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**The Power of Real Options
- Evaluating nuclear energy investments in
Ontario**

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In the future, instead of striving to be right at a high cost, it will be more appropriate to be flexible and plural at a lower cost. If you cannot accurately predict the future then you must flexibly be prepared to deal with various possible futures
~ *Edward de Bono*

Acknowledgments

To successfully complete a project of this magnitude requires a network of support, and we are both indebted to many people.

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Abstract

The Ontario electricity sector is at a critical junction in its history. With decreasing generation capacity and escalating demand, a province-wide shortfall is projected to emerge before the end of the decade. The situation has predetermined that capital investments in new installed generation capacity will have to be made in order to ensure a stable and reliable supply. The objective of this thesis is to evaluate capital investment decisions that will be made in the near future. We place particular emphasis on nuclear generation, which will continue to play a major role in meeting base load needs. More specifically, we consider decisions to invest in new nuclear generation and refurbishment of existing plants. In order to evaluate these investment decisions in a flexible manner, we will employ the real options methodology. The real options approach is relevant in the context of strategic energy investment planning due to its superior ability in dealing with uncertainties and incorporating management's flexibilities into the valuation process. Our findings confirm that the real options approach uncovers hidden strategic value and provides critical insights to the investment decision making process.

Keywords:

Electricity, investment, real options, flexibility, uncertainty, net present value, Ontario, nuclear power plant, nuclear refurbishment.

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Chapter 1 - Introduction

1.1 – Background

Managerial flexibility has been considered an enigma for many years from the perspective of investment decision makers. Though management and the ultimate investment decision makers have long recognized flexibility as a valuable attribute, the actual application of a specific value to this element has never been quite as simple and straightforward as the identification of the flexibilities themselves. Traditional capital budgeting techniques, such as the net present value rule, fail to account for managerial flexibility and present investment decisions as "now or never" propositions (Dixit and Pindyck, 1994). This drawback of time-honoured techniques has been resolved to a great extent by the development of real options theory.

The real options approach incorporates a strategic road map where management can take advantage of their flexibility and thus make better and more informed strategic decisions (Mun, 2006). The real options framework explicitly accounts for the risks and uncertainties inherent in the operational or investment decision making process, something which traditional methods fail to do. By actively making use of potential advantages and avoiding likely disadvantages through flexible management, the real options approach thus effectively measures the value of managerial flexibility and strategic leverage in investment decisions. As such, real options successfully capture an intrinsic value for flexibility and thus provide improved estimates of the investment's expected value, something which is overlooked by traditional, static investment evaluation techniques (Carlsson and Majlender, 2005).

In recent years, the electricity industry in many worldwide jurisdictions has moved to a liberalized, deregulated market. This change has introduced significant financial risks in the sector. The deregulation of electricity markets, alongside mounting environmental restrictions and societal pressures, has increased the uncertainties and impreciseness of the typical energy investment. At the same time, the application of real options theory to the evaluation and assessment of energy investments has increased significantly in recent years (Gnansounou, 2003). Further, Leslie and Michaels (1997) suggest that according to their research and expertise, several

exceptional performers in the energy sector in fact view their investment opportunities as real options. Thus, we can conclude that the escalating uncertainties of modern electricity markets require a more dynamic and flexible approach to the investment decision making process and that a strong candidate for this approach would be the real options method.

1.2 – Research Problem

In our thesis, we aim to look at the particular example of the Province of Ontario in Canada. At the present moment, the Ontario electricity market is at a critical stage in its history. With the province's existing nuclear generating stations all having a project end-life within the next ten to fifteen years, the government's pledge to shut down coal-fired generation by 2009, and growing demand due to population and economic growth, there is a looming supply and demand gap as is illustrated in *Figure 1.1* below. The main challenge facing Ontario's decision makers therefore is to determine how to fill this gap by assessing the various supply options available. Simultaneously, the plan that is developed for Ontario now must be robust, flexible and recognize the adaptive nature of planning, as stated by the Ontario Power Authority (OPA).

Figure 1.1 - Ontario's Looming Supply and Demand Gap
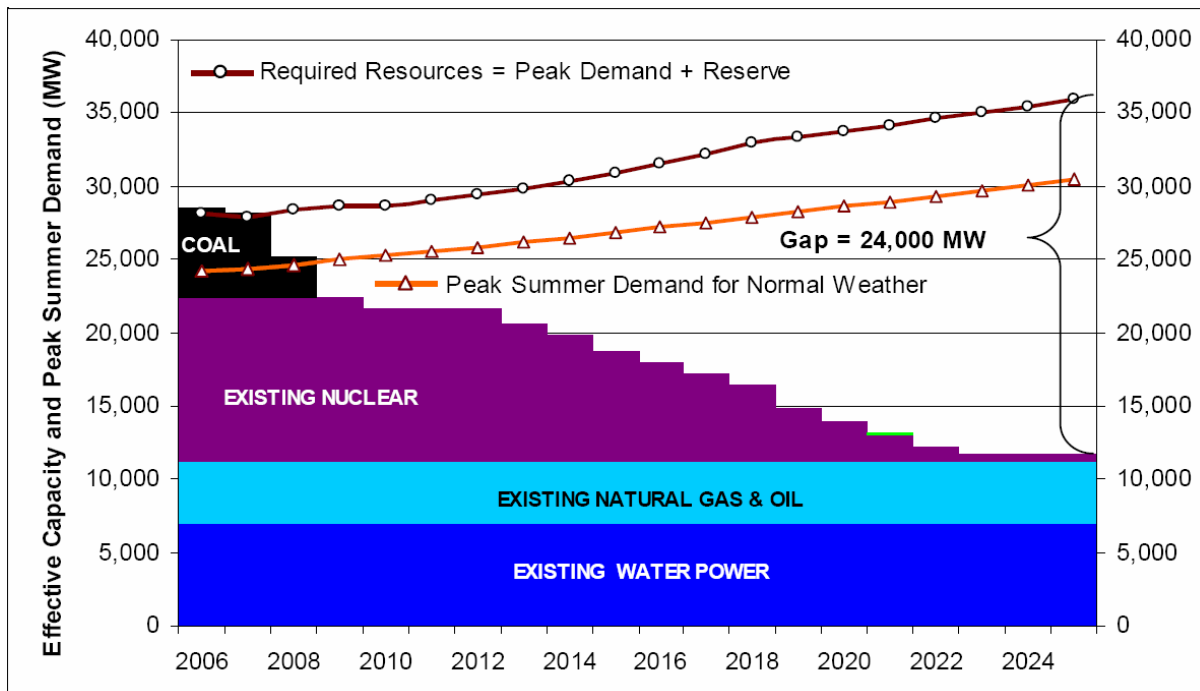
Source: OPA (2005)

The deregulation of the Ontario electricity market has introduced new risks and uncertainties in the form of volatile electricity and fuel prices, construction costs, and so on. Thus, the energy sector in Ontario now requires a more flexible way to approach the capital investment and operational decision making process. Considering that investments in new installed generation capacity are inevitable and will have to be made in order to ensure a sufficient and reliable electricity supply, applying the real options methodology to the case of Ontario is ostensibly appropriate.

More specifically, the Ontario Power Authority has declared that the Province of Ontario will require between 9,400 to 12,400 MW of nuclear power to be added by 2025 in their *Supply Mix Advice Report*. Combining this fact with nuclear power's importance in meeting the Province's base load needs, we therefore recognize and focus on two categories of nuclear energy capital investment decisions that will have to be made in the near future by Ontario's decision makers. These include decisions to invest in (1) new nuclear generation and (2) refurbishment of existing plants. In order to evaluate these particular capital investment decisions in a flexible manner, we will employ the real options methodology.

1.3 – Purpose

Given the existing situation in Ontario and the perceptible applicability of the real options methodology in evaluating investment decisions, the goals and objectives of our thesis are:

1. Introduce the existing situation in the Ontario electricity market, including the immediate issues and challenges and the looming supply and demand gap

2. Examine the potential of capital investment decisions in nuclear energy in Ontario, specifically investments in new nuclear power plants and refurbishment of existing plants

3. Apply the Real Options methodology to the outlined alternatives, due to its superior ability in dealing with uncertainties and incorporating management's flexibilities

4. Evaluate and analyse the appropriateness of the real options approach in the investment decisions outlined

1.4 – Scope and Methodology

Solving a diverse problem such as the overall electricity supply mix is a complicated process and is beyond the scope of our thesis. By focusing on the issue of capital investments in nuclear technology, we were more able to concentrate on the specific concerns facing new nuclear and refurbishment projects. Moreover, our approach has some added value in that we were able to utilize the real options technique using actual data for real-life challenges facing Ontario's decision makers. With regards to methodology, we applied two different approaches when valuating our given alternatives, built upon previously designed models. First, by identifying specific phases in each investment project as proposed by Graber & Rothwell (2005), we were able to establish sequential points where options exist. Secondly, following the approach of Rothwell (2004), we were able to calculate "trigger values" for the net revenue, initial investment and construction costs, or values at which the investor will be indifferent between investing or not. Utilizing and building upon these two methods was valuable in that they are both clear and logical, but also because they are quite distinct from each other and combine favourably to give a more extensive perspective of the investment.

1.5 – Thesis Outline

The remainder of this report is organized in the following fashion: *Chapter 2* follows by presenting the Theoretical Framework for this study. Initially, we introduce the real options approach from a theoretical perspective. We then go on to discuss how real options have been used in energy investments by way of a comprehensive literature review. *Chapter 3* presents the current state of affairs in the Ontario electricity market and building on the theory presented in *Chapter 2* a detailed problem formulation is presented. *Chapter 4* presents a thorough synopsis of the two models utilized in our thesis. Subsequently, *Chapter 5* outlines the statistical assumptions, data values and methodologies employed in making our calculations. Our model results are revealed and discussed in *Chapter 6*. Finally, *Chapter 7* presents our conclusions, lessons learned, and suggestions for future research in this area.

Chapter 2 – Theoretical Framework

The first objective of this chapter is to acquaint the reader with the real options concept from a theoretical perspective. The second part of this chapter aims to analyze the applicability of real options theory in energy investments. This is accomplished by surveying the uncertainties and flexibilities central to a typical energy investment and by conducting a comprehensive literature review. Though the application of real options theory to energy investments is still a fairly recent notion, a number of interesting articles have been written on this exact subject. Our literature review will concentrate on how real options have been applied to capital investment decisions, as this is the overall focus of our thesis.

2.1 – Real Options Theory

The real options methodology has been derived from financial options theory in order to value investments in real, as opposed to financial, assets. Like financial options, real options give the owner the right, but not the obligation, to take action.

2.1.1 – The Drawbacks of Traditional Valuation Techniques

In the area of capital budgeting techniques, discounted cash flow analysis (DCF) is currently the most widely used approach (Graham et al, 2001). The DCF method implies determining the investment's future cash flows, discounting them back to the present time with an appropriate rate of return and then subtracting the initial investment. While this model works well under certain conditions, it should be adjusted in the case when future events are not totally predictable. Decision tree analysis is one of the ways to value a project using the probabilistic distribution of possible outcomes. Scenario and sensitivity analyses are also used to evaluate and account for the sources of uncertainties.

Traditional methods fail to incorporate the fact that management can change the project's parameters in response to new market conditions. The main drawback of the DCF approach therefore is the assumption that the investment decision is a "now or never" opportunity. The notion that investments have to be made today or should not be made at all implies that a given

decision cannot be postponed. Because of this shortcoming, traditional valuation techniques often underestimate the actual value of the investment.

2.1.2 – Real Options and the Theory of Financial Options

The real options method implies the possibility of managerial intervention during the life of the project. Though the idea of managerial flexibility is logical well understood by practitioners, it is usually not considered to correspond to any value in the investment's returns (Carlsson and Majlender, 2005). The real options approach (ROA) represents a means of capturing the intrinsic value of future opportunities when making investment decisions.

First developed by Myers in 1977, real options theory is a relatively new approach in capital budgeting. It has been derived from the theory of financial options in order to value investments in real, as opposed to financial, assets. An option is a right, not an obligation, to trade a given asset in the future at an established future price known as the exercise or strike price. A *call option* gives a right to buy an asset; therefore, the profit is either zero (if the market price is greater than the exercise price, in which case the option is not exercised) or the difference between the exercise price and the market price (since the asset can be sold at the strike price and immediately bought at the market price). A *put option* gives a right to sell an asset for a price known in advance. The outcome is opposite to that of the call option. In terms of when the option can be exercised, an American option implies that the right can be exercised any time before maturity, whereas a European option allows the holder to exercise the option only at the maturity date.

In 1973, Black, Scholes and Merton created their eminent pricing formula to value options. They showed that it is possible to combine risky and risk-free investments in a portfolio and earn a risk-free rate of return. This so-called *replicating portfolio* is constructed in such a manner that as the price of a risky asset goes down (up), the price of the relevant risk-free asset goes up (down) by the same value, resulting in no change. As such, the portfolio value is not sensitive to market uncertainties.

The value of a financial option depends on the current market price (S), exercise price (K), time to maturity (T), the volatility of market prices (σ), and the risk-free rate (R_t). Given volatility measures and time to expiration, the appropriate probabilities for any future price can be estimated. This presents the potential of weighing each scenario for future outcomes. Therefore, in the real options

approach, the investment will still have a positive option value if there is a possibility that the price will go above production costs.

As depicted in *Figure 2.1,* real options take advantage of upside potential and, at the same time, eliminate downside risk.

Figure 2.1: Traditional Scenario Analysis vs. Real Options Valuation
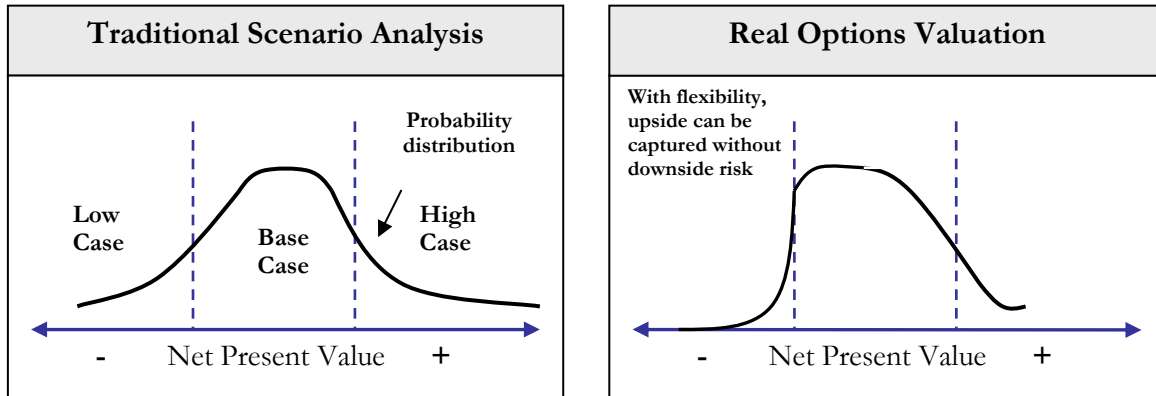
Source: Frayer and Uludere, 2001

In summary, real options correspond to financial options theory by setting the present value of the project as the stock price (S), the value of investment as the exercise price (K), the time the decision may be deferred as the time to maturity (T), time value of money as the risk free rate (R_f), and the volatility of return of the project as the volatility of return on stock (σ). Furthermore, Leslie and Michaels (1997) show that the value of an option is decreased due to cash outflows during the project life as well as an increase in the present value of the investment; meanwhile, the time to maturity, the exercise price (in the case of a call), the volatility of returns and the risk free rate are positively related to the option value.

As mentioned before, the main difference between the NPV method and the real options approach is that the latter methodology treats uncertainty as a positive factor, which can result in an increased value of the investment. However, it is important to note that the two methods do not necessarily oppose but rather complement each other. According to Trigeorgis (1993), the real options approach doesn't necessarily have to be considered the be-all and end-all in terms of valuation techniques; rather, it should be considered a part of an expanded NPV analysis.

The expanded "strategic" NPV is equal to the static "passive" NPV plus the value of real options:

$$NPVstrategic = NPVstatic + RO.$$

2.1.3 – Requirements for Real Options

Following Pindyck et al (1994), real options are present only if:

- the investment is completely or partially irreversible
- there is a substantial uncertainty regarding the outcome of the investment
- management possesses flexibility to affect the project in the future
- the timing of the investment contains some leeway

In order for real options to exist, there essentially has to be some sort of uncertainty in the asset's underlying value. Additionally, management must possess an appropriate amount of flexibility in order to be able to react to a given situation in a suitable manner. Hence, we can see that uncertainties and flexibilities are two important requirements in the real options framework. Accordingly, we will focus on these two keywords quite a bit throughout our thesis.

2.1.4 – Stages of the Real Options Valuation

The real options valuation process may be divided into two major parts: the *strategic layer* and the *valuation layer* (Brautigam and Esche, 2003).

The *strategic layer* includes:

1. Identification of existing uncertainties
2. Search for ways to respond to resolved uncertainties
3. Consequent identification of the real options embedded in the project

While some options are inherent in the strategy and project description and do not require initial investment (e.g. option to defer the investment), others remain unknown and should be uncovered and acquired before the project starts running (e.g. option to switch between alternative inputs or outputs).

The *valuation layer* contains the following steps:

1. Calculation of the NPV of the investment (since the ROA is a complementary technique and does not eliminate the static value of the future cash flows)
2. Specification of the key inputs into the model such as the volatility, exercise price, etc.
3. Recognition of linked uncertainties and design of relevant correlated options

4. Identification of the stochastic processes that the uncertain variables follow
5. Choice of valuation techniques to estimate the option
6. Final computation of the real option's value

The real options valuation thus may often turn out to be a rather complicated process requiring extensive mathematical and statistical knowledge. While the Black and Scholes pricing formula works well to evaluate standard European options, it cannot be applied for most real options. The main limitation of the Black & Scholes model is the assumption that the market prices of the asset are supposed to be log normally distributed and to follow the Markov process, an assumption which is often violated for real assets.

Figure 2.2: Real Option Valuation Process: Strategic & Valuation Layer
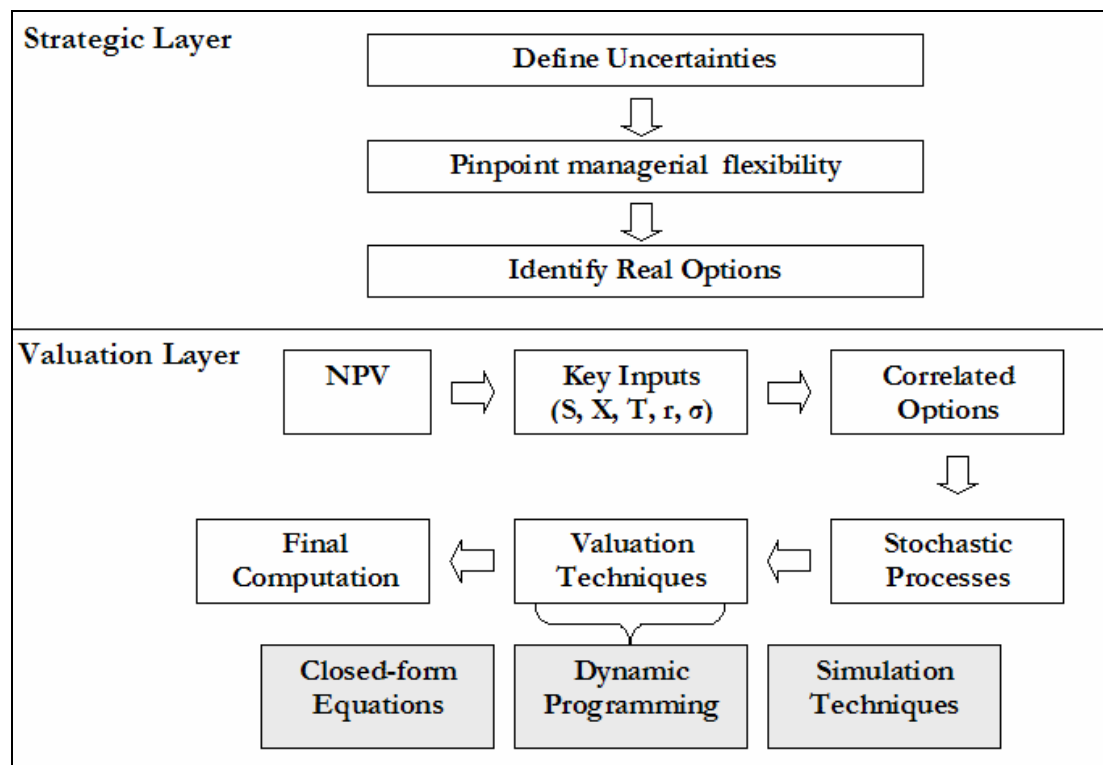
Source: Own design, using (Brautigan & Esche, 2003), (Graber & Rothwell, 2003) and (Mun, 2006).

2.1.5 – Valuation Techniques

With regards to the valuation techniques, there exist three main methods to calculate the option's value:

1. *Closed-form equations* (e.g. the B&S formula) – The main drawback is that some options may have positions so complex that the unique formula does not exist. The model is also built on a number of specific assumptions that cannot be violated.

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2. *Simulation techniques* (e.g. Monte Carlo simulation) – While providing a possibility to imply different types of stochastic processes, the simulation can be time-consuming and costly. The Monte Carlo method is path-dependent and therefore cannot deal with particular options, such as American options, without critical adjustments.
3. *Dynamic programming* (e.g. binomial trees) – The binomial tree structure can deal with multiple uncertainties, path independence and various stochastic processes. However, if the process is path-dependent, the number of nodes increases exponentially, making the valuation too cumbersome. Yet, the binomial tree is arguably the most illustrative and intuitively appealing method of all.

2.1.6 – Potential Limitations of the Real Options Approach

Miller and Park (2002) give a detailed overview of the potential problems that arise when using the real options approach. For some of the real option methodologies, Geometric Brownian motion cannot be chosen as an appropriate stochastic process. Secondly, the foundation of the option pricing theory is in the tradability of the financial assets and since real assets may be not traded, this often leads to difficulties in estimating the volatility and pattern of prices. Thirdly, the usage of the risk free rate of return is justified by the fact that the replicating portfolio may be constructed where the risky assets provide the risk free rate of return. Being a key assumption in financial theory, it does not hold when applying to real options due to the non-traded nature of real assets. Fourth, the exercise price of financial options is assumed to be a lump sum, whereas a real asset's exercise price can be a lump sum or take place several times prior to maturity. Therefore, some aggregated estimate of the strike price should be found. The fifth drawback is that identifying an exact maturity date can be difficult in a real options approach. Many real options have indefinite exercise dates, or exercise dates that are dependent on the state of the project. Finally, the date and the value of the real option dividends, such as licensing fees or cash payouts, may be unknown.

The potential problems do not raise the question whether the theory is applicable or not, but rather imply that there is no unique solution for all the types of real options. As such, a specialized model should be created carefully in each case. We believe that the real options approach is a superior valuation approach that complements traditional DCF techniques and has considerable potential to be studied, developed and broadly used in financial practice.

In recent years, the real options approach has been increasingly gaining favour as an investment valuation technique. Since real options incorporate managerial flexibilities, decision makers who employ this approach are able to more accurately examine and value investment projects. Essentially, real options add value to the investment since they provide an opportunity to make the most of uncertainties and risks as the uncertainties themselves are resolved over time (Gilbert, 2004). The volatility of an investment's future profitability is significantly contingent on the associated uncertainties of the project itself. As such, identifying these uncertainties and their respective influence on the project's cash flows is a very important task. Further, it is safe to say that as more uncertainties and risks are taken into consideration, the variance of the investment's projected future cash flows will increase, thus boosting the potential options-based value of a certain project.

2.2.1 – The Applicability of Real Options in Energy Investments

Given the wide range of uncertainties and flexibilities inherent in energy investment decisions, traditional DCF techniques would underestimate project value due to these method's limitations. The real options technique can therefore prove to be a valuable instrument since it deals with uncertainties in a superior fashion and takes into account management's flexibility in operations management and investment decisions (Gnansounou, 2003).

The deregulation of energy markets in numerous markets around the world has substantially added to the overall risks and uncertainties associated with energy investment decisions. Since electricity and fuel prices are now volatile and fluctuant, substantial challenges have arisen in both the timing and ultimate investment decision making processes. The environment's overall ambiguity is especially important to bear in mind when considering capital investments with long lead times, such as the decision to build new nuclear power plants or refurbish existing nuclear reactors. The specifics of the Ontario electricity market and its deregulated "hybrid market" will be discussed in greater detail in *Chapter 3.2*.

2.2.1.1 – Uncertainties in Energy Investments

For a real option to exist in the first place, the investment's future cash flows must have some sort of underlying uncertainty. As suggested by Dixit and Pindyck (1994), uncertainties are the key value

drivers of a real option, so one of the first steps in a real option valuation is to identify the most important uncertainties. The next step is to actually distinguish the real options that are available. To that end, management must possess the flexibility to be able to respond to these uncertainties as they arise.

In short, some of the causes of uncertainty in electricity production and investment in energy assets include the following:

- Electricity prices
- Fuel costs
- Consumer demand
- Plant availability
- Costs and time of construction (including refurbishment)
- Price of emission allowances
- Weather conditions
- Financial uncertainties (interest rate, foreign exchange rate)
- Societal pressures and political environment

With regards to the last point, it is important to mention the effect societal pressures and/or policy decisions will have on the Ontario market now and into the future. For example, the decision to fully terminate coal-fired generation by 2009[1] and to increase the role of renewable energy will ultimately play a great role in determining Ontario's future supply mix. These are not uncertainties per se, but these decisions certainly present some constraints from the decision maker's point of view.

As a rule, investment projects face a certain amount of uncertainty and ambiguity when it comes to the expected future cash flows. As we can see, there are numerous uncertainties that impact electricity production, future project cash flows and ultimately, the capital investment decision. The main strategic challenge for management then is to distinguish which uncertainties influence the volatility of the project's future cash flows the most (Gilbert, 2004).

In contrast to the previously regulated market, the existing market in Ontario incorporates both financial and operational risks. In view of the fact that modern electricity markets are subject to a wider range of uncertainties and risks, the current environment thus requires a more flexible

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[1] This date itself has changed many times and in fact, it was most recently moved from 2009 to 2014. The ambivalence of the Ontario Government with regards to this date could be considered an uncertainty in its own right.

approach to the investment decision making process. Therefore, it is quite appropriate that real options theory has taken on an increasing role in both the strategic investment planning and operating stages of the electricity sector (Gnansounou et al, 2003).

2.2.1.2 – Managerial Flexibility in Energy Investments

The real options framework endeavours to identify all the uncertainties inherent in an investment and, assuming management has the flexibility to respond to these uncertainties, shapes together an advantageous investment strategy. Now that we have identified a broad listing of uncertainties, it is essential to pinpoint what specific flexibilities managers have in their investment strategy. According to Gnansounou et al, some of the flexibilities available to the investment decision maker include the option to delay, expand, contract, abandon and/or change technology.

From an energy investment viewpoint, we can more specifically identify these flexibilities as such:

- Option to refurbish or repair existing facilities
- Option to shut down (temporarily or completely) out-of-date and/or unprofitable facilities
- Purchasing of electricity on the inter-connected market
- Option to delay, expand, contract, or abandon construction
- Option to switch of modify generation type

The flexibility offered by the real options methodology is particularly enticing in that the overall strategic value of an investment can increase substantially as a result. For example, if fuel costs were abnormally high and management possessed an *option to delay* construction, they could exercise this option and wait until fuel costs returned to their historical levels, thus making the project more profitable.

2.2.2 – Previous Research and Studies

Having identified the uncertainties and flexibilities that are typically encountered in the decision making process, we will now present a comprehensive literature review. The purpose of this review is to demonstrate how the real options approach has been applied to the electricity sector. As can be expected, real options theory has been applied in a wide range of methods in order to evaluate and analyze energy investment decisions.

Hlouskova et al (2002) have indicated that the application of real options in the electricity sector can be divided into two main categories:

1. Operational decisions
2. Capital Investment decisions.

Given the nature of the problem in Ontario, it is necessary for new energy investments in base load power to be made in the near future in order to balance the future supply and demand gap. As a result, we will place our focus on capital investment decisions in both the following literature review and in the overall scope of our thesis.

2.2.2.1 – Real Options in Operational Decisions

Operational decisions, as the name suggests, are based on the operational characteristics of a given generation plant. Operational decisions can be concerned with fuel-switching capabilities, maintenance decisions, locational arbitrage, reservoirs dispatch and most importantly, the unit commitment problem. This last problem can be modeled by a concept known as the *spark spread*. The spark spread is based on the difference, or spread, between the price of electricity and the price of the particular input fuel used to generate it. This spread is significant due to the fact that it essentially determines the economic value of generation assets that produce electricity (Deng et al, 1998). The decision to produce electricity or not thus depends on whether the output price is sufficient enough to cover the input costs. Apart from the electricity and input fuel prices, the spark spread is influenced by the plant's efficiency, otherwise known as the *heat rate*. According to Deng et al, the heat rate is a measure of efficiency and is defined as the number of British thermal units (Btus) of the input fuel required to generate one MWh of electricity.

Following this, we can illustrate the options related to operational decisions:

- Option to shut down production temporarily - if net profit of producing one extra unit does not cover the associated costs
- Option to shut down production permanently - if long-run profits will not be substantial enough to cover the costs
- Option to expand the production - if demand is significant enough and assuming high electricity prices or low input fuel costs

From an options perspective, it would be especially suitable to apply the real options theory to plants used for peaking generation. Peaking power plants, by definition, are plants that are used to meet elevated electricity demand above that which is met by base load and cycling plants. For example,

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Frayer and Uludere (2001) show that when using a real options approach, a peaking gas-fired facility can be shown to be more valuable than a cycling coal-fired plant, even though traditional techniques would have preferred the coal-fired plant. In their analysis, the gas-fired peaking asset's net value increased radically (almost seven times over) when optionality was included.

Eydeland and Wolyniec (2002) model the total cash flow for generation plants under the assumption that the plants can instantaneously react to any significant price changes. They demonstrate that both gas-fired and multi-fuel generation unit cash flows can essentially be modeled as a strip of spark spread options. Their approach, however, is imperfect in that they do not take into account all the physical constraints of power plants such as ramp rates, start-up costs, and heat curves. Gardner and Zhuang (2000), on the other hand, have managed to develop a model which actually handles constraints linked to minimum on- and off-times, minimum dispatch levels, ramp times, and response rates. Using the specific example of thermal power units from New England, they consider eight different case tests and conclude that an options approach quantifies the value of the operating flexibility and is also useful in determining optimal operating policies. Meanwhile, Hlouskova et al (2002) amalgamated backward stochastic dynamic programming with forward Monte Carlo simulation to approach the unit commitment problem from a different perspective. Namely, they proposed that in markets with a liquid spot electricity exchange, the portfolio approach is not necessary and the optimal unit commitment problem can be solved on an individual basis.

The real options approach, therefore, has been shown to be useful in the context of operational decisions being made by power plant operators. The methodology provides management the ability to quantify the value of the operating flexibility of real assets and to reveal optimal operating policies (Gardner and Zhuang, 2000). The application of real options to the unit commitment problem via *spark spread* models is quite developed and is particularly beneficial under uncertain electricity and input fuel prices. Based on our literature review, it is apparent that real options are very useful in terms of operational decision making in that they reveal hidden generation asset value via more efficient and profitable operating decisions.

2.2.2.2 – Real Options in Capital Investment Decisions

In addition to operational decisions, the real options methodology has also been applied in the category of energy capital investments. In the energy sector, capital investment decisions are

generally related to choices regarding the construction of new plants or refurbishment of existing plants.

As such, some of the options related to capital investment decisions include:

- Option to defer the investment
- Option to stage the investment (modularity)
- Option to install fuel-switching equipment
- Option to install scrubbers to reduce emissions

The impending supply and demand gap in Ontario has effectively predetermined that a combination of new generation, refurbishment, conservation and improvement of the transmission grid's reliability in the coming years will have to somehow fill this gap (ECSTF, 2004). This indicates that sizeable capital investments will certainly be made in new generating stations and the decision to refurbish certain existing generating stations will also be considered. For this reason, when conducting our research, we chose to focus on the application of the real options methodology to capital investment decisions.

Carlsson and Majlender (2005) introduce the concept of a *giga-investment*, or a very large project with a long life cycle (such as a power plant). They hypothesize that under traditional evaluation approaches, capital invested in *giga-investments* (i.e. projects costing more than 300 million USD and with a lifecycle of 15-25 years or more) is not productive or profitable. This is mostly due to the high risk as well as the array of uncertainties involved in such an investment. However, they illustrate that a real options approach gives much different results than the traditional discounted cash flow (DCF) approach. The real options technique enables management to better deal with uncertainties and to value the strategic advantages embedded in the construction of the power plant.

Harri Laurikka has published several excellent articles in which he discusses the impacts of emissions trading and other climate policy instruments on power capacity investments. In (Laurikka, 2005[1]), he looks at the implications of the European Union Emissions Trading Scheme (EU ETS) on power capacity investments in a deregulated market. Three specific power plant types are surveyed: a gas-fired condensing plant, a hydro power plant with a reservoir, and an off-shore wind power farm. The findings suggest that emissions trading would potentially increase the expected return for all three technologies. In (Laurikka, 2005[2]), the real options approach is employed to explore how

investments in Integrated Gasification Combined Cycle (IGCC) plants are affected by the EU ETS. The results strongly indicated that a DCF approach would produce biased results whereas a real options approach would create enhanced results. However, given the characteristics of the IGCC plant, using real options would also make the investment appraisal very complex. Further, the country-specific situation in Finland is investigated by contemplating how the EU ETS will affect the size, timing and cash flows in power plant investments (Laurikka and Koljonen, 2005). Two real options – the *option to wait* and the *option to alter operating scale* – are taken into consideration. The conclusions show that a simple NPV approach ignores these options, which is a significant omission for technologies with high variable costs, such as coal-fired plants.

In their paper "Restoring the Nuclear Option in the U.S.: A Real Options Approach," Graber and Rothwell (2005) demonstrate that the real options methodology explicitly accounts for the risks and uncertainties faced by a nuclear plant developer. Furthermore, as new information about electricity prices and plant investment costs arise, the real options approach bestows management with the flexibility to decide whether to continue or abandon the investment project. This is in direct contrast to DCF methods, which do not allow this type of flexibility. Utilizing decision trees, Graber and Rothwell show that when a nuclear construction project is modeled as a set of chronological, independent phases, the option-based value far exceeds the DCF-based value and in fact justifies the initial investment in the nuclear plant. The specific phases Graber & Rothwell identified are: (1) selection of supplier and technology, (2) procurement of license to construct and operate a nuclear power plant, and (3) initiation of construction and plant start-up. It follows that there are two specific instances where options exist – after phase 1 (*option to apply for license*) and after phase 2 (*option to construct*). The real options approach assumes that, if necessary, management has the flexibility to abandon the plant at any time and save unspent funds. With volatile future electricity prices and uncertain production and construction costs, the results show that applying real options reveals a strategic value that is not achievable under NPV analysis. This discrepancy ultimately leads to contrasting decisions under the two approaches, with the option value far outweighing the NPV assessment.

In Rothwell (2004)[2] and Rothwell (2004)[3], the author takes a slightly different approach to the same problem. Instead of identifying specific phases, Rothwell calculates "trigger values," which are explicit values at which the investor would be indifferent between investing and not investing.

Trigger values are calculated for net revenues (R^*), total construction costs (I^*), and the total construction cost per kW (K^*). For example, assuming a trigger value K^* of \$2,000/kW, investors would be indifferent between ordering a new nuclear power plant and waiting for new information at this figure. However, if the actual construction cost per kW turned out to be higher than the trigger value K^*, the investor would decide to wait (does not invest). Likewise, setting the net revenue trigger value to be R^*, if the expected net revenues were less than R^*, management would choose to wait. In these articles, Rothwell simulates the uncertainties and net revenues by means of Monte Carlo simulation. In doing so, he is able to take into account the different uncertainties and unknown operating costs. Further, he applies the real options approach by assessing the nuclear investment's probability distribution of net revenues. The author assumes that percentage changes in net revenue follow a proportional Brownian motion with a normal distribution and that uncertain net revenues are correlated with a portfolio of tradable assets. Rothwell also considers how price risk, output risk and cost risk can be mitigated. The tools available to control these different risks include financial instruments and contracts as well as physical assets, such as natural gas peaking units. By mitigating the risks of investing in a nuclear power plant, Rothwell is able to illustrate the sensitivity of the trigger values. In taking the electricity market price, capacity factor and production costs as uncertain and applying the real options approach, Rothwell proves the value of this approach as opposed to the traditional DCF methods. It is particularly interesting to consider how the various trigger values adjust if the values and/or variance of one of the underlying uncertainties is modified.

Gollier et al (2005) expand on the idea of investing in nuclear power plants by considering the option of investing in a large power plant versus investing in a sequence of smaller, modular power plants. Building a flexible sequence of smaller nuclear plants allows management to make sequential choices (abandonment of the project, waiting for new information) and to take into consideration cost uncertainties associated with the investment. Essentially, the authors attempt to compare the benefits of the large nuclear plant project due to increasing returns to scale versus the benefits of modularity due to its flexibility and reduced risk. The modularity approach has higher production costs but the advantage of this approach is that it intrinsically establishes options from plant to plant. Namely, after the first module has been constructed, the decision makers have the option to abandon the project, wait for new information, or go ahead and invest in the second module. Like Rothwell (2004)[2], their approach defines a trigger value P^*, which defines the price threshold at which

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it is economically sound to invest. Through the use of real options, Gollier et al illustrate that a modular investment allows management the flexibility to adapt to certain risks and uncertainties, hence making this alternative more attractive than the irreversible investment in a large nuclear power plant.

2.3 – Establishing Real Options as a Suitable Valuation Tool

Having pored over a substantial number of articles and studies, we determined that two specific approaches stood out in terms of their overall appeal and applicability to Ontario's specific situation. The articles by Rothwell (2004[2], 2004[3], and 2005) and Graber & Rothwell (2005) introduce two distinctive ways to examine a nuclear power plant investment project. By calculating trigger values for net revenue (R^*), total construction costs (I^*), and the total construction cost per kW (K^*), Rothwell is able to define specific values at which the investor will be indifferent between investing or not. On the other hand, the article by Graber & Rothwell (2005) identifies three explicit phases in a nuclear power plant investment project. Consequently, the authors establish two sequential points where options exist. Assuming management has the flexibility to act accordingly, this approach uncovers a valuable strategic value and provides critical insights to the investment decision making process.

Both of these approaches had substantial bearing on the methodologies employed in our thesis. They were particularly appealing to us in the sense that they were clear, easy to understand and applicable to the current situation in Ontario. These articles will be discussed in greater detail in *Chapter 4*, where we present a comprehensive overview of the approaches and theoretical models employed in our paper.

In this chapter, we have introduced real options from a theoretical and practical viewpoint. In doing so, the real options approach has been established as a suitable valuation tool from the perspective of energy investments. Since this approach integrates managerial flexibility, it adds value to the overall investment in the sense that management has the ability to make the most of any uncertainties and risks. Ultimately, however, the real options approach is most useful when used as a complimentary tool together with traditional valuation techniques. The following chapter will present the specific

situation in Ontario and substantiate why the current state of affairs in Ontario warrant the use of real options.

Chapter 3 – Problem Formulation & the Application of Real Options in Ontario Nuclear Energy Investments

In *Chapter 2*, the main focus was to show how and why the real options methodology has been applied from the viewpoint of the electricity sector. This was achieved by way of a literature review and by presenting some specific examples. In *Chapter 3*, we will introduce the existing state of affairs in the Ontario electricity market and in doing so, we will make clear and justify why real options is a valid technique to utilize for this specific market. Furthermore, we will formulate the main problems our thesis tackles and illustrate how we plan to answer these questions.

3.1 – Ontario's Looming Supply and Demand Gap

The Ontario electricity sector is at a noteworthy and critical stage in its history. *Figure 1.1* in *Chapter 1.2* illustrated the province-wide shortfall that is projected to emerge before the end of the decade. The looming supply and demand gap in the province of Ontario is a consequence of the combination of decreasing generation capacity and growing demand.

The dwindling supply is an amalgamation of a few factors: the impending end-life of several nuclear units, the provincial government's decision to shut down all coal-fired generation by 2009, and the overall lack of investment in installed generation capacity in the past decade. *Figure 3.1* illustrates the amount of installed nuclear capacity that will be nearing its end-of-service date in the next ten to fifteen years. These dates indicate potential decision making points where the choice will have to be made whether to refurbish these plants or take them out of service.

Figure 3.1 - Ontario's Nuclear End-of-Service Dates
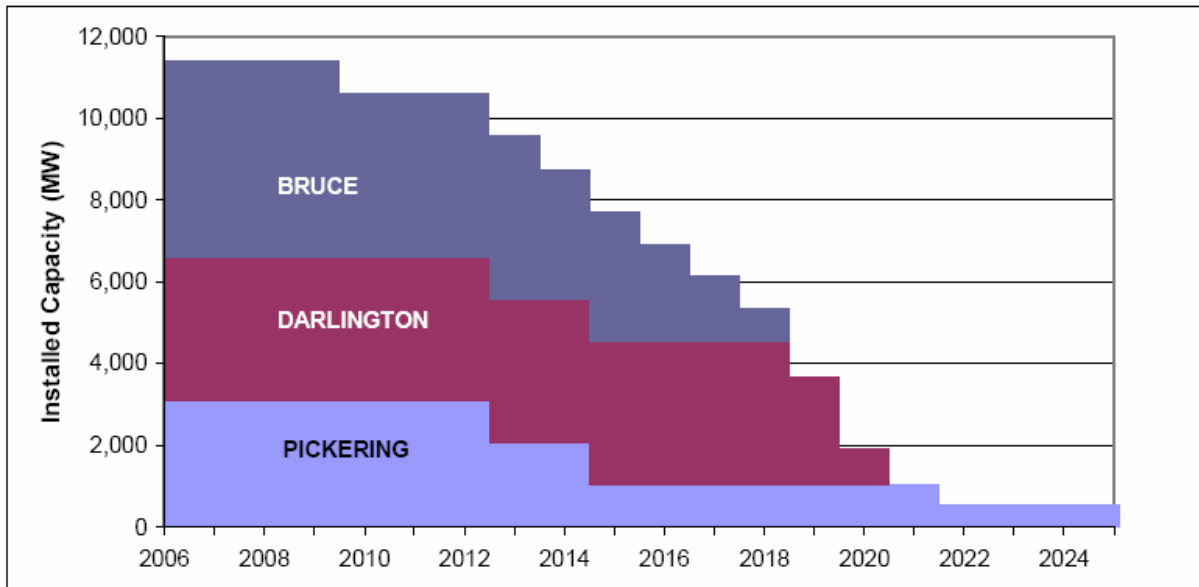
Source: OPA (2005), with advice from IESO and nuclear operators.

In addition to the diminishing supply, Ontario has experienced higher-than-expected population and economic growth, particularly in the Greater Toronto Area. *Figure 3.2* below illustrates Ontario's electricity consumption per capita under the expectation that Ontario's population will increase at an annual growth rate of 1.1%. The 0.9% demand growth figure implies a lower consumption per person in the future, while the 1.8% figure implies an increase in use per person (OPA, 2005).

Figure 3.2 - Ontario Electricity Consumption per Capita
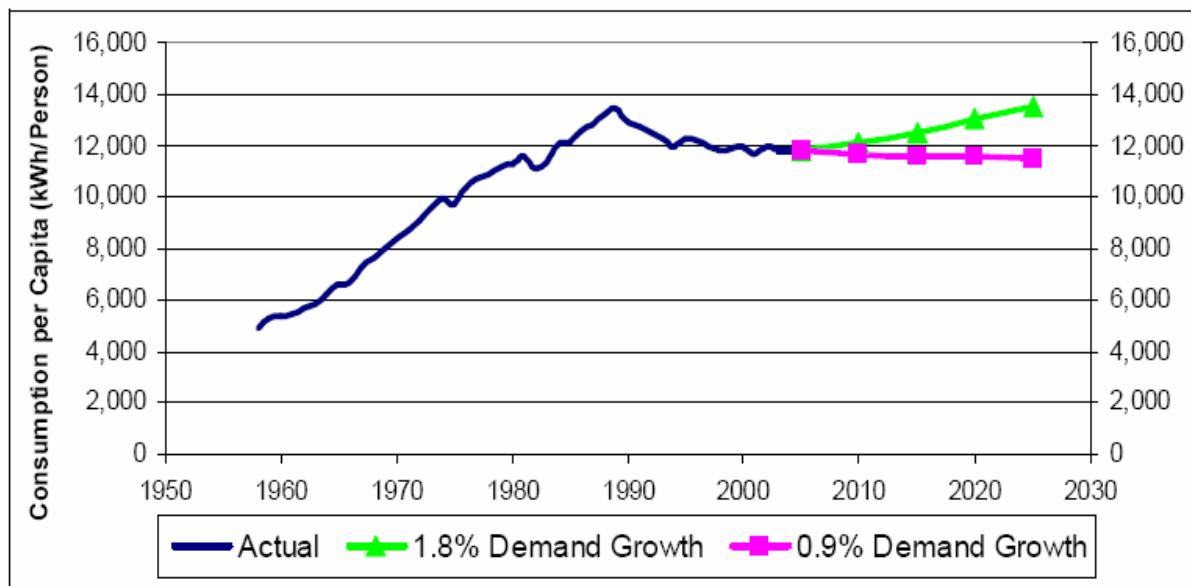
Source: OPA (2005), with advice from ICF Consulting.

All of these issues have combined to create a situation in which there is an anticipated gap of approximately 24,000 MW – 80% of Ontario's current capacity – by 2025 (OPA, 2005). Short-term procurement plans are in place and at this point look to be substantial enough to balance the supply and demand in the near future. In another ten years, however, the increasing demand and nuclear end-of-service dates would potentially combine to overwhelm the system's ability to meet the provincial demand.

If an appropriate amount of demand reduction and new or refurbished generation capacity is not made available, Ontario will be reliant on external electricity supply, energy costs will increase and be even more unstable, and the overall system reliability could be put to the limits.

3.2 – The Deregulation of the Ontario Electricity Market

One of the main reasons why a real options approach is appropriate in the context of the Ontario electricity market is due to the deregulation of the market that has taken place in the last several years. As mentioned before in *Chapters 1* and *2*, the electricity market in Ontario, and on a global scale to a wide extent, has gone through a significant transformation in recent years. The liberalization and opening of the Ontario electricity market to competition has introduced several new uncertainties and risks.

3.2.1 – The New Risks and Uncertainties of Deregulated Markets

Deregulation, societal pressures and environmental restrictions have all combined to considerably modify the targets and goals of electricity organizations. In the preceding regulated environment, electricity was supplied at fixed rates and the only uncertainty was electricity demand and the likelihood of technical failures. Thus, the previous environment was vulnerable to *operational risk* and the challenge was to make sure that the electricity supply was sufficient enough to meet consumer demand (Hlouskova et al, 2002).

The modern liberalized electricity market encompasses new risks and uncertainties. These include volatile electricity and fuel prices for inputs such as gas or coal, to name but a few. As a result, there is now a *price* or *financial risk* that electricity firms must take into consideration as well, as proposed by

Hlouskova et al (2002). Additionally, other factors such as the costs and time of construction or the price of emission allowances have to be taken into account.

3.2.2 – Ontario's "Hybrid" Electricity Market

The Ontario electricity market itself is an interesting case to consider. Though the deregulation process formally started in 2002, the Ontario market is not fully deregulated and is now recognized as a "hybrid market." This denotes that the market combines both competitive market elements (e.g. the wholesale price is set by the market through the balancing of supply and demand performed by the Independent Electricity System Operator) and regulated market elements (e.g. retail prices are regulated by the Ontario Energy Board and the responsibility for resource and system planning has been given to the OPA). It is generally accepted that the hybrid model is not sustainable in the long run and that Ontario's electricity market will have to gradually move towards a fully open and competitive structure. Accordingly, the Electricity Act of 1998 (Ontario Regulation 424/04) expressly instructed the OPA to "identify and develop innovative strategies to encourage and facilitate competitive market-based responses and options for meeting overall system needs."

Therefore, the plan is for Ontario's electricity market to eventually develop into a competitively structured system. This will include a market place open to Ontario customers where several suppliers will meet the provincial demand in the short-, medium- and long-term. The future market structure will thus consist of a sizeable number of uncertainties and both operating and investment decisions will be largely affected by these risks.

3.3 – Ontario's Base Load Power Needs

Power plants can be typically divided into three categories depending on their role in meeting electricity demand. These categories are: (1) base load, (2) cycling or intermediate, and (3) peaking plants. Our thesis is expressly concerned with the base load category of power plants and more specifically, nuclear power. Characterized by high start-up costs and low ramp rates, base load plants effectively run at all times apart from instances of repairs, maintenance or forced outages and, in the case of Ontario, constitute a majority of the installed generation capacity and electricity production.

Figure 3.3 illustrates how Ontario typically meets its base and peak loads. As we can see, hydro and nuclear can be identified as sources that meet the standard Ontario base load; coal generation is generally used for intermediate loads, meaning these plants are on-line during peak hours but shut off during off-peak hours (ECSTF, 2004). Generating sources that meet peaking generation are suited for short periods of operation and are sensitive to market prices. These sources include storable hydroelectric plants and natural gas plants.

Figure 3.3 - The Roles of Base Load and Peaking Generation in Ontario
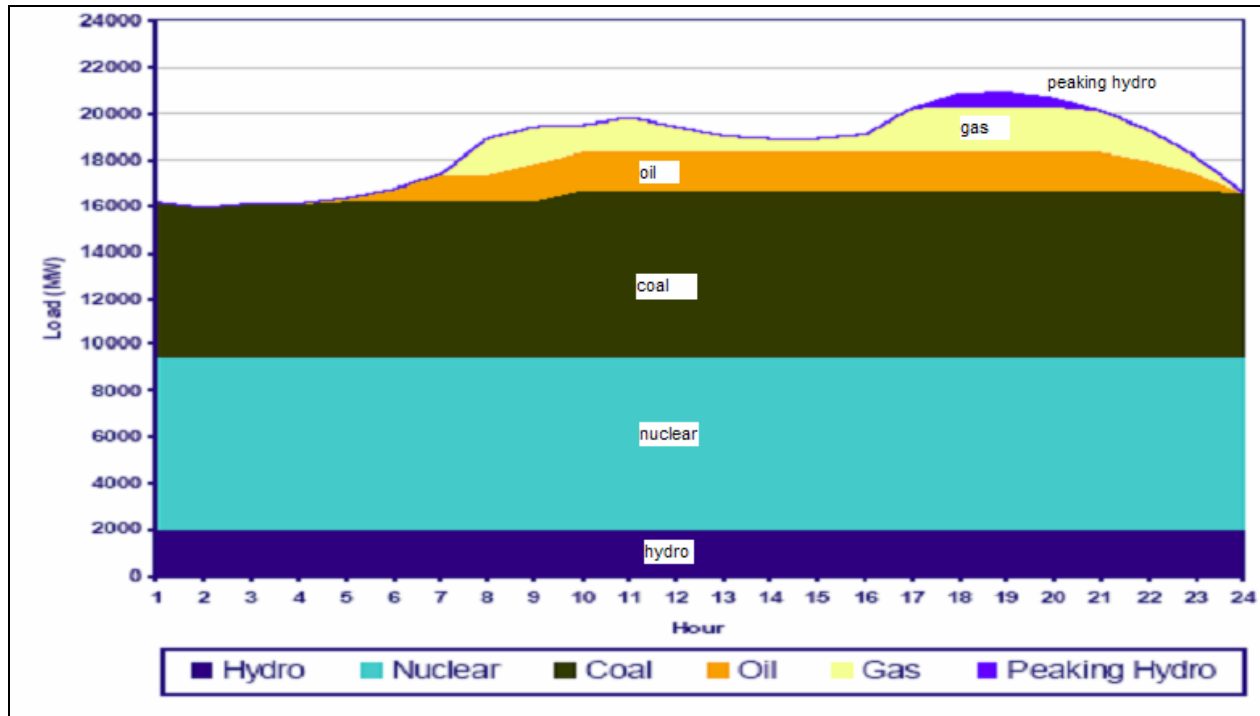
Source: ECSTF, 2004

The main point to take away from the above figure is to notice the large contributions made by nuclear and coal power in meeting consumer demand in Ontario. Considering that coal-fired generation is due to be entirely shut down province-wide in the near future and that existing nuclear plants will be nearing their end-of-service in the same timeframe, it becomes apparent that new supply sources that will meet the provincial base load demand are a necessity. Though hydroelectric power plays an evident role in meeting the provincial base load demand, nuclear power is without question the more important generation type considering the size of its contribution.

3.4 – The Ontario Power Authority's Supply Mix Advice

The Ontario Power Authority (OPA) is the organization responsible for the development of the provincial *Supply Mix Advice* and *Integrated Power System Plan* (IPSP), which is the comprehensive plan that outlines the proposed strategy for Ontario's electricity system, now and into the future. As stated by the Ontario Power Authority in their *Supply Mix Advice Report (Vol. 1, December 2005)*, significant resolutions must be made soon in order to ensure an adequate and reliable supply in the short- to long-term future. This is due to the plethora of risks involved in such sizeable investments, as well as the long lead times required in the decision making process.

Figure 3.4 below presents an in depth summary of the recommendations made by the Ontario Power Authority to the Minister of Energy. The main points to observe in the figure include:

- The role of nuclear generation is not anticipated to change, both in terms of installed generation capacity and electricity production. In terms of electricity production, nuclear generation will account for approximately 50% of total production.
- The role of renewables is expected to increase, with installed generation capacity rising from 26% in 2005 to 36-37% in 2015-2025. In terms of electricity production, renewables are projected to increase from 23% in 2005 to the 40% mark by 2015, which is a significant increase.
- The role of gas-fired generation will grow in the short-term (i.e. next ten years), but will gradually be replaced by renewables in the long-run.
- Coal-fired generation will be completely shut down and will not play a role in the future supply mix.
- Conservation and demand management will reduce total demand, especially in the long-run.

Figure 3.4 - The Ontario Power Authority's Supply Mix Advice

(%)	2005	2015	2020	2025	(%)	2005 (Estimate)	2015	2020	2025
Nuclear	37	32	32	35	Nuclear	51	48	48	50
Renewables	26	36	37	37	Renewables	23	40	42	43
Gasification	0	1	1	1	Gasification	0	1	1	1
Gas	16	31	30	27	Gas	7	11	9	6
Coal	21	0	0	0	Coal	19	0	0	0

(MW)	2005	2015	2020	2025	(TWh)	2005 (Estimate)	2015	2020	2025
Nuclear	11,397	11,000	12,000	15,000	Nuclear	79	76	81	89
Renewables	7,855	12,000	14,000	15,500	Renewables	36	64	71	77
Gasification	0	125	250	250	Gasification	0	2	2	2
Gas	4,976	10,500	11,000	11,000	Gas	11	17	15	11
Coal	6,434	0	0	0	Coal	29	0	0	0
Total	30,662	33,625	37,250	41,750	Total	155	159	169	179

Source: OPA, 2005

In constructing the proposed future supply mix, the OPA had to initially recognize three guiding principles that were already established by the Ontario Government as priorities:

1. Coal-fired generation is to be shut down by 2009 and will not play a role in the future supply mix
2. Conservation and Demand Management (CDM) measures would be advanced in order to create a "conservation culture" in Ontario
3. Renewable energy sources would significantly increase in the new supply mix

3.4.1 – Conservation & Demand Management and Renewable Energy

Taking these priorities into account, the OPA was able to generally outline their supply mix advice as such:

1. Conservation and other forms of demand management will be a major part of the plan, and is expected to reduce demand in the long-run
2. Renewable energy sources, such as wind, biomass, small hydro and solar power, will increase in both installed generation capacity and electricity production

Assuming CDM measures and new renewable sources meet their set targets, the combination of these two elements would in fact be sufficient to meet Ontario's electricity demand growth by 2025 (OPA, 2005). However, as we have outlined before, coal-fired generation will be shut down by 2009 and several nuclear units have their project end-life within the next 10 to 15 years. This means that the lost coal-fired generation capacity will have to be replaced and that a decision will have to be made regarding nuclear refurbishment and/or the construction of new generation capacity.

3.4.2 – Natural Gas-fired Generation and Nuclear Generation

The OPA supply mix advice continues to discuss the roles of natural gas-fired and nuclear generation:

3. Natural Gas-fired generation will play an important role, especially to meet intermediate and peak load
4. Nuclear generation, through refurbishment and/or new generation, will continue to play a major role in meeting base load needs

According to the OPA, gas-fired generation would not be suggested as a base-load alternative due to the environmental and financial risks it would pose in this role. However, if operated appropriately, natural gas-fired generation could be advantageous as a peaking generation source. As we saw in *Figure 3.4*, nuclear generation will continue to be the main source of energy in Ontario, particularly for base load purposes. This means that nuclear generation's share in the province's supply mix will somehow have to be maintained. Ontario's most pressing need in the long term then is clearly related to base load supply, which signifies that new nuclear plants and/or refurbishment of existing nuclear plants will have to be taken into consideration.

Table 3.1 - Characteristics of Potential Supply Sources

Fuel	Prime Use	Fuel Cost	Capital Cost	Environmental Impacts	Risks/Impediments
Nuclear	Base load	Low	High	Low Emissions	Delays and cost overruns
Natural Gas	Peaking, intermediate	High	Low	Low emission rates	Supply and price volatility

Source: ECSTF, 2004

Table 3.1 displays the characteristics for the two alternatives that have been identified as logical and preferred solutions to helping solve this capacity challenge. The Electricity Conservation & Supply Task Force (ECSTF) studied different scenarios and singled out nuclear generation – both new generation and refurbishment – as the clear choice for base load use.

3.5 – Detailed Research Problem Formulation

We have previously stated that the focus of our thesis would be on capital investment decisions as opposed to operational decisions. The existing situation in Ontario has predetermined that investments in new installed generation capacity will have to be made in order to ensure a stable and reliable electricity system. Having reviewed the major elements of the Ontario Power Authority's suggested solution, and bearing in mind our focus on capital investments, we identified nuclear generation as a particular point of interest.

The decision to concentrate on nuclear generation was based on a number of interconnected reasons. First of all, the role of nuclear generation is not expected to change from the current situation where 50% of the province's electricity needs are met by nuclear power. This indicates that sizeable additions of nuclear generation capacity will have to be made to the system. More explicitly, the OPA states that Ontario will need between 9,400 to 12,400 MW of nuclear power to be added by 2025. These additions should be realized through installation of new generation, rebuilding on existing sites and/or refurbishment of existing units where it is economically feasible to do so. Finally, considering that these alternatives will inherently involve large capital investment decisions

with somewhat long construction lead times, this suggests that comprehensive financial investigations will have to be carried out for these different alternatives.

Consequently, we propose to evaluate two categories of nuclear energy capital investment decisions that will have to be made in the not-too-distant future by Ontario's decision makers. These include:

1. Investment in a new nuclear power plant, where we will compare the two main candidates for Ontario's next generation of nuclear reactors – Enhanced CANDU 6 and ACR-1000
2. Refurbishment of existing nuclear units, using the case of Pickering B nuclear generating station as a specific example

3.5.1 – Applying Real Options to Ontario Nuclear Energy Investments

In order to evaluate these investment decisions in a flexible manner, we will employ the real options methodology. As discussed in *Chapter 2*, a real options approach is relevant in the context of strategic energy investment planning due to its superior ability in dealing with uncertainties and incorporating management's flexibilities into the decision making process.

3.5.1.1 – New Nuclear Generation

The construction of a new nuclear power plant is unquestionably a large capital investment decision involving a long lead time. Though the actual construction of the reactors may take anywhere from two to four years per unit, the total investment timeframe usually lasts twice as long (or more) as the actual construction itself. Without going into too many details, the investment also involves long periods of research, feasibility testing, license procurement, and so on. As such, the investment in a "new build" nuclear project should clearly not be deemed a "now or never" decision.

As suggested by Graber & Rothwell (2005), a nuclear plant construction schedule can be broken down into a number of phases. Assuming the phases are sequential and relatively independent, real options can be identified after the first two phases. From the viewpoint of a "new build" project, we therefore find it interesting to consider what an *option to abandon* after the first two phases could offer in terms of the project's strategic value. For example, what if electricity prices were much lower than expected or conversely, what if production costs shot up drastically? Since Ontario's market has only been partially deregulated since May 2002, it is somewhat hard to define specific electricity price trends; accordingly, the trend and volatility of electricity prices could have a substantial impact on the

plant's projected revenues. Further, initial construction costs for nuclear plants in Ontario have in the past experienced serious cost overruns, so this would certainly be another point to contemplate.

We chose to compare two different nuclear technologies in this analysis. According to the Atomic Energy of Canada Limited (AECL), the Enhanced CANDU 6 and ACR-1000 have been singled out as the two alternatives for Ontario's next batch of nuclear generating stations. The two technologies have diverse technical and cost-related characteristics, which will probably lead to quite different plant values using the traditional NPV approach. Introducing optionality may present a point of view that would not be available using traditional approaches; this could ultimately result in accepting a project that looks unprofitable, or vice versa. This essentially translates to an *option to continue* in the projects that look unprofitable using traditional approaches.

3.5.1.2 – Nuclear Refurbishment

The investment decisions we outlined above are highly intricate investment decisions that comprise several stages within the overall decision itself. As in the new nuclear generation evaluation, the choice to refurbish an existing power plant is a complex process involving a feasibility study, procurement of materials, outage and contingency planning, site preparation, and then finally the return to service. Hence, it is also evidently not a simple "now or never" decision.

In this analysis, we use the real-life case of the Pickering B nuclear plant, which is currently in the middle of a refurbishment feasibility assessment by Ontario Power Generation. As in the previous analysis, we specified different stages or phases of the overall investment process; these were based on recommendations outlined by OPG in their Pickering B Refurbishment Study. Namely, the phases we utilized are a feasibility assessment, a planning stage, and finally the refurbishment stage. Yet again, our approach offers an *option to abandon* after the first two phases if it is simply unprofitable to continue. This has some real-life significance considering the enormous cost overruns that were experienced as part of the Pickering A refurbishment. Original estimates to rebuild the four reactors at Pickering A were approximately $1.1 billion total. However, the original assessment neglected to review a host of economic issues, and did not intensely look at the cost comparisons of energy alternatives (Sierra Club of Canada, 2003). The end result was a cost from $3 to $4 billion, a staggering excess over the initial estimate. Given that the Ontario decision makers will undoubtedly

take the Pickering A experience into account this time around, we strongly believe that a real options approach is appropriate in this situation.

The Pickering B facility is made up of four units (each at 516 MW). Our model considers the refurbishment and return to service of two units (1032 MW total) at the start. We then consider the *option to expand* and the feasibility of the next two units being refurbished and brought back to service. Splitting up the overall project in this fashion offers a considerable amount of flexibility – not only do the power plan operators have the *option to abandon* the plant in the initial stages if the economic feasibility is unfavourable, they now also have the *option to expand* in case the refurbishment is completed within the specified budget. The OPA has indicated that the decision makers responsible for these decisions now have more experience in the management of nuclear projects in the current environment and while this may be true to an extent, our approach accounts for any unforeseen events and could potentially add a significant amount of strategic value to the refurbishment project.

3.5.2 – Justification and Innovativeness of our Approach

In this thesis, we do not aim to solve all of the problems facing the Ontario electricity market. Rather, we have chosen to take a more focused approach on a specific and identifiable problem – namely, the foreseeable lack of base load generation capacity by means of nuclear power. To the best of our knowledge, the real options approach has not been explicitly applied to the Ontario energy sector in the manner which we have proposed.

The empirical application of real options theory to the specific problem we have outlined is the most interesting and, at the same time, the most challenging part of our thesis. Some of the data in our models could be regarded as exclusive or somewhat restricted information. However, given that we have been in close contact with some of the major players in the Ontario energy sector – including the Ontario Power Generation, Atomic Energy of Canada Limited, and especially the Ontario Power Authority – we have managed to obtain fairly accurate, if not actual, data for a great deal of the variables we utilize. We could have used artificial or made-up data to explore the real options approach in itself. Then again, we would have considered this to be less gratifying from our perspective and are pleased that we could apply the real options technique using actual data and real-life challenges.

Furthermore, whereas simpler real options models only account for volatility and changes in electricity or fuel prices, we aimed to be as comprehensive as possible in our modeling approach. To that end, we attempted to incorporate real values and anticipated uncertainties into the model for all the relevant factors.

Chapter 4 – Model Design & Application

In the previous chapter, we presented a detailed research problem and established the specific alternatives we consider in our thesis and how the real options approach can be applied in each case. As outlined in *Chapter 2.3*, we place particular emphasis on the methodologies used in the articles by Rothwell (2004[2], 2004[3], and 2005) and Graber & Rothwell (2005). This chapter gives a more thorough and comprehensive look at these methodologies and how we applied them in our thesis.

4.1 – Modeling Nuclear Energy Investments

Before moving onto a theoretical review of the models utilized in our approach, it is important to consider how the value of the given projects will be calculated in the first place. Considering we are using a real options approach, identifying the key uncertainties is an imperative step. This issue has been looked at in *Chapter 2.2.1.1* and will be discussed in greater detail in *Chapter 5*.

What we are more concerned with at this point is discussing the calculation of a given project's cash flows or net revenues. To that end, a net revenue formula for power plants was used as a basis for our models. This model is partially based on the approach used by Rothwell (2005), with some small adjustments on our part.

Nuclear power plant total revenues per year can be calculated as:

$$Total\,\mathrm{Re}\,v = P_{EL} \cdot CF \cdot MW_{year} \qquad (1)$$

where
- P_{EL} is the electricity commodity price (\$/MWh)
- CF is the capacity factor (%)
- MW_{year} is the maximum dependable capacity of the plant (in MWh/year)

The capacity factor is a ratio of the total amount of electricity produced for a given time period over the total amount of electricity that could have been produced at maximum output. Thus, it follows that if the capacity factor was 100%, or if the plant is running at all times, the actual electricity produced would be equal to the maximum capacity of the plant (MW_{year}). Assuming a plant of size

1000 MW, the maximum dependable capacity is equal to 1000 MW times the number of hours in a year (8760), or 8,760,000 MWh. A capacity of factor of 80%, for example, signifies that the plant is running at 80% capacity, meaning that total electricity produced is 80% of 8,760,000 MWh ($CF \cdot MW_{year}$), or 7,008,000 MWh. It is rather uncommon for a capacity factor to be 100%. This is due to power plant failures and/or routine maintenance, but more logically because the demand for that much electricity does not exist on a continuous basis.

In our model, the production costs are a combination of the fuel costs, variable OM&A (Operations, Maintenance and Administration) costs, and fixed OM&A costs. We label this the Nuclear PUEC, or Production Unit Energy Cost.

$$PUEC = Fuel\, costs + OM\,\&\,A_{variable} + OM\,\&\,A_{fixed} \qquad (2)$$

Subtracting equation (2) from equation (1) gives us the net revenue or profit:

$$Net\, Revenue = Total\, Rev - PUEC \qquad (3)$$

In this closed-form solution model, the uncertainties in P, CF and PUEC lead to ambiguity in future net revenues. Therefore, it is quite valid to simulate net annual revenues based on the simulations of its uncertain components.

The project net present value is the sum of discounted future revenues minus the total investment costs and can be calculated as such:

$$NPV = Net\, Revenue / \delta - Inv \qquad (4)$$

where

- *NetRevenue* is net annual revenues
- δ is the appropriate discount rate
- *Inv* represents the investment costs
- tax issues are ignored for the sake of simplicity[2]

Simulating electricity prices and output and input parameters can be combined to generate a probability distribution of the NPV. If the mean NPV is negative, the investor would decide not to

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[2] The fact that tax issues are not incorporated into the study will not affect the essential conclusions. However, the greater the value of the capital recovery factor, the greater the potential error incurred as a result of neglecting taxes.

invest using the conventional approach. However, this is exactly where real options can come in and give a complementary view of the investment by considering the investor's flexibilities. We will now focus on two alternative approaches we utilized in order to value the optionality embedded in our specific investment projects.

4.2 – Model Descriptions

In carrying out our evaluations of the given investment projects, we employed the following approaches:

1. Valuing a project as a set of independent chronological phases – founded on Graber & Rothwell (2005)
2. Valuing a project by calculating trigger values that define the state when an investor is indifferent between accepting and not accepting the investment – founded on Rothwell (2004[2], 2004[3], 2005)

Both approaches have the same aim, which is to identify the financial attractiveness of an investment. However, each method uses different ways to uncover the solution, which we believe further enhances our evaluation. Essentially, the two approaches are complementary rather than interchangeable; combining these methodologies would give a potential investor or manager a broader insight into the problem at hand and the potential to make a superior final decision.

4.2.1 – Identification of Phases & Valuation of Options

As described before, energy investments, and nuclear investments in particular, can be classified as so-called *giga-investments* due to their large size and a long life cycle (Carlsson and Majlender, 2005). The decision to construct a new nuclear power plant or to refurbish existing reactors is a lengthy, complex and multi-faceted issue. Consequently, the investment decision can be modeled as a sequence of phases, each with their individual features, costs and timeframes.

As carried out earlier by Graber & Rothwell (2005), we identified three investment phases for the projects considered; these will be described in greater detail in *Chapter 5*. While the number of phases can differ according to the characteristics of the market, regulatory requirements and the features of the given project, we believe that the provided approach is illustrative enough to offer a sound idea of how these specific investments would be evaluated. The identified stages are chronological and assumed to be relatively independent of each other.

While standard valuation techniques imply that the entire investment project is a "now or never" decision, the real options approach considers other basic actions. First, there is an option to delay the decision for some time in the future until more favourable market conditions appear. Secondly, in case the market does not favour the investment anymore, there is an option to abandon the project before all investment costs have been incurred.

Figure 4.1 gives a general idea of how the phased real options approach will work. The horizontal axis represents the time each phase lasts, while the vertical axis represents the total investment costs. So with each phase, we move to the right (depending on how long the phase lasts) and upwards in terms of costs (depending on how much the phase costs). After phase I is completed, the first option can be exercised, where the exercise price is equal to the costs of phase II. If the first option is exercised, the investment will enter phase II. As in the first option, the second option will be available only after phase II is finished. Upon paying the exercise price for the second option, the investment would then enter phase III. The two options are basically moments in time where the investor has a right, but not an obligation, to decide whether to continue with the project or to abandon.

Figure 4.1 – Phases and Options of the Decision Making Process
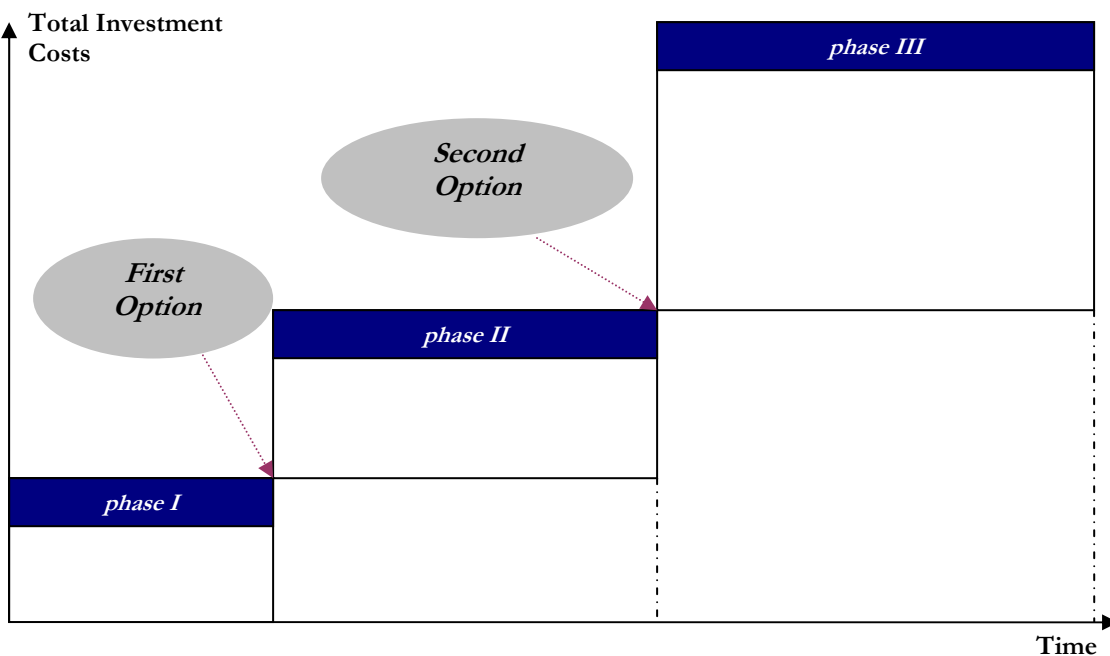
This approach is tantamount to the sequential compound option approach, which is explained well in Mun (2006). The underlying variable of the second option is the present value of the total project, which is a random variable that depends on the behaviour of the electricity prices, operating costs and the capacity factor. The underlying asset of the first option is the value of the second option, which implies that if the second option is worth more than it costs to purchase, the first option should be exercised. Both options are European options since they can be exercised only after the relevant phase has been completed.

The exercise price is the investment required to exercise the option. For the first option, the exercise price is equal to the costs of completing the second stage, whereas for the second option it is the costs incurred during the third stage. Due to the large time span between the time when the decision to invest in a nuclear project is made and when the plant actually starts producing energy, the total costs incurred at the three stages are uncertain. The values for each stage can be based on publicly available information, historical values, or estimates made by decision makers who possess significant knowledge of the industry.

Table 4.1 - Characteristics of the Nuclear Sequential Options

	First Option	Second Option
Maturity Date	Phase I completion	Phase II completion
Exercise Price	Phase II costs	Phase III costs
Option Type	European Call	European Call
Underlying Asset	Second Option	PV of Project

The main difference between standard financial options and these particular energy options is that in the latter case, both the plant value (the underlying asset for the second option) and the total investment (which defines the exercise price for the options) are uncertain. The project's value is not known with certainty since it depends on such random variables as the electricity price, the capacity factor and the production costs. Further, the investment expenditures are indefinite because construction costs might change in the future.

4.2.1.1 – Dealing with the Multiple Uncertainties

The above-mentioned model includes uncertainties in the option exercise prices, which is not the case for financial options or real options. This would lead to problems in terms of valuating the options in the correct manner. Dixit (1992) suggests that the problem can be solved through the use of the ratio V/I, where V is the present value of the underlying asset and I is the present value of the total investment. Since the underlying asset is a random variable itself with multiple sources of uncertainty affecting its behaviour, the logical solution to the valuation problem is to combine the uncertainties into a single volatility measure. This multiple uncertainty technique proposed by Dixit is discussed in greater detail in *Appendix A*. In terms of estimating the volatility based on historical data, Monte Carlo simulation is a suitable tool through the use of the following formula:

$$\sigma = \sqrt{\sigma_V^2 + \sigma_I^2 + 2\rho\sigma_V\sigma_I} \qquad (5)$$

where

- σ is the combined volatility
- σ_V is the volatility of the underlying asset
- σ_I is the volatility of the total investment
- ρ is the correlation between the underlying and the total investment.

The above approach replicates the concept used in financial theory of derivatives valuation; as such, the option is written not on the price of the asset, but rather on the return that the asset is generating.

4.2.1.2 – The Valuation of the Options

In our approach, we have chosen to use a dynamic programming valuation tool (binomial trees) among all the valuation techniques presented in *Chapter 2.1.5*. Binomial trees are relatively easy to build and can be effortlessly adjusted to new information and inputs as needed. The last quality will be especially appreciated when looking at the nuclear refurbishment alternative.

Since we are dealing with sequential compound options, the valuation has to be performed backwards and starts with the valuation of the underlying asset. Following the discussion in the preceding section, the underlying asset is the V/I ratio.

Binomial lattices can be solved using a *risk-neutral probability measure* and *up and down factors*, which are determined in the following manner (Hull, 2005):

$$p = \frac{e^{r\Delta t} - d}{u - d} \quad (6)$$

$$u = e^{\sigma\sqrt{\Delta t}}; d = -e^{\sigma\sqrt{\Delta t}} \quad (7)$$

where

- Δt is the length of the step in the tree
- σ is the volatility of the underlying ($\sigma_{V/I}$ to be precise – the parameter can be estimated by using simulation techniques as described above)
- r is the risk free rate
- *u* is the magnitude of the upper movement
- *d* is the magnitude of the down movement.

Once the tree depicts the possible future patterns of the underlying asset and the appropriate exercise price (X_{III}, or the costs of phase III in proportion to the total investment) is defined, the second option can be calculated at the binomial tree's end nodes:

$$V_{CO} = Max(0; {}^{V_P}\!/\!_I - X_{III}) \quad (8)$$

And by using

$$f = e^{-r\Delta t} \left[pf_u + (1 - p)f_d \right] \quad (9)$$

at all the other nodes, where *f* represents the value at a particular node, f_u represents the value of the node one step above, and f_d is the node one step below.

Once all the nodes representing the second option's value are identified, the first option can be calculated. Since the first option matures after phase I, the nodes representing points in time after this stage have been completed and are considered irrelevant. The value of the option can be found by using the following technique:

$$V_{LO} = Max(0; {}^{V_{CO}}\!/\!_I - X_{II}) \quad (10)$$

The first option's exercise price is equivalent to the costs incurred during the second stage of the investment, taken as a ratio to the total investment value (X_{II}). Equation (10) is applied to value the final node and equation (9) is used to value all the other nodes.

By multiplying the value of the first option by the initial investment, one gets the present value of the project adjusted for the embedded optionality in the investment ($V_{LO} \cdot I$). Since the costs for the second and third stages have already appeared in their respective exercise prices, the only costs left to be incorporated into the analysis are the first stage costs. By subtracting the first stage costs from the plant's present value, we acquire the final option value of the investment. If this value is positive, the investment should be undertaken; if negative, it should be abandoned. The strategic value, therefore, is the difference between the final option value and the static net present value.

Correspondingly, the above calculations have to be replicated in order to check the decision to exercise the second option. Therefore, an appropriate monitoring system should be developed and implemented accordingly.

4.2.1.3 – Extension of the Model for Nuclear Refurbishment Alternative

This section exhibits the peculiarities of the refurbishment alternative considered in our approach. Moreover, this extension of the model provides a good understanding of how the model can be improved and specifically tailored to reflect real-life conditions and situations.

As outlined in *Chapter 3.5.1.2*, we have approached the refurbishment issue in a specific manner. Namely, we first evaluate the economic feasibility of refurbishing two of the four existing reactors at the Pickering B facility. The decision to refurbish the last two reactors will not be made at the outset. However, if the initial refurbishment proves to be a profitable venture and assuming market conditions do not change for the worse, the subsequent refurbishment of the last two reactors would then be considered.

The possibility to refurbish two more plants in the future can be regarded as an *option to expand* since it represents a right, but not an obligation, to expand the plant's operational capacity and profit from potentially favourable market conditions. The expansion factor estimates the proportion of the expected increase in net revenues.

Since both the refurbishment costs and future revenues are uncertain, we have to employ the V/I ratio again to evaluate the option value. The *option to expand* is calculated by constructing the binomial tree with the following payoff structure:

$$V_{Exp.O.} = Max((V/I)_T; (V/I)_T * Exp.factor - Exp.costs) \quad (11)$$

where $(V/I)_T$ represents the simulated reactor value at the final nodes of the decision tree. Equation (9) is then applied to estimate the values of all the interval nodes.

The values estimated in this tree are therefore considered to be the underlying variables for the second option, since they represent the future values of the reactors and include the option of further expansion. All other valuation steps are consistent with those described in *Chapter 4.2.1.2.*

4.2.2 – Trigger Values

The second valuation approach, as outlined by Rothwell in his assorted articles, implies calculating specific "trigger values" that define the specific point at which an investor is indifferent between investing in the project or not.

As described above, the net present value of a power plant depends on a host of variables, including the electricity price, the capacity factor, operating costs, and the initial investment. Since a number of these variables are uncertain, it is possible to modify their values in order to define the threshold leading to positive investment decisions.

Based on equation (4), the net present value of a project is the discounted yearly revenues (R) minus the initial investment. This implies that the focal decision making rule is for expected revenues to be greater than the adjusted value of the investment.

$$NPV = \frac{R}{\delta} - I > 0 \Rightarrow R > \delta \cdot I \quad (12)$$

The trigger value (R^*) represents the situation where the NPV is exactly equal to 0 and the investor is completely indifferent whether to invest in the project or not.

$$R^* = \delta \cdot I \quad (13)$$

Therefore, when future revenues are over and above this threshold value, the project is deemed profitable and warrants investment:

$$R > R^* \quad (14)$$

According to the approach created by Dixit (1992), since the investment decisions are more flexible than a simple "now or never" opportunity, the value of postponing the investment (that is Ω) can be found as such:

$$\Omega = B \cdot R^\gamma \quad (15)$$

where B is a parameter characterizing the investor's indifference between investing and waiting, as depicted in the formulas:

$$\frac{R^*}{\delta} - I = B \cdot R^{*\gamma} \Rightarrow \quad (16)$$

$$B = \left(\frac{R^*}{\delta} - I \right) / R^{*\gamma} \quad (17)$$

Since one of the model's assumptions states that the commodity prices follow Geometric Brownian motion, the solution to this quadratic equation gives the following value of γ:

$$\gamma = \frac{1}{2} \left\{ 1 + \left[1 + \frac{8\delta}{\sigma^2} \right]^{1/2} \right\} \quad (18)$$

where σ is the volatility of the net revenues. For a detailed derivation of the above formula, please refer to *Appendix B*.

Taking the first derivative of both sides of equation (16) gives:

$$\frac{1}{\delta} = \gamma \cdot B \cdot R^{*\gamma-1} \quad (19)$$

Therefore, the trigger value of future revenues can be expressed by means of the volatility parameter, the value of the initial investment, and the capital recovery factor in the following manner:

$$R^* = \frac{\gamma}{\gamma - 1} \cdot \delta \cdot I \quad (20)$$

The trigger value for the initial investment (I^*) is consequently equal to:

$$I^* = \frac{(\gamma - 1) \cdot R^*}{\gamma \cdot \delta} \quad (21)$$

Finally, by incorporating the plant size (W) and the investment trigger value (I^*), the construction cost trigger value (K^*) can be found:

$$K^* = \frac{I^*}{W} = \frac{(\gamma - 1)}{\gamma \cdot \delta} \frac{R^*}{W} \quad (22)$$

It follows that the investment should be undertaken today if the actual construction costs (on a $/kW basis) are less than the trigger value K^*. The sensitivities of the trigger values and risk premium are discussed in greater detail in (Rothwell, 2005) and are summarized in *Appendix C*.

This chapter has presented the mathematical fundamentals of the methodologies utilized in our thesis. All formulas aside, the main concept to grasp from this chapter is that while the two methods are quite diverse, they both have the same aim. In the end, the methodologies should be recognized as complementary rather than interchangeable, and the fusion of the model's individual results will ultimately prove to be advantageous from the decision maker's point of view.

Chapter 5 – Statistical Assumptions, Data & Methodology

In this section, we will describe all the data, statistical assumptions and methodologies involved in our computations. Specifying authentic values was a focal point for us in view of the fact that we had aspirations of applying the real options methodology to real-life problems. All pertinent facts and figures for the Enhanced CANDU 6, ACR-1000 and Pickering B refurbished plants are shown and discussed in the following sections. We stress that all values were either publicly available or based on consultations with the Ontario Power Authority.

We begin this chapter by discussing the Monte Carlo simulation method, which we were able to emulate thanks to the *Crystal Ball* software package.

5.1 – The Monte Carlo Simulation Method

One of the main aspects of our approach was the supposition that the uncertainties inherent in energy investments are not static. Rather, we chose to handle these uncertainties as random variables by assigning appropriate probability distributions. In doing so, we were able to apply a degree of realism that would not be possible if we had instead used static, fixed values.

In view of the fact that Microsoft Excel does not have a simulation function, we would only be able to create single-point, deterministic spreadsheet models in Excel. Alongside single-point estimates, other conventional approaches used to handle uncertainty include scenario analysis and "what-if" analysis. However, all three of these methods have more cons than pros. Most notably, these approaches do not take variation into account and reveal only given ranges of outcomes, not probabilities.

The Monte Carlo simulation method, on the other hand, expresses both probabilities and ranges of outcomes. Thus, when uncertainty abounds, it is suggested to use Monte Carlo simulation in order to assess the appropriate probabilities of future cash flows (Mun, 2006). While it is technically possible to get the same results using an infinite number of "what-if" series, the same (if not better) results can be obtained using Monte Carlo simulation in a fraction of the time.

To compensate for the lack of an outright simulation function in Excel, we utilized the *Crystal Ball* software package in order to create stochastic Monte Carlo simulation models and to assign suitable probability distributions to the uncertainties in our models. Instead of using deterministic spreadsheet models or an infinite number of "what-if" cases, *Crystal Ball* allowed us to rapidly create thousands of alternative scenarios for analysis. As such, we were able to gain some extremely valuable insights into our results that would not have been possible otherwise.

5.2 – Specification of the Data

As previously mentioned, we could have used artificial or estimated values in order to examine and demonstrate how the real options approach can be used in energy investments, especially from the perspective of the Province of Ontario. In many academic papers, the author is required to hypothesize and make assumptions on part, if not most, of the numbers employed in the study and subsequent analysis. This is due to a variety of reasons but the issue of confidentiality is typically the main constraint, as it was in our case. Simply put, a lot of the information required in such large capital investments is considered privileged, for obvious reasons.

At the same time, given that we are examining real-life problems in our thesis, we made a great effort to obtain actual data and figures for our models. This was possible due to the various publications released by organizations such as the Atomic Energy of Canada Limited (AECL), the Canadian Energy Research Institute (CERI), the Independent Electricity System Operator (IESO), the Ontario Power Authority (OPA), and Ontario Power Generation (OPG), among others. However, we are particularly indebted to the Ontario Power Authority for their additional support and advice.

As described in *Chapter 3.2.1*, the main uncertainties driving the ultimate decision in our problems included the commodity price, plant performance, production costs and construction costs. We also had to take the plant size, construction time and expected service life into account. In evaluating the Enhanced CANDU 6 and ACR-1000 nuclear plants, we therefore made sure to account for each plant's distinct characteristics when comparing them side by side. With respect to the refurbishment study, we also considered the characteristics of the Pickering B reactors. All data and the discount rate are considered to be in nominal terms.

5.2.1 – Enhanced CANDU 6 and ACR-1000

In evaluating the Enhanced CANDU 6 and ACR-1000 reactors, the methodology we followed was the same for both alternatives. However, as mentioned above, each reactor type has different characteristics so we accounted for this when making our calculations.

5.2.1.1 – Electricity Commodity Prices

To begin with, it is important to make a distinction between the commodity prices received by generators and prices paid by customers (retail prices). The retail price charged to final customers is comprised of commodity charges, delivery, regulatory, wholesale market services, conservation and debt retirement (OPA, 2006). However, we only take the commodity price paid to generators into consideration since our analysis evaluates the profitability of the power plant itself. It is essential to understand that the power plants in our investigation will be paid a pre-determined price based on a contractual agreement with the OPA. The Ontario Power Authority is willing to enter such long-term price agreements in order to secure a reliable future supply. This price will be different from the retail price, wholesale price and even the spot prices usually paid to generators; this last price is set by the market and controlled by the IESO and is known as the Hourly Ontario Energy Price, or HOEP. In addition, these plants will not be subject to any adjustments when the price is different from the HOEP, which is the case for a large portion of OPG's generation. Rather, the plant will sell their output to the IESO at a pre-determined price according to the contract signed with the OPA.

In their latest *Integrated Power System Plan* Discussion Paper, "Integrating the Elements – A Preliminary Plan," the Ontario Power Authority presented the assumed electricity commodity costs that would be paid out as part of the contractual agreements just mentioned. For new nuclear plants, the OPA allocated a lower bound of $65/MWh and an upper bound of $80/MWh. Similarly, refurbished nuclear plants had a range of $63/MWh to $80/MWh. We utilized these approximate price ranges in our calculations.

In terms of forecasting electricity prices, two stochastic price models are typically mentioned as being appropriate in the associated literature: mean-reversion and Geometric Brownian motion. Several

authors have applied a mean-reverting jump diffusion model to electricity spot prices. This approach, however, has been shown to be more appropriate in forecasting short-term prices because shorter time periods tend to have a more compact range of prices. Further, since Ontario's market has only been deregulated since May 2002 and the prices are still adjusting to some extent, it is a tough task to discern any specific patterns or mean in the Ontario electricity commodity price. As suggested by Ronn (2002), Rothwell (2004), Graber (2005) and several other authors, forward electricity prices have been shown to follow Geometric Brownian motion (GBM) with a drift. GBM is a popular stochastic process where the logarithm of the random value follows a Brownian motion, and is useful for processes that can never take on negative values, such as electricity commodity prices. Using the *Crystal Ball Real Options Analysis Toolkit*, we were able to apply the GBM process to forecast Ontario electricity prices for both new and refurbished nuclear plants. For new nuclear plants, we used $70/MWh as the standard starting value, 0.0009 for the drift and a standard deviation of 4.5%. The results can be seen in *Figure 5.1* below and in more detail in *Appendix D*. In our calculations, we utilized the prices represented by the *Average* data series. For this forecast, the average price over time was $72.02/MWh and the standard deviation was $3.74/MWh. Based on the stipulated contract for new nuclear plants, the results seen in *Figure 5.1* were deemed appropriate.

Figure 5.1: Electricity Commodity Prices, 2013-2042 – New Nuclear Plants
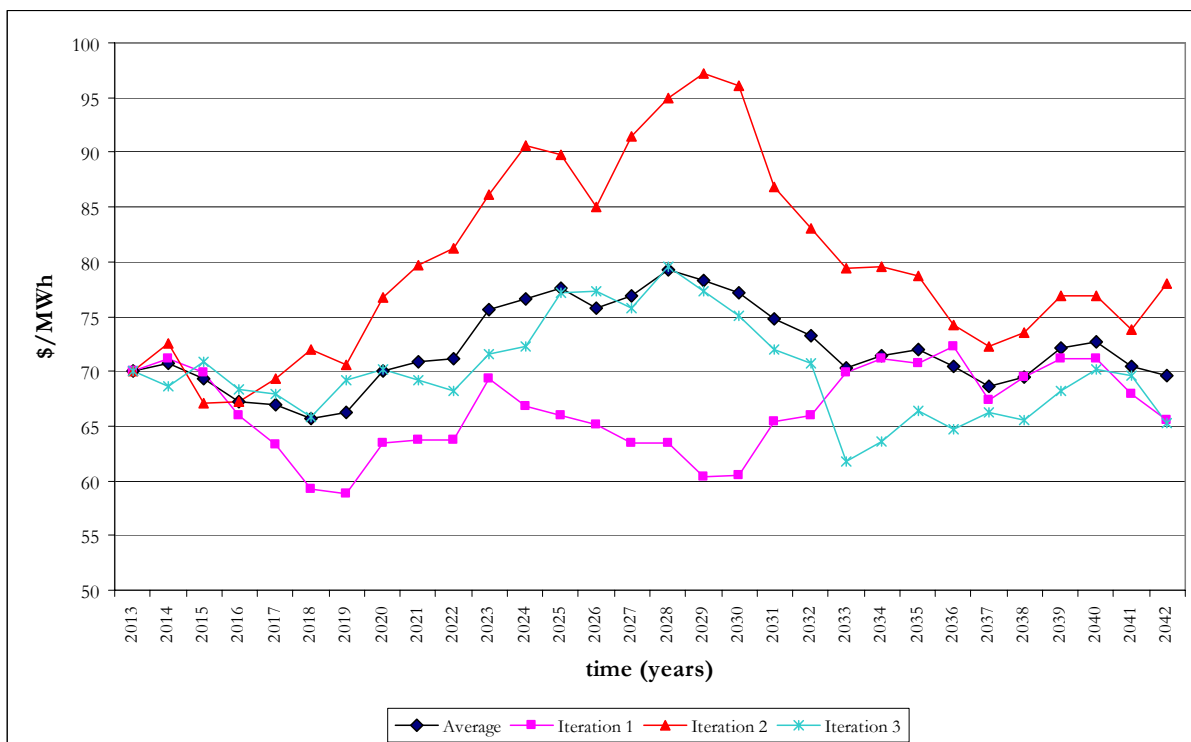
5.2.1.2 – Plant Size and Maximum Capacity

For the Enhanced CANDU 6 alternative, we considered a dual-unit plant. According to the AECL, due to technical advancements new units can have a target output of 750 MW gross per unit. Therefore, a dual-unit plant (1500 MW) would be able to have a maximum dependable capacity of 13,140,000 MWh, equal to 1500 MW times the number of hours in a year (8760).

The ACR-1000 has a gross output of 1200 MW per unit and accordingly, we assumed a single-unit would be built. This was because from an output perspective, it would be more sensible to compare a single-unit ACR-1000 (1200 MW) with the dual-unit Enhanced CANDU 6 (1500 MW), and also because a dual-unit ACR-1000 (2400 MW) goes above and beyond the new nuclear requirements projected by the OPA. In terms of maximum dependable capacity, the single-unit ACR-1000 would have a figure of 10,512,000 MWh.

5.2.1.3 – Capacity Factor

The AECL estimated that the average lifetime capacity factor for CANDU 6 reactors was 88% and that in 2003, the top three CANDU 6 units achieved an average capacity factor of 97%. Based on consultations with the OPA and OPG, we applied a triangular distribution to the CANDU 6 capacity factor with a minimum of 82%, a maximum of 97% and a likeliest value of 88%.

Figure 5.2 - Enhanced CANDU 6 - Capacity Factor Distribution
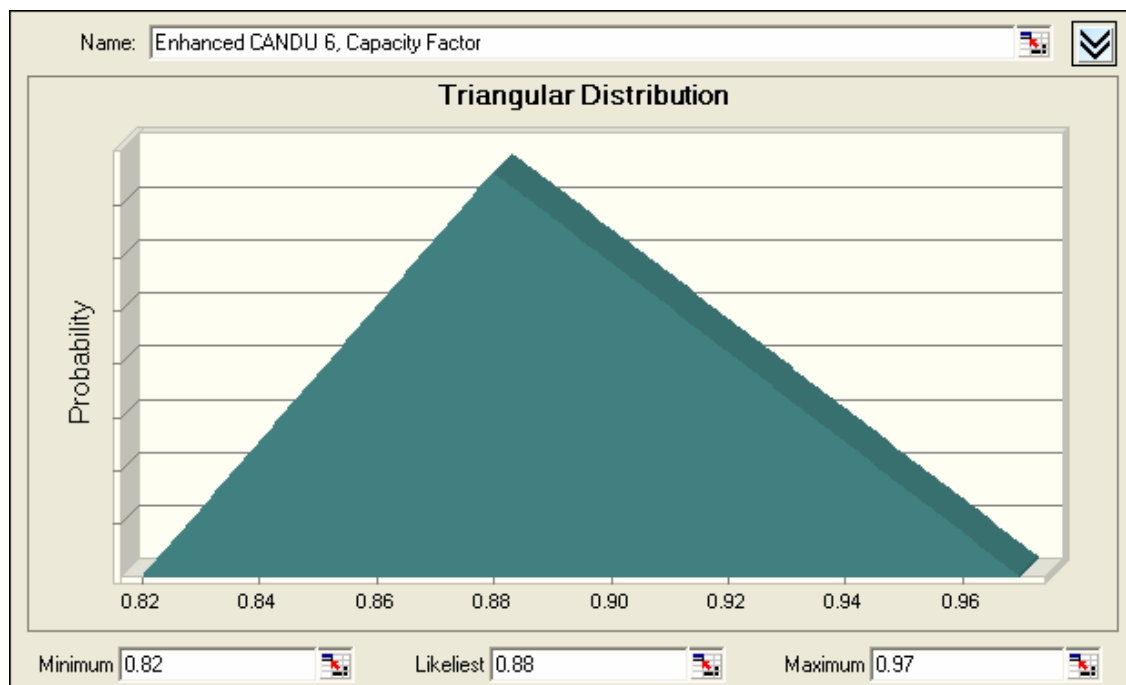
As mentioned before, the ACR-1000 technology combines the experience of CANDU 6 with new and improved CANDU concepts and enhanced safety, economics and operability (AECL, 2005). The AECL has projected a lifetime capacity factor of 90% for this reactor type. Based on this, we applied a triangular distribution to the ACR-1000 capacity factor with a minimum of 82%, a maximum of 97% and a likeliest value of 90%.

Figure 5.3 - ACR-1000 - Capacity Factor Distribution
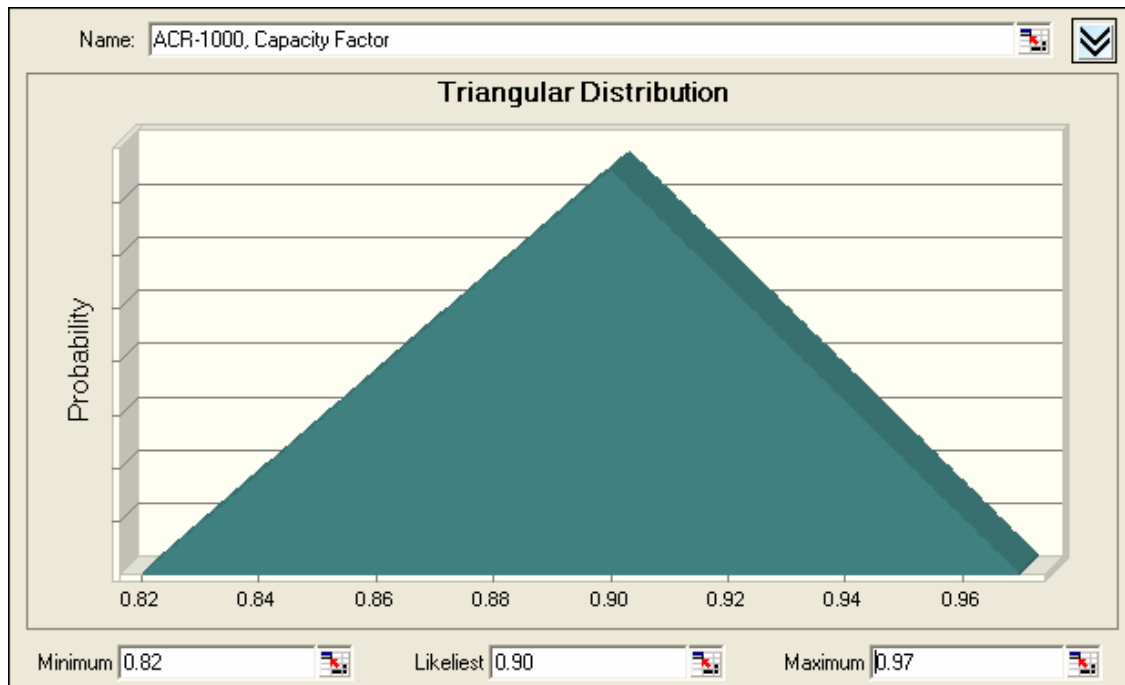
5.2.1.4 – Nuclear Production Unit Energy Costs

As previously stated in *Chapter 4.1*, we combined the fuel costs, variable OM&A (Operations, Maintenance and Administration) costs, and fixed OM&A costs to estimate our own Nuclear Production Unit Energy Cost (PUEC). The PUEC is a measure of the cost of producing a unit of electricity and is used to assess the cost efficiency of nuclear generation assets (OPG, 2006). According to the OPA, new nuclear power plants are expected to have the following approximate costs: fuel cost of \$2.70/MWh, variable OM&A expenses of \$3.10/MWh and fixed OM&A expenses of \$115/kw$_{year}$. By converting the fixed OM&A costs to \$/MWh units, we obtained fixed OM&A costs of approximately \$13.13/MWh. Combining these 3 costs together, we calculated a Nuclear PUEC of \$18.93/MWh.

However, historical PUEC costs have been more than twice as high as this value. According to OPG's 2005 Annual Report, PUEC values were $39.20/MWh and $39.70/MWh in 2004 and 2005, respectively. As such, for the base case, we made an assumption that actual PUEC costs would initially be 20% higher than initially calculated ($22.72/MWh). Furthermore, we also made a logical assumption that PUEC costs will grow with time. This can be due to a variety of factors, such as inflation, higher labour costs, and other unexpected risks. Therefore, in our simulations, Nuclear PUEC costs rose by 3% per year. The same costs and assumptions were applied to the ACR-1000 reactors. Please refer to *Appendix D* for detailed PUEC values.

5.2.1.5 – Weighted Average Cost of Capital

The weighted average cost of capital (WACC) is the rate at which firms evaluate capital projects or investments. It is based on the expected returns of a company's securities and the company's capital structure. The Ontario Power Authority has typically utilized three separate discount rates in their reports – 5%, 8.5% and 11%. Instead of choosing one of the outer values, we chose to utilize 8.5% as the WACC in our calculations. A WACC of 8.5% is based on an inflation rate of 2%, a tax rate of 36.1%, nominal debt cost of 7%, nominal equity cost of 12%, and a debt-to-equity ratio of 70/30 (OPA, 2006).

5.2.1.6 – Construction Costs

Construction costs for both the Enhanced CANDU 6 and ACR-1000 were obtained from reports by the AECL and CERI. The Enhanced CANDU 6 has construction costs of $2120/kW. Assuming a dual-unit plant (1500 MW), total construction costs would be equal to $3.18 billion.

The ACR-1000 has significantly smaller construction costs in comparison to the Enhanced CANDU 6 reactor. With construction costs of $1920/kW, this indicates a 10.4% relative difference, which is quite significant. Total construction costs for the ACR-1000 amount to just above $2.3 billion.

5.2.1.7 – Construction Time and Expected Service Life

According to the AECL, the Enhanced CANDU 6 construction schedule lasts 54 months from first concrete to in-service. The ACR-1000, in addition to its lower construction costs, also has a shorter expected construction time at 48 months from first concrete to in-service. This difference is important to consider from the perspective that the ACR-1000 has a prospect of selling electricity

and making money 6 months quicker than the Enhanced CANDU 6. This dissimilarity is taken into account in the cash flow calculations.

The expected service life for both plant types is up to 60 years. However, as suggested by the AECL, based on replacement of fuel channels and refurbishment of the plant after 30 years of operation, we extend the cash flow analysis out for 30 years. This is an imperative distinction to make since it is likely the given plant would be either temporarily laid down for a refurbishment feasibility assessment or would in fact be refurbished at that time.

Chapters 5.2.1.1 to 5.2.1.7 have been summarized in *2*below.

Table 5.1 - Power Plant Characteristics - Enhanced CANDU 6 and ACR-1000

Characteristic	Enhanced CANDU 6	ACR-1000
Electricity Commodity price	Forecasted using GBM and a range of $65-80/MWh	
Plant size	1500 MW (dual-unit plant)	1200 MW (single-unit plant)
Maximum capacity	13,140,000 MWh	10,512,000 MWh
Capacity factor	mean=88%, min=82%, max=97%	mean=90%, min=82%, max=97%
Nuclear PUEC	$22.72/MWh, increasing by 3% per year	
WACC	8.5%	
Construction costs	$2120/kW	$1920/kW
Construction time	54 months	48 months
Expected service life	30 years	

5.2.1.8 – The Phase Costs and Discounting of the Initial Investment

We will now review the investment timeline by considering the lengths and costs of the sequential phases and associated options.

Figure 5.4 - New Nuclear Plant – Phases & Investment Schedule
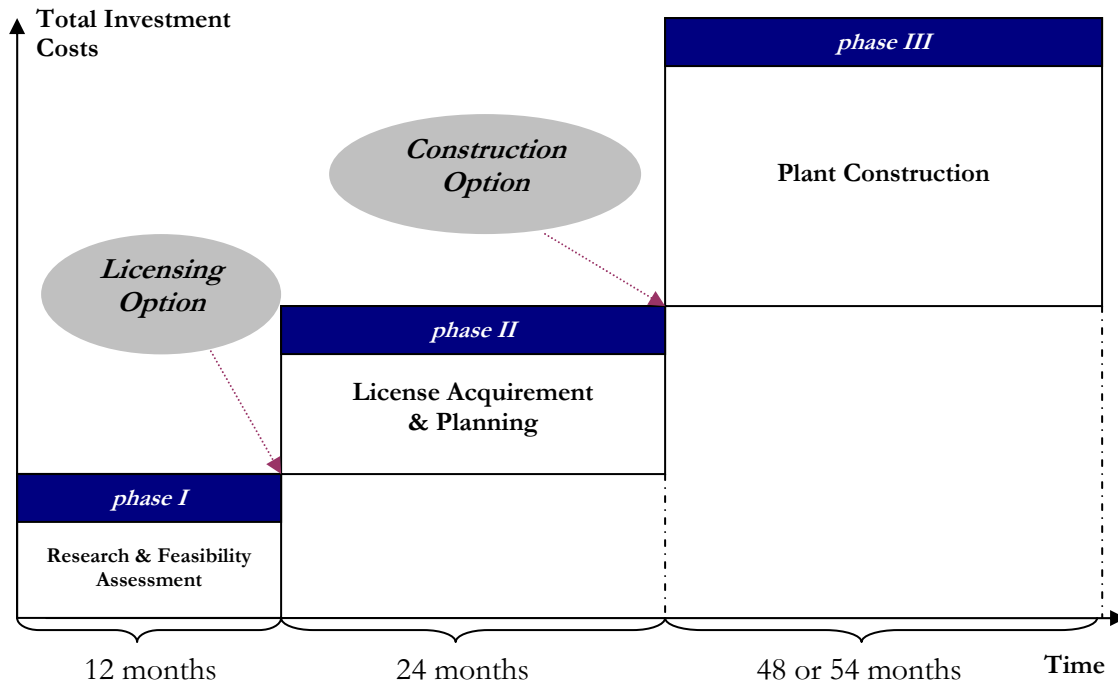
Figure 5.4 describes the phases and associated costs for both of the Enhanced CANDU 6 and ACR-1000 power plants while *Table 5.2 and 5.3* present the individual phases and costs for these two technologies. In the above figure, the horizontal axis represent the time in months that each phase lasts. The vertical axis corresponds to total investment costs and as we can see, the total costs grow from phase to phase. In this instance, we see that the initial phase I cost of $50 million has been made already. This is a valid assumption since research is in fact currently being carried out on potential new nuclear technologies in Ontario. Phase II, the license procurement and planning stage, lasts two years for both technologies. More importantly, the licensing option is to be made in one year's time from the present time, or the same amount of time left in phase I (keeping in mind phase I is already underway). Finally, we consider Phase III. As discussed before, the construction phase, if entered, costs $3.18 billion ($2.5 billion PV) for the Enhanced CANDU 6 and $2.3 billion ($1.8 billion PV) for the ACR-1000 and last 48 or 54 months, respectively, from first concrete to in-service. The construction option is to be made in three year's time. Considering that the costs for phase II and III will be made sometime in the future, the appropriate discount factor has to be applied in order to calculate a present value total investment cost. We can see that this value is equal to approximately $2.73 billion in the case of the Enhanced CANDU 6 project.

Based on *Figure 5.4*, it is important to mention that we assume that the payments are made in lump sums rather than being spread out over a given time period. This may or may not be the case in real life, but it is an assumption that has to be made on our part in order to simplify the calculations and analysis.

Table 5.2 - Enhanced CANDU 6 - Phases and Costs

	Cost ($M)	Length (years)	Disct. Factor Calculation	Discount Factor	PV of Costs ($M)
Phase I	50	1	-	1	50
Phase II	210	2	$1/(1+WACC)^1$	0.92165	193.55
Phase III	3180	4.5	$1/(1+WACC)^3$	0.78291	2489.65
	3440	**7**			**2733.20**

In order to apply a degree of uncertainty regarding the CANDU 6 investment costs, we utilized a maximum extreme distribution in order to capture this effect. This can be seen in *Figure 5.5* below, where we can observe the mean investment value to be $2.82 billion. We made a simplifying assumption that a given investment could only vary upwards, indicating the notion that investment costs would not be lower than expected. Under this distribution, the investment will cost no less than the $2.73 billion figure calculated above in *Table 5.2*. However, since the investment is somewhat uncertain, it could potentially cost up to 14% more ($3.2 billion) if, for example, there were any cost overruns.

Figure 5.5 - Enhanced CANDU 6 - Investment Probability Distribution
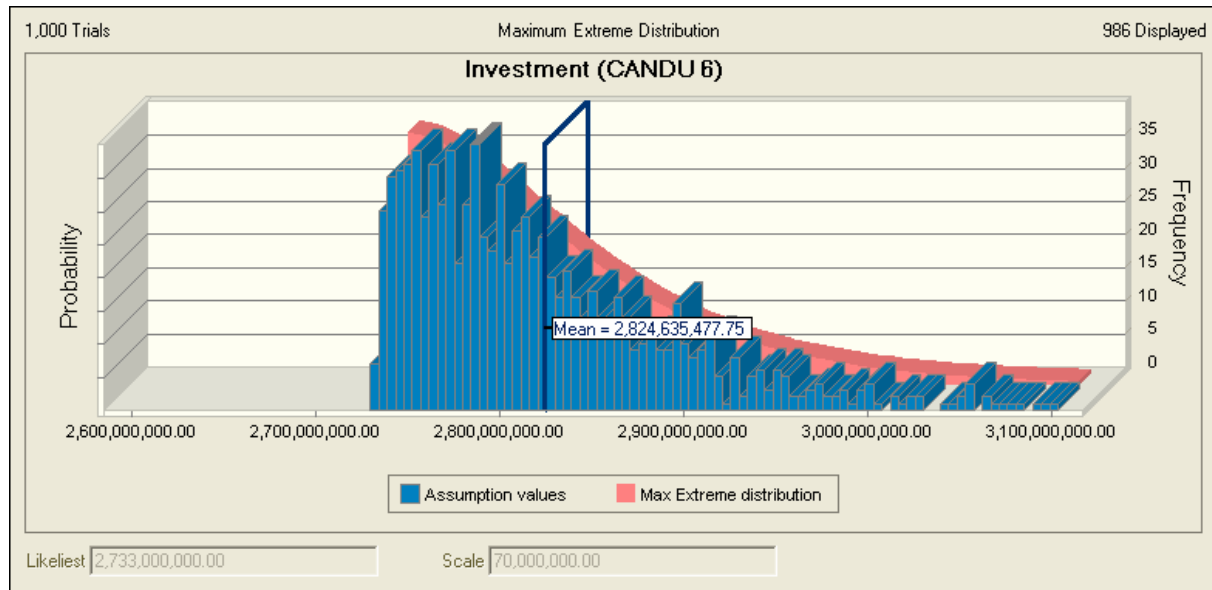
Table 5.3 below illustrates the investment timeline for the ACR-1000 power plant. The main difference to notice is that the length of phase III is shorter by 6 months in comparison to the Enhanced CANDU 6 power plant. The cost of phase III is lower on both a total and $/kW basis, due to the ACR-1000's superior construction costs. Additionally, we assumed that the procurement of licenses would be slightly higher for the ACR-1000 at $260 million. We propose this based on the fact that the ACR-1000 is a newer and untested technology and procuring a license for this plant type could potentially be a bit more costly than for the proven CANDU 6 technology. Applying the proper discount rate to the expenditures gives a present value total investment cost of about $2.1 billion.

Table 5.3 - ACR-1000 - Phases and Costs

	Cost ($M)	Length (years)	Disct. Factor Calculation	Discount Factor	PV of Costs ($M)
Phase I	50	1	-	1	50
Phase II	260	2	$1/(1+WACC)^1$	0.92165	239.63
Phase III	2304	4	$1/(1+WACC)^3$	0.78291	1803.82
	2614	**6.5**			**2093.45**

As with the Enhanced CANDU 6 power plant, we applied a degree of uncertainty to the investment cost for the ACR-1000. *Figure 5.6* below illustrates that in our simulations, the ACR-1000 had a mean investment value of approximately $2.2 billion, with a potential maximum value of $2.5 billion.

Figure 5.6 - ACR-1000 - Investment Probability Distribution
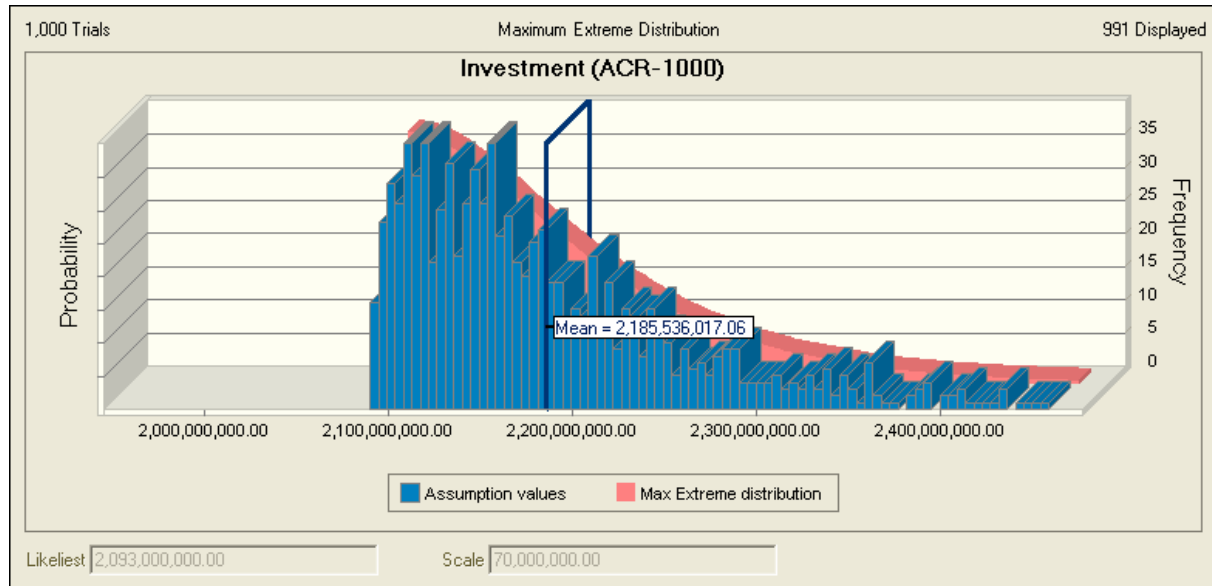
5.2.2 – Pickering B Refurbishment

This section will follow the same structure as the previous section. However, since many factors will carry over from the new nuclear analysis, we will condense the following discussion appropriately.

5.2.2.1 – Electricity Prices

As described previously, we employed the Geometric Brownian motion stochastic process to simulate price forecasts for each facility type. The OPA estimated the refurbished nuclear commodity price to range from $63/MWh to $80/MWh.

In similar fashion, we employed GBM to forecast commodity prices for the refurbishment case, as seen in *Figure 5.6* below. We employed a standard starting value of $68/MWh, 0.001 for the drift and a standard deviation of 4.5%. The average price over the forecast period was $72.70/MWh, with a standard deviation of $5.06/MWh. Again, we used the *Average* data series seen below in our model calculations; the full results for the GBM forecasting process can be seen in *Appendix D*.

Figure 5.7 - Electricity Commodity Prices, 2013-2042 - Pickering B Refurbishment
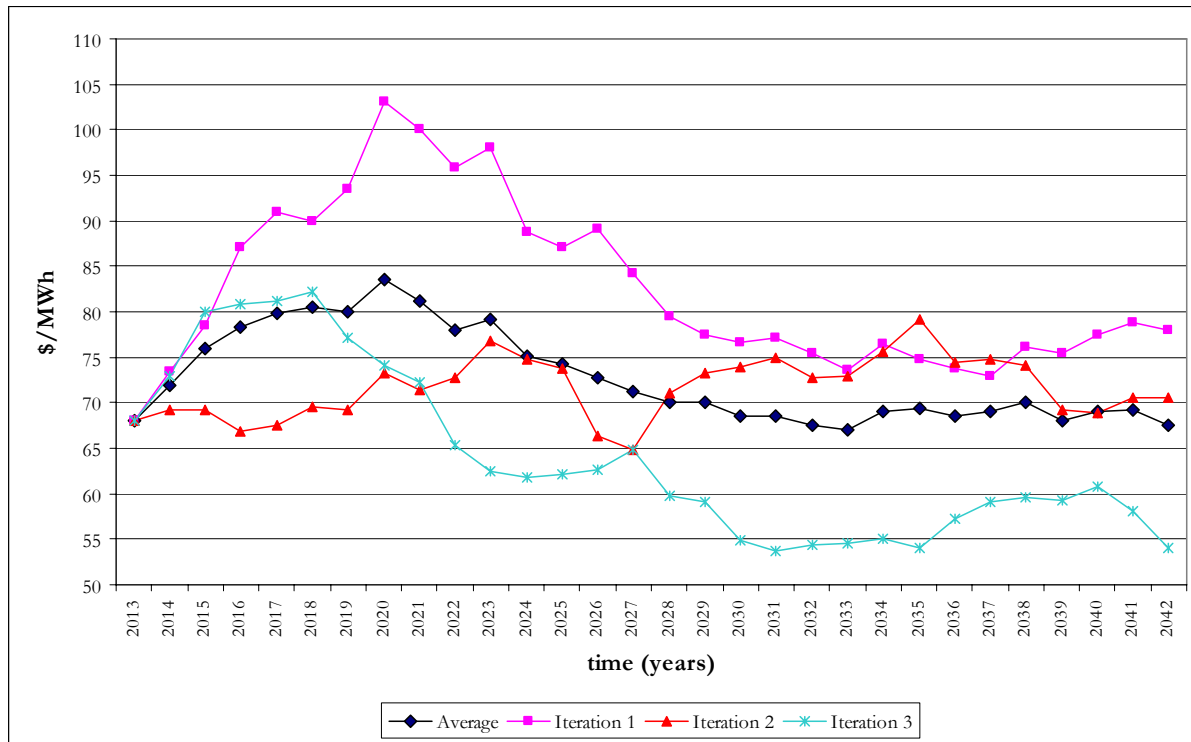
5.2.2.2 – Plant Size and Maximum Capacity

Pickering B has an installed capacity of 2064 MW (4 units x 516 MW). According to OPG, the Pickering B Refurbishment Study is already underway and its main purpose is to evaluate the economic feasibility of refurbishing the 4 units. In our approach, we evaluated the potential to initially refurbish the first two units, and so our plant size is equal to 1032 MW. This equates to a maximum dependable capacity of 9,040,320 MWh.

5.2.2.3 – Capacity Factor

According to the AECL, the Pickering 7 and Pickering 8 units achieved capacity factors of 97.8% and 93.6% in 2005, respectively. This shows that the Pickering B units have the potential for very high capacity factors. Based on these figures and consultations with OPA and OPG, we assumed a minimum CF of 82%, a maximum of 96% and a likeliest value of 88%.

Figure 5.8 - Pickering B - Capacity Factor Distribution
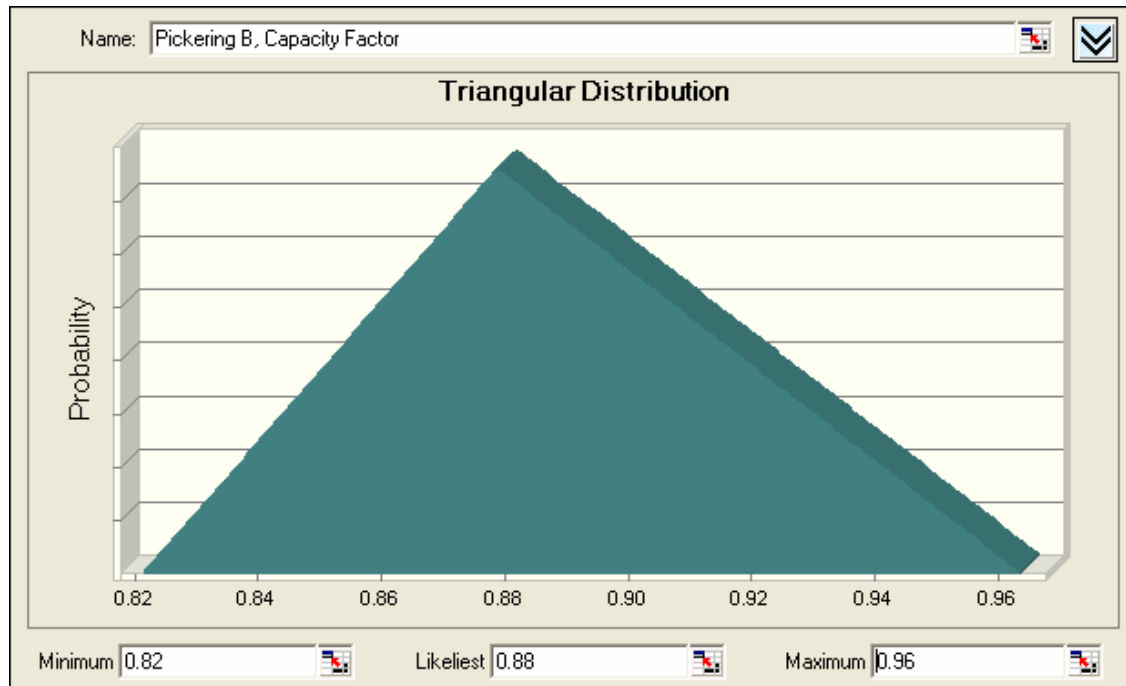
5.2.2.4 – Nuclear Production Unit Energy Costs

The Nuclear Production Unit Energy Costs in the refurbishment analysis were the same as in the new nuclear analysis – namely, the PUEC had a starting value of $22.72/MWh and grew by 3% per year due to various risks.

5.2.2.5 – Weighted Average Cost of Capital

As in the Enhanced CANDU 6 and ACR-1000 analyses, we employed a WACC of 8.5% to the refurbishment study.

5.2.2.6 – Construction Costs

Based on advice from the OPA and Navigant Consulting's December 2005 report, we found that total estimated costs for nuclear refurbishment amounted to $1.35 to $1.5 billion per unit. In our study, we assumed a total cost of $2.7 billion, which amounts to roughly $2,616/kW.

5.2.2.7 – Construction Time and Expected Service Life

The OPA indicated that expected construction time was 2 to 3 years per unit. Since we assumed two units would be refurbished initially, we assumed a combined construction time of 4 years before the units would be able to return to service. In terms of expected service life, the Ontario Power Authority suggested an additional 30 years would be a good estimate, and this is the figure we employed in our evaluation. *Table 5.4* below summarizes *sections 5.2.1.1* to *5.2.1.7*.

Table 5.4 - Power Plant Characteristics - Pickering B

Characteristic	Pickering B
Electricity Commodity price	Forecasted using GBM and a range of $63-80/MWh
Plant size	1032 MW (Units 5 and 6)
Maximum capacity	9,040,320 MWh
Capacity factor	mean=88%, min=82%, max=96%
Nuclear PUEC	$22.72/MWh, increasing by 3% per year
WACC	8.5%
Construction costs	$2616/kW
Construction time	60 months
Expected service life	30 years

5.2.2.8 – The Phase Costs and Discounting of the Initial Investment

Figure 5.9 and *Table 5.5* describe the phases and associated costs for the refurbishment of Pickering B. The total construction cost of $2.7 billion includes the feasibility study ($50 million), the planning stage ($200 million), and the outage execution and return to service ($2.45 billion).

Figure 5.9 - Nuclear Refurbishment – Phases & Investment Schedule
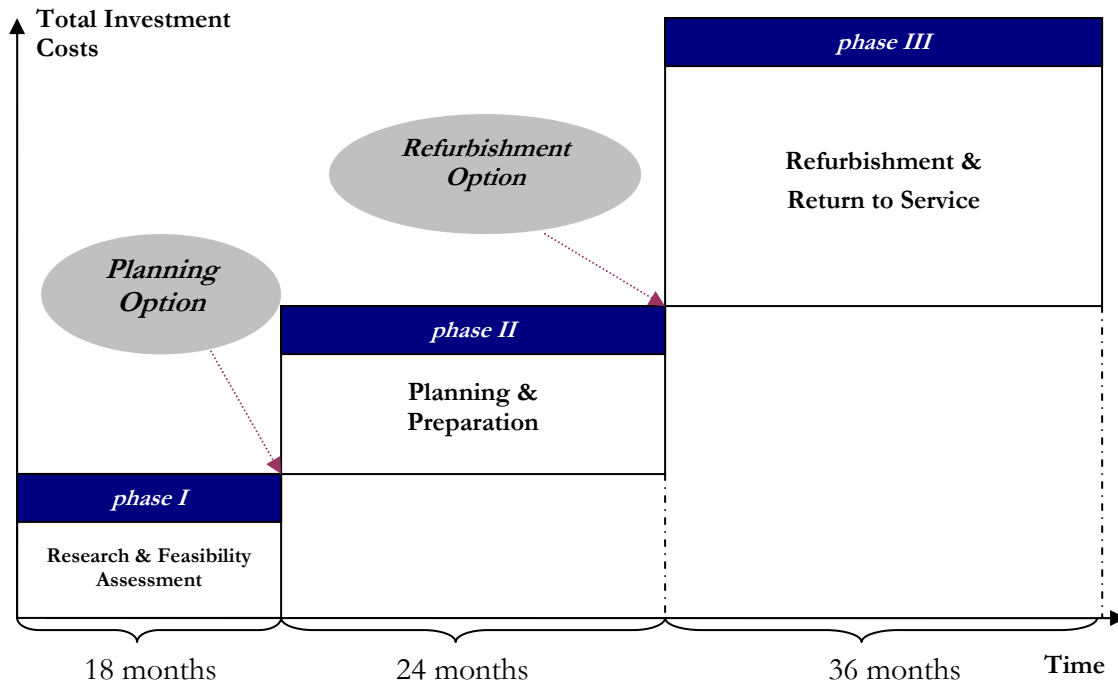
As in the previous case, we assume that phase I has already been entered and the $50 million cost is therefore regarded as a sunk cost. Again, this is a valid presumption since the OPG-led Pickering B refurbishment study is in its feasibility assessment stage. The decision to enter the planning and preparation stage (phase II) is to be made in one and a half years. The planning stage costs $200 million and last two years, at which point the option to refurbish will be encountered. Phase III covers site preparation, refurbishment and return to service; this phase costs $2.45 billion and lasts for four years. All told, it will be seven and a half years before the refurbished plants would be able to generate power again. Applying the WACC of 8.5%, the present value total investment cost is $2.07 billion.

Table 5.5 - Pickering B - Phases and Costs

	Cost ($M)	Length (years)	Disct. Factor Calculation	Discount Factor	PV of Costs ($M)
Phase I	50	1.5	-	1	50
Phase II	200	2	$1/(1+WACC)^{1.5}$	0.88482	176.96
Phase III	2450	4	$1/(1+WACC)^{3.5}$	0.75161	1841.46
	2700	**7.5**			**2068.42**

Figure 5.10 displays the maximum extreme distribution applied to the Pickering B investment costs. The mean investment was about $2.15 billion, with a potential maximum level of $2.5 billion (indicating 20% cost overruns). In future studies, it would have been interesting to apply a higher variance from the mean in an upward direction given the historical problems encountered with the refurbishment of the Pickering A reactors.

Figure 5.10 - Pickering B - Investment Probability Distribution
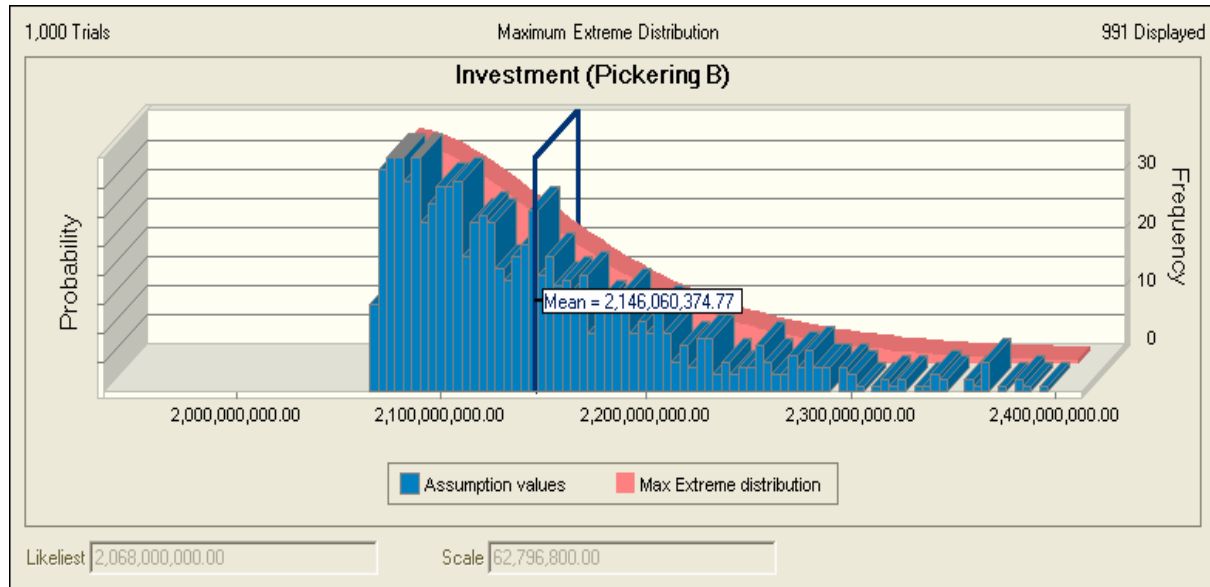
5.3 – Calculation Methods

Having discussed the specification of the data and figures utilized in our models, this section presents and illustrates the calculation methods that have been implied while valuing investments.

5.3.1 – Calculation of Free Cash Flows, Present Values, Net Present Values

In this section, we will quickly illustrate how we calculated the plant's future cash flows, present value and net present value by using the *Crystal Ball* software. For illustrative purposes, *Table 5.6* below shows a portion of the calculation process for the ACR-1000 reactor, with column *C* representing the first year of production (2013) and column *AF* representing the last year of production (2042). Detailed calculations can be seen in *Appendix D*.

Table 5.6 - Sample Crystal Ball calculations (ACR-1000)

	A	B	C		AF
1	year		2013	→	2042
2	time to construction	0	7	→	36
3					
4	MW plant		1200		1200
5	MWh per year (max. dep. capacity)		10512000		10512000
6					
7	GBM Price Forecast ($/MWh)		70		69.60
8	Commodity price ($/MWh)		Norm distr.		Norm distr.
9	Capacity Factor (%)		Tri distr.		Tri distr.
10	Revenue ($)		C5*C8*C9	→	AF5*AF8*AF9
11					
12	Fuel cost ($/MWh)		2.7		2.7
13	Variable OM&A ($/MWh)		3.1		3.1
14	Fixed OM&A (115$/kwyr)		13.13		13.13
15	Nuclear PUEC ($/MWh)		22.53		53.53
16	Total Nuclear PUEC ($)		236800670.4	→	562725672.3
17					
18	FCF		C10–C16	→	AF10–AF16
19					
20	WACC		0.085		0.085
21	Discount factor		0.5649		0.0530
22	PV of FCF		C18*C21	→	AF18*AF21
23					
24					
25	PV of project (ACR-1000)	sum(C22:AF22)			
26	Investment (ACR-1000)	Max extr distr.			
27	Project NPV (ACR-1000)	B25-B26			
28	V/I (ACR-1000)	B25/B26			

In the above table, Cells *C8* and *AF8* have normal distributions and are strongly based on the commodity prices forecasted using Geometric Brownian motion. The GBM price forecast is used as the mean value and a standard deviation of 0.50 is applied in order to allocate a given amount of uncertainty to the forecast price itself. The capacity factor figures in cells *C9* and *AF9* are based on a triangular distribution of with a minimum of 82%, a maximum of 97% and a likeliest value of 90%. The revenues (cells *C10* to *AF10*) received by the plant are a combination of the maximum dependable capacity and capacity factor (which combine to show how much the plant has been used over the year) and the commodity price received for the output. Total Nuclear PUEC costs in cells *C16* and *AF16* are equal to Nuclear PUEC ($/MWh) multiplied by the maximum dependable capacity (10,512,000 MWh). Free Cash Flows (FCF) are calculated on a yearly basis and are based on the customary revenues minus costs calculation. *Cells C22* to *AF22* discount the FCFs by the

appropriate discount factor, based on a WACC of 8.5%. The discount factor is calculated using the

formula $\dfrac{1}{(1+WACC)^t}$, where t corresponds to the year.

Cells B25 to *B28* show us the most interesting information in our analysis. The project present value (*B25*) is simply a sum of the discounted present value FCFs. The investment (*B26*) has a maximum extreme distribution and is based on the discussions in *Chapter 5.2.1.8* and *5.2.2.8*. The Net Present Value of the project (*B27*) is equal to the project value minus the investment, in PV terms. Finally, we calculate the V/I ratio in cell *B28*; as discussed in *Chapter 4.2.1.1*, this ratio is essential in our decision tree analysis approach.

5.3.2 – Calculation of Options Values

In order to estimate the options, binomial trees were chosen as a valuation tool. The calculation of the option values implies one tree evaluating the underlying variable and another valuation tree calculating how much the option is worth.

The exercise prices of the first and the second options for both new nuclear and refurbishment alternatives are calculated as the ratios of the costs incurred at the corresponding phase to the total investment. The exercise price for the first option incorporates the costs of the second phase, while the exercise price for the second option is based on the costs of the third stage.

The ratios for Enhanced CANDU 6, ACR-1000 and Pickering B are presented in *Table 5.7, 5.8 and 5.9* correspondingly.

Table 5.7: Enhanced CANDU 6 – V/I Ratio

	PV of Costs ($M)	I*/I Ratio
Phase I	50	0.01829
Phase II	193.55	0.07081
Phase III	2489.65	0.91089
	2733.20	

Table 5.8: ACR-1000 – V/I Ratio

	PV of Costs ($M)	I*/I Ratio
Phase I	50	0.02388
Phase II	239.63	0.11446
Phase III	1803.82	0.86165
	2093.45	

Table 5.9 - Pickering B – V/I Ratio

	PV of Costs ($M)	I*/I Ratio
Phase I	50	0.02417
Phase II	176.96	0.08556
Phase III	1841.46	0.89027
	2068.42	

For the sake of illustrative simplicity, *Figure 5.11* depicts a small part of the binomial valuation of the underlying variable (V/I ratio) for the refurbishment alternative.

Figure 5.11 - Pickering B – V/I Ratio Binomial Valuation
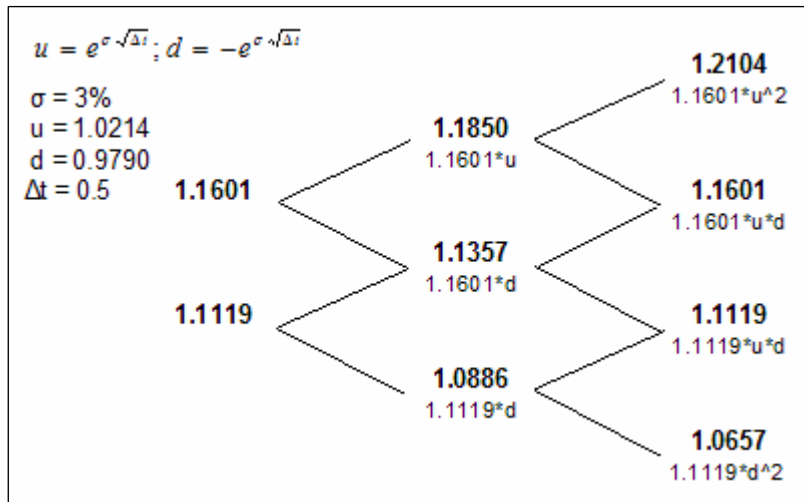
The option to expand is written on the V/I ratio. The part of the option' valuation that corresponds to the values shown in *Figure 5.11* and the formulas and input parameters is presented in *Figure 5.12*.

Figure 5.12 - Pickering B – Binomial Valuation of Option to Expand
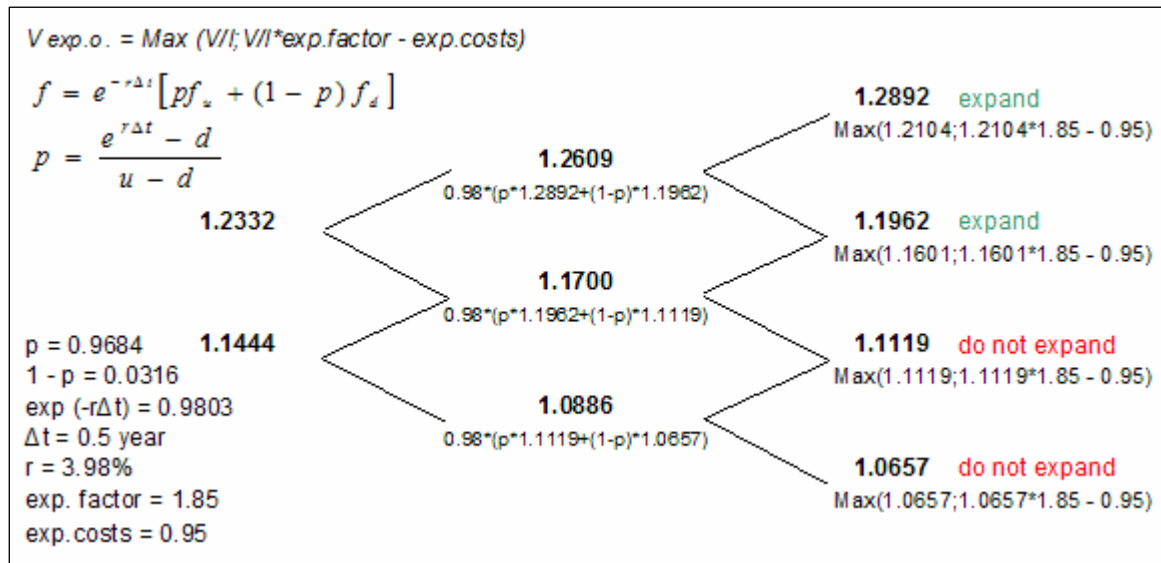
The second option is written on the expansion option in the refurbishment case and on the V/I ratio in the new nuclear construction case. *Figure 5.13* present the binomial valuation of the option to refurbish.

Figure 5.13 - Pickering B – Binomial Valuation of Option to Refurbish
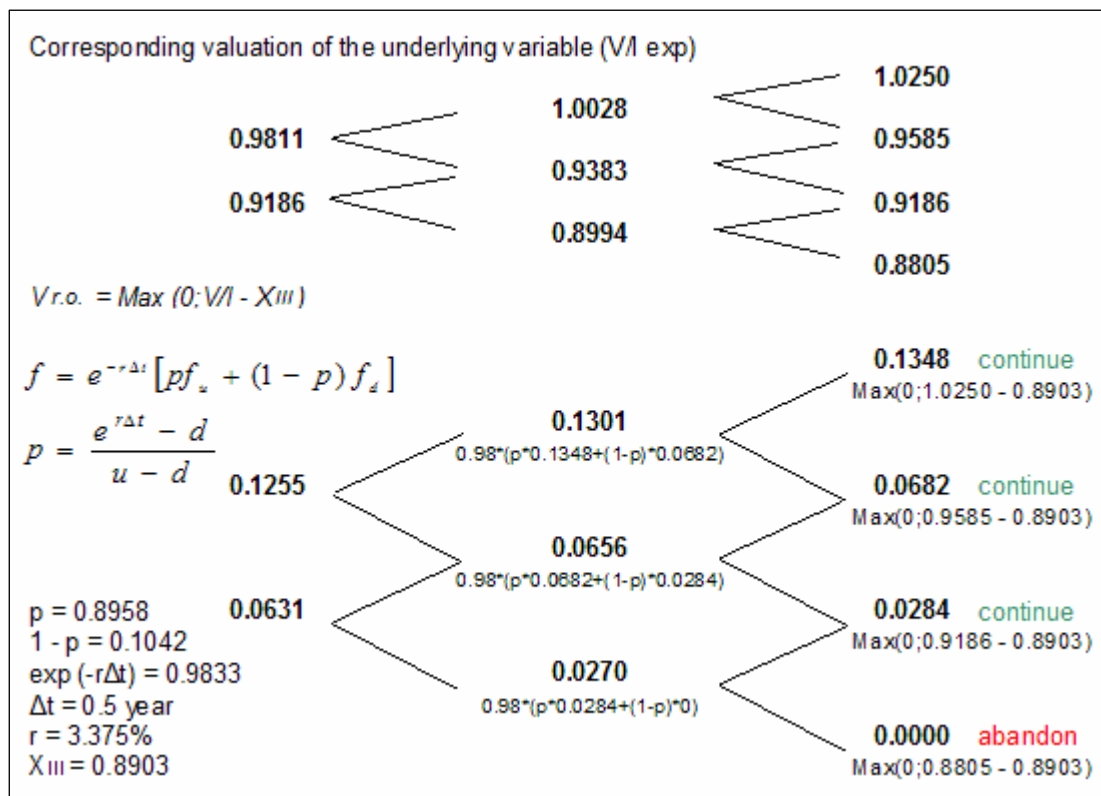
The first option is written on the second option and is characterized by the same payoff structure except for the difference in the strike price that was discussed before. The risk free rate is equal to 3.98% and corresponds to the nominal interest rate on the long-term (more than 10 years) marketable bonds issued by the Canadian government on the 4th of December[3].

5.3.2 – Calculation of Trigger Values

The trigger values were calculated based on the formulas provided in *Chapter 4.2.2*. *Table 5.8* illustrates how the values were calculated for Enhanced CANDU 6.

Table 5.10 – Trigger Values Calculation for Enhanced CANDU 6

	CANDU 6	Formulas
Net Revenues (R*) per year	368 448 267	
Volatility of Net Revenues	1,508%	
Discount Rate (δ)	8,5%	
γ	27,85	0,5*(1+SQRT(1+(8*B4/(B3^2))))
W (size of the plant)	1 500 000	
Risk Premium (RP)	0,003166	B4/(B5-1)
Trigger Value for Investment (I*)	4 179 028 734	(((B5-1)*B2)/(B5*B4))
Trigger Value for Construction Costs (K*)	2786	(B8/B6)
Elasticity of K* w/r to δ	-0,98172	(B4*(B5/(B5-1))*2/((B3^2)*(B5^2)) *(1/SQRT(1+8*B4/(B3^2))))-1
Elasticity of K* w/r to σ	-0,01828	(-2*(B4/((B3^2)*B5*(B5-1)))/SQRT(1+(8*B4/(B3^2))))
Elasticity of RP w/r to δ	0,50914	2*(B4/((B3^2)*(B5-1)))/SQRT(1+(8*B4/(B3^2)))

In this chapter, we have explained the statistical assumptions and methodologies involved in our models. In addition, we have described all the data and figures used in our approach. Overall, the main function of this chapter was not only to describe the assumptions, data and methodologies we utilized, but moreover, to explain it in such a manner that our study could be replicated in the future.

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[3] http://www.bankofcanada.ca/en/rates/bonds.html

Chapter 6 – Results & Discussion

This chapter exhibits the detailed results from our models and presents a discussion of our findings. Firstly, we show the present value and net present value distributions for each of the alternatives considered. Following this, we go on to discuss the staged approach, the V/I ratio and the binomial lattice valuations. Finally, we talk about the trigger values, which define the maximum threshold for total investment costs and construction costs on a $/kW basis.

6.1 – New Sources of Nuclear Power: Enhanced CANDU 6 vs. ACR-1000

As mentioned before, the two primary candidates for "new build" nuclear projects are the Enhanced CANDU 6 and ACR-1000 technologies. The ACR-1000 reactor is a new technology that is purportedly superior to all other forms of power generation, according to the AECL. The ACR-1000 design is presumed to have lower construction costs ($/kW) and higher capacity factors.

6.1.1 – Present Value of the Project

The present values of the Enhanced CANDU 6 and ACR-1000 nuclear power plants are calculated as the discounted sum of the simulated future free cash flows. The results depicted in *Figure 6.1* and *Figure 6.2*, based on 1000 Monte Carlo simulation trials, show that the CANDU 6 dual-unit plant is expected to generate revenues of $2.73 billion in comparison with ACR-1000 revenues of $2.31 billion. The main explanation for the difference in projected returns comes from the fact that the CANDU 6 (1500 MW) has a higher plant capacity than the ACR-1000 plant (1200 MW). Revenues on a $/kW basis are $1820/kW and $1925/kW for the CANDU 6 and ACR-1000, respectively. This indicates that in relative terms, the ACR-1000 generates higher revenues.

Figure 6.1 - Enhanced CANDU 6 - PV Distribution
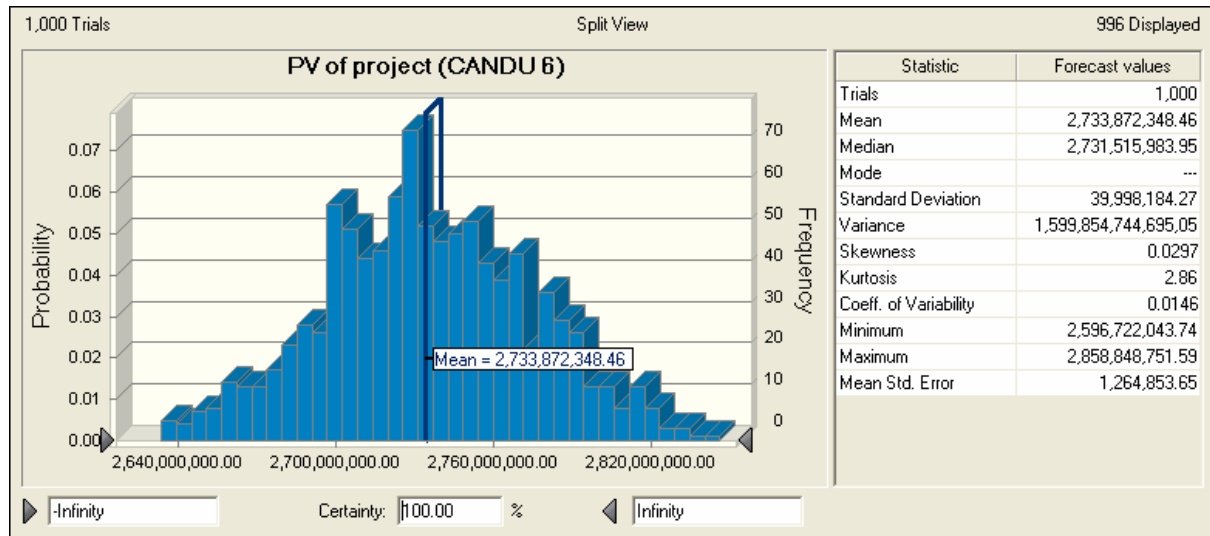
Figure 6.2 - ACR-1000 - PV Distribution
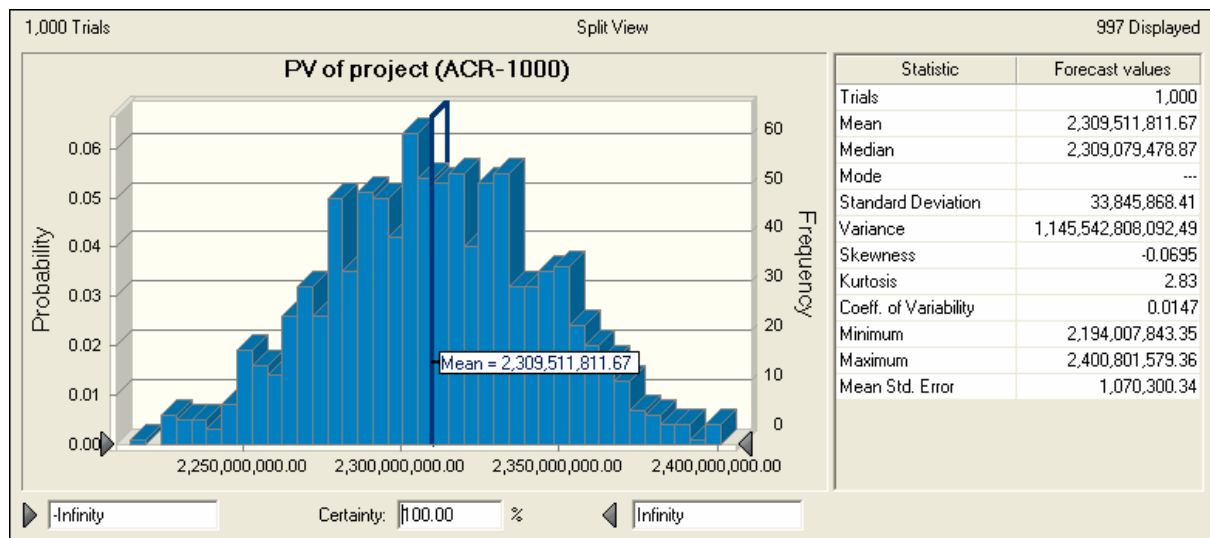
6.1.2 – Net Present Value of the Project

The plant NPV is the present value of the projected free cash flows less the present value of the initial investment. As discussed in *Chapter 5.2.1.6*, the investment required to build a plant is significantly higher for CANDU 6 than for ACR-1000. *Figure 6.3* illustrates the distribution of the net present values for the Enhanced CANDU 6 plant. The average value of the investment is negative and equals $90.7 million in losses. If the decision was made based solely on these results, the project would be abandoned. However, there is a 12.44% chance for the project to be profitable, as depicted by the blue area on the below graph.

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Figure 6.3 - Enhanced CANDU 6 – NPV Distribution
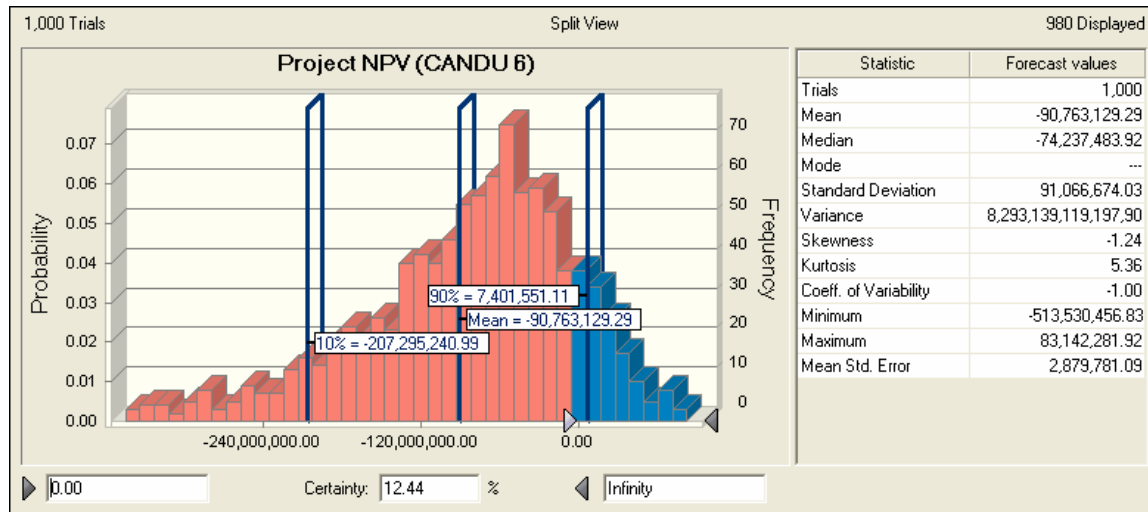
The distribution of the net present value of the ACR-1000 is shown below in *Figure 6.4*. The projected mean value of the investment is nearly $124 million. Though the project seems very favourable, there is still approximately a 9% chance that the investment project may experience losses.

Figure 6.4 - ACR-1000 – NPV Distribution
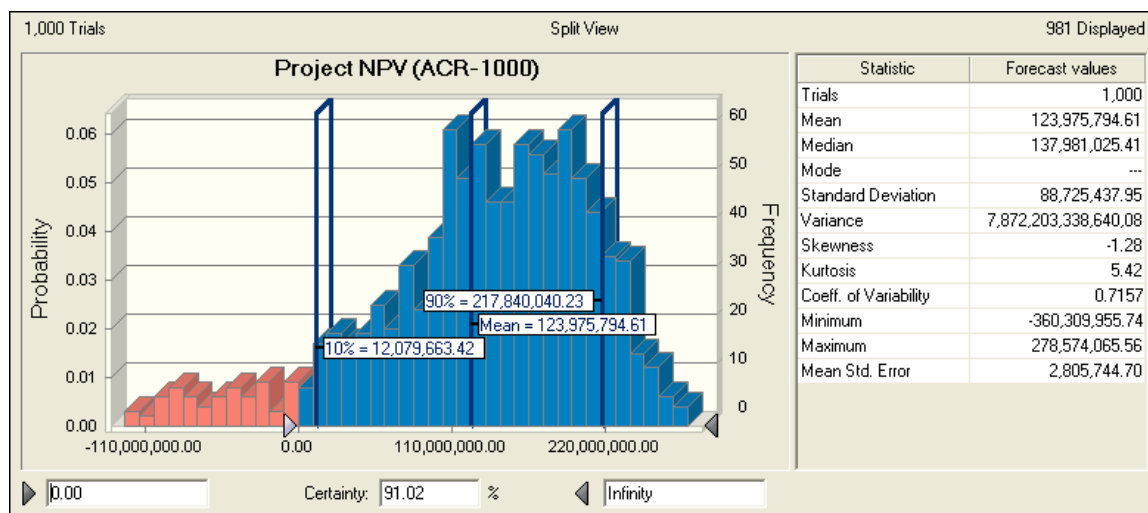
6.1.3 – Phases, V/I Ratio, and the Option to Abandon

In this section, we present the results from the implementation of the real options approach in which we divided the overall decision process into three different phases. In doing so, we evaluate the decision maker's flexibility to choose between continuing and abandoning the project after each phase. We will start with the results for CANDU 6.

Figure 6.5 presents the distribution of the V/I ratio, which is equal to the present value of the nuclear plant over the present value of the initial investment. The mean value is 0.97, which is consistent with the previous negative NPV result. The volatility of the V/I ratio can be found by dividing the standard deviation (0.03) by the mean value (0.97), which equals 3.093%.

Figure 6.5 - Enhanced CANDU 6 – Distribution of V/I
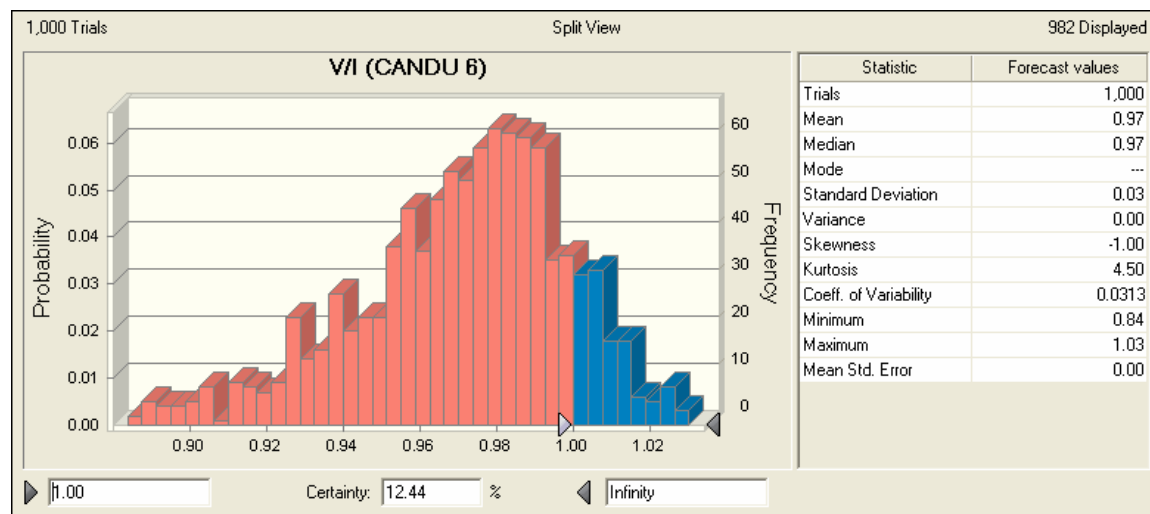
Following the discussion on binomial tress at the end of *Chapter 5*, the binomial valuation of the V/I ratio for three years is depicted below in *Figure 6.6*.[4]

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[4] For illustrative purposes, *Figure 6.6* presents the shortened version of the binomial tree. The full tree includes smaller time steps and can be found in *Appendix E*. The same applies to all the binomial valuations presented in this chapter.

Figure 6.6 - Enhanced CANDU 6 - Binomial Valuation of V/I Ratio
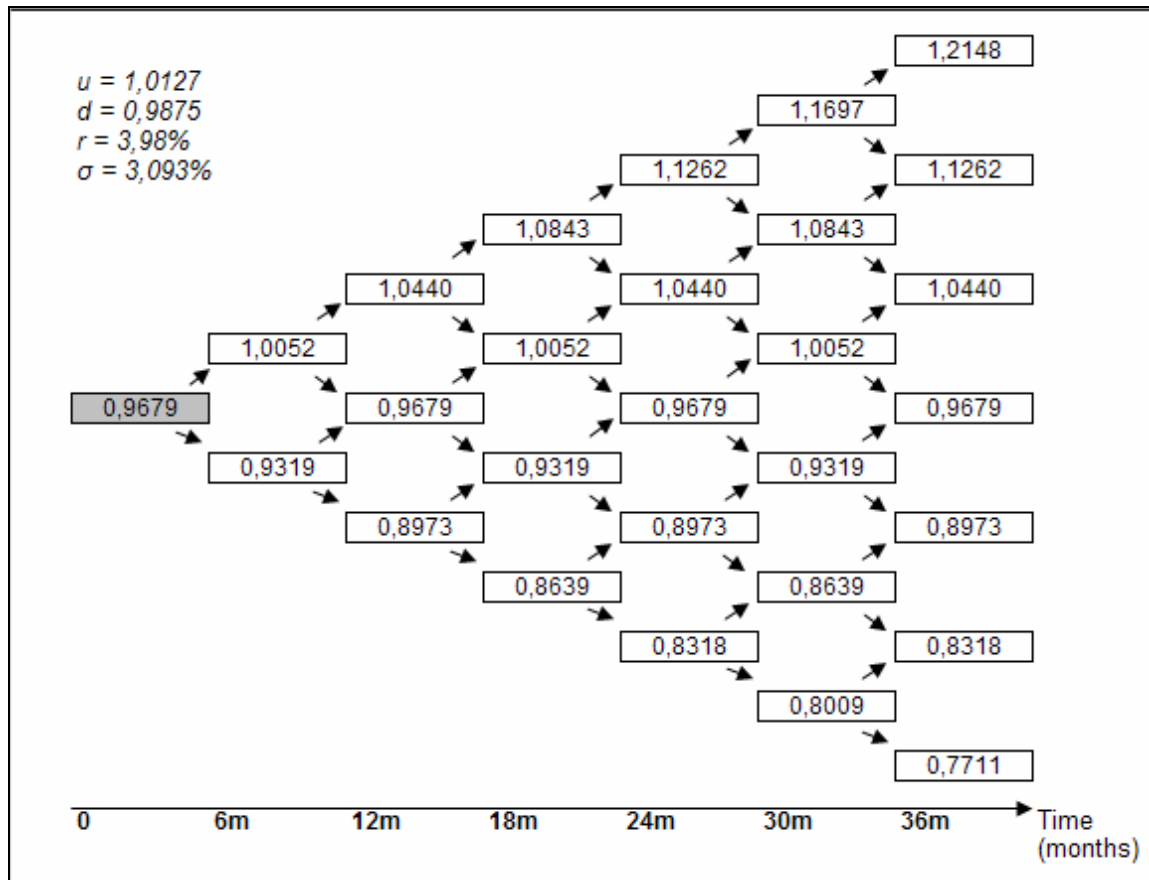
The V/I ratio is the underlying variable for the construction option, which matures in three years and values the right to abandon or continue the project. *Figure 6.7* presents the binomial valuation of the construction option, which is worth 0.1624 as a fraction of the initial investment. The binomial lattices illustrate that even though the NPV for the Enhanced CANDU 6 plant is found to be negative, there is a chance that the investment will turn out to be profitable under favourable market conditions.

Figure 6.7 - Enhanced CANDU 6 - Binomial Valuation of Construction Option

$payoff = max\ (0;\ V/I - X_{III})$
$X = 0,908$
$p = 0,7604$
$r = 3,98\%$
$\sigma = 3,093\%$
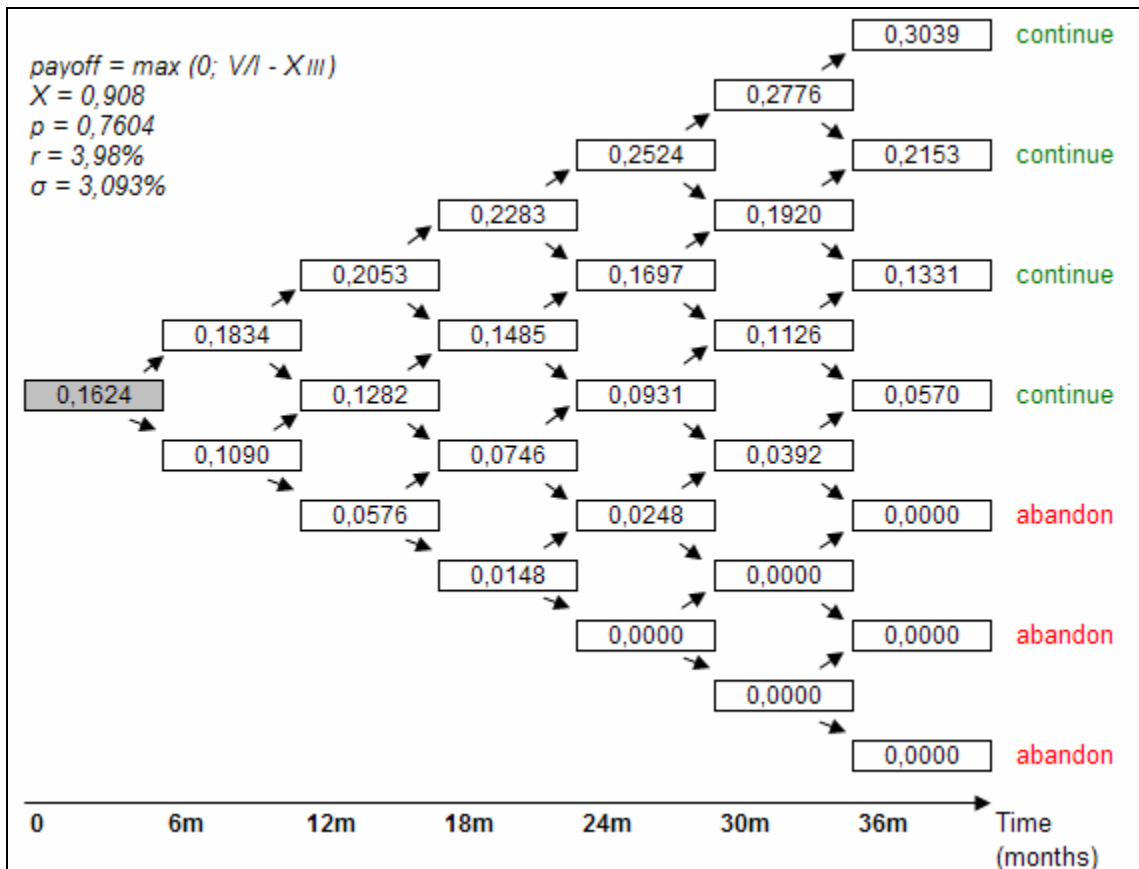
The licensing option is written on the construction option and presents the right to continue or abandon the project before the licensing stage begins, which is exactly one year after the project has been launched (assuming phase I is already underway). *Figure 6.8* presents a binomial valuation of the option and shows that it is worth 0.0940 as a fraction of the mean initial investment, or about $265.5 million.

Figure 6.8 - Enhanced CANDU 6 - Binomial Valuation of Licensing Option

$payoff = max\ (0;\ V/I - X_{II})$
$X = 0,0743$

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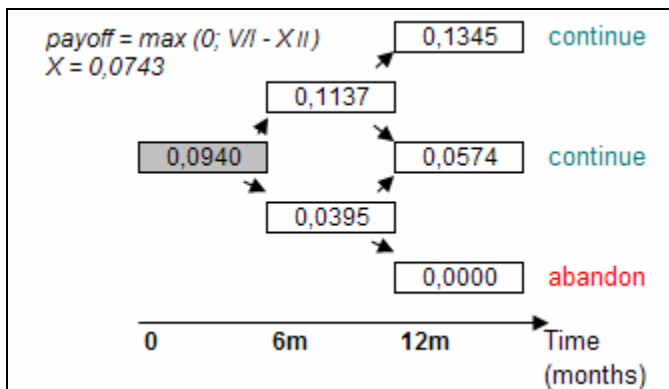
The licensing option takes into account the costs related to both the licensing phase and the construction phase. Consequently, the final option value of the CANDU 6 power plant is equal to the licensing option's value ($265.5 million) less the costs of the first stage ($50 million), as can be seen in *Table 6.1*. Therefore, the final option value is $215.5 million as opposed to the static value of negative $90.7 million. Since NPV techniques do not capture the strategic value, the difference between the two values ($215.5 – (-$90.7 million)) is termed the Strategic RO Value. This is essentially the added value the investor receives by using the real options approach. We can see that we get entirely different results using traditional valuation techniques and the real options approach. Standard valuation techniques showed the Enhanced CANDU 6 project to be highly unprofitable. Meanwhile, the project turned out to be financially promising when incorporating the value of managerial flexibility. We can observe this in *Figures 6.7* and *6.8*, where the *option to continue* is favoured to the *option to abandon*. The strategic and option values are shown in *Table 6.1*.

Table 6.1 - Enhanced CANDU 6 – Strategic and Option Values

Enhanced CANDU 6 Results	
Option Value	$265,515,734
Phase I costs	$50,000,000
Final Option Value	$215,515,734
Static NPV	- $90,763,129
Strategic RO Value	$306,278,863

Moving on to the ACR-1000 project, *Figure 6.9* displays the distribution of the V/I ratio. The mean value is 1.06 and the standard deviation is 0.04, which together imply a volatility of 3.77% in the project's returns. The blue area represents the probability of the investment being profitable.

Figure 6.9 - ACR-1000 - Distribution of V/I
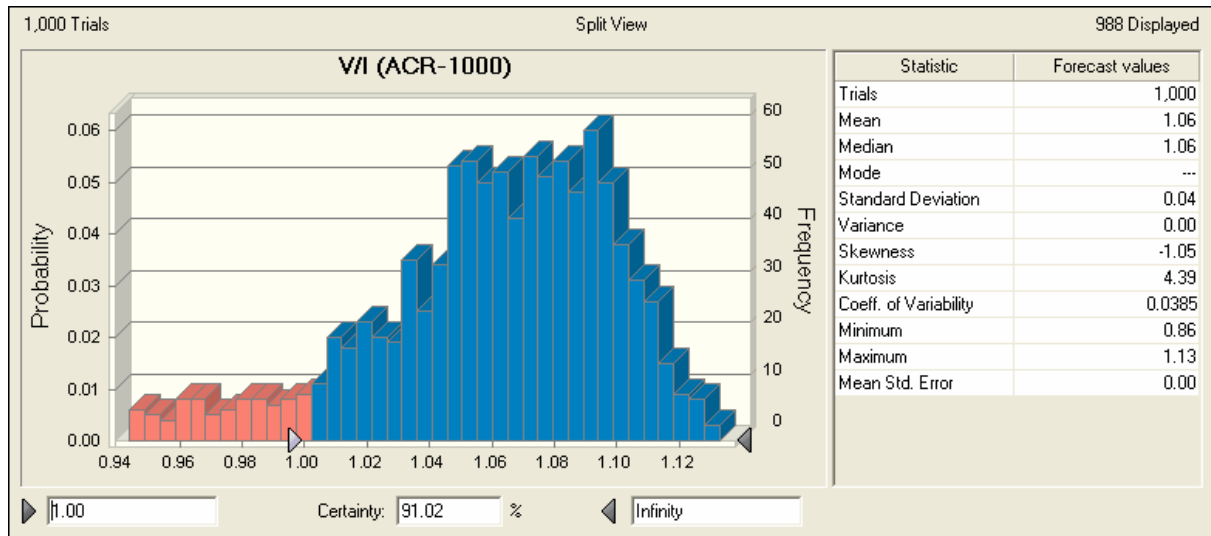
The binomial valuation of the V/I ratio for the ACR-1000 project is presented in *Figure 6.10*.

Figure 6.10 - ACR-1000 - Binomial Valuation of V/I Ratio
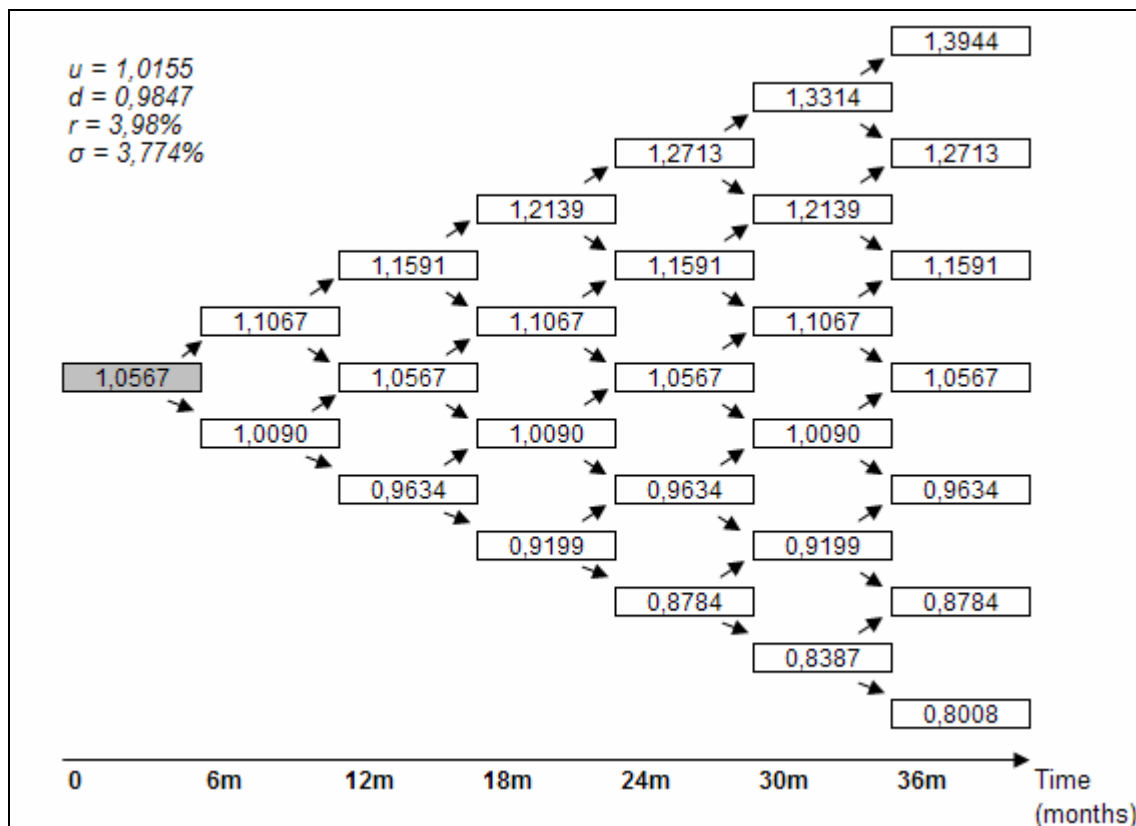
The construction option is worth 0.2974 as a fraction of the initial investment. The valuation is shown in *Figure 6.11* below.

Figure 6.11 - ACR-1000 - Binomial Valuation of Construction Option
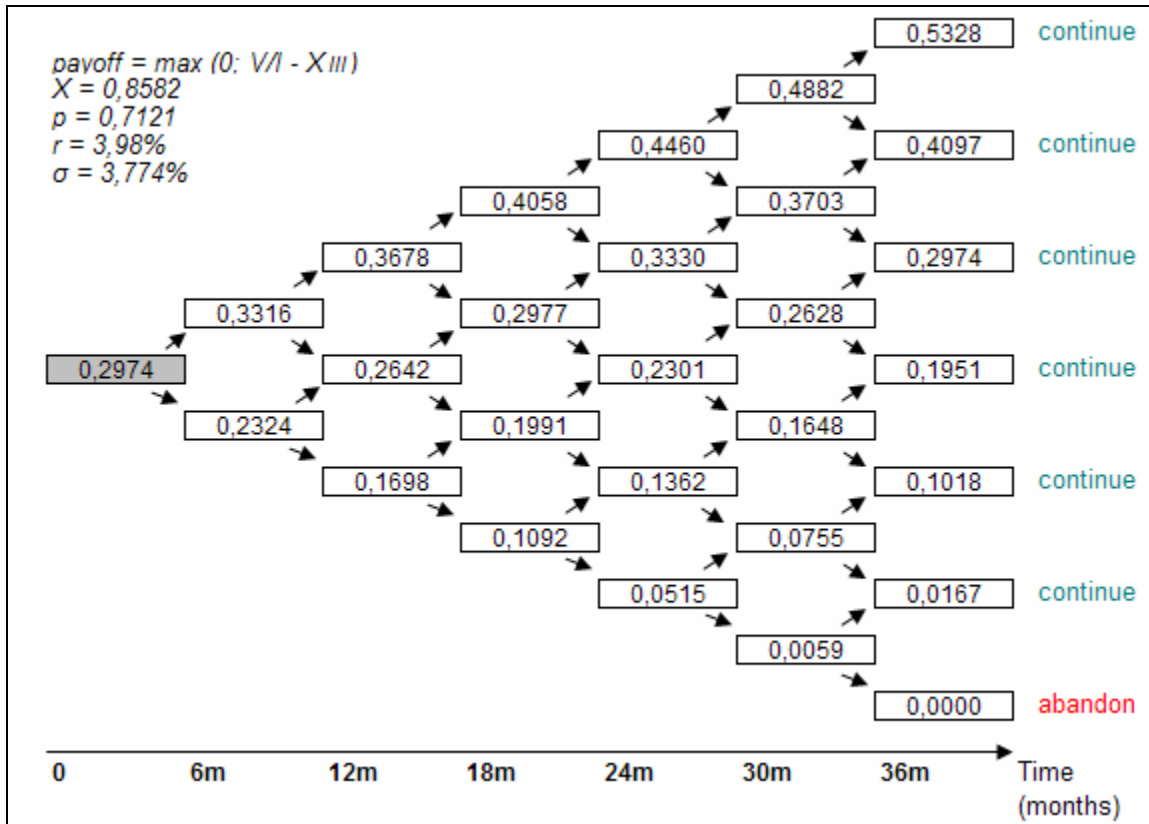
As illustrated in *Figure 6.12*, the licensing option is written on the construction option and is worth 0.1867 as a fraction of the initial investment, or roughly $408 million.

Figure 6.12 - ACR-1000 - Binomial Valuation of Licensing Option
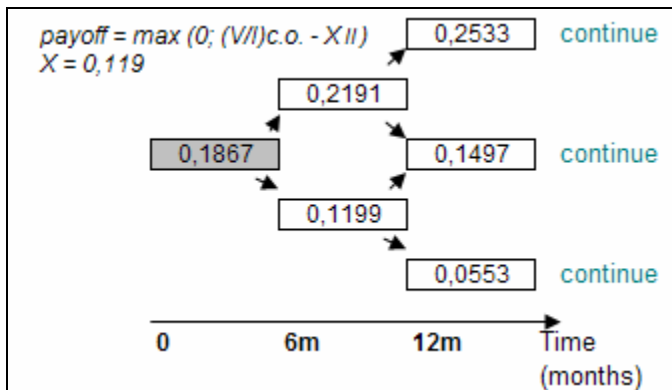
As shown earlier in *Figure 6.4*, there is only a slight chance that the ACR-1000 investment project would turn out to be loss-making. This is consistent with the findings in *Figure 6.12,* which show that the investor will definitely not choose to abandon the project after the first phase. However, in *Figure 6.11* (and the related table in *Appendix D*), we see that there is indeed a slight chance that the project would be abandoned after the second phase. This displays significant value from the investor's perspective, who of course wishes to avoid such worst-case scenarios.

Table 6.2 displays the ACR-1000 strategic and option values. Taking flexibility into account leads to a final options value of $358 million that far outweighs the static NPV of $124 million. Though the static NPV approach is positive at $124 million, it still undervalues the project to some extent. Introducing a real options approach captures the project's strategic value; the difference between the two results ($358 million - $124 million) is equal to $234 million, and is defined as the Strategic RO Value.

Table 6.2 - ACR-1000 – Strategic and Option Values

ACR-1000 Results	
Option Value	$408,039,574
Phase I costs	$50,000,000
Final Option Value	$358,039,574
Static NPV	$123,975,795
Strategic RO Value	$234,063,779

6.1.4 – Calculation of Trigger Values

The trigger values approach incorporates the mean value of forecasted future net revenues per year as well as the volatility of these revenues. *Table 6.3* summarizes the inputs used and the final results involved in the calculation of the aforementioned trigger values.

Table 6.3 - Enhanced CANDU 6 & ACR-1000 - Trigger Values Calculation

	Enhanced CANDU 6	ACR-1000
Net Revenues (R*) per year (in future dollars)	368,448,267	299,788,600
Volatility of Net Revenues	1.508%	1.421%
Discount rate (δ)	8.5%	8.5%
γ	27.85	29.51
W (size of the plant)	1,500,000 kW	1,200,000 kW
Risk Premium	0.003166	0.002981
Trigger Value for Initial Investment (I*)	**$4,179,028,734**	**$3,407,408,058**

Actual Value for Initial Investment (I)	$2,824,635,478	$2,185,536,017
Trigger Value for Construction Costs (K*)	**$2786/kW**	**$2840/kW**
Actual Value for Construction Costs (K)	$2120/kW	$1920/kW
Elasticity of K* with respect to δ	- 0.98172	- 0.98276
Elasticity of K* with respect to σ	- 0.01828	- 0.01724
Elasticity of the risk premium with respect to δ	0.50914	0.50862

The initial investment trigger value for the Enhanced CANDU 6 plant is $4.18 billion as opposed to the actual value of $2.82 billion. The same trigger value for the ACR-1000 equals $3.41 billion and is substantially higher than its actual value of $2.18 billion. From the trigger value perspective, therefore, this means that both proposed investments should be undertaken, despite the fact that the static NPV for the CANDU 6 is negative. This result is consistent with the results from the previous section describing the staged approach.

The calculated trigger values of the construction costs (K*) for both technologies do not differ considerably; they are $2786/kW for the CANDU 6 and $2840/kW for the ACR-1000. However, the main point to bring across here is that the ACR-1000 plant has more leeway in terms of the difference between its actual construction costs ($1920/kW) and the trigger value ($2840/kW). Taking the percentage difference in these values, we see that the ACR-1000 has a difference of 47.9%, whereas the Enhanced CANDU 6 only has a percentage difference of 31.4%. This is due to the lower construction costs and higher anticipated capacity factor of the ACR-1000 in comparison to the CANDU 6 power plant. This basically reiterates that the ACR-1000 is a superior technology.

The elasticity estimates show the sensitivity of the results to any changes in the input parameters. For example, the elasticity of the CANDU 6 construction costs with respect to the discount rate is equal to –0.98172 and implies that a 1% increase in the discount rate will result in a 0.98172% decrease in the trigger value of the construction costs. Assuming a 10% discount rate (a 17.65% relative increase over the original value of 8.5%), the trigger value for construction costs would be $2303/kW (a 17.33% decrease from the original value of $2786/kW). The negative relationship between the K* trigger value and the discount rate is intuitively logical – the higher the discount rate, the lower the present value of future net revenues and hence, the lower the value of the initial investment that would define a zero NPV, which of course corresponds to the threshold of investor's indifference. For the ACR-1000, a 1% increase in the discount rate results in a 0.98276% decrease in the trigger value of the construction costs.

The elasticity of the construction costs with respect to the volatility of future net revenues for CANDU 6 equals -0.01828 and implies that a 1% increase in the variance of the revenues results in a 0.01828% decrease in the trigger value of the construction costs. Likewise, the elasticity parameter for ACR-1000 with regards to the volatility is -0.01724.

The risk premium shows the difference between the discount rate adjusted to the uncertainties in the net revenues and its actual value. The adjustment factor is calculated as $(\gamma - 1)/\gamma$ (see *Chapter 4.2.2*) and has a value that is very close to 1 for both CANDU 6 and ACR-1000 (0.9641 and 0.9661 respectively). Therefore, the risk premium factor is very small for both cases. The risk premium's elasticity with respect to the volatility of the net revenues shows how sensitive the risk premium factor is to changes in the uncertainties of future returns.

6.1.5 – Comparison and Deductions

The analysis provided in this section aims to value potential investments in the construction of new nuclear power plants by looking at two specific technologies. While standard valuation techniques are able to account for uncertainty by either estimating the average forecasted NPV or using a risk-adjusted discount rate, they fail to value the managerial flexibility embedded in the project and often significantly underestimate the investment's true potential.

The first part of our analysis is based on the notion that the owner of the plant has an opportunity to revise his decision before all the investment costs are incurred. This idea is made evident through the identification of valid, logical phases that can fundamentally partition the investment into stages. Thus, the decision makers have the *option to continue* and the *option to abandon* twice, after phases I and II. Therefore, when contemplating whether to undertake the investment or not, the investor values the potential gains of the project in contrast to the risk of squandering the costs required to complete phase I of the project. This situation corresponds to the main idea of financial options, where the buyer of an option faces limited downside risk and theoretically unlimited potential profits. Given that the investor has two chances to walk out on the project, the value of the investment is thus calculated based on these two sequential options.

The second part of the analysis calculated trigger values for the initial investment (I*) and construction costs (K*) in order to define the specific value at which the investor will be indifferent between investing or not.

The results for the enhanced CANDU 6 show that the static net present value analysis and the real options approach lead to different and opposing results. As shown in *Figure 6.13*, the static NPV is negative and accordingly, the investment would typically be abandoned. However, the final option value (and thus the strategic RO value) is positive and signals the financial attractiveness of the project. Comparing the actual investment costs with their trigger values also shows that both the CANDU 6 and ACR-1000 projects are worth investing in. However, it is quite apparent that based on its characteristics, the ACR-1000 is the better alternative.

Figure 6.13 - Enhanced CANDU 6 – Static NPV vs. Final Option Value
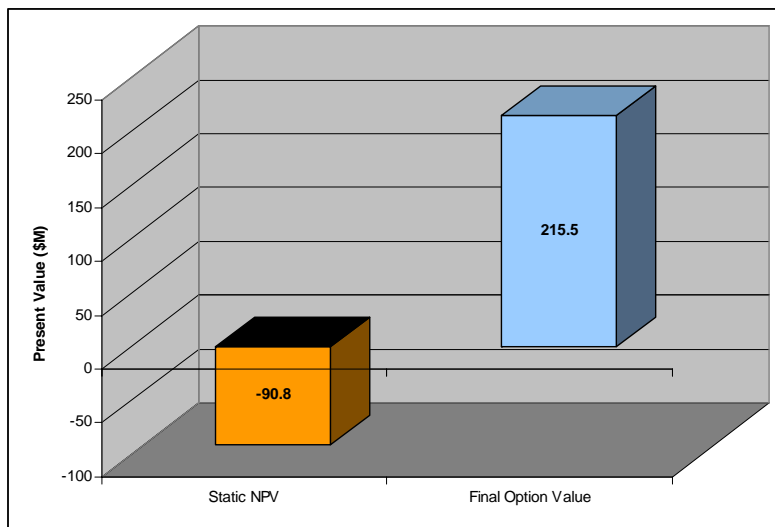
While both the static NPV rule and the real options approach lead to positive investment evaluations for the ACR-1000, the second approach shows that the option value of the plant is much higher than the static value owing to the fact that possible downside losses are limited by incorporating managerial flexibility. The static NPV and final option value can be seen in *Figure 6.14* below.

Figure 6.14 - ACR-1000 – Static NPV vs. Final Option Value
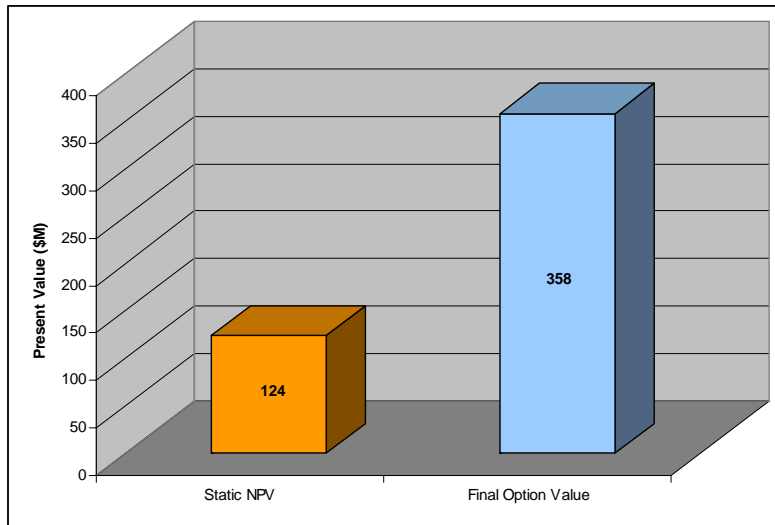
6.2 – Nuclear Refurbishment: Pickering B

This section exhibits our evaluations for the Pickering B refurbishment alternative.

6.2.1 – Present Value of the Project

The present value distribution for the Pickering B refurbishment is presented in *Figure 6.15*. As can be seen, the project has a mean value of $2.135 million.

Figure 6.15 - Pickering B – PV Distribution
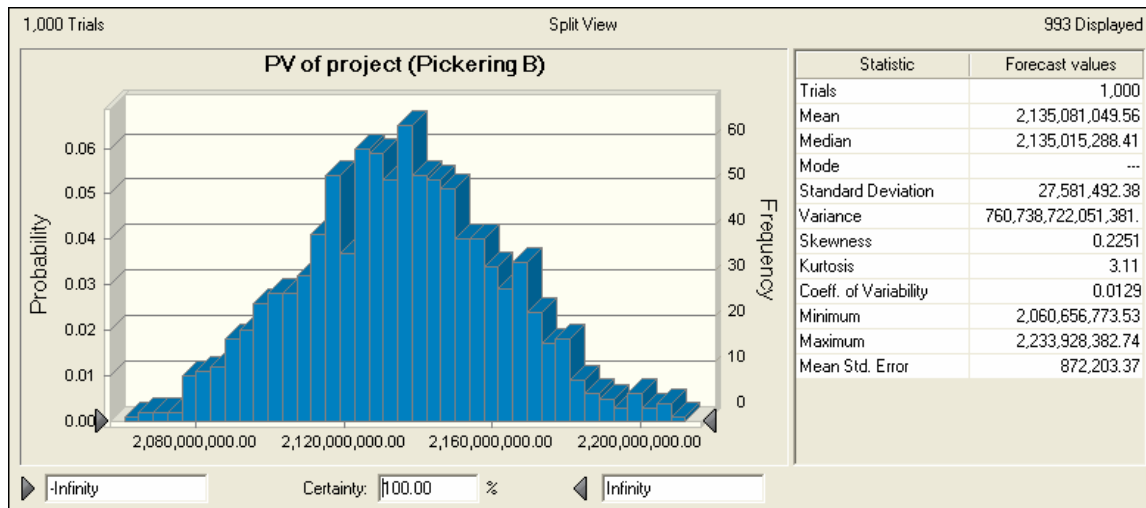
6.2.2 – Net Present Value of the Project

The distribution of the refurbishment project's NPVs is displayed in *Figure 6.16* and has a mean value of –$8.13 million. The project has a 52% certainty of being a positive NPV project but we see that the overall distribution is heavily skewed to the left. A decision made today and only based on the approach suggested by standard valuation techniques would recommend abandonment of the project based on its negative NPV value. However, the investment has some hidden potential which can be valued using a real options view.

Figure 6.16 - Pickering B – NPV Distribution
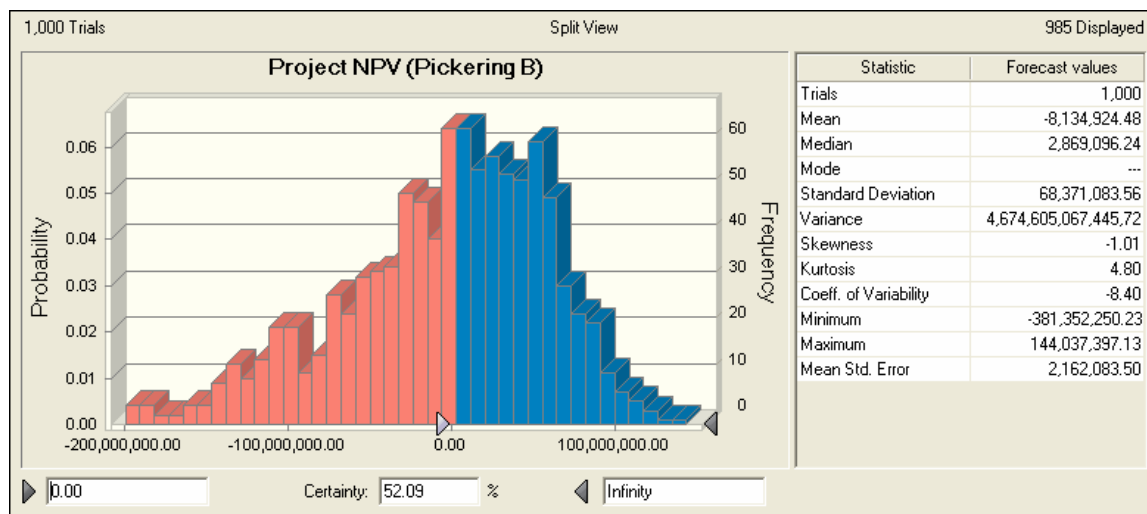
6.2.3 – Phases, V/I Ratio, and the Option to Abandon

The valuation of the V/I ratio for Pickering B is presented in *Figure 6.17* and illustrates a mean value of 1.00 and a standard deviation of 0.03, implying a 3% volatility.

Figure 6.17 - Pickering B - Distribution of V/I
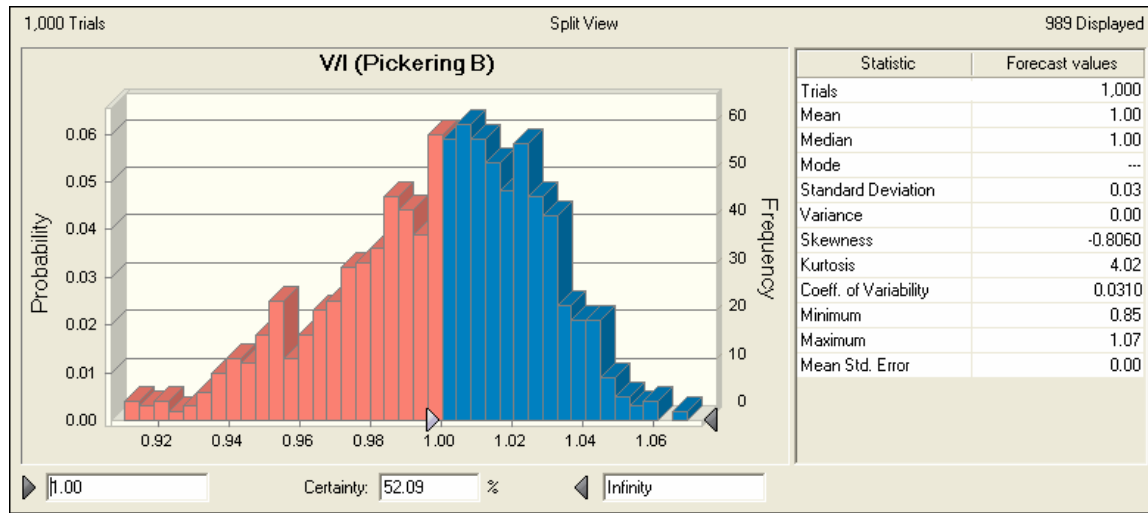
Figure 6.18 illustrates the valuation of the V/I ratio for seven and a half years, which is the amount of time from project start to return to service of the refurbished units.

Figure 6.18 - Pickering B - Binomial Valuation of V/I ratio
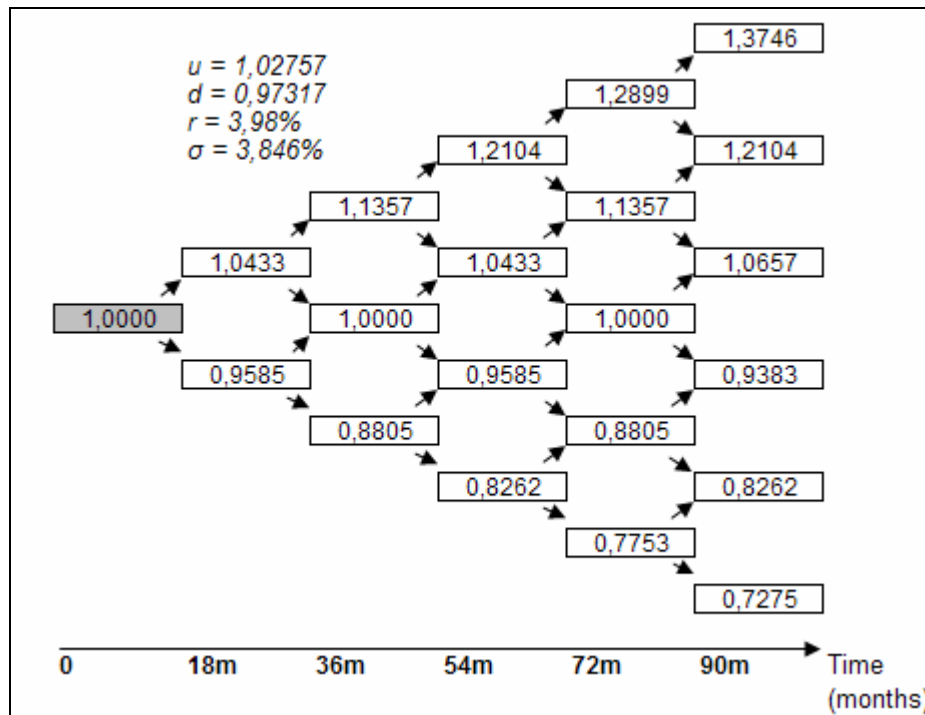
As described in *Chapter 3.5.1.2*, the refurbishment case differs from the "new build" alternative due to the expansion opportunities embedded in the project. After 7.5 years, the decision makers will have a right to reconstruct two more reactors, if it is economically feasible to do so. Therefore, we

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value the subsequent *option to expand.* The binomial valuation of the expansion option is presented in *Figure 6.19* below.

Figure 6.19 - Pickering B - Binomial Valuation of Expansion Option
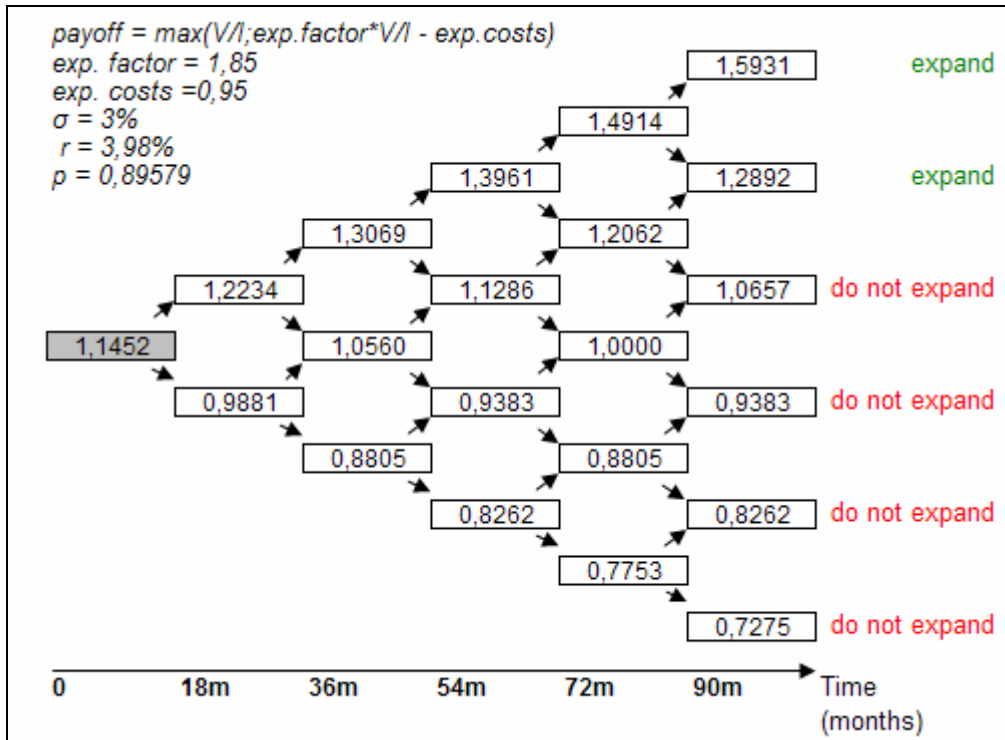
The tree illustrates that the option can be exercised if the market behaves favourably; this results in a new value for the V/I ratio of 1.1452.

The expansion factor shows how revenues will potentially grow if the two subsequent reactors are refurbished. By the time second pair of reactors will be refurbished and returned to service, a few years will have passed. As result, the expansion option will not lead to a doubling of the revenues, as may be predicted at first glance. Our estimation shows that the expansion factor is approximately equal to 1.85, assuming it would take another 2 to 4 years before the second pair of reactors would be fully operational. The expansion costs are expressed as a ratio of the refurbishment costs of the last two reactors over the refurbishment costs of the initial two reactors. We assume that it would be cheaper to refurbish the second pair of reactors since any expenses related to the feasibility assessment and the planning stage could be reduced quite significantly. The value of the expansion costs in this model is therefore 0.95.

The refurbishment option, which is exercised before the final stage of reconstruction is scheduled to start, is therefore written on the strategic value of the V/I ratio. The option's valuation is presented in *Figure 6.20* below and results in a value of 0.3859.

Figure 6.20 - Pickering B - Binomial Valuation of Refurbishment Option
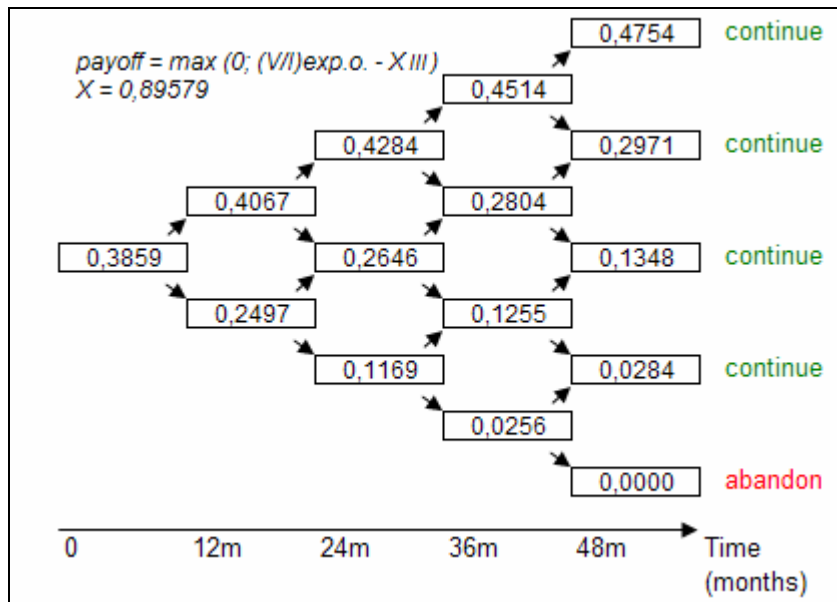
The planning option is written on the refurbishment option and matures before the planning stage begins. Its valuation is depicted in *Figure 6.21* below.

Figure 6.21 - Pickering B - Binomial Valuation of Planning Option
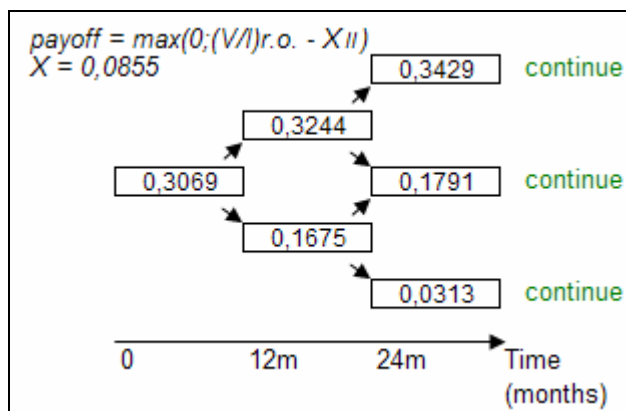
The option costs 0.3069 as a fraction of the initial investment ($658 million) as shown in *Table 6.3* below.

Table 6.4 - Pickering B – Strategic and Option Values (including the *Option to Expand*)

Pickering B Results	
Option Value	$658,625,929
Phase I costs	$50,000,000
Final Option Value	$608,625,929
Static NPV	- $8,134,924

Accounting for phase I costs, the strategic NPV of Pickering B (including expansion optionality) equals $608 million as opposed to its static net present value of –$8.1 million. However, comparing these two figures may be a bit misleading in that the static NPV was calculated on the assumption that only two reactors are refurbished. *Table 6.4* accounts for this difference and explains the results for the project if we momentarily exclude the *option to expand*. Comparing the two final option values shows that the expansion option basically doubles the project's overall value.

Table 6.5 - Pickering B – Strategic and Option Values (excluding the *Option to Expand*)

Pickering B Results	
Option Value	$347,106,810
Phase I costs	$50,000,000
Final Option Value	$297,106,810
Static NPV	- $8,134,924

6.2.4 – Calculation of Trigger Values

Table 6.5 summarizes how the trigger values are calculated for the Pickering B refurbishment case.

Table 6.6 - Pickering B - Trigger Values Calculation

Pickering B	
Net Revenues (R*) per year (in future dollars)	266,017,616
Volatility of Net Revenues	1.404%
Capital recovery factor (δ)	8.5%
γ	29.87
W (size of the plant)	1,032,000 kW
Risk Premium	0.002944
Trigger Value for Initial Investment (I*)	**$3,024,841,469**
Actual Value for Initial Investment (I)	$2,147,115,306
Trigger Value for Construction Costs (K*)	**$2931/kW**
Actual Value for Construction Costs (K)	$2616/kW
Elasticity of K* with respect to δ	-0.98298

Elasticity of K* with respect to σ	-0.01702
Elasticity of the risk premium with respect to δ	0.50851

According to the trigger values approach, the refurbishment project should be abandoned if the initial investment is worth more than $3.02 million. The actual value of $2.15 million is substantially less than this trigger value and therefore implies that the investment should be undertaken. This outcome is consistent with the results obtained when applying the phases approach. The other results exhibited in *Table 6.5* are very similar to the ones acquired for the new nuclear alternatives as described in *Chapter 6.1.4*.

6.2.5 – Deductions

The valuation of the refurbishment alternative differs greatly from that of the new nuclear alternative due to the expansion opportunities embedded in the Pickering B investment project. The traditional NPV approach fails to incorporate such expansion opportunities into its analysis, since the decision whether to expand or not will only happen after the first two reactors have been refurbished and thus depends on future conditions. The option to expand increases the returns on the project from 1 to 1.1452 in terms of the V/I ratio.

As in the CANDU 6 alternative, the NPV analysis and the ROA lead to contrasting decision results, as can be seen in *Figure 6.22*. Further, this graph shows the added value gained from including the *option to expand*. Both strategic NPVs are positive in comparison with the negative static NPV.

Figure 6.22 - Pickering B - Static NPV vs. Final Option Value (incl. & excl. expansion option)
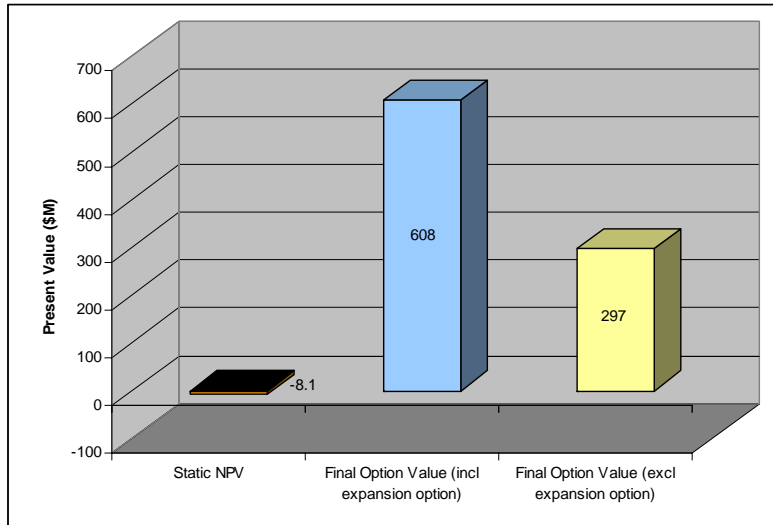
The trigger value approach also verifies that the refurbishment alternative should be initially undertaken. However, in the refurbishment case, the trigger value approach is limited in relation to the staged approach. This is because the trigger values are based on a single value of the yearly revenues and their associated volatility; as such, it cannot integrate future opportunities such as expansion. It is arguable whether the expansion option can be reflected in the model's input parameters. However, despite their potential limitations, trigger values are useful in that they provide a logical and understandable bottom line threshold for investors.

Chapter 7 – Conclusions & Recommendations

It appears that many of the energy investment decisions being made in Ontario today are strongly influenced by ideologies and preconceived notions, such as the decision to shut down all coal-fired generation or the belief that Conservation and Demand Management measures will save the day. Rather than allowing their decisions to be driven by idealistic beliefs, Ontario's decision makers should take a realistic, fair-minded and flexible approach to the problem at hand.

Established priorities, such as those set by the Government of Ontario, should of course be taken into consideration, but they must not override sound economic advice. Ideally, Ontario's future supply mix should be able to combine both high environmental standards and solid economic benefits. The bottom line, however, is that power plant operators have to be held accountable for the successful and efficient operation of its assets, both from a production and economic point of view.

7.1 – Summary of Findings

Chapter 6 presented a detailed and comprehensive overview of the results obtained in our valuation approach. Through the identification of specific phases in the given investments, we were able to value the different alternatives by means of a sequential compound option. In addition, we were able to use the approach developed by Rothwell in his various articles in order to calculate trigger values for the initial investment and construction cost. Ultimately, by applying the real options methodology, we were able to show that a static NPV approach would typically undervalue a given investment since it fails to acknowledge managerial flexibility properly.

7.1.1 – New Sources of Nuclear Power: Enhanced CANDU 6 vs. ACR-1000

As described in *Chapter 3*, the role of nuclear generation in Ontario is not expected to change from the current situation in which nuclear power provides 50% of the province's electricity needs. Given the various factors in play, this signifies that new nuclear power plants will have to be built in the near future. Given the long lead times involved in these decisions, feasibility and economic assessments are in fact already underway for "new build" nuclear projects.

In our approach, we identified two specific technologies that have been outlined by the AECL and the Ministry of Energy as likely candidates for new nuclear power in Ontario. The important thing to consider is that the two plants have differing characteristics, which were quite apparent in our analysis.

The static NPV figures for the Enhanced CANDU 6 and ACR-1000 plants were –$90.7 million and $124 million, respectively. The main reason for this discrepancy was due to the ACR-1000 technology's lower investment costs and superior capacity factor. Under traditional approaches, the ACR-1000 project would definitely be accepted whereas the CANDU 6 project would be soundly rejected. However, in using the real options approach, we were able to show that the static NPV did not capture the strategic value linked to managerial flexibility. The strategic NPVs of the two plants were significantly higher when using the real options approach.

Intuitively, the real options approach is particularly beneficial in cases like the Enhanced CANDU 6 investment project. Namely, by incorporating managerial flexibility, the real options methodology can uncover hidden strategic value in the plant through the *option to abandon*. However, the real options approach is also useful in evaluating the ACR-1000 plant. Though the ACR-1000 investment clearly looks to be a favourable one, there is still some chance – 8.98% to be exact – that the market conditions could worsen, resulting in losses. In this case, the right to abandon the project presents an authentic value for the decision makers.

As such, we can conclude that in choosing these two specific technologies, we coincidentally exhibited the considerable and fundamental power of real options. In the Enhanced CANDU 6 project, real options uncovered a hidden asset value via the use of the *option to continue*, wherein the project was taken on even though the static NPV would have rejected the investment. On the other hand, the ACR-1000 project displayed the power of the *option to abandon*, in the case where market conditions changed drastically enough to make the ACR-1000 project an unprofitable one.

7.1.2 – Nuclear Refurbishment: Pickering B

The issue of nuclear refurbishment is a particularly hot and current topic in Ontario. A considerable amount of installed nuclear capacity is or will be nearing its end-of-service dates within the next decade or so. The Pickering A refurbishment was completed a few years ago, the Bruce A restart

project is currently in progress, and the Pickering B refurbishment study is presently in its feasibility assessment stage.

Our model for the Pickering B facility considered the initial refurbishment and return to service of two reactors. As in the "new build" alternative, we employed a phased approach and utilized the *option to abandon* and *option to continue*. In addition, however, we accounted for the potential continuance of the refurbishment to include the second pair of reactors via an *option to expand*.

The static NPV valuation for the Pickering B alternative was neither overly positive nor negative with a 52% certainty of having a positive NPV. However, the mean NPV was –$8.1 million, meaning the project would have been rejected under the traditional approach. Incorporating managerial flexibility, though, increased the strategic value of the project. This was a particularly sizeable influence when the *option to expand* was accounted for. Yet, taking into account the expansion factor and costs, the expansion option was not always a favourable choice.

In general, we can conclude that the real options approach was able to effectively consider how a staged refurbishment process could be valuated. The *option to abandon* the project in the first two phases added a strategic value to the project, as did the *option to expand* the refurbishment to the second pair of reactors.

7.2 – Lessons Learned

Thanks to help from the Ontario Power Authority and various other organizations, we were able to gather authentic data for a substantial amount of the variables we utilized in our models. Though the real options approach is attractive and stimulating in its own right, we were able to apply actual numbers to real-life problems that exist in Ontario, making our approach even more beneficial. As such, the lessons we learned in applying this approach encompassed both general and specialized perspectives.

7.2.1 – Real Options in Energy Investments

In a general sense, we can deduce that the real options approach is certainly relevant to energy-related capital investment decisions. This is for a variety of reasons. Energy investments are

immense and complex undertakings, involving billions of dollars and countless inter-related decisions. Accordingly, they are driven by numerous variables, many of which are uncertain and hard to predict. Further, energy investment decisions are not "now or never decisions." For example, before the decision to construct a nuclear power plant is made, there is a significant amount of time devoted to research, technological studies, license procurement, planning, and so on. If, at some point in the earlier stages of the project, it is recognized that the project will be ultimately loss-making, the decision makers undoubtedly have the authority to abandon the project before more losses are incurred. This is where real options come in: traditional valuation techniques ignore this flexibility, whereas the real options methodology does not.

Though it may not be the be all and end all of valuation approaches, we have shown that the real options approach is quite valuable if used in a complimentary manner with other valuation techniques. From the various articles written on the spark spread phenomenon, it is apparent that the power of real options in operating decisions is established to some extent. The focus of our thesis, however, was on capital investment decisions in nuclear energy projects, and there is significantly less literature available on this particular topic. From our perspective, it is quite sensible to approach complex, multi-faceted energy investment decisions through the use of a real options approach, especially given that many markets worldwide are already, or will soon be, fully deregulated.

7.2.2. – Real Options in Ontario

As we have established throughout our thesis, the Ontario electricity market is in a quite special situation at the present time. Though we chose the particular focus of nuclear energy investment decisions in Ontario, the reality is that we could have applied a real options approach to most, if not all, of the electricity market decisions being made in Ontario at the present time.

Nuclear energy in Ontario has faced many problems in recent history. Both new construction and refurbishment projects have experienced serious cost overruns. More recently, the Pickering A refurbishment came under heavy criticism for its cost overruns, where it more than tripled initial cost estimates. From a real options perspective, it would be interesting to consider whether the Pickering A refurbishment would have been modified if a real options approach had been applied. Rather than

stubbornly carrying on with the overly expensive project, an option to abandon the project probably could have saved millions (if not billions) of dollars in the end.

As suggested by the OPA, designing an optimal supply mix is a challenging and complex task given that there isn't a single resource superior to others in all areas – namely, environmental impact, reliability, costs, and ability to effectively meet base, cycling and peak loads (OPA, 2005). This suggests that a employing a flexible, real options portfolio approach to the problem would be quite logical.

7.3 – Suggestions for Future Research

Our suggestions for future research in this area mostly stem from identifying specific problem areas and then contemplating how the real options methodology could be applied in an appropriate manner. From a theoretical perspective, however, we believe that there are a few questions that are as of yet unanswered. First of all, we believe it would be interesting to consider a flexible, real options approach to investing in a power plant with fuel-switching capabilities. Further, we find it rather surprising that nuclear refurbishment projects have not been valued using the real options technique, given the project type's special characteristics, which are rather ideal for an option approach.

In terms of applying the real options technique to Ontario-specific problems, there are a few general areas of interest. First of all, we would propose a flexible approach to the shut-down of the province's coal-fired generation. As stated previously, the end-date specified by the Ontario government has been changed a few times now, indicating that the choice to shut down coal-fired generation in such a short time may be more ideological than rational. With technology that limits coal emissions now available, "clean coal" technology is more of a reality now than in the past. We would propose a real options approach to valuing whether installing coal scrubbers and other "clean coal" technologies would be economically (and environmentally) feasible. The problem could be developed even further when accounting for emission costs.

As mentioned, a real options portfolio approach for the Ontario market would also be an interesting problem to undertake. Though the model would be complicated in terms of its design, the potential benefits of such a methodology would be potentially endless.

Lastly, we would suggest a further development of the Pickering B refurbishment case proposed in our study. With the Pickering A refurbishment cost overruns still lingering on the minds of many Ontario taxpayers, Ontario's decision makers simply cannot make another similar blunder. Given that one of the guiding principles the OPA identified in its Supply Mix Summary was *flexibility* – or the potential to adapt to changing conditions – we strongly believe that Ontario's decision makers should start utilizing the real options approach at this point in time.

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Appendix A

Multiple Uncertainties Valuation Techniques

Since it is derived from the theory of financial options, the real options methodology implicitly assumes that there is a single uncertainty affecting the option's value. However, more often than not, there are two or more random variables that influence the company's decision making process. For instance, when both investment costs (*I*) and the discounted value of future net revenues from the project (*R*) are uncertain, both the project value and the option to invest represent functions of two variables, *V(R,I)* and *F(R,I)* correspondingly.

Mathematically speaking, the valuation of such an option is understandably more complicated than if the uncertainty were caused by one parameter only. However, in some cases, a simplification of the problem is possible by reducing the task to one state variable. This technique was outlined by Dixit in his 1992 article "Investment and Hysteresis."

Both the project's revenues and the costs of investment are influenced by the same macroeconomic factors, which is illustrated by a non-zero correlation between them. Assuming that both random variables follow Geometric Brownian motion:

$$\frac{dR}{R} = \alpha_R dt + \sigma_R dz_R \quad (1)$$

$$\frac{dI}{I} = \alpha_I dt + \sigma_I dz_I \quad (2)$$

where

$$E\left[dz_R^2\right] = dt, \quad E\left[dz_I^2\right] = dt, \quad E\left[dz_R dz_I\right] = \rho\, dt \quad (3)$$

As soon as the investment is undertaken, the uncertainty in the costs of initial investment is irrelevant for the purposes of valuing optionality. The value of the project is equal to:

$$V(R) = \frac{R}{\mu_P - \sigma_P} \quad (4)$$

where

$$\mu = r + \phi \rho_{xm} \sigma \qquad (5)$$

and where

- μ_P is the risk-adjusted rate appropriate to R
- r is the risk-free interest rate
- ρ_{xm} is the discount rate
- ϕ is the market price of risk

Intuitively, it is clear that a project with higher future revenues and lower investment costs will be regarded to be more attractive. Considering that we have a portfolio of one unit of the option, m units short in the revenue and n units short in the investment costs, Dixit shows that we can imply Ito's Lemma to get the following result:

$$d(F - mR - nI) = (F_R - m)dR + (F_I - n)dI + \frac{1}{2}(F_{RR}\sigma_R^2 R^2 + 2F_{RI}\rho\sigma_R\sigma_I RI + F_{II}\sigma_I^2 I^2)dt \qquad (6)$$

By setting $m = F_R$ and $n = F_I$, we can make the portfolio riskless. The sure capital gain over the time interval from t to $t + dt$ is:

$$\frac{1}{2}(F_{RR}\sigma_R^2 R^2 + 2F_{RI}\rho\sigma_R\sigma_I RI + F_{II}\sigma_I^2 I^2)dt \qquad (7)$$

Since the investor also has to make a payment corresponding to the convenience yields on the revenue and the cost of investment in order to hold the short position, we can equate the riskless return on the portfolio and the sure capital gain less the payment for holding a short position:

$$\frac{1}{2}(F_{RR}\sigma_R^2 R^2 + 2F_{RI}\rho\sigma_R\sigma_I RI + F_{II}\sigma_I^2 I^2) + \qquad (8)$$
$$(r - (\mu_R - \alpha_R))RF_R + (r - (\mu_I - \alpha_I))IF_I - rF = 0$$

The option is immediately exercised when:

$$F(R,I) = V(R) - I = \frac{R}{\mu_R - \alpha_R} \qquad (9)$$

with the following boundaries:

$$F_R(R,I) = V'(R) = \frac{1}{\mu_R - \alpha_R}, \quad F_I = 1 \quad (10)$$

Some problems arise due to the unknown nature of the boundary conditions. This is because analytical solutions are rarely available, while numerical solutions are almost always extemporized. However, the problem in the present case can be characterized by the relevant homogeneity which allows us to reduce the uncertainty to one dimension.

If both future revenues and the costs of investment are doubled, the value of the project will double as well (the linear relationship, see *Equation (4)* in *Chapter 4*). The decision is therefore dependable on the ratio $p = \dfrac{R}{I}$ and the value of the option is:

$$F(R,I) = I\, f\left(\frac{R}{I}\right) = I\, f(p) \quad (11)$$

where *f(p)* is to be determined.

The differentiation results in:

$$F_R(R,I) = f'(p), \quad F_I(R,I) = f(p) - p\, f'(p), \quad (12)$$

By substituting the last two equations into equation (8), Dixit show that:

$$\frac{1}{2}(\sigma_R^2 - 2\rho\sigma_R\sigma_I + \sigma_I^2)p^2 f''(p) + ((\mu_I - \alpha_I) - (\mu_R - \alpha_R))pf'(p) - (\mu_I - \alpha_I)f(p) = 0 \quad (13)$$

The solution is:

$$f(p) = \frac{p}{\mu_R - \alpha_R} - 1 \quad (14)$$

with the following conditions:

$$f'(p) = \frac{1}{\mu_R - \alpha_R}, \quad f(p) - p\, f'(p) = -1 \quad (15)$$

Therefore, the fundamental quadratic is:

$$Q = \frac{1}{2}(\sigma_R^2 - 2\rho\sigma_R\sigma_I + \sigma_I^2)\beta(\beta - 1) + ((\mu_I - \alpha_I) - (\mu_R - \alpha_R))\beta - (\mu_I - \alpha_I) = 0 \quad (16)$$

Denoting β_1 as the larger root of the equation (16), Dixit illustrates that:

$$\frac{R*}{I*} = p* = \frac{\beta_1}{\beta_1 - 1}(\mu_R - \alpha_R) \quad (17)$$

The last equation defines the ray that separates the area of waiting from the area of investing in the space of (R,I). If either σ_R or σ_I decrease, both β_1 and the multiple $\beta_1/(\beta_1 - 1)$ will increase. Yet, the greater correlation between the revenues and the costs of investment results in less uncertainty over their ratio and subsequently reduces the value of waiting.

Appendix B

Value of Waiting

Based on (Dixit, 1992), the value of the postponing an investment, defined as Ω in *Chapter 4*, can be calculated according to the following principle:

$$\Omega = \begin{cases} B \cdot R^{\gamma} & if \ R \leq R^{*} \\ \dfrac{R}{\delta} - I & if \ R \geq R^{*} \end{cases} \quad (1)$$

where

- R is net revenues
- R^{*} is the trigger value for net revenues
- δ is the discount rate
- I is the initial investment
- B and γ are two constants whose introduction is helpful for the model's development.

In equation (1), B is a multiplicative constant that defines the condition when an investor is indifferent between investing and not investing, i.e. the value of waiting is equal to the value of investing immediately.

$$\frac{R^{*}}{\delta} - I = B \cdot R^{*\gamma} \implies \quad (2)$$

$$B = \left(\frac{R^{*}}{\delta} - I \right) / R^{*\gamma} \quad (3)$$

The calculation of parameter γ is based on the assumption that the plant's net revenues follow Geometric Brownian motion with a non-zero trend growth rate μ and a proportional variance per unit σ^2:

$$E[dR] = \mu R dt \quad (4)$$
$$Var[dR] = \sigma^2 R^2 dt \implies \quad (5)$$
$$E[dR^2] = (E[dR])^2 + Var[dR] = \mu^2 R^2 dt^2 + \sigma^2 R^2 dt \quad (6)$$

The expected value of waiting is therefore equal to:

$$E[d\Omega] = \Omega'(R)\,E[dR] + \frac{1}{2}\Omega''(R)E[dR^2]$$

$$= \Omega'(R)\mu\,R\,dt + \frac{1}{2}\Omega''(R)\left[\mu^2 R^2 dt^2 + \sigma^2 R^2 dt\right] \tag{7}$$

In equilibrium, the expected value of waiting should equal the normal return that is $\delta\Omega dt$:

$$\delta\,\Omega\,dt = \Omega'(R)\mu\,R\,dt + \frac{1}{2}\Omega''(R)\left[\mu^2 R^2 dt^2 + \sigma^2 R^2 dt\right] \tag{8}$$

By dividing both sides of the equation by dt and letting dt go to zero, we get:

$$\frac{1}{2}\sigma^2 R^2 \Omega''(R) + \mu\,R\,\Omega'(R) - \delta\,\Omega(R) = 0 \tag{9}$$

The positive value of waiting (assuming that B=1 for the sake of simplicity) is equal to:

$$\Omega(R) = R^\gamma \tag{10}$$

Therefore, substituting equation (10) into equation (9) gives the following result:

$$\frac{1}{2}\sigma^2\gamma(\gamma-1) + \mu\gamma - \delta = 0 \tag{11}$$

Assuming that the plant's future revenues show a zero growth rate and γ can take up only positive values, Dixit illustrates that the value of γ can be subsequently found as:

$$\gamma = \frac{1}{2} + \frac{1}{2}\sqrt{1 + \frac{8\delta}{\sigma^2}} \tag{12}$$

Appendix C

Sensitivity Analysis of Trigger Values

As shown in (Rothwell, 2005), the approximation of total construction costs depends on such uncertain variables as the capital recovery factor, the volatility of future revenues and the initial investment itself. Consequently, the size of this dependency can be evaluated by finding the appropriate elasticity parameters.

Changes in the discount rate (δ) will influence the construction cost (K) estimate and this effect can be expressed by the elasticity of K^* with respect to δ:

$$\varepsilon_{K,\delta} = \left\{ \delta \cdot \frac{\gamma}{\gamma-1} \cdot \frac{2}{\delta^2} \cdot \frac{1}{\gamma^2} \cdot (1+\frac{8\delta}{\sigma^2})^{-1/2} \right\} - 1 \quad (1)$$

Similarly, Rothwell shows that the elasticity of construction costs with respect to the volatility of future revenues (σ) can be found in the following way:

$$\varepsilon_{K,\sigma} = \left[\frac{-2\delta}{\sigma^2 \gamma(\gamma-1)} \right] \cdot \left[1 + \frac{8\delta}{\sigma^2} \right]^{-1/2} \quad (2)$$

The uncertainty in net revenues is described by the ratio $(\gamma-1)/\gamma$. Dividing the discount rate by this ratio, we obtain the discount factor that is adjusted to additional risk. By then subtracting the original discount rate from this value, Rothwell estimates the approximate risk premium (RP) embedded in the project:

$$RP = \frac{\delta\gamma}{\gamma-1} - \delta = \frac{\delta}{\gamma-1} \quad (3)$$

The elasticity of the risk premium with respect to the volatility of future net revenues can be found as such:

$$\varepsilon_{RP,\sigma} = \left[\frac{2\delta}{\sigma^2(\gamma-1)} \right] \cdot \left[1 + \frac{8\delta}{\sigma^2} \right]^{-1/2} \quad (4)$$

Appendix D

Table D.1 - Calculation of PV, NPV, FCF's for Enhanced CANDU 6

Year	0	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	21.5	22.5
MW plant		1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
MWh per year (max. dep. capacity)		13140000	13140000	13140000	13140000	13140000	13140000	13140000	13140000	13140000	13140000	13140000	13140000	13140000	13140000	13140000	13140000
GMB Price Forecast ($/MWh)		70	70.75	69.31	66.22	66.9	65.7	66.22	70.09	70.85	71.09	75.65	76.57	77.59	75.83	76.91	79.34
Commodity price ($/MWh)																	
Capacity Factor (%)																	
Revenue ($)																	
Fuel cost ($/MWh)		2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Variable OM&A ($/MWh)		3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Fixed OM&A (115$/kwyr)		13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13
Nuclear PUEC ($/MWh)		22.716	23.397	24.099	24.822	25.567	26.334	27.124	27.938	28.776	29.639	30.528	31.444	32.388	33.359	34.360	35.391
Total Nuclear PUEC ($)		298488240	307442887	316666174	326166159	335951144	346029678	356410568	367102886	378115972	389459451	401143235	413177532	425572858	438340044	451490245	465034952
FCF		-298488240	-307442887	-316666174	-326166159	-335951144	-346029678	-356410568	-367102886	-378115972	-389459451	-401143235	-413177532	-425572858	-438340044	-451490245	-465034952
WACC		0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085
Discount factor		0.5423	0.4999	0.4607	0.4246	0.3913	0.3607	0.3324	0.3064	0.2824	0.2603	0.2399	0.2211	0.2038	0.1878	0.1731	0.1595
PV of FCF		-161884098	-153677991	-145887863	-138492625	-131472262	-124807769	-118481108	-112475153	-106773648	-101361159	-96223036	-91345370	-86714960	-82319271	-78146404	-74185066

Year	23.5	24.5	25.5	26.5	27.5	28.5	29.5	30.5	31.5	32.5	33.5	34.5	35.5	36.5	37.5
MW plant	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
MWh per year (max. dep. capacity)	13140000	13140000	13140000	13140000	13140000	13140000	13140000	13140000	13140000	13140000	13140000	13140000	13140000	13140000	13140000
GMB Price Forecast ($/MWh)	78.27	77.21	74.75	73.22	70.35	71.42	71.93	70.42	68.63	69.5	72.06	72.71	70.45	69.6	68.56
Commodity price ($/MWh)															
Capacity Factor (%)															
Revenue ($)															
Fuel cost ($/MWh)	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Variable OM&A ($/MWh)	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Fixed OM&A (115$/kwyr)	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13
Nuclear PUEC ($/MWh)	36.453	37.546	38.672	39.833	41.028	42.258	43.526	44.832	46.177	47.562	48.989	50.459	51.973	53.532	55.138
Total Nuclear PUEC ($)	478986001	493355581	508156248	523400936	539102964	555276053	571934334	589092364	606765135	624968089	643717132	663028646	682919505	703407090	724509303
FCF	-478986001	-493355581	-508156248	-523400936	-539102964	-555276053	-571934334	-589092364	-606765135	-624968089	-643717132	-663028646	-682919505	-703407090	-724509303
WACC	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085
Discount factor	0.1470	0.1355	0.1249	0.1151	0.1061	0.0978	0.0901	0.0831	0.0766	0.0706	0.0650	0.0599	0.0552	0.0509	0.0469
PV of FCF	-70424533	-66854625	-63465681	-60248527	-57194454	-54295196	-51542905	-48930131	-46449802	-44095204	-41859963	-39738029	-37723659	-35811400	-33996075

Values in green cells are subject to assumptions. Values in blue cells are calculated by Crystal Ball

Table D.2 - Calculation of PV, NPV, FCF's for ACR-1000

year	0	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
MW plant		1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200
MWh per year		10512000	10512000	10512000	10512000	10512000	10512000	10512000	10512000	10512000	10512000	10512000	10512000	10512000	10512000	10512000
GMB Price Forecast ($/MWh)		70	70.75	69.31	66.22	66.9	65.7	66.22	70.09	70.85	71.09	75.65	76.57	77.59	75.83	76.91
Commodity price ($/MWh)																
Capacity Factor (%)																
Revenue ($)																
Fuel cost ($/MWh)		2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Variable OM&A ($/MWh)		3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Fixed OM&A (115$/kwyr)		13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13
Nuclear PUEC ($/MWh)		22.53	23.40	24.10	24.82	25.57	26.33	27.12	27.94	28.78	29.64	30.53	31.44	32.39	33.36	34.36
Total Nuclear PUEC ($)		236800670	245954310	253332939	260932927	268760915	276823742	285128455	293682308	302492778	311567561	320914588	330542025	340458286	350672035	361192196
FCF		-236800670	-245954310	-253332939	-260932927	-268760915	-276823742	-285128455	-293682308	-302492778	-311567561	-320914588	-330542025	-340458286	-350672035	-361192196
WACC		0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085
Discount factor		0.5649	0.5207	0.4799	0.4423	0.4076	0.3757	0.3463	0.3191	0.2941	0.2711	0.2499	0.2303	0.2122	0.1956	0.1803
PV of FCF		-133774939	-128060895	-121569329	-115406828	-109556712	-104003146	-98731097	-93726295	-88975193	-84464929	-80183297	-76118706	-72260154	-68597197	-65119920

year	0	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
MW plant		1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200
MWh per year		10512000	10512000	10512000	10512000	10512000	10512000	10512000	10512000	10512000	10512000	10512000	10512000	10512000	10512000	10512000
GMB Price Forecast ($/MWh)		79.34	78.27	77.21	74.75	73.22	70.35	71.42	71.93	70.42	68.63	69.5	72.06	72.71	70.45	69.6
Commodity price ($/MWh)																
Capacity Factor (%)																
Revenue ($)																
Fuel cost ($/MWh)		2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Variable OM&A ($/MWh)		3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Fixed OM&A (115$/kwyr)		13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13
Nuclear PUEC ($/MWh)		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Nuclear PUEC ($)																
FCF																
WACC		0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085
Discount factor		0.1662	0.1531	0.1412	0.1301	0.1199	0.1105	0.1019	0.0939	0.0865	0.0797	0.0735	0.0677	0.0624	0.0575	0.0530
PV of FCF																

Values in green cells are subject to assumptions. Values in blue cells are calculated by Crystal Ball

Table D.3 - Calculation of PV, NPV, FCF's for Pickering B

year	0	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
MW plant		1117	1117	1117	1117	1117	1117	1117	1117	1117	1117	1117	1117	1117	1117	1117
MWh per year		9784920	9784920	9784920	9784920	9784920	9784920	9784920	9784920	9784920	9784920	9784920	9784920	9784920	9784920	9784920
Commodity price ($/MWh)																
Capacity Factor (%)																
Revenue																
Fuel cost ($/MWh)		2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Variable OM&A ($/MWh)		3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Fixed OM&A (115$/kwyr)		15.44	15.44	15.44	15.44	15.44	15.44	15.44	15.44	15.44	15.44	15.44	15.44	15.44	15.44	15.44
Nuclear PUEC ($/MWh)																
Total Nuclear PUEC																
FCF																
WACC		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Discount factor		0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486
PV of FCF																

year	0	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
MW plant		1117	1117	1117	1117	1117	1117	1117	1117	1117	1117	1117	1117	1117	1117	1117
MWh per year		9784920	9784920	9784920	9784920	9784920	9784920	9784920	9784920	9784920	9784920	9784920	9784920	9784920	9784920	9784920
Commodity price ($/MWh)																
Capacity Factor (%)																
Revenue																
Fuel cost ($/MWh)		2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Variable OM&A ($/MWh)		3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Fixed OM&A (115$/kwyr)		15.44	15.44	15.44	15.44	15.44	15.44	15.44	15.44	15.44	15.44	15.44	15.44	15.44	15.44	15.44
Nuclear PUEC ($/MWh)																
Total Nuclear PUEC																
FCF																
WACC		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Discount factor		0.1351	0.1228	0.1117	0.1015	0.0923	0.0839	0.0763	0.0693	0.0630	0.0573	0.0521	0.0474	0.0431	0.0391	0.0356
PV of FCF																

Values in green cells are subject to assumptions. Values in blue cells are calculated by Crystal Ball

Table D.4 - Results from Monte Carlo Simulation of Electricity Prices for 30 years

Time	0	1	2	3	4	5	6	7	8	9	10
Average	70	70.75	69.31	67.22	66.9	65.7	66.22	70.09	70.85	71.09	75.65
Iteration 1	70	71.19	69.94	65.99	63.34	59.29	58.85	63.47	63.77	63.74	69.27
Iteration 2	70	72.49	67.14	67.28	69.39	72.04	70.57	76.69	79.65	81.28	86.09
Iteration 3	70	68.56	70.86	68.38	67.98	65.78	69.24	70.12	69.12	68.25	71.59

Time	0	11	12	13	14	15	16	17	18	19	20
Average	70	76.57	77.59	75.83	76.91	79.34	78.27	77.21	74.75	73.22	70.35
Iteration 1	70	66.85	65.93	65.15	63.46	63.49	60.39	60.51	65.47	65.9	69.87
Iteration 2	70	90.56	89.71	85.04	91.5	94.94	97.14	96.06	86.83	83.08	79.43
Iteration 3	70	72.29	77.14	77.29	75.77	79.6	77.29	75.05	71.95	70.68	61.76

Time	0	21	22	23	24	25	26	27	28	29	30
Average	70	71.42	71.93	70.42	68.63	69.5	72.06	72.71	70.45	69.6	68.56
Iteration 1	70	71.15	70.68	72.29	67.36	69.46	71.12	71.1	67.86	65.55	64.23
Iteration 2	70	79.52	78.68	74.27	72.29	73.49	76.91	76.9	73.84	78.04	76.91
Iteration 3	70	63.58	66.44	64.69	66.25	65.54	68.15	70.14	69.65	65.21	64.56

GBM Properties	
Mean	70
Drift	0.0009
Volatility	4.5

Appendix E

Figure E.1 - Binomial Valuation of V/I (PV of Nuclear Plant to Initial Investment) for Enhanced CANDU 6

Figure E.2 - Binomial Valuation of Construction Option for Enhanced CANDU 6

payoff = max(0; V/I - X III)
X = 0,908
σ = 3,0928%
r = 3,98%
T = 3 years
Δt = 0,1667
p = 0,76039

Time	Values (top to bottom)
0	0.1624
2m	0.1693, 0.1444
4m	0.1763, 0.1511, 0.1266
6m	0.1834, 0.1579, 0.1331, 0.1090
8m	0.1906, 0.1648, 0.1397, 0.1153, 0.0915
10m	0.1979, 0.1718, 0.1464, 0.1217, 0.0976, 0.0743
12m	0.2053, 0.1790, 0.1533, 0.1282, 0.1038, 0.0802, 0.0576
14m	0.2129, 0.1862, 0.1602, 0.1349, 0.1102, 0.0861, 0.0631, 0.0416
16m	0.2205, 0.1936, 0.1673, 0.1416, 0.1166, 0.0923, 0.0687, 0.0465, 0.0271
18m	0.2283, 0.2010, 0.1744, 0.1485, 0.1232, 0.0985, 0.0746, 0.0517, 0.0311, 0.0148
20m	0.2362, 0.2086, 0.1817, 0.1554, 0.1298, 0.1049, 0.0806, 0.0572, 0.0356, 0.0177, 0.0060
22m	0.2442, 0.2163, 0.1891, 0.1625, 0.1366, 0.1114, 0.0868, 0.0629, 0.0404, 0.0210, 0.0075, 0.0013
24m	0.2524, 0.2241, 0.1966, 0.1697, 0.1435, 0.1180, 0.0931, 0.0689, 0.0456, 0.0248, 0.0094, 0.0017, 0
26m	0.2607, 0.2321, 0.2042, 0.1770, 0.1505, 0.1247, 0.0995, 0.0749, 0.0512, 0.0292, 0.0117, 0.0023, 0, 0
28m	0.2690, 0.2401, 0.2119, 0.1844, 0.1576, 0.1315, 0.1060, 0.0812, 0.0570, 0.0340, 0.0146, 0.0030, 0, 0, 0
30m	0.2776, 0.2483, 0.2198, 0.1920, 0.1649, 0.1384, 0.1126, 0.0875, 0.0630, 0.0392, 0.0180, 0.0040, 0, 0, 0, 0
32m	0.2862, 0.2566, 0.2278, 0.1996, 0.1722, 0.1454, 0.1194, 0.0939, 0.0691, 0.0449, 0.0221, 0.0053, 0, 0, 0, 0, 0
34m	0.2950, 0.2651, 0.2359, 0.2074, 0.1797, 0.1526, 0.1262, 0.1005, 0.0754, 0.0509, 0.0270, 0.0070, 0, 0, 0, 0, 0, 0
36m	0.3039, 0.2737, 0.2441, 0.2153, 0.1872, 0.1598, 0.1331, 0.1071, 0.0817, 0.0570, 0.0328, 0.0093, 0, 0, 0, 0, 0, 0, 0

Terminal (36m) decision labels (top to bottom): continue, continue, continue, continue, continue, continue, continue, continue, continue, continue, continue, continue, abandon, abandon, abandon, abandon, abandon, abandon, abandon

Time axis: 2m 4m 6m 8m 10m 12m 14m 16m 18m 20m 22m 24m 26m 28m 30m 32m 34m 36m → Time (months)

Figure E.3 - Binomial Valuation of Licensing Option for Enhanced CANDU 6

						0,1345	continue
payoff = max(0;(V/I)c.o. - X II)					0,1275		
X = 0,0743				0,1205		0,1082	continue
T = 1 year			0,1137		0,1014		
Δt = 0,1667		0,1070		0,0948		0,0825	continue
	0,1004		0,0883		0,0760		
0,0940		0,0819		0,0697		0,0574	continue
	0,0756		0,0635		0,0513		
		0,0574		0,0452		0,0330	continue
			0,0395		0,0272		
				0,0222		0,0093	continue
					0,00707		
						0	abandon

2m   4m   6m   8m   10m   12m   Time

Figure E.4 - Binomial Valuation of V/I (PV of Nuclear Plant to Initial Investment) for ACR-1000

V = 2 309 511 812
I = 2 185 536 017
σ = 3,7736%
r = 3,98%
T = 3 years
Δt = 0,1667
u = 1,01553
d = 0,98471

Figure E.5 - Binomial Valuation of Construction Option for ACR-1000

payoff = max(0; V/I - X_III)
X = 0,858158
σ = 3,7736%
r = 3,98%
T = 3 years
Δt = 0,1667
p = 0,71215

0.5328 continue
0.5177
0.5028 0.4905 continue
0.4882 0.4760
0.4739 0.4617 0.4494 continue
0.4598 0.4477 0.4355
0.4460 0.4340 0.4219 0.4097 continue
0.4324 0.4204 0.4084 0.3963
0.4190 0.4072 0.3952 0.3832 0.3711 continue
0.4058 0.3941 0.3823 0.3703 0.3583
0.3929 0.3813 0.3695 0.3577 0.3457 0.3337 continue
0.3802 0.3687 0.3570 0.3453 0.3334 0.3214
0.3678 0.3563 0.3447 0.3330 0.3213 0.3094 0.2974 continue
0.3555 0.3441 0.3326 0.3210 0.3094 0.2976 0.2857
0.3435 0.3322 0.3208 0.3093 0.2977 0.2860 0.2742 0.2622 continue
0.3316 0.3204 0.3091 0.2977 0.2862 0.2746 0.2628 0.2510
0.3200 0.3089 0.2977 0.2863 0.2749 0.2634 0.2517 0.2400 0.2281 continue
0.3086 0.2976 0.2864 0.2752 0.2638 0.2524 0.2408 0.2292 0.2174
0.2974 0.2864 0.2754 0.2642 0.2529 0.2416 0.2301 0.2185 0.2069 0.1951 continue
0.2755 0.2645 0.2534 0.2422 0.2309 0.2196 0.2081 0.1965 0.1848
0.2538 0.2428 0.2317 0.2205 0.2092 0.1978 0.1863 0.1747 0.1630 continue
0.2324 0.2214 0.2103 0.1991 0.1878 0.1763 0.1648 0.1532
0.2113 0.2003 0.1891 0.1779 0.1666 0.1551 0.1436 0.1319 continue
0.1904 0.1793 0.1682 0.1569 0.1456 0.1341 0.1226
0.1698 0.1587 0.1475 0.1362 0.1248 0.1134 0.1018 continue
0.1493 0.1382 0.1270 0.1157 0.1043 0.0928
0.1292 0.1180 0.1068 0.0955 0.0841 0.0725 continue
0.1092 0.0981 0.0868 0.0755 0.0640
0.0896 0.0784 0.0671 0.0557 0.0442 continue
0.0702 0.0591 0.0477 0.0361
0.0515 0.0403 0.0289 0.0167 continue
0.0337 0.0229 0.0118
0.0179 0.0084 0 abandon
0.0059 0
0 0 abandon
0
0 abandon

Time (months): 2m 4m 6m 8m 10m 12m 14m 16m 18m 20m 22m 24m 26m 28m 30m 32m 34m 36m

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Figure E.6 - Binomial Valuation of Licensing Option for ACR-1000

payoff = max(0;(V/I)c.o. - XII)						0,2533	continue
X = 0,119					0,2417		
T = 1 year				0,2303		0,2177	continue
Δt = 0,1667			0,2191		0,2066		
		0,2081		0,1957		0,1832	continue
	0,1973		0,1850		0,1726		
0,1867		0,1745		0,1622		0,1497	continue
	0,1642		0,1519		0,1396		
		0,1419		0,1296		0,1173	continue
			0,1199		0,1076		
				0,0981		0,0858	continue
					0,0766		
						0,0553	continue

$payoff = max(0;(V/I)_{c.o.} - XII)$
$X = 0,119$
$T = 1\ year$
$\Delta t = 0,1667$

2m   4m   6m   8m   10m   12m   Time

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Figure E.7 - Binomial Valuation of V/I (PV of Nuclear Reactors to Initial Investment) for Pickering B

V = 2 142 897 383
I = 2 142 897 383
σ = 3%
r = 3,98%
T = 7,5 years
Δt = 0,5
u = 1,02757
d = 0,97317

Figure E.8 - Binomial Valuation of Option to Expand for Pickering B

payoff = max(V/I;exp.factor*V/I - exp.costs)
exp. factor = 1,85
exp. costs =0,95
σ = 3%
r = 3,98%
T = 7,5 years
Δt = 0,5
p = 0,96841

6m	12m	18m	24m	30m	36m	42m	48m	54m	60m	66m	72m	78m	84m	90m	
														1.5931	expand
													1.5584		
												1.5245		1.4875	expand
											1.4914		1.455		
										1.4589		1.4233		1.3862	expand
									1.4272		1.3922		1.3559		
								1.3961		1.3619		1.3262		1.2892	expand
							1.3657		1.3321		1.2972		1.2609		
						1.336		1.3031		1.2688		1.2332		1.1962	expand
					1.3069		1.2746		1.2411		1.2062		1.17		
				1.2784		1.2468		1.2139		1.1797		1.1444		1.1119	do not expand
			1.2506		1.2196		1.1874		1.1539		1.1194		1.0886		
		1.2234		1.193		1.1614		1.1286		1.095		1.0657		1.0657	do not expand
	1.1967		1.1669		1.136		1.1038		1.0712		1.0433		1.0433		
1.1707		1.1415		1.1111		1.0796		1.0478		1.0214		1.0214		1.0214	do not expand
	1.1166		1.0868		1.056		1.0251		1.0000		1.0000		1.0000		
1.0922		1.063		1.0329		1.0028		0.979		0.979		0.979		0.979	do not expand
	1.0397		1.0102		0.9811		0.9585		0.9585		0.9585		0.9585		
		0.9881		0.9598		0.9383		0.9383		0.9383		0.9383		0.9383	do not expand
			0.939		0.9186		0.9186		0.9186		0.9186		0.9186		
				0.8994		0.8994		0.8994		0.8994		0.8994		0.8994	do not expand
					0.8805		0.8805		0.8805		0.8805		0.8805		
						0.862		0.862		0.862		0.862		0.862	do not expand
							0.8439		0.8439		0.8439		0.8439		
								0.8262		0.8262		0.8262		0.8262	do not expand
									0.8089		0.8089		0.8089		
										0.7919		0.7919		0.7919	do not expand
											0.7753		0.7753		
												0.759		0.759	do not expand
													0.7431		
														0.7275	do not expand

1.1452

Time (months)

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Figure E.9 - Binomial Valuation of Refurbishment Option for Pickering B

payoff = max(0;(V/I)exp.o. - X_{III})
X = 0,85587
T = 4 years
Δt = 0,5

6m	12m	18m	24m	30m	36m	42m	48m	
							0,47543	continue
						0,46324		
					0,45135		0,38437	continue
				0,43976		0,37409		
			0,42845		0,36408		0,2971	continue
		0,41741		0,35431		0,28866		
	0,40665		0,3448		0,28044		0,21355	continue
0,39616		0,33552		0,27243		0,20691		
(0,38592)	0,32648		0,26464		0,20045		0,1348	continue
0,31767		0,25706		0,19418		0,13008		
	0,24967		0,18809		0,12552		0,06819	continue
		0,18218		0,12111		0,06561		
			0,11685		0,06312		0,02838	continue
				0,06072		0,02694		
					0,02557		0	abandon
						0		
							0	abandon

Time

Table E.10 - Binomial Valuation of Planning Option for Pickering B

payoff = max(0;(V/I)r.o. - X_{II})
X = 0,119

0m	6m	12m	18m	24m	
				0,34289	continue
			0,33354		
		0,32443		0,25924	continue
	0,31556		0,25165		
(0,30691)		0,24426		0,17908	continue
	0,23707		0,17318		
		0,16745		0,10253	continue
			0,09831		
				0,03129	continue

Time

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Figure E.11 - Binomial Valuation of Refurbishment Option for Pickering B (without considering Option to Expand)

```
                                                                    0,29469    continue
        payoff = max(0;(V/I) - XIII)                     0,28736
        X = 0,85587                            0,2802              0,38437    continue
        T = 4 years                0,27322             0,23917
        Δt = 0,5          0,26641              0,23302             0,19829    continue
                  0,25976              0,22703             0,19298
          0,25327              0,22119             0,18781             0,21355    continue
    0,24693              0,21549             0,18276             0,14871
0,24075              0,20993             0,17785             0,14447             0,10973    continue
    0,2045               0,17306             0,14033             0,10628
          0,16839              0,13631             0,10293             0,06819    continue
                  0,13239              0,09967             0,06561
                          0,0965              0,06312             0,02838    continue
                                  0,06072             0,02694
                                          0,02557                     0     abandon
                                                            0
                                                                     0      abandon

        6m        12m       18m       24m       30m       36m       42m       48m      Time
```
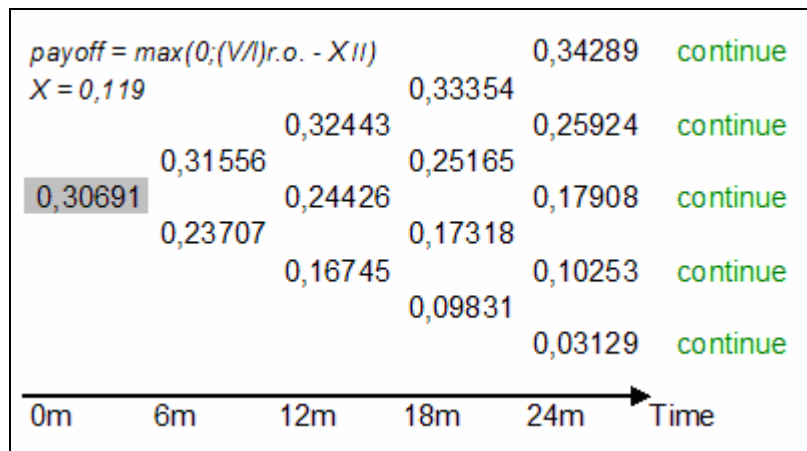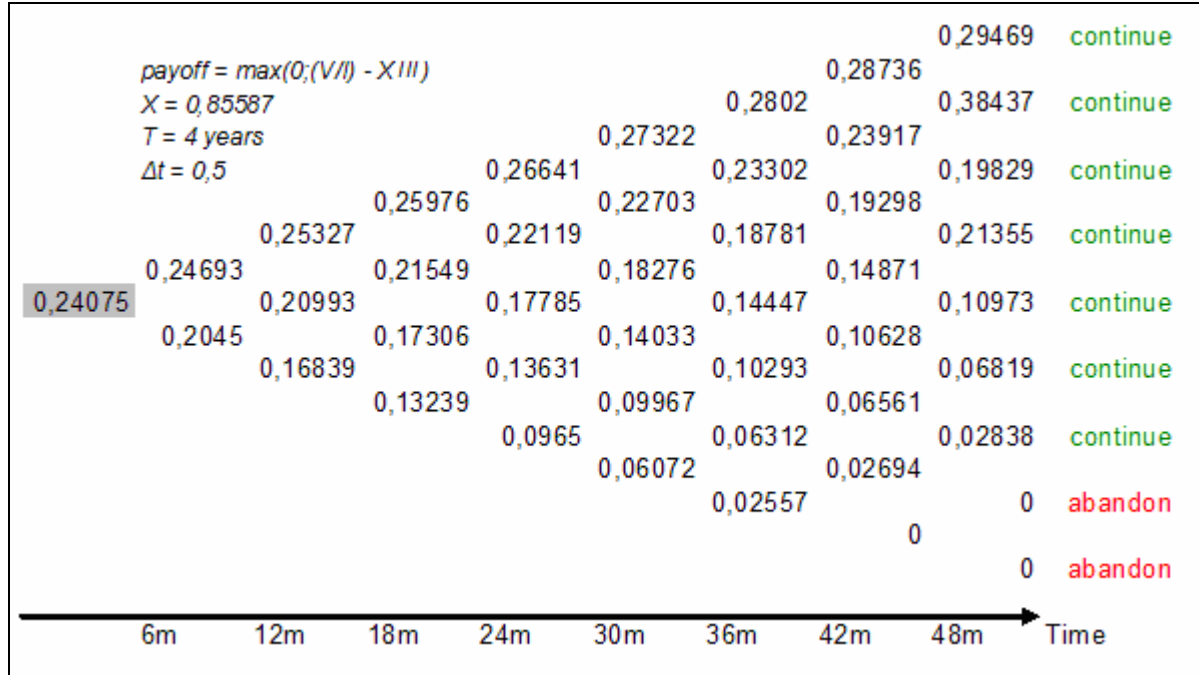
Figure E.12 - Binomial Valuation of Planning Option for Pickering B (without considering Option to Expand)

```
    payoff = max(0;(V/I)r.o. - XII)         0,18085    continue
    X = 0,119                    0,17588
                      0,17105             0,13563    continue
            0,16633              0,13161
0,16174              0,12771             0,09229    continue
        0,1239               0,08918
                0,08617             0,05075    continue
                        0,04852
                                0,01094    continue

0m        6m       12m       18m       24m      Time
```

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