprises or SOEs (Genesis Energy, Meridian Energy, and Mighty River Power). The remaining two, Contact Energy and TrustPower, are publicly owned. Given the relative size of the companies (see Appendix C), Genesis and Meridian are conceivably the most able to effectively construct and run a nuclear plant with government support.

It has been argued that nuclear generation tends to be more attractive when constructed by a state-owned provider (Roques, Nuttall, & Newbery, 2006). The reasoning is that such providers can generally guarantee output requirements over a longer time-horizon than private competitors, and exploit the low operating costs and economies of scale inherent in the technology. It is unlikely that a nuclear plant could or would be constructed at an efficient scale by one of the private competitors in the generation market, at least given their size in the New Zealand market.

Nevertheless, there are some pitfalls to an SOE undertaking a nuclear power programme. Most existing nuclear reactors have been constructed under such an arrangement, and the experience has been that the associated uncertainties have not always been given due consideration. Specifically, it has been shown that if sufficient weight had been attached to factors such as construction, regulatory and operating performance uncertainties, fuel price fluctuations, predicted prices for alternative energy sources, etc., the calculated cost of capital would have been higher than traditionally estimated (Deutch et al., 2003, p. 37). As with any government-backed venture where the investors do not bear the risks personally, some form of independent oversight is vital.

Complicating the picture is the incumbent (at the time of writing) National party's plans to sell up to half its shares in Meridian and Genesis should it be successful in its bid for re-election in 2011. Such a move would be controversial to say the least, but in terms of the issue at hand, money from the same could be used to fund more capital for the companies, and international ownership could lead to expansion (Collins, 2011). Internationally, electricity supply markets are trending away from vertical integration and towards a more competitive structure. In these cases, future nuclear reactors will have to be built as merchant plants: generators whose construction is not paid for by

the consumer. Investors must bear all the risks of construction, relying on the successful completion and subsequent production of electricity to recoup their costs. In this case, preferences tend towards investments with shorter, less capital-intensive construction times (Deutch et al., 2003, pp. 37-38). It remains to be seen how well nuclear will perform under this marked structure.

Returning to the New Zealand electricity market, domestic demand has been growing by 1.6 percent annually since 1990. The Ministry of Economic Development predicts this will slow to 1.4 percent in the period from 2010 to 2030. New Zealand’s electricity supply is currently dominated by hydro generation, supported by gas, coal, geothermal and wind. 9,486 MW of capacity<sup>4</sup> was used to generate 39,436 GWh of electricity in 2009 (Ministry of Economic Development, 2010a). Under the MED’s reference scenario, which includes a carbon emissions price of \$50/tonne, capacity is predicted to rise to 14,856 MW with 55,127 GWh generated in 2030. This is expected to be achieved primarily<sup>5</sup> by the following increases in generation sources:

<b>Table 2.1: Predicted capacity increases (2010-2030, MW)</b>				
Gas	Coal	Hydro	Wind	Geothermal
1,292	470	1,579	744	905

Source: (Ministry of Economic Development, 2010b)

Notably, the price increases of the last decade are also forecast to continue: projections show the real wholesale electricity price rising from about \$80 MWh to over \$100 by 2030.

Of other alternatives, wind power has thus far experienced the greatest degree of media exposure, and solar power has largely been relegated to private, small-scale use as a result of technological limitations. While New Zealand seems suited for wind power in some respects (availability of land, areas with relatively consistent wind, small population), doubts still surround the ability of wind generation to provide reliable and sufficient power, and it is a relatively expensive source power at this point in time. It also poses some unique challenges in terms of integrating a large share into the national grid. Wind farm locations are largely dictated by the most favourable conditions, often in remote areas far from heavy loads. This necessitates the development of extensive transmission and distribution grids. Consequently, Mitchell argues that the cost figures and proposed investment paths from the MED’s reports are

<sup>4</sup> 56.7% hydroelectricity, 18.4% natural gas, 10.0% coal, 6.9% geothermal, 5.2% wind, 1.6% oil, 1.3% other.

<sup>5</sup> Other sources include oil, biogas, waste heat, and wood.

very optimistic. She asserts that while the best wind sites are competitive with the average cost of gas, the equivalently average wind sites will not be, breaking the above limitations into “transaction costs” (Mitchell, 2008):

1. Higher capital intensity, requiring more upfront investment for equivalent capacity (not unlike nuclear power in this sense).
2. Higher consent costs (under the 1991 Resource Management Act).
3. A lack of economies of scale due to the small size of many projects.
4. The cost of matching demand with the variability of an unreliable source such as wind.

It is unclear exactly how much risk arises from these cost barriers, and exactly what value on carbon emissions would be required to heavily push the future energy mix towards wind power. However, the nature and scale of wind power is such that ultimately it is not really a case of nuclear competing against wind generation; in fact, they could certainly serve as complementary technologies to reduce carbon emissions. Nuclear matches the more traditional model of connecting large, singular sources to the load. As monitoring and control systems have generally been designed for traditional production, they may have to be redesigned as more wind power is employed (Nuclear Energy Agency, 2005b, p. 213). If wind power is not necessarily the answer (or not the entire answer), then attention should be turned to other generation technologies that are capable of meeting power requirements in a sustainable and clean manner, and can be situated in an efficient location.

Two options presently used in NZ are geothermal and – predominantly – hydroelectric power. Hydro, however, faces significant opposition on the basis of numerous environmental concerns. The damming of a river can lead to flooding around the reservoir, fragmentation of the ecosystem, sediment accumulation, riverline erosion downstream, etc. (and obviously, hydro dams cannot simply be placed in any desired location) (McCully, 2001, p. 32). Geothermal also faces significant challenges in terms of efficiency and strict requirements for suitable sites. Table 2.1 above shows capacity growth for both technologies, but the impression is misleading. Projected hydro growth is a result of already-commissioned projects; at present, there are few signs of any new projects on the horizon. The MED’s reference model makes the assumptions that post-2030 the geothermal resource will become exhausted, and any hydro developments will be considerably more expensive than in the past. Gas usage is expected to decline as reserves are depleted (Ministry of Economic Development, 2010b, p. 6). Given the high capital cost of construction and low marginal costs of operation, which will be investigated at length in Chapter 3, nuclear power would be competing as a possible



source of baseload supply (see section 1.1 for an explanation of the term “baseload”). Ultimately, the only viable baseload choices are:

1. Significant geothermal development.
2. The construction of new hydro dams.
3. Continued (and probably expanded) reliance on fossil fuels.
4. The construction of a nuclear plant.

At present, option four is effectively a ‘non-starter’; all analyses conducted in the public sector, notwithstanding the now defunct 1978 Royal Commission enquiry, simply do not acknowledge the possibility. However, New Zealand finds itself facing rising gas prices, limited options for hydro development, and a discomfort with the pollution of coal generation. Under these circumstances, a role might be considered for nuclear power, perhaps as a ‘spiritual successor’ for hydro. The World Nuclear Association (WNA) has theorised two development possibilities for NZ:

*Nuclear power remains an option for New Zealand, using relatively small units of 250-300 MWe each, in power stations located on the coast near the main load centres. A bolder initiative would be to build an 1800 MWe nuclear power station north of Auckland, using two or three larger units. [...] Nuclear is a sustainable option, able to enhance the country's desired image. With minimal aesthetic impact, it would provide the power for Auckland's continued growth, including energy-intensive industry.*  
(World Nuclear Association, 2010c)

Such a scheme would also be advantageous in terms of reducing the geographical imbalance in New Zealand’s electricity sector. At present, the majority of New Zealand’s hydro capacity (which is a key source of baseload supply) is located in the South Island while 64 percent of electricity demand is from the North Island, placing strain on the transmission grid (Ministry of Economic Development, 2010a). Almost a third of the population lives in the Auckland region, so a nuclear power source located to the north could ease this pressure. Notably, this reflects the population shifts over the preceding decades; the 1978 Royal Commission report recommended reactor construction in both the North and South islands (New Zealand. Royal Commission on Nuclear Power Generation in New Zealand., 1978).

With regards to the “Nuclear Power Generation in New Zealand” report, the cost estimates, while specific to New Zealand, are of little use 34 years after the fact. The report pegged the total cost of its recommended programme at 6 billion; today, the cost would undoubtedly be magnitudes greater, not simply for reasons such as inflation, but

also because of the massive rise in nuclear costs over the preceding decades (which is discussed in Chapter 3). What is relevant, however, is that the report saw a nuclear generation option as viable in New Zealand, in terms of safety risks and environmental impact (New Zealand. Royal Commission on Nuclear Power Generation in New Zealand., 1978). The discovery of the Maui gas field was ultimately responsible for derailing the possibility of a nuclear energy programme proceeding; in this respect, the final assertion of the Royal Commission's investigation turned out to be eerily prescient: "the development of suitable alternatives could not only affect this timing but also markedly affect the magnitude of the programme" (New Zealand. Royal Commission on Nuclear Power Generation in New Zealand., 1978, p. 279).

## **2.4 Conclusion**

The motivating question for this thesis is whether discussion over electricity generation options in New Zealand should include nuclear power. Here we have made the first step towards answering that, by considering how it might fit into the domestic generation mix. It is apparent that New Zealand will continue to face growing energy requirements, a natural component of growth in national output. Electricity prices are also projected to continue rising, in part as a result of the ETS. The NZ energy outlook illustrates the changing nature of the market, which is in itself a strong reason for including nuclear in the analyses. Both energy demand and supply options are evolving: an option that may have been untenable 20 years ago is not necessarily so today, let alone in another two decades. By including all potential solutions, policymakers are better able to achieve an optimal result in an environment of dynamic challenges. Nuclear could potentially avoid the pollution of fossil fuels or technical obstacles to wind, and would certainly be attractive if hydro and geothermal are unable to develop significantly post-2030.

With this in mind, the following chapter will examine a range of figures from the OECD in order to gain a clearer perspective on the international experience of nuclear energy's cost competitiveness with competing technologies.



### **3. Economics of Nuclear Power**

Thus far we have briefly examined the evolution of the nuclear industry and the New Zealand electricity market, and discussed the role nuclear could potentially fill in meeting future energy requirements. This chapter turns to the most quantitative component of the analysis: exploring the costs of nuclear reactors, both direct and indirect. In the case of the latter, environmental emissions are the predominant concerns. The following sections divide the costs of nuclear electricity generation into three categories for discussion:

Section 3.1: Construction (and decommission)

Section 3.2: Generation (particularly fuel inputs, which differentiate nuclear from its competition)

Section 3.3: Externalities (pollution effects)

The reason for the separation of generation and construction costs is twofold: first, to enable a better comparison with competing generation technologies (particularly coal), and second, to better understand the high construction, low generation cost structure of nuclear energy. In analysing the economics of a nuclear power solution, the most relevant consideration is how the technology compares to other energy options. Nuclear energy itself is simply a means to an end: the production of electricity, a consumer product and productive input in the economy. The only aim should be to select the most cost-efficient solution for meeting energy needs, subject to considerations of safety and pollution. To this end, the primary focus of comparison is to coal, gas, and wind: as discussed in Chapter 2, these options feature prominently in New Zealand's future energy plans. Post-2030, geothermal and hydro possibilities are expected to be limited. Gas reserves are also in question, implying that unless considerable wind capacity can be developed, it will become increasingly difficult to avoid employing coal generation.

Externalities are also considered in a separate section for two reasons. First, carbon emissions in particular are increasingly important in the light of the public and political focus on global warming. Second, data availability dictates it: estimates of health effects and other externalities from electricity generation are only available from specialised studies (final generation cost figures generally ignore the social costs of production).

Section 3.4 examines the international experience of final generation costs with figures gathered from the OECD and other sources, and it is here that we may draw overall

conclusions about the competitiveness of nuclear-supplied electricity.<sup>6</sup> Finally, section 3.5 provides a brief discussion of the possible indirect macroeconomic effects of a nuclear energy programme.

In general, foreign currencies have been left unadjusted. This is because any comparisons between the various generation options come from the same source or data set. The most important goal of this chapter is to draw useful conclusions about how nuclear energy compares with the alternatives presently used in New Zealand. In other words, the focus is on relative rather than absolute costs. It is worth noting one simplifying factor when comparing electricity generation methods: electricity itself is essentially an example of a perfectly homogenous product. Thus only the price of output needs to be considered; no adjustments for quality or the like are required.

### 3.1. Construction Costs

Unsurprisingly, construction costs are generally very significant for a nuclear plant; there is a range of cost categories that make up the construction of a new reactor. The OECD's Nuclear Energy Agency listed the following items involved in the creation of five reactors (all in different countries):

**Table 3.1: Nuclear construction expense categories**

<b>Direct costs</b>	Land and land rights Reactor plant equipment Turbine plant equipment Electrical plant equipment Heat rejection equipment Miscellaneous equipment Construction
<b>Indirect costs</b>	Design and engineering Project management Commissioning
<b>Other costs</b>	Training Taxes and insurance Transportation Owner's costs Spare parts Contingencies

Source: (Nuclear Energy Agency, 2000, p. 29)

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<sup>6</sup> For more in-depth cost figures, refer to the source report from the OECD report on projected electricity costs. The figures presented here have been primarily limited to total generation costs to reflect the scope of the thesis and focus on drawing useful conclusions.

While any large-scale baseload technology will also experience many of these costs, nuclear energy is likely to see higher equipment, engineering, training, and contingency costs, because of both the more advanced nature of the technology and the associated safety risks (see chapter 4).

The overnight costs for power plants per kWe of capacity in the 2005 OECD report on projected electricity costs were as follows:

**Table 3.2: OECD Overnight Construction Costs**

<b>Plant type</b>	<b>Cost range (USD/kWe)</b>
Nuclear	1,000 to 2,000
Coal (Some plants with carbon capture technology priced higher)	1,000 to 1,500
Gas (Liquid natural gas (LNG) fuelled plants priced higher)	400 to 800
Wind	1,000 to 2,000

Source: Nuclear Energy Agency., 2005 #24@43,35-36,39,54}

While studies from Vujic and Locatelli pegged construction costs at a much higher level:

**Table 3.3: Estimated Construction Costs**

<b>Plant type</b>	<b>Cost range (USD/kWe)</b>
Nuclear	5,300
Coal (Some plants with carbon capture technology priced higher)	2,800 to 5,300
Gas (Liquid natural gas (LNG) fuelled plants priced higher)	1,000 to 2,000
Wind	2,500 to 6,000

Source: (Vujić, Antić, & Vukmirović, p. 3)

**Table 3.4: Estimated Construction Costs**

<b>Plant type</b>	<b>Cost range (USD/kWe)</b>
Nuclear	1,850 – 5,000
Coal (Some plants with carbon capture technology priced higher)	1,250 to 3,000
Gas (Liquid natural gas (LNG) fuelled plants priced higher)	400 to 1,000

Source: (Locatelli & Mancini, 2010, pp. 6371-6372)

Certainly, the construction of a nuclear reactor tends to be expensive in comparison to its fossil-fuelled competitors. However, it is important to note that there are methods for reducing the capital costs. Returning to the Nuclear Energy Agency report, the following are listed (Nuclear Energy Agency, 2000, pp. 5-6):

- Improving construction methods
- Reduced construction schedule
- Design improvement
- Improved procurement processes
- Improved management and contracting procedures
- Size selection

Other options are listed, but these are less relevant to the NZ scenario since no nuclear plants (or plans for such) exist at present, and more than a handful of reactors are unlikely to be required. These options are:

- Standardisation in series construction
- Multiple unit construction
- Regulation and policy measures

With regard to size selection, nuclear reactors do benefit from a particular economic phenomenon, economies of scale. In simple terms, the increases in cost from selecting a larger generation capacity at the time of construction tend to be proportionally smaller than the increase in output itself. In terms of the figures above, where the options were compared in terms of overnight costs, the cost per kWe fell as the total kWe of the reactor increased (until physical limitations were encountered). An analysis from the Nuclear Energy Agency indicates that these economies of scale savings are predominantly derived from engineering and construction services (Nuclear Energy Agency, 2000, pp. 32-33).

Looking over the preceding decades, construction costs trended upwards significantly in the transition from the 1970s to the 1980s. Several large plants were completed in the early 1970s at a price of around US\$170 million; by 1983 the price had risen to \$1.7 billion for the same generation capacity. For 75 new reactors built in the US between 1966 and 1986, the actual average cost of construction exceeded the estimates by 200% (Ahearne, 2011). With the relevant consumer price index rising by a factor of 2.2 over the same time period, inflation is hardly culpable for the bulk of the increase. Cohen attributes these increases to two main components: rising specific costs (materials and labour, which inflated at rates greatly above the general price level) and “regulatory ratcheting” (Cohen, 1990).

Regulatory ratcheting describes United States experience, where the Nuclear Regulatory Commission continued to raise construction requirements (on the basis of safety), without disposing of earlier requirements that were subsequently proven unnecessary. Nuclear power, by its nature, presents almost endless options to improve safety, and the effect of the NRC’s approach was to nearly double the construction time (from seven years to 12 over the period of 1971-1980). The experience suggests that for New Zealand, where undertaking nuclear energy generation would be a significant financial task, finding a correct balance between effective safety requirements and cost-effectiveness is vital. In the words of the International Energy Agency:

*A publicly acceptable balance of safety and cost must be found for the nuclear industry. Safer at any price means “never.”* (Organisation for Economic Co-operation and Development & International Energy Agency, 1998)

Consequently, government involvement could be beneficial in the case of New Zealand undertaking a nuclear energy program. Given the issues regulation uncertainties have posed to the nuclear industry, a committed approach to maximising public safety and ensuring a secure and stable energy supply could yield a more positive experience for this country. Unsurprisingly, issues such as acquiring a site license can prove political challenging, especially at a local level. This is certainly likely to be the case in New Zealand, so sufficient political will would be required at a national level. Such a requirement could prove to be the single greatest challenge to the use of a nuclear energy (see Chapter 5 for an in-depth discussion).

### **3.1.1. Decommissioning**

Decommissioning costs are about 9-15 percent of the initial capital cost of a nuclear power plant (around 300 to 500 USD million). However, when discounted, they contribute only a few percent to the investment cost and even less to the generation



cost. In the US they account for 0.1-0.2 cent/kWh, which is no more than 5 percent of the cost of the electricity produced (World Nuclear Association, 2010a). Estimates for future plant closure costs vary greatly, however, which is of concern to the industry.

According to the NEA, reasons for these variations included (Paffenbarger & International Energy Agency., 2001, pp. 139-140):

- Exchange rate fluctuations
- Confusion between current and discounted monetary units
- Physical differences between different plant types
- Differences in regulatory legislation
- Differences in input costs (e.g. labour)

Provided that a reasonably accurate estimate can be made, the usual procedure is for the utility owner to set aside money at the construction phase to cover decommissioning costs in the future.

Decommissioning is perhaps an under-discussed aspect of nuclear energy (or, at least, the concerns of decommissioning do not seem to be given as much attention as matters relating to the operational phase of a reactor's life). The nature of nuclear power as a whole is perhaps best described as long-term. Reactors take years to construct, operate for decades, in some cases take just as long to be dismantled, and leave wastes that can persist for thousands of years. In the case of decommissioning, Pasqualetti frames the process in terms of "geosocial impacts"; the geographical and social effects of an energy resource and their interactions. An operative nuclear reactor has its own set of effects, such as land usage, influences on transportation networks and worker movements, local community reactions, etc. (Pasqualetti, 1989).

When a nuclear reactor is deemed ready to be taken offline, there are two primary courses of action: immediate dismantlement, or delayed dismantlement (providing time for radioactive decay). There is also the option of entombment, such as was used in response to the Chernobyl meltdown, but this is more akin to an emergency measure. Immediate dismantlement provides continued worker employment (and thus local economic activity), maintaining the social status quo, land values, etc., with an eventual scaling down. Consequently there is less time to accumulate funds for decommissioning, and when discounting is considered the approach is more expensive. Delayed dismantlement allows funds to be set aside over time, but means a more immediate loss of jobs and therefore a lull in the service sector, with land values declining; however, it will also see a later boost in employment when deconstruction is eventually undertaken (Pasqualetti, 1989).

With funds being set aside over time for a delayed dismantling of a decommissioned reactor, basic analyses expect that the vast majority of the costs will be borne by electricity users after the station is closed, with an applied discount rate. Jeffery raises an objection to this: discounting the postponed costs of decommissioning leads to an unfair comparison with other generation options, such as coal, which do not have a similarly difficult and/or dangerous process required of future generation attached to their usage. Jeffery also highlights the problem posed by the interest rate falling below the chosen discount rate: decommissioning funds will likely have to be augmented via a rise in electricity prices. He thus proposes that all funds should be recovered within the operational lifetime of the reactor, and approximates that the unit cost of nuclear power would rise by about 20% as a result. More precise calculations are beyond the scope of this thesis, but any further applied analysis to the New Zealand context would do well to pay attention to decommissioning costs (Jeffery, 1987).

### **3.2. Generation Costs**

Having considered the costs involved in the creation and cessation of a nuclear plant, we now turn to a second dimension: the costs incurred in *producing* the output, namely electricity. These generation costs encompass operation and maintenance (O&M) and fuel costs, which include used fuel management and final waste disposal. These fuel-related costs are usually external for other technologies, but in contrast are generally internalised for nuclear power (i.e. they are handled directly by the utility owner).<sup>7</sup> Waste disposal in the US, for example, is part of a 26 billion USD used fuel program, which is funded by a 0.1 cent/kWh levy (World Nuclear Association, 2010a). This has to the potential to skew comparisons with other technologies. For example, the fuel waste product of coal is essentially the resulting air pollution,<sup>8</sup> but while this waste can cause harmful and economically costly effects, it is not paid for by the generator (see sections 3.3 and Chapter 4).

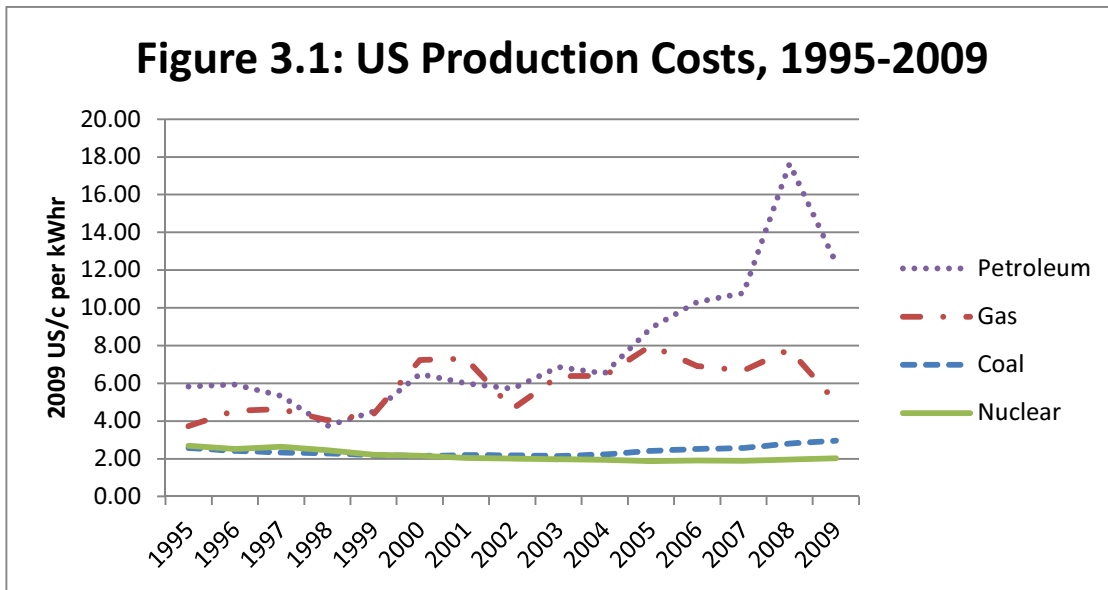
The fundamental attraction of nuclear energy on a cost basis is a result of its low fuel costs compared with coal, oil and gas plants. Despite the need to process, enrich, and fabricate uranium, which accounts for about half of the fuel costs, final prices are still approximately a third of those for a coal-fired plant and between 20 and 25 percent of those for a gas combined-cycle plant (World Nuclear Association, 2010a). Another important advantage for nuclear plants is price stability over time. This can be observed

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<sup>7</sup> One question should be immediately apparent: do the construction and decommissioning phases not also incur external costs? Certainly, they do; however, the available numerical estimations of the externalities associated with power generation are calculated

<sup>8</sup> There are numerous other pollution effects that are often not internalised to the generator: see the following section in conjunction with Appendix D.

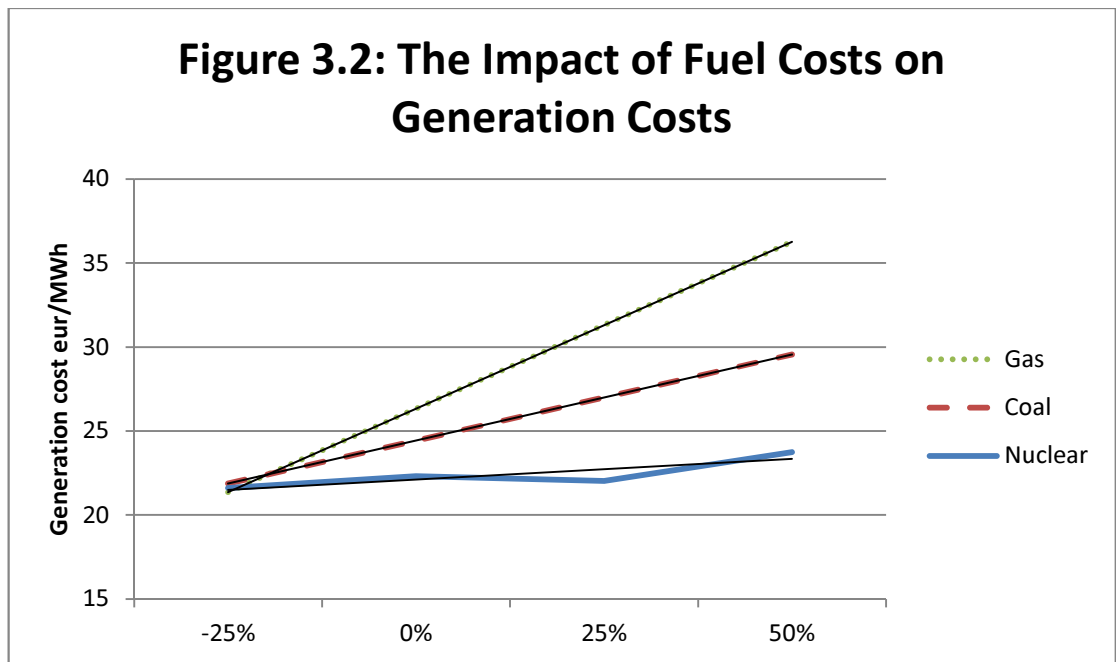
by examining the trends in combined O&M and fuel costs in the US over the last 14 years in comparison to fossil fuel generation technologies:



Source: (Ventyx Velocity Suite, 2010)

This graph demonstrates that nuclear energy has a relatively strong degree of cost stability. Production costs show an overall downwards trend (although with a slight increase in the last two years) and are competitive with coal in the US: in fact, by 2009, nuclear was noticeably cheaper per kWh (2.03c versus 2.97c). Unlike fossil fuel sources, wind is less directly comparable in terms of production costs. Nuclear fuel, like fossil fuel, is available via a market supply mechanism. Wind, conversely, utilises a supply directly derived from the environment, and fuel costs are essentially nil. The scenario is not entirely advantageous, of course; there is also no real response to a lack of wind. As a side note, a rise in O&M costs for nuclear power was observed during the 1980s; as with the simultaneous rise in construction, the cause can be attributed to the increased regulatory activity of the time (Abu-Khader, 2009).

Much of the price stability for nuclear energy can be attributed to the relative robustness of nuclear generation to changes in fuel prices. A Finnish study conducted in 2000 quantifies the sensitivity of generation costs to changes in fuel costs:



Source: (Tarjanne & Rissanen, 2000, p. 9)

The figures show that a 50 percent rise in fuel prices would result in the electricity cost for nuclear rising about 4.5 percent, versus 15.5 percent for coal and 33 percent for gas. A 2008 IAEA analysis reached similar conclusions, finding that a doubling of uranium prices led to a 5-10% increase in electricity generation costs, while doubling fuel costs for coal and gas resulted in a 35-45% and 70-80% increase, respectively (Jewell, 2011). Given the overall upwards trends in fuel prices over the past decade, and the expectation that they will be sustained (Ministry of Economic Development, 2010b, p. 9), this is probably the most important economic distinction in favour of nuclear energy (World Nuclear Association, 2010a).

One conclusion that results from the relatively lower generation costs (and the stability thereof) is that the expected operating life of the plant is very important. The longer a plant is operating, the more time it has to recoup the capital costs through the sale of electricity<sup>9</sup>. Most reactors in existence today were constructed with 30 to 40 year lifespans in mind, although with appropriate refurbishment many are like to see up to 60 years of operation (Paffenbarger & International Energy Agency., 2001, pp. 160-161).

Fuel inputs provide one way in which New Zealand may be able to benefit from technological improvements in building a new reactor: developing a reactor with a

<sup>9</sup> Consider any first-year microeconomics textbook: average total cost falls as fixed costs are distributed over an increasing range of output. The situation here is somewhat analogous; the longer the plant operates, the more electricity it produces, reducing the total cost per unit of output.

higher than typical burnup could be investigated. Average burnup for existing LWR plants is around 33 MWd/kg (megawatt days per kilogram); up to 100 MWd/kg and beyond is technologically feasible. Higher burnup rates unsurprisingly result in higher expenses, specifically in developing appropriate fuels; the benefits are found in lower fuel requirements and lower quantities of waste generated (see section 4.2.2 for a related discussion) (Deutch et al., 2003, p. 56).

Finally, two additional topics related to nuclear fuel should be briefly mentioned. First, there are multiple types of fuel cycles, which is the process from mining to waste disposal. The most common is the once-through fuel cycle (also called an open fuel cycle). In the strictest sense, this is not a cycle per se, since the expended fuel is placed into storage rather than being reprocessed. Other cycles generally take spent fuel and reprocess it for re-insertion into a reactor. However, the technology involved is still expensive, and it has concerns attached over the increased potential for proliferation (see section 5.2) (Schneider, Deinert, & Cady, 2009). Consequently, for a small country looking to adopt a nuclear energy programme, the once-through cycle would be the better choice (Deutch et al., 2003, p. 54).

Secondly, concerns are sometimes raised regarding the possible depletion of uranium supplies. Estimates vary, but even the most pessimistic figures show the currently known supplies lasting for a further 50 years. Including speculative (unverified) supplies extends that estimates to over two centuries (Organisation for Economic Co-operation and Development & International Energy Agency, 1998, p. 15). Considering that there has been almost no exploration for new sources since 1983, given the lack of necessity, and the numerous technological advances may be able to reduce uranium requirements internationally (such as thorium-powered reactors, mentioned in section 2.2.1), depletion does not appear to be a major issue. That being said, resource depletion dynamics are relatively complex in reality, and this makes predicting the future costs of fuelling a reactor difficult at best (although, as noted earlier, the cost of nuclear-generated electricity is relatively price-insensitive). Further development of advanced reactor designs, namely breeder reactors, is limited particularly by the weapons proliferation potential of such designs (Golay, 1995).

### **3.3. Externalities and Emissions Costs**

Externalities are a core concept in economics, and one of the key justifications for government intervention in the market. Also known as an external cost/benefit or transaction spillover, externalities refer to activities of one individual or group that have an effect on a third party which did not consent to the activity. This is one of the

fundamental types of market failure discussed in economics, and is a key justification for government policy intervention in the market. In particular, externalities feature prominently in welfare economics, which seeks to measure the overall welfare of society (i.e. it looks beyond directly measured monetary flows). The principles of societal welfare might suggest policies to ensure prices reflect the true costs of a good or service being exchanged, utilising tools such as taxes and subsidies to achieve this (European Commission, 1995).

Within the context of this cost analysis, there are a number of external costs (negative externalities) associated with non-nuclear methods of electricity generation; for example, the pollution output from fossil fuel stations, which is probably the most easily identifiable. As per Vujic, the environmental impact of electricity generation technologies can be broken down into several categories (Vujić et al.):

1. The use of natural resources (not just fuel, but also land occupation).
2. Thermal pollution.
3. Emission of chemical pollutants.
4. Emission of radioactive particles.
5. Various social and economic effects.

Effects can be direct (e.g. emission exposure) or indirect (e.g. pollution impacting the food chain or other ecological knock-on effects). Consequently environmental impact studies are necessarily very complex in nature, thanks to the wide range of possible effects and the myriad interactions between them. Generally speaking, the generator does not have to take into account the effects of these externalities - such as the damage to human health - when deciding upon the quantity of output. Consequently, it can be said that market failure has occurred: the price of electricity is not reflecting its true costs, and thus a higher than optimal amount will be demanded. The nature of policy responses (of which New Zealand's ETS is one) will not be discussed here.<sup>10</sup> Rather, we shall turn to monetary estimates of the external costs associated with different generation methods and examine how they compare. In turn, this facilitates more accurate conclusions in the following section, which examines the total costs of generation technologies.

From 1991 onwards, a research project called *ExternE – Externalities of Energy* was run by the European Commission, involving numerous research teams across multiple

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<sup>10</sup> There is a vast array of literature investigating this topic, and discussing a range of solutions to internalise externalities does not necessarily contribute to our goal of evaluating the viability of nuclear energy in relation to the other available options.

countries. The project assessed the costs of emissions using a method called “impact pathway assessment” (European Commission, 1995):

*Impact pathway assessment is a bottom-up-approach in which environmental benefits and costs are estimated by following the pathway from source emissions via quality changes of air, soil and water to physical impacts, before being expressed in monetary benefits and costs.*

The main categories examined by the researchers were human health (fatal and non-fatal effects), effects on crops and materials<sup>11</sup>, and global warming effects. A further discussion of the health effects can be found in Chapter 4 (particularly section 4.2), and an in-depth breakdown of the categories is located in Appendix D. The final calculated costs from 1995 are reproduced below for selected generation methods (figures for additional technologies such as hydro can also be found in Appendix E).

**Table 3.5: External costs for electricity production in the EU (Euro-cents per kWh)**

Country	Coal & lignite	Oil	Gas	Nuclear	Wind
Austria			1-3		
Belgium	4-15		1-2	0.5	
Germany	3-6	5-8	1-2	0.2	0.05
Denmark	4-7		2-3		0.1
Spain	5-8		1-2		0.2
Finland	2-4				
France	7-10	8-11	2-4	0.3	
Greece	5-8	3-5	1		0.25
Ireland	6-8				
Italy		3-6	2-3		
Netherlands	3-4		1-2	0.7	
Norway			1-2		0-0.25
Portugal	4-7		1-2		
Sweden	2-4				
United Kingdom	4-7	3-5	1-2	0.25	0.15

Source: (European Commission, 1995)

These results clearly show nuclear as comparing very favourably with fossil fuel methods of baseload generation; in fact, it is only slightly worse than wind. While natural gas - which has historically been a key source of electricity production in New

<sup>11</sup> For example, property damage to buildings from soot accumulation in the case of coal power.

Zealand (see Section 2.3) - does have less of a pollution burden than coal, the importance of the resource in the chemical and petrochemical industries are such that the opportunity cost should be considered to be relatively high. Unfortunately, hydro is not included here, but hydro dams may negatively influence local climate, geological stability, groundwater conditions, and general water quality (Vujić et al.).

Of these health and environmental effects, climate change as a consequence of global warming caused by CO<sub>2</sub> emissions is probably the most publicly discussed aspect, making frequent appearances both in media headlines and in domestic and international political agendas. As a party to the Kyoto Protocol, New Zealand has an obligation to meet certain targets for reducing greenhouse emissions, or account for excesses by purchasing emission units.

Just as with the costs of electricity for nuclear (and any other) technology, environmental impacts are present not only at the generation stage, but also during fuel acquisition and processing, plant construction, etc.. For nuclear energy specifically, the main sources of greenhouse gases, particularly carbon dioxide (CO<sub>2</sub>), are fossil fuels used in uranium extraction and processing, electricity used for enrichment, and fuels used to produce the materials needed for reactor construction. The emissions load can be reduced in the case of enrichment by powering the process with nuclear-generated electricity itself, and/or by employing newer enrichment technologies (as is the usual case in European countries). The following chart, reproduced from the OECD's 1992 report (Nuclear Energy Agency, 1992, pp. 70-71) on the economic impact of nuclear power, demonstrates the levels of CO<sub>2</sub> released from each TWh/y generated by various methods. For comparison, it also shows the CO<sub>2</sub> released during the production of efficiency measures<sup>12</sup> to reduce electricity consumption by an equivalent amount.

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<sup>12</sup> Measures such as additional insulation for homes create greenhouse gases in the manufacturing stage.



**Table 3.6: Carbon Emission Quantities**

TWh/y	<b>Average Total CO2 release p.a. (10,000 tonnes)</b>
<b>Generation method</b>	
Coal-fired	118.2
PWR (diffusion enrichment, older method)	4.6
PWR (centrifuge enrichment, newer method)	0.8
PWR (enrichment powered by nuclear reactor itself)	0.4
FBR	0.4
Hydro	1.8
Wind	1.0
Tidal	1.0
<b>Efficiency measures</b>	
Roof insulation	0.4
Cavity wall insulation	0.4
Low-energy lighting	0.4

Source: (Nuclear Energy Agency, 1992, p. 71)

The table demonstrates that, when combined with a modern enrichment process, nuclear power CO<sub>2</sub> emission levels compare favourably even with those of commonly perceived “clean” technologies such as hydro and wind. By powering the enrichment process with nuclear electricity itself, the emissions levels achieve parity with a variety of measures that actually reduce electricity consumption.

Quantifying the exact costs of greenhouse gases is somewhat more complex, however, especially if the environmental consequences become exponentially more severe with time. The ExternE researchers admit that the range of uncertainty in their calculations is highest for the estimates of global warming effects (European Commission, 1995). While data are limited in terms of estimating the exact effect nuclear generation could have, a 2005 Ministry of Economic Development report investigated the effect of running the Huntly plant on gas and avoiding the construction of any new coal plants. Their results yield a 13 percent decrease in CO<sub>2</sub> emissions, but with a corresponding 25-26 percent rise in electricity prices. Running Huntly on coal but avoiding the construction of any new coal plants yields figures of 5 percent and 18-19 percent, respectively (Ministry of Economic Development, 2005). As of 1 July 2010, the energy sector has been included in the New Zealand Emissions Trading Scheme, which effectively prices the cost of emissions at \$12.50 per tonne (Ministry for the

Environment, 2009). This is integrated into the output price and passed on to consumers. Given that the cheapest sources of electricity generation are typically the high-pollution options (coal, gas, oil), electricity prices will invariably rise. It is questionable how much of an effect the scheme will have on the mix of generation options in the country, since all generation sources are pooled together then distributed across the grid to retailers. While the scheme will make lower carbon emission sources more attractive, reductions in pollution are more likely to arise from a reduction in electricity demand as a response to higher prices than from a switch to lower-pollution technologies (Ministry for the Environment, 2010). Given its cost-competitiveness with other sources of power, nuclear energy seems worth investigating as a means to reduce future emissions while avoiding severe price increases.

### **3.4. Total Costs**

Comparing nuclear to gas reveals two different cost structures for a large electricity generating plant: building a nuclear plant means accepting high upfront costs in exchange for lower production costs (and higher price stability), while gas is generally under half the price for construction of an equivalent capacity, but more expensive to operate (and noticeably more vulnerable to fuel price fluctuations).

When construction, production, and carbon emission costs are integrated into the price of electricity, nuclear energy compares favourably with other generation options. The 2010 OECD report uses levelised lifetime costs and discounted cash flows.<sup>13</sup> At a 5 percent discount rate and a USD 30 per tonne CO<sub>2</sub> cost:

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<sup>13</sup> It should be noted that levelised costs typically employ nominal rather than real cost values, making capital-intensive technologies appear relatively more costly as a result of inflation. The discount rate can be seen as compensating for this.

**Table 3.7: OECD electricity generating cost projections for 2010 onwards (USc/kWh)**

Country	Nuclear	Coal	Coal with Carbon Capture and Storage	Combined Cycle Gas Turbine	Onshore Wind
Belgium	6.1	8.2	-	9.0	9.6
Czech Republic	7.0	8.5-9.4	8.8-9.3	9.2	14.6
France	5.6	-	-	-	9.0
Germany	5.0	7.0-7.9	6.8-8.5	8.5	10.6
Hungary	8.2	-	-	-	-
Japan	5.0	8.8	-	10.5	-
Korea	2.9-3.3	6.6-6.8	-	9.1	-
Netherlands	6.3	8.2	-	7.8	8.6
Slovakia	6.3	12.0	-	-	-
Switzerland	5.5-7.8	-	-	9.4	16.3
US	4.9	7.2-7.5	6.8	7.7	4.8
China <sup>14</sup>	3.0-3.6	3.0	-	3.6	5.1-8.9
Russia	4.3	5.0	6.2	5.8	6.3
EPRI (US) <sup>15</sup>	4.8	7.2	-	7.9	6.2
Eurelectric <sup>16</sup>	6.0	6.3-7.4	7.5	8.6	11.3

Sources: (Nuclear Energy Agency, 2010); (World Nuclear Association, 2010a)

Judging from these figures, the implication is that despite the relatively steep investment costs incurred in reactor construction, the low fuel costs and low emission levels lead to a relatively favourable outcome for nuclear energy. The cost projections under a 10 percent discount rate can be found in Appendix F. With the higher discount rate, nuclear is still cheaper than coal but gas becomes the most favourable, as is to be expected (since a higher discount rate essentially reduces the weighting of future production costs, placing more emphasis on initial capital costs).

A 2004 report from the University of Chicago also compared the levelised power costs of future nuclear, coal, and gas-fired power generation in the USA. The final cost of the

<sup>14</sup> Unlike the other countries on this table, estimates for the cost of gas and coal in China and Russia do not include carbon emission costs. 2.5c is added to coal and 1.3c to gas as carbon emission cost to enable comparison (World Nuclear Association, 2010a).

<sup>15</sup> The Electric Power Research Institute, Inc. (EPRI) conducts research and development relating to the generation, delivery and use of electricity.

<sup>16</sup> The Union of the Electricity Industry (EURELECTRIC) is the sector association which represents the common interests of the electricity industry at pan-European level, plus its affiliates and associates on several other continents.

nuclear reactor options considered ranged from 4.3 to 5.0 USc/kWh<sup>17</sup>, while coal yielded 5.0 to 5.6 and gas (CCGT) 4.5 to 5.5, subject to fuel cost stability (World Nuclear Association, 2010a). These figures place nuclear in an advantageous position, although it should be noted that the estimation of carbon costs (1.5 USc/kWh for coal and 1.0 USc/kWh for gas) is a key factor.

Additionally, figures from the report (summarised in table 3.4 below) demonstrate varying projected electricity costs based on different reactor designs. The overnight capital costs columns reflect reactor design, where the higher cost are more advanced plants. The rows reflect the effect of construction in series: if multiple units are being constructed, the fourth unit should have lower total costs than the first unit as a result of increased efficiency from experience gained. As shown in the table, there are diminishing returns to this effect.

**Table 3.8: Projected electricity costs (USc/kWh)**

Overnight capital cost USD/kW		1200	1500	1800
<b>First unit</b>	7 yr build, 40 yr life	5.3	6.2	7.1
	5 yr build, 60 yr life	4.3	5.0	5.8
<b>4th unit</b>	7 yr build, 40 yr life	4.5	4.5	5.3
	5 yr build, 60 yr life	3.7	3.7	4.3
<b>8th unit</b>	7 yr build, 40 yr life	4.2	4.2	4.9
	5 yr build, 60 yr life	3.4	3.4	4.0

Source: (World Nuclear Association, 2010a)

What we can conclude is that nuclear is definitely competitive with other baseload generation technologies; exactly how competitive depends primarily on the discount rate, although carbon costs are also an important factor. Certainly for the New Zealand application, where carbon emissions are indeed a key component of evaluating future energy plans, nuclear presents an attractive picture. Namely, clean and reliable energy that is cost-competitive with fossil fuel sources. Furthermore, as discussed in section 3.3, there are a range of emissions effects beyond climate change, and these are not included in the above figures. It can reasonably be asserted that – in comparison to coal and gas – nuclear is even more attractive than these figures reveal. While nuclear power generation certainly holds some attraction in terms of providing a potentially cost-

<sup>17</sup> Overnight capital costs of 1,200 to 1,500 USD/kWe, 60 year plant life, 5 year construction, and 90% capacity.

effective form of base load power, it is the low greenhouse gas emission level that is probably the most enticing facet of the technology at present (Golay, 1995).

### 3.5. Macroeconomic Effects

Finally, some consideration will be given to some of the broader, indirect macroeconomic effects that might result from a nuclear power programme. This discussion will be primarily theoretical in nature, with a select few supporting estimates where appropriate (calculating the possible flow-on effects in the economy is largely a matter of the model and assumptions in use, as well as the unique characteristics of a given country). Three areas will be considered in turn: employment effects, the balance of payments, and price stability.

Electricity supply spending, while not insignificant, tends to only be a small part of total spending in OECD countries (3 percent on average). Cost variations between generation technologies are even smaller in turn. The economic differences between supply options, therefore, are largely limited to short-term effects in the economy, with the exception of the flow-on effects of electricity prices on specific industries such as steel and paper manufacturing, where electricity is an extremely significant input (Nuclear Energy Agency, 1992, p. 53).

The nuclear industry is not overly sizeable in terms of employment, even in countries with a major nuclear industry (combined direct and indirect employment in France, circa 1992, was 1.3 percent of the working population), although it is notable for its high proportion of skilled and graduate staff (Nuclear Energy Agency, 1992, p. 53):

**Table 3.9: Nuclear Industry Employment**

Country	Nuclear electricity 1990		Direct Employment	
	Capacity GWe	TWh output/GWe <sup>18</sup>	Total	Qualified %
France	55.8	5.3	160,000	5.8
Japan	30.4	6.3	53,700	20.1
UK	11.2	5.4	44,000	28.4
USA	100.0	5.7	300,000	25.7

Source: (Nuclear Energy Agency, 1992, p. 53)

Certainly, the direct employment deriving from the nuclear industry as a whole is lower than that involved in equivalent coal (and possibly even renewable sources) (Nuclear

<sup>18</sup> Terawatt-hours of output per gigawatt of capacity. These figures demonstrate each country's nuclear capacity is utilised to a similar degree.

Energy Agency, 1992, pp. 54-55). This relationship has been used to argue against nuclear power in countries with domestic coal supplies (Nuclear Energy Agency, 1992, p. 55), although as the OECD report notes, “If employment were the only goal, power production using human treadmills should be preferred” (Nuclear Energy Agency, 1992, p. 55). While this assertion is somewhat hyperbolic in nature, it illustrates a valid point: from the perspective of economics, full employment is not the only goal. Equally important is the efficient use of resources; ideally, all resources are using to their maximum possible productivity. In countries without high levels of chronic unemployment (such as New Zealand), it seems fair to assume that direct cost of lost jobs should not be particularly significant. In the long run, those unemployed should be able to find employment in other sectors of the economy, increasing GDP overall (*ceteris paribus*). This is preferable from the perspective of an economist: by producing the product in question (electricity) using less of a resource (labour), the freed up portion of that resource can be gainfully employed elsewhere, enlarging the economic ‘pie’ for everyone. The stronger direct effect will be the change in electricity prices, which if lower will leave consumers with more disposable income to spend.

The effect on the balance of payments is somewhat more straightforward. Nuclear energy can influence trade balances through the import or export of technology and fuels. New Zealand possesses an indigenous supply of coal, and relatively little in the way of known uranium deposits (at least as of the 1980s, by which point interest in uranium exploration had declined) (Priestley, 2009). Consequently, uranium will almost certainly have to be imported, and the trade balance will worsen, given that none of the country’s present generation methods are reliant on imported fuel (although the effect is not likely to be enormous). Furthermore, New Zealand will likely find itself dependent on overseas institutions and the need to attract international expertise. However, with carbon emissions included in the price under the New Zealand ETS, electricity prices should fall (assuming that nuclear is superseding fossil fuel generation and precluding the need for wind power expansion). On balance, the net effect will depend primarily on how the freed indigenous resources are put to use (Nuclear Energy Agency, 1992, p. 57).

Directly coupled to the issue of imported fuels is that of price stability. As discussed above in section 3.2, fuel costs are a relatively small part of total costs for nuclear energy, and the price of output is much less sensitive to changes. Nuclear power, therefore, does at least provide better leverage against possible price shocks. However, the benefits are not obtainable in a linear fashion when evaluating possible investment; that is, the relationship between additional investment and increased price stability is

not entirely clear. Furthermore, the benefits may be obtained in part simply through the expansion of nuclear generation by other countries. This is somewhat akin to the concept of free-riding: where an individual receives benefit from a non-excludable good. As a country (particularly those utilising oil for electricity generation) increases its share of nuclear energy, it displaces demand for fossil fuels on the global market, thus reducing pressures that can lead to price fluctuations. Studies have attempted to quantify the possible effects, by modelling possible price shocks, but their usefulness is limited, given that the selection of the shock size is arbitrary at best (Nuclear Energy Agency, 1992, p. 60). Still, Canadian studies have shown that in the long-term, the presence of nuclear generation has indeed served to stabilise electricity prices in the country (Nuclear Energy Agency, 1992, p. 60).

### **3.6. Summary**

As can be readily identified, a great proportion of the positive literature on nuclear electricity generation comes from the nuclear industry itself. While this is somewhat unavoidable in practice, since nuclear reactors are a complex technology that is difficult to appraise with the benefits of an ‘inside’ perspective, it must be acknowledged that the nuclear industry itself certainly has motivations for placing a positive spin on the potential prospects for nuclear energy. As demonstrated above, particularly in Section 3.4, there are definitely large risks and a high uncertainty factor when estimating costs for nuclear reactor construction (Kessides, 2010). The serious upwards trend over preceding decades, while explainable, certainly does not engender confidence. The figures quoted above revealed a range in construction costs from USD 1,000/kW up to as high as USD 5,000/kW. This broadly agrees with a wide-ranging 2009 review from the US National Academies, which found that cost estimates have ranged by “more than a factor of two”; specifically, from USD 2,400/kW to as much as USD 6,000/kW (Ahearne, 2011).

The results of this chapter can be summarised fairly succinctly:

1. The construction costs of a nuclear reactor are high compared to competing technologies. Important factors in keeping costs down include making appropriate design and size choices, minimising construction time, and assuring an efficient and focused regulatory environment.
2. Fuel costs are relatively low for nuclear reactors, and the cost of generation is fairly insensitive to fluctuations in the price of fuel. As a result
3. A major advantage of nuclear energy is the low external costs, primarily as a result of low emissions of carbon and other pollutants.

4. Despite the high construction costs, when low generation costs and carbon emissions are taken into account, nuclear has the potential to be cost-competitive with fossil fuel sources, but the large variance factor in estimates is concerning.
5. Ultimately, when applying a cost-benefit analysis to nuclear power, the outcome depends upon the interaction between the costs of nuclear energy itself, the estimated cost of alternative energy sources, and the carbon cost. Under one set of assumptions, nuclear may compare favourably; under another set, it may not (Kennedy, 2007).





## 4. Safety Risks

In the preceding chapter, the direct and indirect costs of nuclear power have been investigated on a numerical basis. This chapter seeks to define the risks of nuclear power, both potential and inherent. One reason for a more in-depth analysis of the associated risks (apart from adding value to the cost-benefit analysis) is simply that the biggest source of opposition facing nuclear power comes from concern over safety: both the dangers posed by a serious accident and the more routine risks from handling and using nuclear fuel. Thus it is important to understand not just the likelihood of a major accident occurring, but the actual consequences in such a case. However attractive nuclear energy may look technologically and from a cost perspective, it will almost certainly never gain support unless public perception of nuclear safety improves.

Safety is an intrinsic and direct part of nuclear costs: construction involves the various requirements of building a reactor that is robust against failure; operation includes maintenance, waste management, etc.; decommissioning is a particularly involved process, due to the dangers of residual radiation and the materials that must be disposed of. However, readily available data are insufficient to quantify exactly what proportion of overall costs is dedicated to safety measures. Therefore, the discussion here seeks to determine if the theoretical dangers of an accepted reactor design are significant enough to notably affect the conclusions from the preceding cost analysis. With this in mind, sections 4.1 and 4.2 focus on two key areas. The first is the concept of major or catastrophic disasters; this is the threat that tends to be held foremost in public consciousness. The aim is to understand the various factors that can result in such a disaster, the associated probabilities, and the ramifications for the construction and operation phases of a nuclear plant's life. The second area focuses on two operational hazards, non-catastrophic radiation releases and waste disposal. In the particular, the second of these concerns poses one of the stronger objections to nuclear energy in informed debate, where concern over catastrophic disasters tends to be less amplified. At this point in time, most nuclear countries are yet to commit to a final long-term storage system for waste, so from an economics perspective it is important to consider what will be involved in the process. Given the uncertainty surrounding waste disposal, which in turn implies uncertainty for the associated costs, some attention will also be given to possible methods for reducing the costs.

Finally, two case studies will be considered: Chernobyl (section 4.3) and Three Mile Island (section 4.4), the two most notable civil nuclear incidents in history. Chernobyl in particular has a very strong grip on public consciousness, so a comprehensive

understanding of the causes of the disaster and the degree of relevance to Western civil nuclear reactors is vital.

As discussed in section 2.3, nuclear would essentially compete with other baseload supply options such as coal, and supplement the existing hydro capacity in New Zealand. These technologies have their own safety risks that need to be evaluated. Envision a hydro dam upriver of a populated area, for example; there are two hydroelectric dams in the US whose sudden rupture would kill 200,000 people (Cohen, 1990). Indeed, the reality is that the collapse of dams has caused more immediate casualties worldwide than any other power generation option (Vujić et al.). In a sense, New Zealand is already accepting widespread use of the generation technology with the worst safety history.

Coal itself is somewhat controversial in terms of the pollution that results from normal operation. The risks of nuclear energy should not be evaluated in a void; some form of electricity generation must be used. It is important to consider the counterfactual, which is the situation that would occur in the absence of a programme. Obviously, a variety of technologies including coal and hydro are being utilised at present, so some level of risk is already being accepted. Still, nuclear power does have the potential for long-term environmental contamination. A serious radiation release can substantially outweigh the threat that can be posed by other means of generation, since the effects will persist for a substantial period of time.

#### **4.1. Major Catastrophes**

Probably the most serious risk associated with a nuclear reactor is the concept of a full-scale meltdown, where molten (and obviously extremely radioactive) fuel escapes from the core structure. The majority of accident scenarios centre on a loss of water, and resulting cooling failure. In a typical reactor a loss of water will retard the nuclear fission process, but the heat still present from radioactivity has the potential to melt the fuel. The possible scenarios include:

1. A break in the cooling system. The water used to transfer heat in nuclear reactor operates at very high temperatures and pressures, and would escape quickly as steam when presented with an escape route. As such, the cooling system warrants high quality in both materials and workmanship. To provide early warnings, this is augmented with an extremely thorough inspection programme, and a variety of leak detection systems. If a breakage occurs despite these preventative measures, an emergency core cooling system (ECCS) exists, which is composed of several independent systems to pump water into the

reactor and cool it. Multiple, independent systems are used in order to provide redundancy: if one fails, another can perform its function.

2. Perhaps more concerning would be a loss in power to the station itself. Such a scenario would prevent water circulation (inoperability of the pumps), and damage the pumps themselves (their seals need water cooling). In fact, in some reactors, being without power for as little as 20 minutes would lead to an actual meltdown (Cohen, 1990, p. ch 6). To guard against this, power is generally brought in from two different off-site sources, and emergency diesel generators are located onsite to provide power (and they themselves are regularly inspected for reliability). Alternative, steam-operated pumps can be used in the coolant system and simply run on steam from the reactor. Any electrical requirements can then be backed up by the presence of batteries.
3. Changes in the reactor (such as to the temperature or chemical composition of the water) or variances in power demand can require the adjustment of control rods to correct the power level. However, in the case of larger variances (most notably in the case of a large reduction in power demand, perhaps from an external grid fault), the standard control rods may not be able to compensate sufficiently. In this case, emergency control rods are immediately inserted to terminate the chain reaction, which is known as “scram”. If the scram system should fail, intense overheating and loss of water would result, similar to scenario 1. As with scenario 1, the ECCS exists as a backup for such an outcome.
4. Earthquakes can cause any of the above scenarios, individually or collectively, and have the potential to also cause damage to the safety systems discussed. Nuclear reactors are thus (obviously) not built on fault lines, and are constructed to be structurally resilient to earthquakes. However, an earthquake with enough intensity can still lead to a meltdown; in such a case, though, the “effects of the meltdown would be a relatively minor addition to the consequences of that earthquake” (Cohen, 1990).
5. The threat of exploitation by terrorist groups is relatively low compared to other safety risks, from a New Zealand perspective, since the terrorism risk for the country as a whole is considered to be low (NZPA, 2002). Of course, the possible hazards posed in such a scenario range into the catastrophic, although such outcomes are considered extremely unlikely under ‘normal’ operation, as discussed above. Still, however unlikely a terrorist attack might be, protection measures would need to be evaluated if construction of a nuclear plant were considered. Certain methods of terrorist attack are analogous to natural disasters such as a fire, and are thus essentially already accounted for. Plant

security would thus be the most important consideration, and could yield some interesting risk analysis and cost-benefit studies (Deutch et al., 2003, p. 50).

Should all the aforementioned safety systems fail, a final line of defence exists: the containment system (sorely lacking in the case of Chernobyl: see section 4.3 for a discussion). A typical system utilises a dualistic approach: thick concrete walls with steel reinforcement and an internal steel lining to resist high pressures, and a selection of measures to reduce radioactivity trapped within (filters, sprinklers, etc.). Thus the barrier protects against an external intrusion of force and traps radiation releases inside, until they can be nullified. In other words, containment only 'needs' to hold for several hours in the case of a meltdown to greatly reduce the possibility of adverse health effects (the important aim is to prevent immediate atmospheric dispersion; within a few hours, some of the radiation could be filtered, and most would simply settle on the walls and internal equipment). Still, such a system (as with any system, in fact) is not infallible. Scenarios exist where, in the 'right' circumstances, containment could be broken or bypassed. Such scenarios become a game of probability, or risk: the chances of multiple layers of defence mutually failing, and the possible consequences thereof.

It should be observed that site selection for a reactor is of particular relevance to New Zealand. Any New Zealand installation would likely be on a coastal or estuarine site with a low seismic risk. As noted by the Royal Commission, most nuclear reactors are built in areas where the seismic risk is considerably lower than that of the majority of New Zealand, where no area can be considered immune from a possible high magnitude earthquake. At the time of the report, no resoundingly suitable sites had been identified, and The Geological Society of New Zealand was uncertain one would ever found. Nevertheless, reactors have been built in Japan and California, which are both high-risk areas for earthquakes (New Zealand. Royal Commission on Nuclear Power Generation in New Zealand., 1978). With respect to Japan, the Fukushima incident is not particularly discouraging. The issues that arose subsequent to the earthquake and tsunami were not a result of directly induced failure to the reactors, but rather failure of the offsite AC supply powering the cooling systems. The reactors themselves actually withstood the 9.0-magnitude earthquake, an impressive demonstration of their robustness (Strickland, 2011). A modern reactor design, without such reliance on external power, combined with a strict and selective code for site selection minimising the potential for seismic disruption, should not pose major concern.

One point of note is that nuclear accidents are often discussed in terms of “worst possible” outcome, some sort of cataclysmic accident, and may be deemed that such a possibility is unacceptable, irrespective of probability. This is essentially a form of the min-max regret approach: the implication is that the maximum possible regret should be minimised. Consequently nuclear power is dismissed on the basis that the technology’s worst case scenario exceeds those of other generation options; in other words, the possible regret that might result from nuclear power is too high. The problem with evaluating something as complex as a major disaster (of any variety) is explained by this excerpt from Cohen (Cohen, 1990) (see Appendix G for the quote reproduced in full):

*In any field of endeavour, it is easy to concoct a possible accident scenario that is worse than anything that has been previously proposed, although it will be of lower probability... It might require a lot of improbable circumstances combining together, like water lines being frozen to prevent effective fire fighting, a traffic jam aggravated by street construction or traffic accidents limiting access to fire fighters... consider the possibility of the fire being spread by glowing embers to other cities which were left without protection because their firefighters were off assisting the first city; or of a disease epidemic spawned by unsanitary conditions left by the conflagration spreading over the country...*

While seemingly exaggerated in nature, this verbal illustration poses a genuine point: whether or not nuclear power should be disregarded on the basis of a possible negative outcome. In practical terms, how improbable is a major nuclear accident? Several studies have been undertaken by the US Nuclear Regulatory Commission (NRC) that use probabilistic risk analysis. Three studies have been undertaken: WASH-1400 (and a criticism by the Union of Concerned Scientists, or UCS, an organisation opposed to nuclear power), NUREG-1150, and SOARCA<sup>19</sup>. WASH-1400 and the UCS report will be discussed here, as their results are readily available in an understandable form. NUREG-1150 was published in 1991 as a successor to the RSS, and used more advanced probabilistic risk analysis techniques (as well as examining plants with improved safety measures). Compared to the RSS figures below, it found the probabilities of a core accident to be lower, and predicted cancer deaths to be about around third (Rasmussen, 1990).

WASH-1400, or the Reactor Safety Study (RSS) was published by the NRC in 1975. UCS published their probabilities in 1977. Furthermore, in 1979 the NRC themselves

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<sup>19</sup> SOARCA utilises advanced computer models and simulation tools; however, it was still in progress at the time of thesis completion.

accepted an independent revision to the RSS, which demonstrated flaws in the uncertainty values (although not the probabilities themselves, which will still be quoted here) (Cohen, 1990).

The RSS estimates predict a serious reactor meltdown around once in 20,000 years of operation. The key term is “operation”: if four reactors are operating simultaneously, then a meltdown is expected to occur once every 5,000 years of actual time. The UCS report estimates one meltdown in 2,000 years of reactor operation. Considering the history thus far (World Nuclear Association, 2011):

- 14,000 years of commercial reactor operation.
- Two notable incidents, Chernobyl and Three Mile Island, in that timespan (see sections 4.3 and 4.4).
- 12,000 years of marine reactor operation.
- Three Russian submarines have experienced near-meltdown events.

The case studies at the end of this chapter investigate the two commercial events in detail, but it can be said that no Western-type nuclear reactor has experienced a true meltdown, despite the UCS estimates predicting one (several, if you include US submarine operation) by this point.

Bearing in mind that the following figures are calculated for the US<sup>20</sup>, the consequences of the meltdown event predicted in these analyses should be considered. In most scenarios the containment is expected to maintain its integrity for an extended period of time, resulting in no fatalities. In an extreme scenario (1 out of 100,000 meltdowns), the death count could approach 50,000. On average, the RSS forecasts 400 fatalities per meltdown; the UCS figure is 5,000. Staying within the context of the US, coal burning power plants are estimated to cause anywhere from 10,000 to 30,000 deaths per year (Krewski et al., 2000) (Cohen, 1990). The higher figure is considered fairly robust, but even employing the lower bound, for the nuclear industry to pose as much of a threat to human life as coal burning, there would need to be 25 meltdowns per year by the RSS average, or 2 per year according to the UCS.<sup>21</sup> As stated before, no Western-type reactor has ever experienced a true meltdown, which makes the rejection of nuclear energy as unsafe questionable, given the presence of a technology that is more harmful in reality.

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<sup>20</sup> New Zealand has a relatively low population density, so the effects of any type of large-scale disaster would likely be lower on average.

<sup>21</sup> For the RSS figures, this implies 500,000 reactors in operation, which is clearly not a realistic possibility. Even the UCS estimates would require 4,000 reactors in operation to keep pace with the conservative estimate for coal pollution deaths.

It is true that air pollution is to some extent a ‘silent killer’, and thus is not particularly alarming.<sup>22</sup> From an economics viewpoint however, the argument that nuclear accidents are worse since they are a more readily observable and perhaps visceral event is largely irrational. When allocating resources, choices should be made on the basis of social costs and benefits. The deaths from operating a coal plant may not weigh on public consciousness, but they still pose a very real economic cost (e.g. in terms of healthcare). Expressed bluntly, a technology that results in more deaths has higher external costs (as demonstrated in section 3.3), irrespective of popular opinion. A similar phenomenon is seen when valuing the cost of a fatality in transport safety, where the willingness to pay for the statistical prevention of a death is much higher for high-profile accidents (such as train or air travel) than for road travel (Jones-Lee, 2002).

However, the vast majority of deaths that might result from a nuclear reactor accident would themselves be difficult to detect on an individual basis, materialising only as slight increases in the cancer rate. In the worst-case scenario from the RSS, the majority of deaths are expected to result from cancer, manifesting as an increase in the individual risk of cancer by 0.5 percent. Given the variations in cancer rates between countries, regions, and even individuals (due to a range of risk markers such as smoking), it is unlikely that the increase in cancer-related deaths would be any more noticeable than those from air pollution (Cohen, 1990). Of the 50,000 deaths predicted in this scenario, only 3,500 deaths would be expected to be directly attributable to the meltdown itself. Cohen notes (Cohen, 1990):

*The largest number of detectable fatalities to date from an energy-related incident was an air pollution episode in London in 1952 in which 3,500 deaths directly attributable to the pollution occurred within a few days.*

Such an event is unlike to reoccur in modern times, but so is an equivalent reactor meltdown. The justification for ignoring nuclear power on the basis of an extremely improbable accident is no greater than for any other technology. From a strictly economic perspective, a major nuclear disaster is undesirable because it would be extremely costly for a variety of reasons.<sup>23</sup> That being said, we already accept an electricity generation technology that, based on the above figures, is more dangerous than nuclear energy. Given the array of safety features in modern nuclear reactors, and

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<sup>22</sup> A nuclear bomb dropped in a specific location might cause fewer deaths than coal plants in a year, but clearly it is a more alarming event.

<sup>23</sup> Negative health effects, possible civilian relocation, reactor clean-up, possible serious power shortages, long-term land contamination.



the estimated probabilities of failure at a level required for a major disaster to result, it seems fair to say that the chances of such an event are low enough that a numerical cost-benefit analysis should not require any significant adjustment.<sup>24</sup>

## **4.2. Operational Hazards**

Having considered the possibilities stemming from ‘serious’ reactor incidents, attention can now be turned to a treatment of the day-to-day risks of nuclear energy. In some ways, this is the more important aspect of safety concerns: nuclear power must be a demonstrably safe option to live with, not just robust against major disasters. To this end, two specific issues are examined: radiation dangers (i.e. minor leakages and their repercussions) and nuclear waste disposal.

### **4.2.1. Radiation**

The word “radiation” might best be described as a ‘loaded term’. In the words of the OECD Nuclear Energy Agency (Nuclear Energy Agency, 1991, p. 12):

*The risks associated with radiation also loom large in the unconscious mind of individuals. Radiation has dangers that arouse irrational fear; its source and effects cannot be perceived by the senses: sight, hearing, touch or smell.*

Just as with the larger scale safety concerns around nuclear energy, this quote highlights the importance of quantifying the dangers in a clear manner. In order for a reasoned conclusion to be reached, the stigma of the term needs to be shed in favour of a more scientific evaluation.

Scientifically speaking, radiation is not a singular phenomenon: the effect is not homogeneous, but instead varies depending on the source. Of relevant concern is ionizing radiation, where unstable atoms decay and can damage living tissue in the process, with effects ranging from cancer, tumours, and DNA damage to skin burns, radiation sickness and death with high enough doses. There are six key types (World Nuclear Association, 2010e):

1. Alpha particles: intensely ionizing particles, primarily emitted by natural heavy elements, notably uranium and radium. However, they are unable to penetrate the skin, so they are not dangerous when originating from outside the human body.

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<sup>24</sup> One caution, however, is that in the event of a serious accident nuclear may prompt considerably more public fear and trauma than other disaster types: hence the importance of education.

2. Beta particles: emitted by many radioactive elements. Unlike alpha particles, they can penetrate flesh, and produce an effect similar to sunburn, but they can be shielded by as little as a few millimetres of wood or aluminium.
3. Gamma rays: high energy beams, emitted by many radioactive decay processes, and unlike alpha or beta particles, they are much more penetrating. Consequently they are the primary hazard facing workers dealing with sealed radioactive materials.
4. X-rays: perhaps the most commonly known form of ionizing radiation. They are essentially identical to gamma rays, with the exception that they are not nuclear in origin.
5. Cosmic radiation: while the name may sound like a concept from a comic book, cosmic radiation is actual particles that bombard the earth from space, contributing to background radiation exposure.
6. Neutrons: primarily released by nuclear fission, and thus are generally contained by the core of a nuclear reactor. Therefore they are seldom an issue outside of a nuclear plant, but can be very destructive to human tissue.

Having elaborated on the relevant types of radiation, a unit of measurement is required to evaluate the risk posed by a nuclear program. The standard unit of radiation absorption is the gray: one gray is one joule of energy per kilogram of tissue (inherently allowing for differences in body mass). However, a measure is required that incorporates the inherent differences in the types of radiation and their effect on the human body. One such measure is the sievert (Sv). One gray of beta or gamma radiation is equivalent to one sievert, while one gray of alpha particles is around twenty sievert, and so forth. Thus, when measured in sieverts, radiation sources can be easily compared. In the following discussion, millisieverts (mSv) will be employed, since the sievert is a comparatively large scale for individual human exposure (World Nuclear Association, 2010e).

It is important to understand that radiation is not a phenomenon confined to man-made sources such as reactors or weapons. Energy particles from outer space (simply called cosmic radiation) account for around 0.3 mSv of exposure each year. Radioactive elements in the ground, such as uranium and thorium, generate 0.2 mSv over the same period. Even the earth-derived materials used in buildings, such as bricks, can cause exposure of up to 0.1 mSv annually. Finally, potassium within the human body generates about 0.25 mSv yearly. In total, then, the average person is exposed to roughly 0.85 mSv in total over this period from, or about 0.01 mSv every four days, from these sources alone (Cohen, 1990). In this context, the exposure levels of

historical incidents seem relatively tame. As an example, the Three Mile Island incident saw local exposures (that is, within 16 km) of around 0.08 mSv (World Nuclear Association, 2010h). A leak from a reactor in Rochester, New York, USA (1982) saw no more than 0.003 mSv (Cohen, 1990, p. ch 5).

Within reason, variations in radiation exposure do not appear particularly significant either. Cohen compares Colorado, where the soil's uranium content is high and the altitude reduces atmospheric protection from cosmic rays, to Florida, where the soil is lacking in radioactive elements and the altitude is much lower (Colorado's mean altitude is about 2,070 meters above sea level, while Florida's is only 30) (NSTATE LLC.). In the case of Colorado, natural radiation levels are about 200 percent of the natural average, while in Florida they are 15 percent lower. Tellingly, at the time of Cohen's research, the cancer rate in Colorado was 35 percent below the national average, suggesting that background radiation is not a particularly major cause of cancer. While research still continues into the exact relationship between low-level radiation and cancer, existing studies do indicate that in general, the cancer rate appears to remain relatively constant between areas with low and high levels of background radiation (Krieger). At any rate, a variation of 0.01 mSv that might arise from a reactor leak appears a relatively small adjustment.

To further put such a dosage into context, a dental or chest X-ray generates around 0.1 mSv. Simply using natural gas within a home exposes the inhabitants to an additional 0.09 mSv per year (refer to Appendix H for a list of various mSv exposure levels). It is important to understand that when a measurement like the sievert is used – which factors in the effects of different radiation types – there is no difference between radiation from natural or man-made sources. 1 mSv of exposure from radioactive materials in the soil is the same as 1 mSv of exposure from an X-ray machine. In total, radiation resulting from non-natural sources totals around 15 percent of public radiation exposure each year, mostly medically-related. In the context of the various sources of radiation faced by the general public, possible radiation exposures from non-critical reactor incidents certainly seem extremely low (especially given containment and design technology has definitely not regressed since 1982).

However, consideration must also be given to the radiation dangers posed by the day-to-day operation of a nuclear power source (that is, the entire fuel cycle, including mining). First, those living within range of a nuclear reactor are expected to receive an additional 0.01 mSv each year. In a purely linear sense, then, one would have to live in close proximity to ten reactors for a year to receive the same dosage of radiation as that from a single dental X-ray. At any rate, safety regulations usually set public dose limits

at 1 mSv/year above background levels. For workers involved in the nuclear fuel cycle, the International Commission on Radiological Protection has established the maximum dose at 20 mSv per year, when averaged over five years; the maximum single dose is 50 mSv, along with a stated requirement to keep exposure “as low as reasonably achievable” (World Nuclear Association, 2010e).

In order to mitigate the safety risks posed to workers in various stages of the process, a number of measures are taken. First, and most simply, workers are limited in their exposure time. When possible, distance from radiation sources is also maximised, since intensity decreases with distance. Shielding is an important process: as mentioned earlier, gamma radiation can be effectively blocked with an adequate use of lead, concrete, or water. Thus particularly dangerous materials can be handled remotely (e.g. by machine) in shielded rooms, or underwater. Finally, containment is vital: reactors themselves are closed systems with multiple barriers, both to keep workers safe and to minimise the dangers of any leaks (World Nuclear Association, 2010e).

The average dosage received by Australian uranium mine workers is about 1.5-2 mSv yearly. US nuclear energy workers (i.e., the remainder of the process: fuel treatment, reactor operation, etc) received about 3 mSv yearly. While these figures may seem high compared to the global background radiation average of 2.4 mSv each year, such variations above the average do not have a particularly noticeable effect in terms of cancer or other such symptoms, as demonstrated by the comparison between Florida and Colorado. As a more extreme example, people living in parts of Ramsar, a city in Iran, receive doses of up to 260 mSv annually, yet show no evidence of increased cancer rates or other genetic problems (Ghiassi-Nejad, Mortazavi, Cameron, Niroomand-Rad, & Karam, 2002).

A quote from the World Nuclear Association serves to put the general public’s wariness over nuclear reactors and radiation into perspective:

*Interestingly, due to the substantial amounts of granite in their construction, many public buildings including Australia's Parliament House and New York Grand Central Station, would have some difficulty in getting a licence to operate if they were nuclear power stations. (World Nuclear Association, 2010e)*

Again, in the light of the cost figures from the previous chapter, it seems fair to say that little or no adjustment is required for the possibility of minor leakages. While such events can and do occur, typically they are not severe in scale, and more importantly, they have no appreciable health impacts. In short, the risk posed by radiation releases

is unlikely to appreciably affect the outcome of a more in-depth evaluation of the economic desirability of nuclear energy in New Zealand.

#### **4.2.2. Radioactive Waste**

Waste is a problem inherent and common to all forms of energy generation, even the perceived clean technologies, such as solar energy, which results in waste during the production process of solar cells. The unwanted products of the nuclear cycle, however, are obviously regarded with somewhat more distrust. There may be some justification for this, given their highly radioactive nature. This means that here we are considering dangers somewhat more significant than those of the previous section (Hewitt & Collier, 2000, p. 257). Whilst from the public perspective nuclear power may have connotations of catastrophic meltdowns and radiation releases, in the context of a properly designed and maintained nuclear reactor the thorniest issue appears to be that of long-term waste disposal. The process involves a considerable number of steps: storage, conditioning, packaging, transport, and final disposal (Deutch et al., 2003, p. 55). The exact steps employed are dictated by the chosen fuel cycle, and, specifically, whether spent fuel is to be reprocessed or not.

Radioactive waste can arise in several stages of the energy generation process, and can even be in gaseous or liquid forms. The conventional approach is to convert these wastes into a solid form for disposal and decommissioning. It is these strategies which are vital for the long-term viability of nuclear power. Hewitt and Collier list the following sources for waste products:

1. Uranium mining.
2. Fuel fabrication plant: specifically, the fabrication of plutonium-based fuels produces some low level wastes (although these are less common than uranium-based varieties).
3. Spent (irradiated) nuclear fuel: highly radioactive fission products which are the primary concern of waste disposal.
4. Reprocessing plant: plants for the further use of spent fuel themselves produce some additional wastes, although they are not as significant as the previous.
5. Nuclear reactors: aside from (3), the reactors generate an array of gaseous, liquid, and solid wastes. Notably, when the reactor is due to be decommissioned, and the structural materials which have become slightly radioactive must be carefully disposed of to return the site to normal. As discussed earlier, decommissioning is an obvious financial cost; safety precautions are amongst the reasons for this.

With regard to point 3, and based on the MIT study, the once-through fuel cycle (also known as an open fuel cycle) would appear to be the most practicable and economically feasible approach, especially in the context of beginning a nuclear energy programme (Deutch et al., 2003, p. 54). In the strictest sense, this is not a cycle per se, since the expended fuel is placed into storage rather than being reprocessed. It is the approach most commonly employed in the nuclear energy industry globally, and the one that will be assumed for the rest of this discussion.

In considering the dangers of fission products, an important measure is the *biological half-life*:

*The time needed for any particular radioactive element, taken into the body, to be reduced to half its [radioactivity] level [by] natural excretion processes.* (Hewitt & Collier, 2000, pp. 260-261).

The reasons for this measure, as opposed to the radioactive half-life, can be appreciated by considering two different fission products, caesium-137 and strontium-90. Both have radioactive half-lives in the region of thirty years, but the biological half-life for caesium is 70 days, immensely lower than strontium at 50 years (strontium is absorbed into the bone, hence the significant difference). Another fission product, plutonium 239, has a radioactive half-life of 25,000 years and a biological half-life of 200 years within bone and 500 days within the lung (Hewitt & Collier, 2000). Such figures indicate that the dangers of fission products are somewhat more significant than any likely exposures to low-level radiation; waste disposal strategies are thus a vital component of nuclear generation.

In calculating the hazard posed by nuclear waste, one method is to calculate the time taken for the radioactivity level to fall below that of the original ore used to supply the fuel. Hewitt and Collier provide some estimates for various strategies. When fission products are discharged from a light-water reactor with no reprocessing, it takes around ten millennia for the hazard posed by the waste to fall below that of the original materials. Conversely, when a normal reprocessing procedure is applied, the timespan is reduced to 500 years.<sup>25</sup> Even without such processing, though, the first 1,000 years is the most important phase, during which the materials are highly radioactive although decaying quickly.

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<sup>25</sup> It is interesting to note that the materials continue to decay past the original hazard level; in the long-run, once all fission plants are absent from the planet, the global radioactivity level would actually be lower due to the existence of a nuclear program.

A number of methods are thus available for short term storage. In the very short-run (around ten years), spent fuel can be contained in cooling ponds. After this, additional containment can be used to continue underwater storage. Alternatively, a dry surface storage system can be utilised. Such systems are employed for up to a century as the radioactivity level decays and heat production declines. Underwater or surface (which allow for convection) solutions exist to deal with the issue of heat generation. Once it has declined sufficiently, long-term disposal can be achieved without special consideration (Hewitt & Collier, 2000, pp. 266-267).

At present, most OECD countries dispose of all non-high-level waste in surface or underground repositories. These wastes (which are about 90 percent of total radioactive by-products in nuclear generation) are kept inside specially engineered barriers until their radioactivity has expired. High-level waste and spent fuel, however, is largely kept in temporary storage with the eventual intention of a final disposal solution that will keep the waste isolated for the few thousand years required to nullify all health risks. Some countries that operate with this method have chosen to build their storage systems in such a way as to allow recovery, while others have opted for a more permanent geological solution.

One attractive option is disposal in a salt deposit, for the simple reason that the existence of such a deposit implies the absence of circulating groundwater. This is a key issue for nuclear waste storage, since it is vital that the radioactivity is contained in a localised fashion. For the wastes typically output by a PWR reactor, after about 60 years heat output becomes low enough for a surrounding salt strata to continue absorbing heat without containment reaching critical temperatures (Hewitt & Collier, 2000).

When such salt deposits are unavailable, the alternative option is geological or underground storage. In this case, waste contained within secure canisters is embedded in a stable formation,<sup>26</sup> usually around 1km below the surface. The greatest concern is any possible way for radiation to escape containment. Of all possibilities, underground water supplies making contact and migrating contaminants raise the most concern, and some water exposure is usually unavoidable. Such exposure is insufficient to assist in cooling, but has the potential to leach radioactive materials away, and containment systems have to be built to take this into account (Hewitt & Collier, 2000).

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<sup>26</sup> Obviously an important distinction. An earthquake faultline near a water source would be less than ideal.

Once again considering the US example, the Environmental Protection Agency (EPA) has determined that “the radiation dose from all potential exposure pathways to the maximally-exposed individual living close to a waste disposal site should not exceed [0.15 mSv] per year for the first 10,000 years after final disposition” (Deutch et al., 2003, p. 53). As discussed previously, this is significantly less than the background radiation exposure experience by the average individual; the EPA has determined it to be a 1 in 100,000 annual risk of fatal cancer. While other metrics such as the volume of waste produced and the residual heat levels are important from a technical perspective, as with any aspect of nuclear safety, the threat to human health needs to take precedence (especially important in terms of bolstering public confidence) (Deutch et al., 2003, p. 53). On the whole, the accepted view from scientific and engineering perspectives seems to be that long-term geological disposal (the concept of which is over 40 years old) of high-level waste is feasible, although some concern surrounds the management process (Deutch et al., 2003, p. 54).

The technical consensus on the feasibility of long-term waste disposal is not reflected in the public or political sphere, however. Obstacles to site-selection and development have been significant, to the point that no country aside from the US is expected to have a. operating disposal site before 2020 (Paffenbarger & International Energy Agency., 2001, pp. 188-189). Public opposition has been a major factor contributing to this, although overly optimistic schedules for developing geological sites are also to blame (Paffenbarger & International Energy Agency., 2001, p. 190). In the case of the US, the Yucca Mountain site has been earmarked since 1987 as the primary location for developing a storage facility. However, in 2009, the Obama Administration made the decision not to continue with the permanent underground repository project, eliminating all funding for Yucca Mountain, despite the USD 7.7 billion spent since the inception of the project. Subsequently the Blue Ribbon Commission was appointed in 2010 to devise a new strategy for nuclear waste disposal. Their 2011 draft report recommended the formation of an independent organisation, rather than the domestic US Department of Energy, along with a scheme to funnel nuclear waste fees garnered the price of nuclear-generated electricity to this new body. In January 2012, the commission’s final report was released, proposing a raft of measures for dealing with the final stages of the nuclear fuel cycle (Vujić et al.):

1. A consent-based approach to siting waste facilities.
2. A new organisation dedicated to implementing the programme, with appropriate access to funding.



3. Prompt attention to developing one or more geological disposal facilities, and consolidate storage facilities.
4. Similarly, immediate attention to large scale transport of spent fuel and high-level wastes to the aforementioned facilities.

While the proposed measures do at least provide a good-practice guideline for dealing with nuclear waste, the fact that such a result has taken over three decades to achieve does not inspire confidence. Furthermore, and perhaps more importantly in the case of New Zealand, the issue of disposal costs is paramount. Since there is no real existing case study to learn from, it is difficult to reliably estimate actual costs; however, for a suitably small nuclear programme the costs of storage and geological facilities (which are generally intended for much higher waste quantities) would likely vastly outscale the waste output levels of the reactors themselves. In short, a country of New Zealand's size might require a consolidated international disposal solution (World Nuclear Association, 2012).

Having considered the practical side of waste disposal, some attention should be given to various methods by which the process can be achieved with maximum efficiency, in terms of reducing risk (and creating public confidence) and minimising both short-term and long-term economic costs. The MIT report suggests that several decades of interim storage should be utilised in the disposal process. Their reasons for implementing such a system are (Deutch et al., 2003, p. 55):

- 1) Greater flexibility in the development timeline for a final disposal situation, and greater flexibility to select the most optimal solution.
- 2) Increased opportunity to benefit from future improvements in nuclear waste management technology.
- 3) Retention of the option for reprocessing fuel in the future.

The addition of transitional storage to the waste disposal process seems ideal if New Zealand were to undertake a nuclear energy programme, as it would reduce the pressure to select a final disposal method (allowing more time for site selection, etc). As mentioned briefly in section 3.2, New Zealand could consider developing a reactor with higher than average burnup. If the energy yield of fuel were to be tripled (which is technologically feasible), the quantity of waste for disposal is reduced to a third in practical terms. As noted, higher burnup rates result in higher expenses; this is where the pricing structure of waste disposal services becomes important. In the US, government waste disposal charges are based on each kilowatt hour of energy generated, so there is no particular incentive to pursue a higher burnup design (Deutch

et al., 2003, p. 56). If New Zealand authorities are more closely involved with the development of a nuclear energy programme (given it is unlikely to be solely handled by private industry, as discussed in section 2.3), a more economically efficient outcome might be reached.

#### 4.2.3. Decommissioning

The cost issues of decommissioning a nuclear reactor have been covered in section 3.1.1. In terms of the safety of the process, the radiological hazards presented are actually significantly lower than when the reactor is in operation. This is a consequence of the initial stages of decommissioning, which include the extraction of fuel and the conditioning and removal of radioactive materials and waste from the system (Nuclear Energy Agency, 2005a, p. 37). As the plant is shut down, other hazards such as pressurised and high temperature components are also removed from the equation. The dangers lie in deconstructing the plant's layers of defence, particularly containment. As long as the facility is deconstructed in an appropriate, stepwise manner and decontaminated appropriately, there should be no more danger in decommissioning than in regular operation (Nuclear Energy Agency, 2005a, p. 37).

### 4.3. The Chernobyl Disaster

Even over two decades since the disaster took place, the shadow of Chernobyl still looms over the nuclear industry, at least in public consciousness. As established above, radioactivity releases in the case of non-major incidents are close to negligible, and the chances of a major incident are “extremely improbable” (Cohen, 1990, p. ch 7).

Nevertheless, “extremely improbable” is not “impossible”, and Chernobyl provides a stark illustration of the consequences. In the words of Cohen:

*In that accident, a substantial fraction of all of the radioactivity in the reactor was dispersed into the environment as airborne dust – its most dangerous form. It is difficult to imagine how anything worse could happen to a reactor from the standpoint of harming the public outside. (Cohen, 1990)*

56 people died as a direct result of the accident,<sup>27</sup> mostly fire and rescue workers exposed to the massive radiation release. An assessment from the United Nations Scientific Committee of the Effects of Atomic Radiation estimated around 4,000 cases of fatal thyroid cancer attributable to the radiation release among residents of Belarus,

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<sup>27</sup> While undeniably tragic, it should be noted that about 100 fatal accidents occur in the workplace each year in New Zealand, and a further 700-1,000 workers will die prematurely from workplace-related disease in the same period. It is the possible severe radiation release that comprises the main concern from nuclear power.

Russia, and the Ukraine as of 2002 (United Nations Scientific Committee on the Effects of Atomic Radiation, 2006). An IEAE report corroborated these findings, adding:

*The estimated 4000 casualties may occur during the lifetime of about 600,000 people under consideration. As about quarter of them will eventually die from spontaneous cancer not caused by Chernobyl radiation, the radiation-induced increase of about 3% will be difficult to observe. However, in the most highly exposed cohorts of emergency and recovery operation workers, some increase in particular cancers (e.g., leukemia) has already been observed.*(International Atomic Energy Agency)

Most affected areas have been declared safe by this point in time, but a 30 km radius zone around the reactor site and certain other limited areas still remains restricted, with workers in the area rotating in and out of the region on a regular basis.

At any rate, much controversy and debate has surrounded the investigation into the cause of the Chernobyl disaster, with blame generally being assigned either to human error or reactor design deficiency. Much literature is devoted to this discussion, and will not be reproduced here. What is important to understand is that, irrespective of *cause*, the reactor design dictated the *effect*.

In (very) simple terms, nuclear reactors use the process of nuclear fission to generate heat from a fuel. Circulating water then carries this heat out of the reactor and turns to steam, driving a turbine (which in turn produces electricity). The science is beyond the scope of this thesis, but in essence, the required chain reaction cannot be sustained without a “moderator”<sup>28</sup>. Graphite works very well for this purpose; water can also be used, but only if the uranium fuel is enriched. Otherwise, water simply retards or “poisons” the reaction instead of acting as the moderator. As alluded to in the discussion of nuclear development (refer chapter 2.1), the majority of modern power reactors use water and enriched fuel; in essence, they are basically a large vessel of water with a configuration of fuel rods (Cohen, 1990, p. ch 7).

The use of water as a moderator provides two benefits. First, if the water itself is lost in the case of a malfunction, the reaction also ceases (it cannot continue without a moderator). Secondly, if for some reason the chain reaction should accelerate and the temperature rises (threatening, in the worst case, a meltdown) the water moderator will boil more, causing it to dissipate and reduce in quantity, retarding the reaction in turn. Thus this design type is inherently stable, at least in the sense of reaction speed and temperature (Cohen, 1990, p. ch 7).

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<sup>28</sup> The moderator, in very simple terms, acts to slow down the reaction so that it remains sustainable.

Using a graphite moderator, conversely, creates inherent problems. Water is still required to transfer the heat generated; however, since non-enriched fuel is used, it no longer acts as a moderator, but instead retards the reaction to a degree. If the water is suddenly lost, the reaction speeds up to the full potential of the graphite moderator, generating even more heat with no method to extract it. Also in contrast to the non-graphite design, if the reaction itself accelerates, causing the water to boil and dissipate, the problem becomes inherently worse, with the reaction speeding up even further (Cohen, 1990, p. ch 7).

The obvious question, therefore, is why a graphite-moderator would even be employed. The direct answer is that such a design is intended to produce plutonium for bombs at the same time as generating electricity. For a start, the nature of the reactor is such that it simply produces more plutonium. Secondly, fuel must be extracted within 30 days when creating plutonium. The water-based design is a single large vessel, and extracting the fuel necessitates reactor shutdown; thus the process is undertaken once a year at most. In the case of Chernobyl's reactor, each fuel rod is contained in an individual tube, and easily extracted at any point. Such practicality, however, would be foiled by the use of containment systems such as those used in all Western reactors, and these safety measures must also be foregone. If such a system had been in place, it is entirely likely that the radiation escape might have been prevented altogether (as in the case of Three Mile Island, discussed in the following section). Compounding these various factors was the combustible nature of the graphite moderator, which increased the emission of radioactive particles carried by the smoke (Cohen, 1990, p. ch 7).

There is much that has not been discussed here about the events that lead to the meltdown, the alleged safety culture surrounding the reactor design and operation, and the effects of the disaster. What should be clear, however, is that irrespective of the possibility of a meltdown occurring, a disaster on the scale of Chernobyl simply could not occur in a properly designed and staffed modern nuclear reactor. From an economist's perspective, decision-making should be a rational process. Here, the evidence clearly shows the historical example of Chernobyl, while serving as a warning over not prioritising safety, has no real role in evaluating a modern PWR or its ilk.

#### **4.4. The Three Mile Island Incident**

Three Mile Island demonstrates a very different and entirely more favourable outcome when compared to Chernobyl. As documented by the World Nuclear Association:

*The accident to unit 2 happened at 4 am on 28 March 1979 when the reactor was operating at 97% power. It involved a relatively minor malfunction in the secondary*

*cooling circuit which caused the temperature in the primary coolant to rise. This in turn caused the reactor to shut down automatically. Shut down took about one second. At this point a relief valve failed to close, but instrumentation did not reveal the fact, and so much of the primary coolant drained away that the residual decay heat in the reactor core was not removed. The core suffered severe damage as a result.*

*The operators were unable to diagnose or respond properly to the unplanned automatic shutdown of the reactor. Deficient control room instrumentation and inadequate emergency response training proved to be root causes of the accident.* (World Nuclear Association, 2010h)

However, the containment structure that was so notably absent in the case of Chernobyl worked as intended: around 30 percent of the core melted, but the fuel was contained. Most of the panic surrounding the accident was a result of miscommunication rather than actual danger. Problematic communication between official bodies led to a number of erroneous beliefs:

1. That a 12 mSv reading taken from directly over the reactor after a deliberate venting of radioactive gases was actually taken offsite.
2. A possibility existed that the hydrogen which had formed in the reactor as the result of a chemical reaction might explode (in reality, there was not enough oxygen present in the system for this to occur).
3. The Nuclear Regulatory Commission had ordered an evacuation.
4. A full-scale meltdown could possibly result.

Consequently, a panic-driven exodus resulted, and a storm of controversy erupted both in the media and on the political stage. Yet, amidst hundreds of samples taken by both the US Department of Energy and the Pennsylvania Department of Environmental Resources, no abnormal radiation levels were found; all were far within established health limits (Cantelon & Williams, 1982).

The post-accident evidence demonstrates overwhelmingly that there were no detectable radiological ill-effects. As mentioned earlier, average exposure within 16 km was 0.08 mSv, with peak exposure of 1 mSv (not more than a chest or dental X-ray). Over a dozen major studies (including a 13-year study of 32,000 individuals) showed no abnormal cancer rates, nor any other unusual negative trends in local individuals or the environment. Most important, the accident itself was not a lucky 'near-miss': according to post-analyses, containment would have worked even if the reactor had incurred a complete meltdown and fuel escaped (World Nuclear Association, 2010h).

The Three Mile Island plant was itself comprised of two reactors; only the second suffered serious damage, and necessitated a large-scale clean-up operation. Unit 1 was restarted in 1985, and remains in operation today. In fact, over its subsequent lifespan, the reactor's capability factor (electricity generated as a proportion of the maximum possible) was improved, its generation capacity was updated, workers logged three million hours without any workdays lost to accidents, and the longest continuous operating run of any light water reactor was achieved (616 days, 23 hours) (World Nuclear Association, 2010h). At present, the reactor is slated to continue operated until 2034. Three Mile Island, per se, demonstrates both that nuclear reactors can be robust against critical accidents, and also operate effectively and safely over an extended time period.

This historical experience lends positive support to nuclear generation, especially given the improvements in reactor design and worker training that have occurred since the incident. In the case of the US nuclear industry, an entire collection of performance and safety markers monitored by the internal Institute for Nuclear Power Operations and the World Association of Nuclear Operators have all improved significantly (World Nuclear Association, 2010h). It would be disingenuous to suggest that Three Mile Island was not actually a serious incident; any event involving serious core damage certainly warrants major concern. Nevertheless, it provides some support for the effectiveness of the aforementioned layers of defence (refer to section 4.1 above). From the perspective of a country embarking on a nuclear energy programme, there are literal decades of experience and improvement to benefit from. Once again, if rational decision making is held as the goal, there is little evidence to support dismissing the nuclear option out of hand.

#### **4.5. Summary**

Several conclusions can be drawn from the preceding sections. First, nuclear power is clearly not *unacceptably* unsafe, as is sometimes alleged. Given the numerous safety measures designed to prevent or mitigate the effects of any accidents, catastrophic outcomes are very unlikely. As touched upon at the beginning of this chapter, an analysis of nuclear cannot exist in a void. Electricity will be generated, whether it be by nuclear or another generation option. Compared to high-pollution options such as coal, nuclear can be said to be safer inasmuch as it causes less health and property damage. The results of the case studies are also encouraging. Chernobyl, while a tragic disaster, bears no more relevance to modern reactor designs than the safety record of the Reliant

Robin<sup>29</sup> does to a modern sedan. Three Mile Island actually stands as a testament to safety mechanisms utilised in reactors, where a major internal incident was successful contained. The improvements in safety made as a result further improve the outlook for nuclear power.

The biggest question mark is that of waste disposal. At present, OECD countries utilising nuclear power have yet to utilise a final disposal solution. There are no real technological obstacles to geological disposal of high-level waste: the obstacles lie in site selection and public opposition. The effective abandonment of the US Yucca Mountain project is not encouraging; the eventually results of the Blue Ribbon Commission's recommendations will be instructive.

The ongoing development of nuclear technology, as alluded to in Chapter 2, holds more promise. Newer Westinghouse AP1000 designs offer an excellent example of the improvements in safety systems over the previous generations of nuclear reactors. The design is, from an engineering perspective, simpler than its predecessors, and lends itself to modular construction over a shorter period. It has a smaller construction footprint, requires less maintenance and less operator intervention in the case of accidents, does not require offsite power to run active safety systems, and ultimately uses ambient air as a heat-sink (Vujić et al.). Of particular note are the lowered requirements for operator intervention (in light of the Chernobyl and Three Mile Island incidents), and the absence of a requirement for an offsite power supply.

The preceding chapters have illustrated that there is potential room in New Zealand's future generation mix for nuclear energy, and the technology itself appears cost-competitive when carbon emissions are taken into account. Here it has been shown that the associated safety risks are not, by themselves, crippling to the desirability of the technology; however, the lack of a demonstrable case study for waste disposal is highly concerning. Keeping this conclusion in mind, the following chapter investigates the political treatment of nuclear power in New Zealand, and the issues of public perception in general.

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<sup>29</sup> The Reliant Robin was a notoriously dangerous three-wheeled car (the single wheel was at the front).





## 5. Political and Public Debate

Having established conclusions on the dimensions of cost and risk, attention is turned here to the political and public treatment of nuclear power. These aspects are perhaps the strongest obstacles facing the technology: for nuclear to be included in policy evaluations, they *must* be favourable. Such matters may seem only peripherally related to the more practical concerns of the preceding chapters, but the reality is that politicians and the bureaucracy dictate policy. The nuclear industry itself bears witness to these very real concerns. Without the increasingly negative shift in public opinion on nuclear energy discussed in section 2.2, the global industry would almost certainly be of a significantly larger scale today. Compared to analysing cost and risk, however, political will can be considered largely a singular obstacle; as the IEA expresses (Organisation for Economic Co-operation and Development & International Energy Agency, 1998, p. 26):

*Political issues will either allow nuclear power to proceed, or they will not, leading to its end.*

This expresses the fact that any proposed policy decision will have the necessary support, or it will not. Of course, support can change over time, and past assumptions can be re-evaluated in the light of new evidence. Indeed, it is this potential for public and political opinion to change that provides a purpose for answering the question posed at the start of the thesis. The reality of the policy process is that group and even individual interests, in conjunction with the importance of rhetoric<sup>30</sup>, play a key role. On the basis of the preceding chapters, there is a case for nuclear energy as a *possible* electricity source in New Zealand in the future. Consequently, consideration must be given the state of public opinion and the political stance on nuclear energy, in order to see if debate is as informed as it should be in order to achieve the most economically beneficial outcomes.

Thus, the requirements for nuclear power to proceed in New Zealand are multi-dimensional: public acceptance and political will, and demonstrable cost superiority to solar, hydro, and geothermal energy options (presuming that these options are the primary competition for low greenhouse emission base load supply). Implicit in these requirements is that the country can field the appropriate human resources to support the endeavour of nuclear energy generation and maintain a strict safety culture (Golay, 1995). The challenges of doing so seem steep upon casual consideration; indeed, more in-depth analysis may ultimately prove them to be too steep. However, placing nuclear

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<sup>30</sup> Rhetoric in politics is, in its most basic sense, about the use of language to persuade.

energy on the table as an economic policy option can only prove beneficial: either by providing a grounded, demonstrable affirmation against its use, or by potentially revealing an option for securing the country's energy future while moving closer to our climate change goals.

### **5.1. Public Opinion**

As has been discussed in section 2.2, a major reason for public disapproval of nuclear power is concern over perceived safety risks, both of nuclear plants and their high level of waste. The core of such concerns undoubtedly stems from the fear of serious radiation releases into the surrounding environment from a nuclear station, as embodied by the Chernobyl disaster, a historical event that looms large in public consciousness. As discussed in chapter 4, nuclear safety has made numerous strides since the 1980s (and at least in terms of Western nuclear development, was already at a reasonably robust stage before then, as evidenced by the relatively positive outcome at Three Mile Island – see section 4.4). For nuclear power to proceed politically, the public must first be convinced that a nuclear energy programme would not be unacceptably dangerous. In New Zealand's case, nuclear power may ultimately prove not to be the optimal choice for expanding the electricity generation sector at this time. However, by putting the *possibility* of nuclear solutions back onto the agenda now, increased media and public discourse might result.

Problematically for nuclear power, though, gathering public support requires acceptance of more than just reactor operation. There are also issues of fuel and waste transportation, disposal of low-level radioactive waste, emergency evacuation plans, operation of test reactors, etc.. In short, there is a much wider range of activities to consider than other generation methods alone. As shown in section 4.2.2, long term waste reprocessing and storage is certainly technologically feasible. Similar concerns have also obstructed plans for the reprocessing of waste. These obstacles may also be fuelled, at least in part, by the legacy of nuclear history in the military sector. Under the pressure of the Cold War, nuclear development for military applications was often achieved at the expense of safety precautions, as demonstrated by Chernobyl and discussed in section 4.3. Only a transparent approach to plant operation and waste management coupled with the passing of time will shed the negative associations.

Certainly, then, nuclear opposition is not a unique feature to New Zealand: the technology has faced considerable public opposition in both the United States and Europe. In both regions, large majorities of the public oppose the construction of new nuclear plants, particularly within their individual region (Deutch et al., 2003, p. 71).

Present attitudes seem to support a reduction in coal and oil burning with support for increases in wind and solar generation. In their report on nuclear power, the MIT performed a statistical analysis on survey data gathered in the US and generated several conclusions about the specific attitudes dividing those who support nuclear energy expansion and those who do not.

First, and unsurprisingly, perceived environmental harm has the strongest effect in determining the average individual's stance. The most common perception was that nuclear generation is "moderately harmful", and this was strongly correlated with wanting to reduce nuclear reliance. Those who saw perceived the technology as only "somewhat harmful" tended towards expanding its usage. The second and third most important factors were accident risks and waste disposal. Support is largely constrained to those who believe that waste can be stored safely for many years and that a major accident is unlikely in the next decade; this group, a minority of respondents. Economic costs ranked third in priorities. Interestingly, the issue of climate change had a negligible effect on opinions (Deutch et al., 2003, pp. 71-72).

The second stage of the MIT analysis was to split the sample into two, with one acting as a control group and the other being provided with a mix of information on future energy price projections, toxic waste from fossil fuels, and global warming. When provided with this information, the second group responded with considerably higher support for nuclear power, primarily as a result of the information about energy prices. According to the MIT researchers (Deutch et al., 2003, p. 72):

*The public perceives solar and wind to be inexpensive. When informed that solar and wind are more expensive than fossil fuels or nuclear power, survey respondents showed substantially less support for expanding solar and wind and substantially more support for nuclear power and somewhat more support for coal and oil. Information about global warming again had no effect on public attitudes toward alternative energy sources.*

In short, they found that fears over safety and health risks drive opposition to nuclear energy, while misperceptions over relative prices engender support for solar and wind. It is also interesting to note that, despite the importance placed on global warming by political leaders and the media, public preferences for energy sources seem to essentially ignore it.

These conclusions suggest that the most effective way to bolster public support for nuclear energy would be through education not just on nuclear technology itself, but rather on the relative costs of the alternatives. While safety concerns have a strong

impact on the average individual's stance with respect to a nuclear programme, it appears that economics still reigns supreme. However, it is important to reiterate that this is a US-based study. That country has had an established nuclear energy industry for over half a century, and this familiarity is likely to have resulted in a higher level of public confidence in safety when compared to New Zealand. At any rate, if a nuclear programme ever came to eventuate in New Zealand, a robust implementation with a focus on efficiency and safety would be vital. Quoting again from the MIT report (Deutch et al., 2003, p. 72):

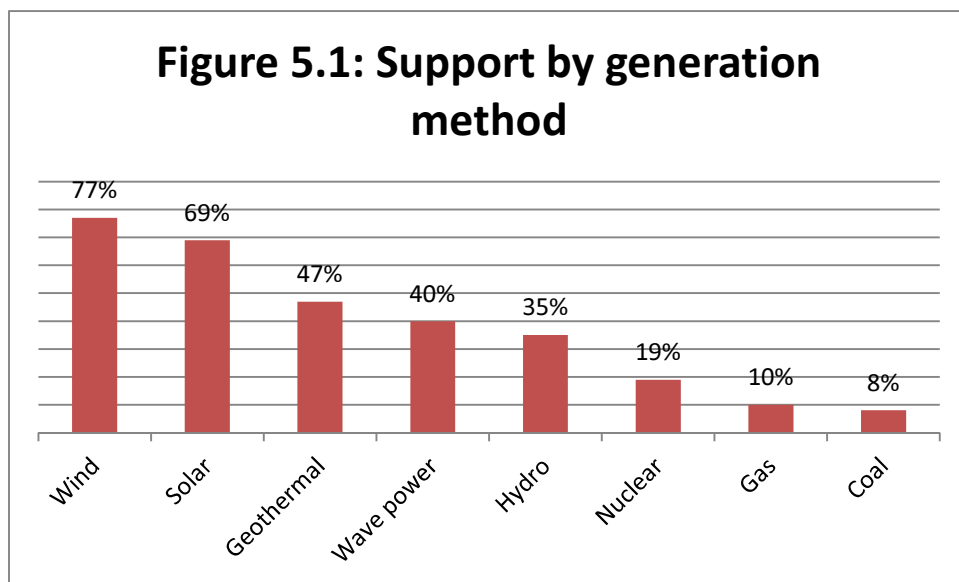
*The surer way to cultivate public acceptance of nuclear power, though, is through the improvement of the technology itself and choosing carefully what nuclear technology to use. Developing and deploying technology that proves uneconomical and hazardous will make [a] growth scenario infeasible. Technology choices and improvements that lower the cost of nuclear power, that improve waste management and safety, and that lessen any environmental impact will substantially increase support for this power source.*

Corner et al.'s study of British public attitudes towards nuclear energy demonstrates the sliding scale of public opinion. By 'reframing' nuclear power as a low-carbon technology, participants were more likely to reach a state of "reluctant acceptance" for nuclear, accepting it as a lesser of two evils, so to speak. The inherent dislike for nuclear energy did not dissipate, but by weighing the perceived risks of nuclear energy against the perceived dangers of climate change and energy security concerns lead to a belief in the possible necessity of nuclear energy (Corner et al., 2011).

It should also be considered that public disapproval or distaste for one option does not necessarily translate into tacit approval for another. Public opinion may express dislike for the construction of nuclear reactors, but it does not necessarily follow that taxpayers therefore have a high willingness-to-pay (WTP) for solar or wind installations, etc. As an example, in a 2009 analysis on the WTP for micro-generation technologies (e.g. ground-source heat pumps, micro wind turbines, etc) by Scarpa and Willis found that while British households significantly valued renewable energy adoption, their WTP was insufficient cover the actual capital costs of these technologies. In short, it cannot be assumed that because the public may evidence distaste for nuclear energy or a desire to be "nuclear-free", they must therefore be willing to bear the costs of alternative energy options (if nuclear proved to be cheaper than the currently considered 'green' generation technologies). Consequently, having nuclear energy as a potential option in the energy policy mix would allow for more informed decision-making in the political

sphere if the public were sufficiently well informed to express their preferences (Scarpa & Willis, 2010).

A 2008 ShapeNZ poll, run by the New Zealand Business Council for Sustainable Development, showed the following levels of support for generation options amongst the respondents:



Source: (New Zealand Business Council for Sustainable Development)

While the results are hardly unsurprising, 1 in 5 New Zealanders supporting nuclear energy is perhaps higher than expected. Notably, support for nuclear was higher than gas and coal combined. Interestingly, in a NZ Herald survey from 2005, 64 percent of NZ chief executive officers said nuclear energy should be investigated as an option for securing New Zealand's energy future (O'Sullivan). One possible explanation for this is that the commercial sector is the fastest growing source of demand for electricity in NZ, implying business executives may be concerned by electricity prices (Ministry of Economic Development, 2010b, p. 6).

## 5.2. The New Zealand Perspective

Continuing to the domestic context, it is interesting to note that New Zealand once planned to embark on a nuclear programme. In 1968, the national power plan first identified the likely need for nuclear power in New Zealand a decade or more in the future, since all the readily-developed hydro-electric sites had been utilized. Plans for a reactor were developed, and a site at Oyster Point on the Kaipara harbour near Auckland was reserved. Four 250 MWe reactors were envisaged, to supply 80 percent of Auckland's needs by 1990. The subsequent discovery of the Maui gas field, along

with coal reserves near Huntly, led to the project's abandonment by 1972. In 1976, the Royal Commission on Nuclear Power Generation in New Zealand was set up to inquire further into the question. Its 1978 report said that there was no immediate need for New Zealand to embark upon a nuclear power program, but suggested that by the early 21st Century, "a significant nuclear programme should be economically possible" (World Nuclear Association, 2010c).

In a book entitled "Energy Security: The foreign policy implications", author Ron Smith has written a fairly aggressive deconstruction of the New Zealand attitude towards nuclear energy. Quoting from the opening paragraph (Smith, 2008, p. 1):

*New Zealand is famously (or notoriously) antinuclear. For many it is a matter of national pride and the stance is seen to bestow a sense of moral virtue (superiority) and the satisfaction of "standing up to the big guy". Anti-nuclearism may be the closest thing we have to a state religion, with the 1987 Act our sacred text and David Lange as our first saint. This gives rise to a certain rigidity in our policy responses, which means that the things we say and the stands we take may not always be in our best interests.*

Smith presents several examples of what he considers a "naïve and simplistic" attitude towards nuclear energy in the political sphere (Smith, 2008, p. 1). One was an official visit to Japan by former Prime Minister Jenny Shipley, where public mention was made of concern over Japan's nuclear programme; an energy programme that can have no possible practical impact on New Zealand, apart from contributing to the on-going energy security of a major trading partner (Smith, 2008, p. 1).<sup>31</sup> Her successor, Helen Clark, publicly fare-welled protestors attempting to intercept shipments through the Tasman that were bound for the Japanese nuclear industry, despite the utter lack of danger posed. A revealing quote comes from former Minister of Energy Pete Hodgson, with respect to a 1992 shipment of plutonium oxide heading to Japan: "if the ship sank passing by New Zealand, New Zealand would have to be evacuated... the alternative would be death" (Smith, 2008, p. 1). In fact, in the words of Andrew McEwan, former director of the New Zealand National Radiation Laboratory, it was "highly improbable that there would be any leakage of material and if there was it would sink to the ocean floor because of its density" (Smith, 2008, p. 1). In short, New Zealand's political representatives have done little to demonstrate an understanding of nuclear safety, nor a desire to become more familiar.

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<sup>31</sup> Smith also points out that the 55 reactors operating in Japan were equivalent to burning 70 million tons of oil.

New Zealand is not truly nuclear free. In addition to the radioactivity occurring in nature (discussed extensively in section 4.2.1, radioactive isotopes and devices are employed in hospitals, universities, and private industry. The accumulated nuclear waste is stored in a repository located in Christchurch. Nuclear materials are occasionally shipped through our ports (Smith, 2008, p. 2). In terms of public discourse, perhaps the most prominent aspect of ‘nuclear-free’ New Zealand is the ban upon nuclear-powered ships. This stance has certainly slowed the development of closer trade relations with the United States, and also threatens to hamper commercial and civilian activities in the future if rising oil prices begin to encourage an expansion of nuclear propulsion in maritime development (Smith, 2008, p. 2). More to the point, the ban on nuclear-powered ships is questionable, given the existence of a commission of inquiry report dismissing its underlying justifications. Specifically, the Special Committee on Nuclear Propulsion of 1992 stated “The likelihood of any damaging emission or discharge of radioactive material from nuclear powered vessels, if in New Zealand ports, is so remote that it cannot give rise to any rational apprehension” (Smith, 2008, p. 2).

Non-proliferation is the key concern of a nuclear programme in terms of international politics. Proliferation refers to the spread of nuclear materials usable for weapons development to countries not recognised under the international Nuclear Nonproliferation Treaty. It is important to note that nuclear power generation does not necessarily result in nuclear weapon capability: refer to section 4.3 for a discussion of the Chernobyl disaster, which is of specific relevance to this point. Modern reactors do not produce the materials needed for warheads; rather, the reactor has to be built specifically for that task, and energy production takes a back seat. Also relevant is the choice of fuel cycle. As discussed in section 4.2.2, a once-through fuel cycle would probably be the most suitable for New Zealand. Provided that spent fuel is moved into long-term geological repository within a reasonable period of time, this is usually adequate to protect against proliferation. (Deutch et al., 2003, p. 67)

Certainly, concerns about proliferation are not significant enough to justify dismissing nuclear power as a generation source. Such a move serves little real purpose except to reduce the available options, which in terms limits the potential to reach an optimal and efficient outcome in the electricity generation sector. A Ministry for the Environment website intended to provide information about climate change in New Zealand and the effects of the ETS provides a telling quote:

*Nuclear energy has been considered in the past as an option, but is not consistent with wider environmental goals, and high economic costs mean that nuclear energy is not*

*an option for New Zealand. There are no plans to change legislation to provide for nuclear energy.* (Ministry for the Environment, 2010)

The stance essentially amounts to an off-hand dismissal of the nuclear option. Data from across the OECD indicates that nuclear is cost-competitive with other options when environmental considerations are taken into account, as discussed in Chapter 2. Given that the choice of generation mixes to secure New Zealand's energy future include coal and gas, one cannot help but question what exactly these environmental goals are.

Mitchell, in her work on the political economy of sustainable energy, describes New Zealand's political paradigm as being somewhat similar to that of the UK, although unlike in the UK there is no rigorous separation of public and private, and the government still has a majority stake in many of the main energy companies (this, however, looks to be changing). She provides the following descriptions of the "ethos" of the country:

1. Decisions should be made through the market place.
2. Economic analysis should be a building block of policy.
3. There is a limited need for innovation (and whatever innovation is required can be set in play through "linear and predictable policies").

Mitchell's sum assertion is somewhat telling: "The net effect of this paradigm is a disjuncture between the vocal pro-sustainability announcements of the Prime Minister and the policies put in place" (Mitchell, 2008, p. 162). New Zealand also has, in Mitchell's estimation, the perspective of a "technology taker" built on a perception of costs: since New Zealand is a relatively small country, it cannot contribute to technology development on the scale of 'major' economies. Thus the country adopts a wait-and-see approach, attempting to minimise costs by picking proven winners. A by-product of this approach is a lack of spending on the development of skilled labour (e.g. R&D, universities, student courses, etc.) with the net result that New Zealand has relatively stagnant skills in the energy sector and, relevantly, "few people arguing for different energy pathways" (Mitchell, 2008, p. 176).

### **5.2.1. Considerations for the Future**

The Draft New Zealand Energy Efficiency and Conservation Strategy of December 2006 was intended to investigate the "best outcomes for the environment, the economy and society" (Smith, 2008, p. 3), finding means of reducing greenhouse emissions through economically competitive and reliable energy technologies. In other words, the specific



goal was to develop a “reliable and resilient system delivering New Zealand sustainable low-emissions energy” (Smith, 2008, p. 3). Upon casual observation, and casting all disingenuity aside, nuclear power would appear – at the very least – to have the potential to meet all these objectives; yet in the subsequent 70 pages of the strategy document, not once is it even named. Bluntly put, it seems somewhat incongruous to profess these goals and not even justify the exclusion of a major potential solution.

Quoting again from Smith:

*In early 2006 Australian Prime Minister, John Howard, expressed the opinion that Australia “would be foolish” not to adopt nuclear power... It is widely recognised that we have problems in energy security and economic supply, especially if we wish to reduce our greenhouse emissions. On the face of it nuclear power offers the lowest greenhouse footprint of all the competing technologies, with the highest degree of siting flexibility and the least degree of environmental disturbance. It is the safest of all the major energy technologies and the most reliable. It is also cost competitive with coal and gas and significantly cheaper than wind and solar power.*

This specific quote was reproduced because it so elegantly summarises the conclusions reached in Chapters 2 through 4. These conclusions, however, are only of use if they can engender support, or at least acknowledgement.

Public support is often sufficient to motivate political change over time, especially in democracies, although influence can flow in the other direction, through media campaigns and other initiatives. However, the concept of a nuclear programme in New Zealand faces a circular problem, since there is neither public nor political support on a significant scale. Without a better understanding of the cost and safety aspects of nuclear energy, the majority of New Zealanders will most likely remain opposed to it. Without a significant increase in public support, policymakers are unlikely to change their attitude over the technology. Still, the economic challenges of meeting New Zealand’s energy needs are more likely to force a change at the governmental level, so it is worth discussing how interactions with an unreceptive public might best be handled.

The OECD Nuclear Energy Agency (NEA) suggests that winning public confidence will require involving the public in decision-making through mechanisms such as organised debates and referenda. In turn, this requires a comprehensive dissemination of information related to nuclear costs and safety to the public. This has largely not been achieved, even in many countries with operating nuclear programmes, and the result is an uninformed and often emotionally founded public perspective (Nuclear Energy Agency, 1991, pp. 71-72). Information needs to be delivered in a non-promotional

manner, so that individuals feel free to form their own opinion. A balance between scientific terminology and over-simplification is also important. Clear and consistent communication with the media would be vital, and should involve all groups associated with the programme (scientists, economic policymakers, and regulatory officials).

The risks of nuclear energy would likely be the most important part of any information that might be communicated with public. Nuclear power plants are unfamiliar objects in the public consciousness, especially in New Zealand (Nuclear Energy Agency, 1991, pp. 71-72). Similar to the anomaly of transport valuation mentioned in section 4.1, there is a tendency to be more accepting of familiar risks, like those of driving a car. Information on this topic needs to be concrete and expressed in familiar terms (Nuclear Energy Agency, 1991, p. 76). For example, based on the findings of section 4.1, it could be expressed that a serious accident in a nuclear reactor is so infrequent that it would not be expected more than once in 20,000 years, and even then casualties would probably not exceed New Zealand's yearly road toll. Nevertheless, predicting how the public would interpret information is difficult at best: "[merely] giving information on routine events at nuclear power plants could be perceived by some people as tangible proof of the danger" (Nuclear Energy Agency, 1991, p. 77).

In short, communicating with the public needs to be about providing the necessary means for them to make individual assessments on the costs and benefits of nuclear energy. Attempting to *convince* the public only serves to frame nuclear power as a unique case, rather than as simply another option in the choice of energy solutions (Nuclear Energy Agency, 1991, p. 79). If objective and informed debate is to be achieved, nuclear needs to become more familiar.

### **5.3. Summary**

The preceding three chapters have demonstrated that there is no concrete, justifiable reason for omitting consideration of the nuclear option in future energy plans. For this to be the case there would need to be some defining and major negative aspect to nuclear power that is apparent to the most casual of observers. It has been shown here that this is not the case. There are disadvantages, but this is true of any generation technology. The potential disadvantages of nuclear energy are no more a reason to ignore it than those of burning coal or damming a river are for their respective technologies. From the perspective of economic welfare, nothing is gained by eliminating a possible avenue that may lead to a more efficient allocation of resources.

This chapter has demonstrated that nuclear energy has been largely side-lined from discourse, and the comments that do appear in the political sphere are often

misinformed. Nevertheless, surveys reveal that there is actually some public support for the technology (a considerable amount, in fact, amongst business executives). In terms of educating the public over the conclusions of Chapters 3 and 4 on costs and safety risks, the focus needs to be on clear, defined channels of communication and de-emphasising nuclear as a special case. If consumers begin to perceive nuclear as a safe and cost-effective source of electricity, and are given channels through which to interact participate in the decision-making process, a nuclear programme could certainly be viable.

The next chapter concludes with a discussion of the findings on nuclear's possible role, its cost-competitiveness and safety, and the political treatment (or lack thereof).



## 6. Conclusion

This thesis began by raising a single question: is there sufficient economic evidence to justify an outright dismissal of nuclear power as a possible energy source? To answer this, a series of subtopics on the economic viability of nuclear power were systematically investigated. Chapter 2 began by examining the history of the technology, highlighting its rapidly evolving nature. It subsequently investigated New Zealand's electricity sector, illustrating its consistently growing nature, and the challenges posed by the varying disadvantages of different generation sources. Existing hydro projects can only meet growth in demand for a finite period of time, geothermal options and gas reserves are limited, coal is highly polluting, and wind is expensive and difficult to integrate with the grid in large quantities. In this context, nuclear could potentially act as a baseload supply option, specifically to meet Auckland's energy demands.

Given that nuclear power could conceivably fit into future electricity generation mixes, Chapter 3 looked to the OECD experience with nuclear to evaluate its cost-competitiveness, specifically against coal, gas, and wind, since these technologies currently have the most potential post-2030. Nuclear was shown to have relatively high construction costs but low generation costs (and a notable robustness against fuel price fluctuations). The deciding factor is the integration of external costs. In terms of a financial analysis, when a carbon emissions price or an emissions cap and trading scheme are taken into consideration, nuclear becomes relatively more attractive compared to traditionally cheap fossil fuel options. Given that NZ has actually implemented a carbon trading scheme, and made commitments under the Kyoto Protocol, this is a strong point in favour of nuclear energy. Critically, however, the cross-section of literature on the costs of construction reveals a high variance, as well as a significant burden of investment in infrastructure and skilled labour, which presents doubts as to the viability of a nuclear energy programme for a country as small as New Zealand. In this sense, the advancement of nuclear technology also holds promise, particularly the concept of SMRs, or Smaller Modular Reactors. Such reactors are standardised, factory built and transportable, relatively simple in design, and have lower capital costs and shorter instalment times (Vujić et al.). By their nature they are particularly flexible, able to be grouped into a large capacity plant or used in isolated locations with low-tech infrastructure. By opening policy debate to the concept of nuclear energy, the country might be better positioned to take advantage of the technology at such a time as it becomes practically and economically viable.

Chapter 4 investigated the most controversial aspect of nuclear power: safety. First, nuclear power is not an inherently unsafe technology. It is certainly not a ticking time-bomb, permanently poised on the edge of a disastrous meltdown. In the case of public perception, there is a predominant focus on the worst possible outcomes of a nuclear accident, a focus which is disingenuous at best. In the US context, when compared to the quantified damage from coal-burning, nuclear is shown to be much less harmful in practice (even employing the most conservative estimates available, the US would have to operate 4,000 reactors for the expected fatality count to equal that of coal pollution). The public's image of nuclear power is largely bound up in the Chernobyl disaster and the Three Mile Island incident. However, as shown in the case studies of Chapter 4, Chernobyl is simply not applicable to the Western model, and Three Mile Island is essentially a success story in terms of nuclear safety. These conclusions are interesting, and perhaps even surprising: the dual purpose of the Chernobyl reactor and the effects those design decisions have upon safety are not often quoted when the disaster is discussed.

Finally, Chapter 5 looked to at the interactions between public opinion, politics, and nuclear power. The most relevant conclusion here is that the public and political spheres are often misinformed on the costs and safety risks of nuclear energy. Public opinion is a serious obstacle to any possibility of a nuclear programme. Overcoming this would involve a significant effort to establish clear communication with the public and ideally to treat them as a partner in the decision-making process.

It is worth reflecting for a moment on the term "public opinion", which is used in the preceding discussion, and indeed in a wide range of studies, with very little inherent qualification. In a sense, the term conveniently divorces the 'general' public from the political sphere and from policymakers, and it is tempting to view public opinion as little more than a statistic, that may hinder or assist policy agendas. In truth, the public is a collection of individuals - just as policymakers are - each with their own unique preferences (and, some would say, biases). Consider then the comments from Dana Mead, chairman of the MIT governing body, who observed the nuclear power is the most polarising form of electricity generation, with 11% of those polled in 2007 asserting that nuclear energy should not be used at all (the highest percentage of people opposed to any generation technology) (Ahearne, 2011). However, it does not seem reasonable to assert that the 'typical' individual should be any more versed in the facts, figures and forecasts surrounding nuclear reactors than they are for, say, coal-burning stations. Conversely, it does seem reasonable to expect policymakers in a specific sphere such as a energy sector would be well-versed on the 'pros and cons' of all

options. Yet, referring back to this project's introduction, nuclear electricity generation is all but non-existent in domestic policy discussion. With respect to the research question posed, clearly nuclear power in New Zealand is not a question of economics, seeing as there is no economic analysis to speak of, and thus no particular degree of insight separating the perspective of policymakers from that of the general public.

Ultimately, within the limitations of this study, the concept of nuclear energy in New Zealand holds potential, if not promise. Several key factors weigh heavily against the relatively small scale of deployment that would be required domestically:

1. The high capital and construction costs.
2. The significant investment in human resources and infrastructure required.
3. The difficulty of disposing of spent nuclear fuel and other high level wastes, particularly on a small scale.

Those more critical of nuclear studies have pointed to the general history of the nuclear evidence and drawn the conclusion that nuclear power, as it stands, is simply not competitive from an economic perspective, requiring "massive subsidies to force them into the supply mix" (Ahearne, 2011). With movement towards a more privatised electricity supply sector, nuclear energy as it currently stands appears highly unattractive, posing a significant burden on taxpayer funding. Ultimately, it is the large variance seen in the estimates for these costs (or, in the case of waste disposal, the lack of any real successful case study) that is the most discouraging. From the literature examined, it would seem that cost, not safety, is the prohibitive factor for nuclear power. Furthermore, in the specific case of New Zealand, there is no domestic infrastructure to support the technological requirements of construction and waste disposal as a result of New Zealand's nuclear-free status, meaning some degree of reliance upon overseas institutions during the initial stages. The discussion of New Zealand's political economy (with respect to the energy sector) in the preceding chapter certainly has some implications for nuclear power. Inasmuch as the political paradigm includes economic analysis as a building block of policy, it is difficult to justify the complete omission of nuclear power in the policy mix. Conversely, the limited drive for innovation, the present lack of a genuine urgency for climate change policy, and the cautious approach to low-risk technology adoption do much to explain the absence of nuclear technology from discussion (Mitchell, 2008). Certainly the attitude of prioritising 'least-cost' options and a reluctance to invest in technological development would not lend themselves to embarking on a nuclear energy programme.

Realistically speaking, the adoption of nuclear energy in New Zealand would extremely unlikely in the near future. Such an occurrence would likely require multiple motivating factors, such as:

1. A much stronger sense of urgency regarding climate change.
2. Easily adopted reactor designs with a proven track record of economic viability.
3. A demonstrated and affordable long-term solution to waste disposal.

In short, the findings of this resource project are that, on balance, nuclear power is probably not a viable undertaking for New Zealand at present, although for economic reasons rather than safety concerns. However, with myriad issues surrounding climate change concerns, the continued advancement of nuclear technology, and the ever-evolving nature of New Zealand's energy requirements, it seems reasonable to assert that nuclear power, as an option for electricity generation, should be made a question of economics; i.e., it should at least be included as a potential option in policy discussion.

However the international experience with nuclear power is interpreted, regardless of what weightings are applied the advantages and disadvantages of the technology, there is simply no compelling case for dismissing it entirely out of hand. If we as economists hold up efficiency as a chief goal, we can hardly be assured of the optimality of any decisions when a major technological option is ignored. NZ desires clean, reliable power that is also inexpensive. Nuclear may or may not be able to fill that need.

Discovering if it can be preferable to continued ignorance. A policy decision built upon an evaluation of all possible solutions should engender more confidence, all things held equal, than one where the choices are arbitrarily limited. Ideally, this thesis can contribute towards overcoming the public and political misperceptions discussed in Chapter 5.

Certainly, several issues and uncertainties surround the concept of a nuclear energy program, and they have been identified in the thesis, and reiterated above. It will be informative to observe the international experience as policymakers grapple with public opinion. Successful implementation of the US Blue Ribbon Commission's recommended strategies would go a long way towards overcoming this problem (Vujić et al.). Proliferation is also a politically loaded issue. The existence of a nuclear reactor brings with it several security risks: the potential for misuse of facilities and operations to develop technology or materials with the ultimate goal of nuclear weapon capabilities, and the possibility of outside interests obtaining materials for misuse (Deutch et al., 2003, p. 2). However, in the case of the former, nuclear technology



developed solely for electricity generation (as would be suitable for New Zealand) does not readily lend itself to this. As for the latter, it is largely a matter of appropriate security mechanisms.

Despite these concerns, however, the conclusion still remains clear: nuclear power has considerable potential, particularly if the trend of growing concern over environmental change and carbon emissions continues, and ignoring it in policy evaluations weakens the potential to achieve the best means of securing New Zealand's energy future. Furthermore, today's economics is not necessarily tomorrow's economics, and nuclear technology continues to improve. If the next generation of reactors to be constructed can provide successful case studies, and if the development of nuclear technology continues to yield safer reactor designs that are more flexible in their implementation, they may be a very appealing solution to New Zealand's energy needs. Bringing the nuclear option into discussion will only serve to strengthen policy decisions now and in the future. In the words of Kennedy: "Economics risks associated with keeping the nuclear door open would appear to be limited" (Kennedy, 2007, p. 3715).

As a parting note, the three key investigative topics of this thesis offer numerous avenues for future research. An analysis focused entirely on the cost dimensions of nuclear power could provide a more detailed breakdown, going as far as to evaluate the exact costs of building a reactor in New Zealand (including factors such as exchange rates, the need to acquire international expertise, etc.). A cost-benefit analysis of this nature could also advance the economic perspective of the topic as a whole with a specific focus on solutions to the weaknesses of many existing analyses. Namely:

1. Establishing internationally acceptable/compatible definitions for the basic variables of nuclear power plant costing.
2. Developing a methodology that accounts for the unique and diverse set of risks inherent in nuclear generation investment.
3. Constructing a comprehensive framework for estimating the external costs and benefits of nuclear power.
4. Acquiring a larger array of actual construction cost data rather than estimates.

The large variance in nuclear cost studies and forecasts is primarily a result of the different assumptions used by various researchers. As an example, with regards to the first point listed above, there is still no internationally accepted standard for what exactly comprises the capital costs of nuclear plants. Fundamentally, most analyses lack a microeconomic basis, which certainly provides a strong motivation for further research into the field, whether for a New Zealand application or not. Reactor safety

might be investigated in further detail, perhaps considering the comparable safety of different Western reactor designs, or attempting to quantify a relationship between cost and safety. The interaction between nuclear technology and the public and political sphere is a major topic in itself, and is relevant to a number of academic fields outside of economics. It is the author's hope that this topic will prompt further investigation, and policy decisions surrounding New Zealand's future energy needs might be better informed.



## Appendix A

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Country or area	Nuclear share of generation mix (%)	Nuclear electricity production (TWh)	Nuclear electricity production (TWh)
	2009	2008	2009
Argentina	7.0	6.8	7.6
Armenia	45.0	2.3	2.3
Belgium	51.7	43.4	45.0
Brazil	3.0	14.0	12.2
Bulgaria	35.9	14.7	14.2
Canada	14.8	88.6	85.3
China:			
- Mainland	1.9	65.3	65.7
- Taiwan	20.7	39.3	39.9
Czech Rep	33.8	25.0	25.7
Finland	32.9	22.0	22.6
France	75.2	418.3	391.7
Germany	26.1	140.9	127.7
Hungary	43.0	14.0	14.3
India	2.2	13.2	14.8
Japan	28.9	240.5	263.1
Korea, S	34.8	144.3	141.1
Lithuania	76.2	9.1	10.0
Mexico	4.8	9.4	10.1
Netherlands	3.7	3.9	4.0
Pakistan	2.7	1.7	2.6
Romania	20.6	7.1	10.8
Russia	17.8	152.1	152.8
Slovakia	53.5	15.5	13.1

Slovenia	37.9	6.0	5.5
South Africa	4.8	12.7	11.6
Spain	17.5	56.4	50.6
Sweden	34.7	61.3	50.0
Switzerland	39.5	26.3	26.3
UK	17.9	52.5	62.9
Ukraine	48.6	84.3	77.9
USA	20.2	809.0	796.9
TOTAL		2601.0	2558.0

Source: (World Nuclear Association, 2010f)

## Appendix B

### Nuclear power plants in commercial operation

Reactor type	Main Countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised Water Reactor (PWR)	US, France, Japan, Russia, China	265	251.6	enriched UO <sub>2</sub>	water	water
Boiling Water Reactor (BWR)	US, Japan, Sweden	94	86.4	enriched UO <sub>2</sub>	water	water
Pressurised Heavy Water Reactor 'CANDU' (PHWR)	Canada	44	24.3	natural UO <sub>2</sub>	heavy water	heavy water
Gas-cooled Reactor (AGR & Magnox)	UK	18	10.8	natural U (metal), enriched UO <sub>2</sub>	CO <sub>2</sub>	graphite
Light Water Graphite Reactor (RBMK)	Russia	12	12.3	enriched UO <sub>2</sub>	water	graphite
Fast Neutron Reactor (FBR)	Japan, Russia	2	1.0	PuO <sub>2</sub> and UO <sub>2</sub>	liquid sodium	none
Other	Russia	4	0.05	enriched UO <sub>2</sub>	water	graphite
	TOTAL	439	386.5			

Source: (World Nuclear Association, 2010d)

## Appendix C

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### New Zealand Generating Companies (2008)

Company	Capacity MW	Generation GWh	Revenue	Employees	Customers	Ownership
Contact Energy	2,070	11,035	2,756m	1,000	650,000	public ownership
Genesis Energy	1977	9,126	2,482m		700,000	state-owned enterprise
Meridian Energy	2,601	11,914	2,604m		183,000	state-owned enterprise
Mighty River Power	1,369	5,954	1,172m	752	391,000	state-owned enterprise
TrustPower	594	2,018	681m	340	222,000	public ownership

Source: 2008 annual reports (available from the respective companies' websites)

## Appendix D

### ExternE Impact Pathway Effects

Impact Category	Pollutant / Burden	Effects	
Human Health – mortality	PM <sub>10</sub> , PM <sub>2.5</sub> , SO <sub>2</sub> , O <sub>3</sub>	Reduction in life expectancy due to short and long time exposure	
	Heavy Metal (HM), Benzene, Benzo-[a]-pyrene	Reduction in life expectancy due to short and long time exposure	
	1,3-butadiene		
	Diesel particles, radionuclides		
	Accident risk	Fatality risk from traffic and workplace accidents	
	Noise	Reduction in life expectancy due to long time exposure	
	Human Health – morbidity	PM <sub>10</sub> , PM <sub>2.5</sub> , O <sub>3</sub> , SO <sub>2</sub>	Respiratory hospital admissions
PM <sub>10</sub> , PM <sub>2.5</sub> , O <sub>3</sub>		Restricted activity days	
PM <sub>10</sub> , PM <sub>2.5</sub> , CO		Congestive heart failure	
Benzene, Benzo-[a]-pyrene		Cancer risk (non-fatal)	
1,3-butadiene, Diesel particles, radionuclides, Heavy Metal (HM)		Osteoporosis, ataxia, renal dysfunction	
PM <sub>10</sub> , PM <sub>2.5</sub>		Cerebrovascular hospital admissions, Cases of chronic bronchitis, Cases of chronic cough in children, Cough in asthmatics, Lower respiratory symptoms	
Mercury		Loss of IQ of children	
O <sub>3</sub>		Asthma attacks	
		Symptom days	
Noise		Myocardial infarction, Angina pectoris, Hypertension, Sleep disturbance	
Accident risk		Risk of injuries from traffic and workplace accidents	
Building Material		SO <sub>2</sub> , Acid deposition	Ageing of galvanised steel, limestone, mortar, sand-stone, paint, rendering, and zinc for utilitarian buildings
		Combustion particles	Soiling of buildings
Crops	NO <sub>x</sub> , SO <sub>2</sub>	Yield change for wheat, barley, rye, oats, potato, sugar beet	
	O <sub>3</sub>	Yield change for wheat, barley, rye, oats, potato, rice, tobacco, sunflower seed	
	Acid deposition	Increased need for liming	
	N, S deposition	Fertilising effects	



Global Warming	CO <sub>2</sub> , CH <sub>4</sub> , N <sub>2</sub> O	World-wide effects on mortality, morbidity, coastal impacts, agriculture, energy demand, and economic impacts due to temperature change and sea level rise
Amenity losses	Noise	Amenity losses due to noise exposure
Ecosystems	Acid deposition, nitrogen deposition, SO <sub>2</sub> , NO <sub>x</sub> , NH <sub>3</sub>	Acidity and eutrophication, 'PDF' of species
Land use change		'PDF' of species

Source: (European Commission, 1995)

## Appendix E

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External costs for electricity production in the EU (in EUR-cent per kWh\*\*)

Country	Coal & lignite	Peat	Oil	Gas	Nuclear	Biomass	Hydro	Wind
Austria				1-3		2-3	0.1	
Belgium	4-15			1-2	0.5			
Germany	3-6		5-8	1-2	0.2	3		0.05
Denmark	4-7			2-3		1		0.1
Spain	5-8			1-2		3-5		0.2
Finland	2-4	2-4				1		
France	7-10		8-11	2-4	0.3	1	1	
Greece	5-8		3-5	1		0-0.8	1	0.25
Ireland	6-8	3-4						
Italy			3-6	2-3			0.3	
Netherlands	3-4			1-2	0.7	0.5		
Norway				1-2		0.2	0.2	0-0.25
Portugal	4-7			1-2		1-2	0.03	
Sweden	2-4					0.3	0-0.7	
United Kingdom	4-7		3-5	1-2	0.25	1		0.15

Source: (European Commission, 1995)

## Appendix F

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### OECD electricity generating cost projections for 2010 onwards (USc/kWh), 10% discount rate

Country	Nuclear	Coal	Coal with CCS	Gas CCGT	Onshore wind
Belgium	10.9	10.0	-	9.3-9.9	13.6
Czech R	11.5	11.4-13.3	13.6-14.1	10.4	21.9
France	9.2	-	-	-	12.2
Germany	8.3	8.7-9.4	9.5-11.0	9.3	14.3
Hungary	12.2	-	-	-	-
Japan	7.6	10.7	-	12.0	-
Korea	4.2-4.8	7.1-7.4	-	9.5	-
Netherlands	10.5	10.0	-	8.2	12.2
Slovakia	9.8	14.2	-	-	-
Switzerland	9.0-13.6	-	-	10.5	23.4
USA	7.7	8.8-9.3	9.4	8.3	7.0
China*	4.4-5.5	5.8	-	5.2	7.2-12.6
Russia*	6.8	9.0	11.8	7.8	9.0
EPRI (USA)	7.3	8.8	-	8.3	9.1
Eurelectric	10.6	8.0-9.0	10.2	9.4	15.5

Sources: (Nuclear Energy Agency, 2010); (World Nuclear Association, 2010a)

## Appendix G

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*In any field of endeavour, it is easy to concoct a possible accident scenario that is worse than anything that has been previously proposed, although it will be of lower probability. One can imagine a gasoline spill causing a fire that would wipe out a whole city, killing most of its inhabitants. It might require a lot of improbable circumstances combining together, like water lines being frozen to prevent effective fire fighting, a traffic jam aggravated by street construction or traffic accidents limiting access to fire fighters, some substandard gas lines which the heat from the fire caused to leak, a high wind frequently shifting to spread the fire in all directions, a strong atmospheric temperature inversion after the whole city has become engulfed in flame to keep the smoke close to the ground, a lot of bridges and tunnels closed for various reasons, eliminating escape routes, some errors in advising the public, and so forth. Each of these situations is improbable, so a combination of many of them occurring in sequence is highly improbable, but it is certainly not impossible.*

*If anyone thinks that is the worst possible consequence of a gasoline spill, consider the possibility of the fire being spread by glowing embers to other cities which were left without protection because their firefighters were off assisting the first city; or of a disease epidemic spawned by unsanitary conditions left by the conflagration spreading over the country; or of communications foul-ups and misunderstandings caused by the fire leading to an exchange of nuclear weapon strikes. (Cohen, 1990)*

## Appendix H

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### Radiation Levels

<b>Living near a nuclear power station</b>	0.01 mSv/year
<b>Road construction material</b>	0.04 mSv/year
<b>Using natural gas in the home</b>	0.09 mSv/year
<b>Chest X-ray</b>	0.1 mSv single dose
<b>Dental X-ray</b>	0.1 mSv single dose
<b>Consumer products</b>	0.11 mSv/year
<b>Smoking cigarettes (1 pack/day)</b>	0.15-0.2 mSv/year
<b>Mammogram</b>	0.3 mSv single dose
<b>Cosmic radiation</b>	0.31 mSv/year
<b>Natural radioactivity in the human body</b>	0.4 mSv/year
<b>Plutonium-powered pacemaker</b>	1.0 mSv/year
<b>Radon in average household</b>	2.0 mSv/year
<b>Typical background radiation</b>	2.4 mSv/year
<b>Air crew occupation in middle latitudes</b>	5.0 mSv/year (up to)
<b>Air crew flying New York – Tokyo (polar)</b>	9.0 mSv/year
<b>CT Scan (head and body)</b>	11.0 mSv single dose
<b>Gastrointestinal series (upper &amp; lower)</b>	14.0 mSv single dose
<b>Lowest level at which any increase in cancer is clearly evident</b>	100 mSv/year
<b>Criterion for relocating people after Chernobyl accident</b>	350 mSv/lifetime
<b>Temporary radiation sickness such as nausea and decreased white blood cell count</b>	1,000 mSv single dose
<b>Death within a month for roughly half the recipients</b>	5,000 mSv single dose

**Death within several weeks**

10,000 mSv single  
dose

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**Source: (World Nuclear Association, 2010e); (US Department of Energy, 2004)**

## Overview of Terms

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The discussion in this research project includes a number of terms relating to nuclear power and electricity generation as a whole. Some of these may be unfamiliar to the reader, so this section provides a selection of brief definitions:

**kW/MW/GW/TW** are abbreviations for kilowatt, megawatt, gigawatt, and terawatt. A watt is a unit of power, which is the rate at which energy is generated and consumed.

**kWe/MWe/GWe/TWe** stands for kilowatt-electric, megawatt-electric, etc., which is the power output of an electric power plant at an instantaneous moment in time.

**kWh/MWh/GWh/TWh** stands for kilowatt-hour, megawatt-hour, etc., which is the amount of energy expended in an hour. A kilowatt-hour is a kilowatt of power used for an hour. Consumer power usage is usually billed using this system, and total electricity generation figures use these measurements as well.

**Baseload** supply is the electricity available to meet baseload demand, the minimum expected consumer demand at any time.<sup>32</sup> It is most commonly generated by fossil fuel, hydroelectric, geothermal, solar<sup>33</sup>, or nuclear source. These technologies are relatively cheap to operate and provide stable delivery of power, but have high fixed costs as a result. Peak supplies meet the excess of demand over baseload supply; most commonly, they are gas turbines (although these can also be used for baseload supply), since their output can be rapidly adjusted based on conditions. In contrast to baseload supplies, their fixed costs are low and their marginal costs high. Wind, notably, cannot be classified under either category: wind turbines do not have the steady output of baseload supplies, and neither do they respond to grid demand like peak supplies. Consequently, in the presence of wind generation, peak supplies have to be adjusted in response to both consumer demand and to the wind supply itself.

**Nuclear** works, in the simplest possible terms, by inducing spontaneous fission (the splitting of neutrons) in uranium, or less commonly plutonium. When the neutrons split, an extreme amount of heat is released, which is used to turn to boil water into steam and drive a turbine which produces electricity.

- **Pressurised Water Reactor (PWR)** is the most common reactor type in Western usage, and uses light water both as the coolant and to moderate the

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<sup>32</sup> National electricity demand fluctuates considerably depending on the time of day (usually peaking around evening hours).

<sup>33</sup> When augmented with a storage system to provide electricity output overnight.

reaction (see section 4.3 for a further discussion). There are two subtypes: the more common **light water reactor (LWR)**, where the heat from fission is transferred to a secondary water loop to generate steam, and the **boiling water reactor (BWR)**, where the water is allowed to actually boil in the reactor.

- **Burnup** refers to the amount of energy extracted from a unit of fuel before it is removed from the reactor. The term is so named since reactors predominantly 'burn' – extract heat from – fissile material. An analogous way of explain it is to compare it to a car's fuel efficiency.

**Geothermal** plants harness sub-surface heated water or steam for the same purpose as a nuclear plant, to drive a turbine and generate electricity.

**Levelised costs** are average costs of producing electricity including capital, finance, owner's costs on site, fuel and operation over a plant's lifetime, with provision for decommissioning and waste disposal (World Nuclear Association, 2010a).

**Overnight costs** are the construction costs as if the project were completed overnight; that is, with no interest incurred (otherwise, interest costs make technologies with longer construction periods appear relatively more expensive than they are).



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