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ESD.71: Engineering Systems Analysis for Design
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Real Options Application Portfolio

The Potential of Nuclear Power in Portugal:
Determining If and When To Include Nuclear Power in Portugal's Energy Supply Portfolio

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ABSTRACT

This application portfolio presents a Real Options analysis that helps understand if and when nuclear energy should be introduced into Portugal's energy portfolio mix given uncertainties in the price of natural gas and the potential introduction of carbon taxes. Portugal is significantly dependent on fossil fuel imports and at present does not have any nuclear power capabilities. The European Union, however, has established as common objectives "sustainable development, competitiveness, and security of supply" as basis for a European Energy Policy framework. Nuclear power could be an interesting alternative that would contribute to Portugal achieving these objectives.

We consider two different systems, one fixed, the other flexible. The first consists of a large natural gas turbine combined cycle (NGCC) power plant with a production capacity of 1000 MWe and no potential for growth. The flexible system consists of a smaller NGCC power plant with a production capacity of 750 MWe and the embedded potential for growth through different alternatives. These include expanding its NGCC production capabilities, developing nuclear power capabilities to create a hybrid system, or a mixture of both.

These alternative designs are evaluated first, by using a two-stage decision analysis, and second, by using a lattice analysis. The two-stage decision analysis evaluates which of the two designs is preferable. Given the assumptions made for the purposes of this exercise, I found that the flexible design is desirable, and that one would generally opt for expanding the system by adding nuclear power production capabilities to it. This first analysis also illustrated the effect of carbon taxes on the system, showing that the implementation of these taxes makes nuclear power a more attractive choice.

The lattice analysis gives the opportunity to explore when the fixed 1000 MWe NGCC power plant would be forced to shut down given the uncertainty in natural gas prices, and therefore identify when a put option on the system would be valuable. Unless the price of natural gas suddenly increases to more than twice its current price of US$ 7 per mmBTU, the option to shut down the plant has no value for the case under consideration because it would not be exercised. The lattice analysis was also useful in determining when a call option in the system would be desirable. I compared the net revenue of the flexible 750 MWe NGCC power plant with the same system after expansion has occurred through an added 500 MWe of nuclear potential. I found that the call option is worth acquiring in order to take advantage of the upside potential of the system.

The main goal of this project was to explore different approaches to valuing flexibility in the design of a system. This was achieved by using both the two-stage decision analysis and the lattice analysis to evaluate the various design alternatives. The results show that flexibility is generally a desired characteristic in the system, for it allows both to avoid downside risk and to take advantage of upside potential. The exercise was also useful in identifying the strengths and weaknesses of these two types of analyses.

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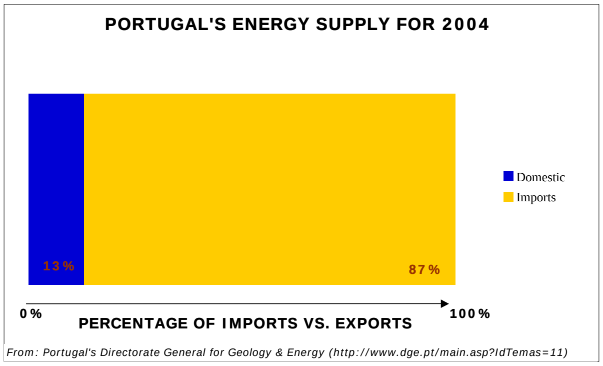
1. DEFINING THE SYSTEM

Is nuclear power technology a viable option for Portugal to address its future energy needs and reduce its emissions of greenhouse gases (GHG)? If so, how can the country best introduce this particular technology to its energy portfolio mix? To answer these questions I will use real options analysis to determine when a switch to nuclear power from natural gas would be economically viable given uncertainties in the political and economical spheres, through carbon taxes and the price of natural gas, respectively.

1.1 Context

Figure 1.1 shows Portugal's dependence on energy supply imports, which account for almost 87% of the country's energy needs. Most of the country's supply comes from fossil fuels – oil in particular (see Figure 2.1). At present, Portugal does not have any nuclear energy capabilities. Portugal's lack of nuclear capabilities sharply contrasts with that of the European Union (EU), particularly since the largest electricity contribution in the EU in 2003 came from nuclear power (21% of installed capacity and 33% of electricity production).[1] An interest in developing these capabilities has been expressed in Portugal, but no action has been taken up to date.[2]

Portugal's future energy and environment policy scenario must be explored in the context of its membership in the EU. The EU has set as targets an increase in the renewable energy technologies' share of electricity production to 22.1% by 2010, coupled with the integration and liberalization of the European electricity market.[3] Furthermore, it has established as common objectives "sustainable development, competitiveness, and security of supply" as basis for a European Energy Policy framework.[4] It is also important to mention that Spain and Portugal are working on merging their electricity markets to conform the Iberian Electricity Market (MIBEL).



From: Portugal's Directorate General for Geology & Energy (http://www.dge.pt/main.asp?IdTemas=11)

Figure 1.1: Portugal's Energy Supply Imports & Exports for 2004.[5]

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[1] Euratom Supply Agency Advisory Committee Task Force on Security and Supply. Final Report of the Task Force. June 2005 [http://ec.europa.eu/euratom/docs/task_force_2005.pdf, last viewed 10/02/06]

[2] EIA Country Analysis Brief [http://www.eia.doe.gov/emeu/cabs/portugal.html, last viewed 10/02/06]

[3] EIA Country Analysis Brief [http://www.eia.doe.gov/emeu/cabs/portugal.html, last viewed 10/02/06]

[4] [http://ec.europa.eu/euratom/ar/ar2005.pdf, last viewed 10/02/06

[5] Portugal's Directorate General for Geology & Energy [http://www.dge.pt/main.asp?IdTemas=11, last viewed 10/02/06]

1.2 System Concepts

To address the question of when and how it would be convenient for Portugal to introduce nuclear power to its energy portfolio, I consider two different system concepts:

1. Fixed System:
   Building a large natural gas turbine combined cycle (NGCC) power plant, with no potential for growth. The production capacity of the large NGCC power plant is set to be 1000 MWe.

2. Flexible System:
   Building a small NGCC power plant, with a production capacity of 750 MWe, with potential for growth in the future through either of the following alternatives:
      i. Expanding after three years the NGCC capabilities by 500 MWe
      ii. Expanding after three years by combining 250 MWe of NGCC with 250 MWe of nuclear power
      iii. Expanding production capacity after three years with 500 MWe of nuclear production capacity, or
      iv. Maintaining original size.

As was mentioned earlier, I will examine which of these choices is the best option based on the future price of natural gas and the potential introduction of carbon taxes. It is expected that a high price of natural gas, coupled with an expensive carbon tax, will be conducive to making nuclear power a more attractive energy production option in Portugal, as elsewhere.

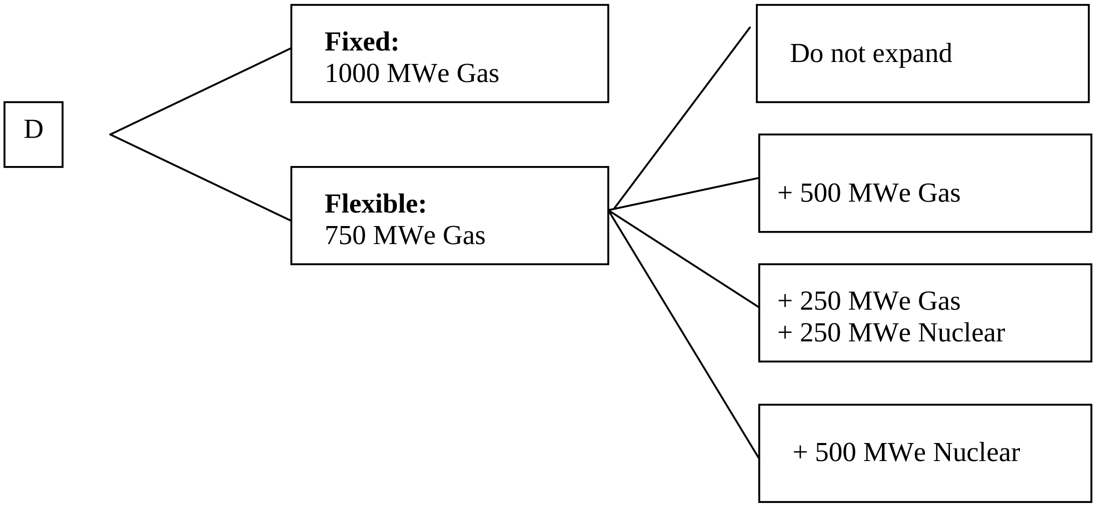


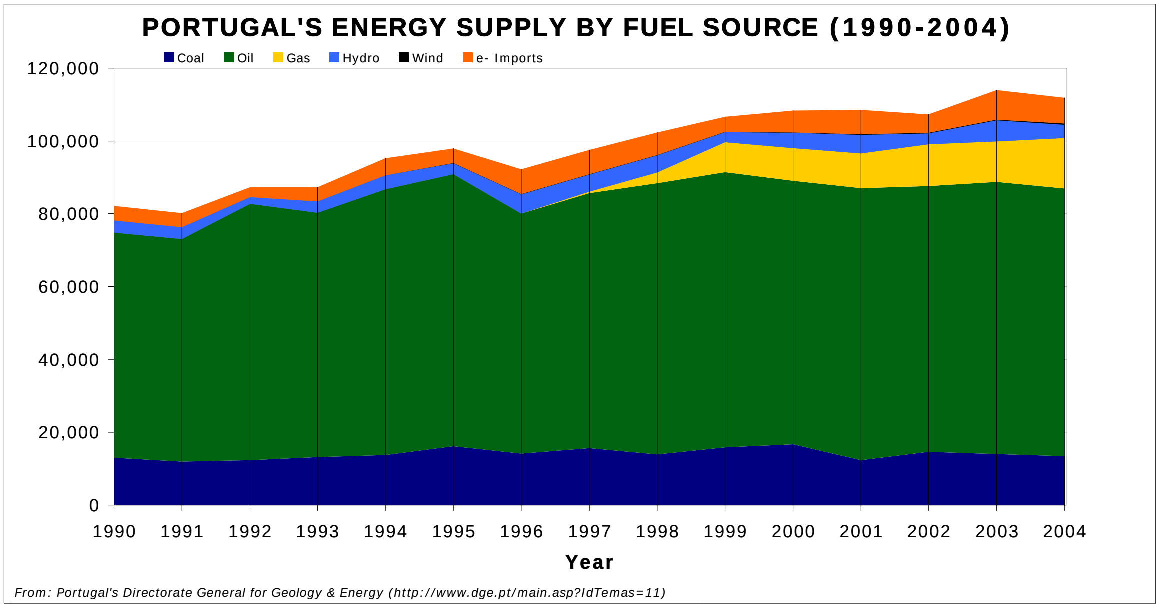
Figure 1.2: Diagram of System Design Choices

2. DEFINING THE SALIENT UNCERTAINTIES

In this section we define the major uncertainties relevant to the system under consideration. The system's overall performance is subject to various categories of uncertainty. What follows is a description of some of the uncertainties that affect the natural gas and nuclear power systems in question, and that will likely influence the deployment strategy for nuclear capabilities in Portugal. I also include a discussion of how each uncertainty will be treated.

2.1 Future demand for electrical power

Figure 2.1 shows the current fuel sources of Portugal's energy supply. It is evident that Portugal is significantly dependent on fossil fuels (oil in particular), and that the energy demand in the country is increasing (which leads to an increase in imports and energy supply balance). One can see that the role of natural gas as a source of energy in Portugal has also been increasing in the last couple of years. At the moment, the contribution from renewable energy resources to the supply mix is small. Portugal is aiming at increasing its wind and solar energy capabilities in order to meet the required renewable-produced electricity targets of the EU, however. The demand for electrical power from pure or hybrid nuclear energy plants will depend not only on the total demand for electrical power, but also on how much renewable energy technologies contribute to meeting the country's increasing energy demand in the future, and on how much traditional sources continue to contribute to Portugal's energy supply.


PORTUGAL'S ENERGY SUPPLY BY FUEL SOURCE (1990-2004)

From: Portugal's Directorate General for Geology & Energy (http://www.dge.pt/main.asp?IdTemas=11)

Figure 2.1: Portugal's Energy Supply by Fuel Source, 1990 - 2004.[6]

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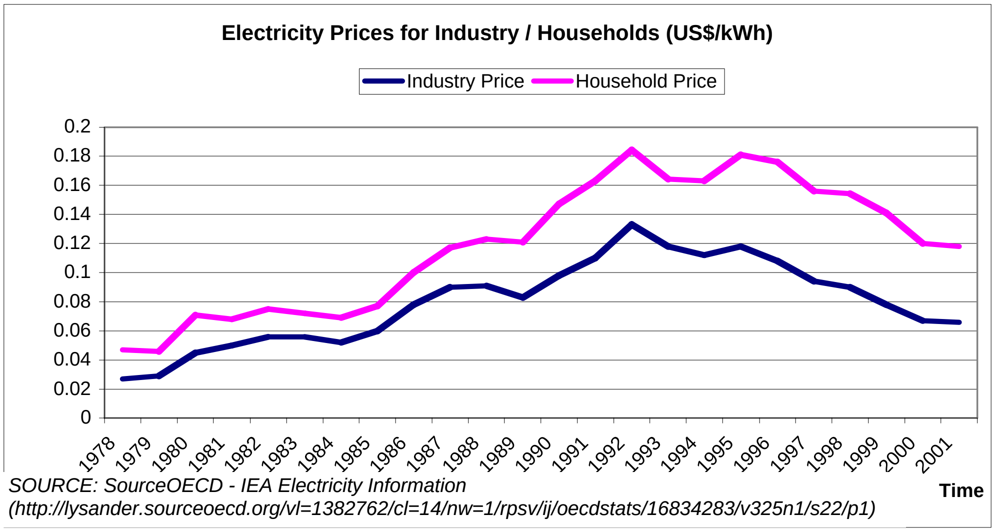
[6] Portugal's Directorate General for Geology & Energy [http://www.dge.pt/main.asp?IdTemas=11, last viewed 10/02/06]

For the purposes of this exercise, and based on the International Energy Agency's World Energy Outlook 2004 prediction that world primary energy demand will expand by almost 60% by 2030[7], I assume that the different system options considered here will enjoy sufficient demand for the electricity they produce, and that energy demand will increase linearly. In MIT's interdisciplinary study "The Future of Nuclear Power"[8] it is estimated that electricity consumption in Portugal will increase from 41.1 billion kWhrs to 61 billion kWhrs between 2000 and 2050, which is equivalent to a linear annual growth in electricity consumption of 0.4 billion kWh per year. The current contribution of natural gas to Portugal's energy supply is of 12%[9], and as shown in Figure 3, it is growing. For this exercise I am assuming 20% of the electricity demand will be met by natural gas.

2.2 Cost of Electricity

The cost of electricity is an important uncertainty variable because it directly affects the system's revenue throughout its lifetime. Figure 2.2 shows what the price of electricity in Portugal was between 1978 and 2001. For the analysis of the two possible scenarios, we take the electricity price to be US$ 0.14 per kWh. The future liberalization of the electricity market will have an effect on the cost of electricity, and it is unlikely to remain equal to US$ 0.14 per kWh. In order to keep this project of a manageable size, however, I assume it will remain the same for the time period under consideration.



SOURCE: SourceOECD - IEA Electricity Information (http://lysander.sourceoecd.org/vl=1382762/cl=14/nw=1/rpsv/ij/oecdstats/16834283/v325n1/s22/p1)

Figure 2.2: Electricity Prices in Portugal, 1978 - 2001.[10]

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[7] International Energy Agency. World Energy Outlook 2004. Page 31.

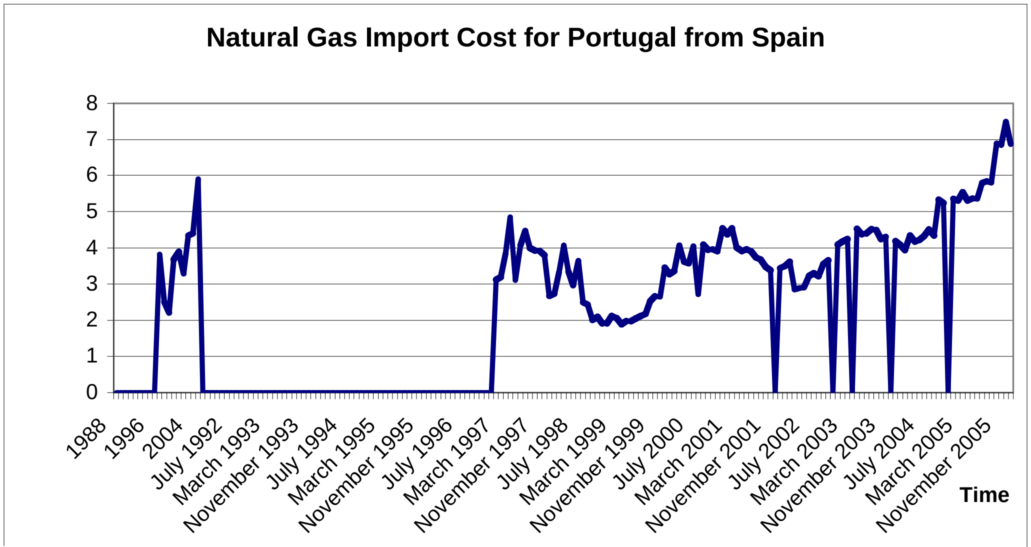
[8] MIT. "The Future of Nuclear Power – An Interdisciplinary Study" Appendix Chapter 5

[9] Entidade Reguladora dos Serviços Energéticos: http://www.erse.pt/vpt/entrada/factosenumeros/enquadramentoenergetico/estruturadaenergiaprimariaem2003/estruturadaenergiaprimariaem2003.htm (last viewed 10/27/06)

[10] SourceOECD – IEA Electricity Information [http://lysander.sourceoecd.org/vl=1382762/cl=14/nw=1/rpsv/ij/oecdstats/16834283/v325n1/s22/p1, last viewed 10/03/06]

2.3 Prices of Natural gas

The price of natural gas will have a significant influence on the economic viability of each system possibility. As shown in Figure 2.3, the price of natural gas has been increasing in the last couple of years, and has shown variability in the last 5 years of between US$3 and US$7 per MBtu. For the purposes of this analysis exercise, I take the current price of natural gas to be US$7.



SOURCE: SourceOECD - IEA Energy Prices and Taxes
(http://puck.sourceoecd.org/vl=1414725/cl=25/nw=1/rpsv/ij/oecdstats/1683626x/v345n1/s10/p1)

Figure 2.3: Natural Gas Import Cost for Portugal from Spain, 1988 - 2005.[11]

2.4 Government Intervention

The principal form of government intervention we are concerned with in this analysis is the introduction of carbon taxes. By implementing these, the government would be improving the competitiveness of nuclear power and making the flexible design pathway more attractive. We consider this possibility by examining the effect of what a carbon tax of US$ 100 and US$ 200 per tonne-C would have on the system. These values are based on the carbon taxes implemented by Sweden since 1991 (Sweden originally introduced a tax of US$ 100 per ton, and in 1997 raised it to US$ 150), and are used to understand the effect such a policy would have on the competitiveness of each system.

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[11] SourceOECD – IEA Energy Prices & Taxes [http://puck.sourceoecd.org/vl=1414725/cl=25/nw=1/rpsv/ij/oecdstats/1683626x/v345n1/s10/p1, last viewed 10/03/06]

3. DEFINING SYSTEM DESIGN TO BE ANALYSED

I will use the base case input parameters presented in MIT's interdisciplinary study on "The Future of Nuclear Power"[12] for both NGCC and nuclear electricity generation options. These figures are presented in Table 3.1:

Parameter	**Units**	**NGCC**	**Nuclear**
Overnight Cost	*US$ / kWe*	500	2,000
Fuel Cost	*US$ / mmBTU*	Varies	0.47
Fixed O&M	*US$ / kWe / yr*	16	63
Variable O&M	*US$ millions / kWh*	0.52	0.47
Plant Life	*Years*	40	40
Heat Rate	*BTU/kWh*	7200	10400
Carbon Intensity of Fuel	*Kg-C/mmBTU*	14.5	-

Table 3.1: Input Parameters for NGCC and Nuclear Power Plant

For the purposes of this exercise, it is assumed that the cost of electricity in Portugal will remain close to the present value of approximately US$ 0.14 per kWh. The future liberalization of the electricity market will have an effect on the cost of electricity, and this is unlikely to remain constant in reality. The scope of this project is too narrow to consider such variability, however, and future work is necessary to study how the uncertainty in price of electricity will affect the systems under examination.

The uncertainty considered in this exercise is the cost of electricity production based on the cost of natural gas and the possible implementation of carbon taxes. I consider the possibilities of the cost of natural gas remaining at approximately the same value of today, which based on the information presented above is of US$ 7 per mmBTU, or increasing to US$ 8 per mmBTU or US$ 9 per mmBTU This range is a direct result of the outcome lattice developed to model the uncertainty of natural gas prices (Section 5.2). It will be shown that natural gas prices are likely to increase in the future by US$ 1 to US$ 2.

I also consider the possible implementation one year after the plant has been operational of a Carbon Tax of either US$ 100 or US$ 200 per tonne-C. As was mentioned earlier, these values are based on the carbon taxes implemented by Sweden since 1991 (Sweden originally introduced a tax of US$ 100 per ton, and in 1997 raised it to US$ 150), and are used to understand the effect such a policy would have on the competitiveness of each system.

3.1 Assessing Economic Competitiveness

In order to evaluate the different design options I calculated the net present value (NPV) of each one in an Excel worksheet. Table 3.2 shows the inputs used in the worksheet. As was indicated earlier, the input values are largely based on those presented in MIT's interdisciplinary study on The Future of Nuclear Power. The only exceptions are the

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[12] Beckjord, Eric, et al. The Future of Nuclear Power – An Interdisciplinary MIT Study. United States. Massachusetts Institute of Technology (2003)

percentage contribution of natural gas to meeting Portugal’s supply, which was obtained from Portugal’s Energy Services Regulatory Agency[13], and the variable inputs of the price of natural gas and the carbon taxes. Table 3.3 shows the worksheet for years 0, 5 and 10 for the case of the small plant NGCC plant with no added production capabilities.

Price of Electricity	US$ / kWh	0.14
Overnight Costs		
Overnight Cost NGCC	US$/kWe	500
Overnight Cost Nuclear	US$/kWe	2000
NGCC-Specific Characteristics		
Heat Rate	BTU/kWh	7200
Carbon Intensity of Fuel	kg-C/mmBTU	14.5
Nuclear-Specific Characteristics		
Heat Rate	BTU/kWh	10400
Operating Expenses		
Carbon Emissions Tax	US$ / tonne-C	100
Fuel Cost: Gas	US$ / mmBTU	7
Fuel Cost: Uranium	US$ / mmBTU	0.47
Fixed O&M: Gas	US$ / kWe / yr	16
Fixed O&M: Nuclear	US$ / kWe / yr	63
Variable O&M: Gas	mills / kWh	0.52
Variable O&M: Nuclear	mills / kWh	0.47
Discount Rate		0.15
Inflation		0.02

Table 3.2: Input Values for NPV Worksheet

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[13] Entidade Reguladora de Serviços Energéticos, ERSE [http://www.erse.pt/vpt/entrada/factosenumeros/enquadramentoenergetico/estruturadaenergiaprimariaem2003/estruturadaenergiaprimariaem2003.htm, last viewed 12/11/2006]

Year		0	5	10
Actual Demand	TWh/year	41.1	43.1	45.1
Demand for Electricity from Natural Gas	TWh/yr	8.22	8.62	9.02
Price of Electricity	US$ / kWh	0.14	0.14	0.14
Original Plant Size				
Natural Gas Production Capacity	MWe	750	750	750
Additions to Original Plant				
Increased Natural Gas Production Capacity	MWe	0	500	500
Added Nuclear Production Capacity	MWe	0	0	0
Total Production Potential	TWh / year	0	10.95	10.95
Total Actual Production	TWh / year	0	8.62	9.02
Overnight Costs	US$ million	375.00	0.00	0.00
Carbon Tax				
Carbon Tax	US$ million / yr	0.00	89.99	94.17
Implemented?	1 = yes, 0 = no	0	1	1
Operating Expenses				
Fuel Cost: Gas	US$ million / yr	0.00	616.71	712.50
Fixed O&M: Gas	US$ million / yr	0.00	20.00	20.00
Variable O&M: Gas	US$ million / yr	0.00	4.48	4.69
Fuel Cost: Uranium	US$ million / yr	0.00	0.00	0.00
Fixed O&M: Nuclear	US$ million / yr	0.00	0.00	0.00
Variable O&M: Nuclear	US$ million / yr	0.00	0.00	0.00
TOTAL EXPENSES	US$ million / yr	375.00	731.19	831.36
Revenue	US$ million / yr	-375.00	475.61	431.44
Discounting Factor		1.00	2.01	4.05
Present Value	US$ million	-375.00	236.46	106.65
Net Present Value (NPV)	US$ million	1621.02		

Table 3.3: Sample from NPV Worksheet

4. TWO-STAGE DECISION ANALYSIS OF ALTERNATIVE DESIGNS

Using the inputs and NPV worksheets introduced in Section 3 of this report, I developed a decision analysis tree to estimate the expected values and optimal strategy over two periods by carrying out a two-stage decision analysis of the alternative designs.

In order to calculate the expected values of each different design option, and for the purposes of this exercise, I randomly assigned probability values for the uncertain factors under consideration. These are presented in Tables 4.1 and 4.2. The probabilities used to determine the likelihood of the three different natural gas prices considered are roughly based on the uncertainty model developed by lattice and the resulting natural gas price probability distribution function for a period of 10 years, presented in Section 5 (Figure 5.1).

Gas Price (US$ / mmBTU)	Probability
7	0.3
8	0.5
9	0.2

Table 4.1: Probability of Future Gas Prices

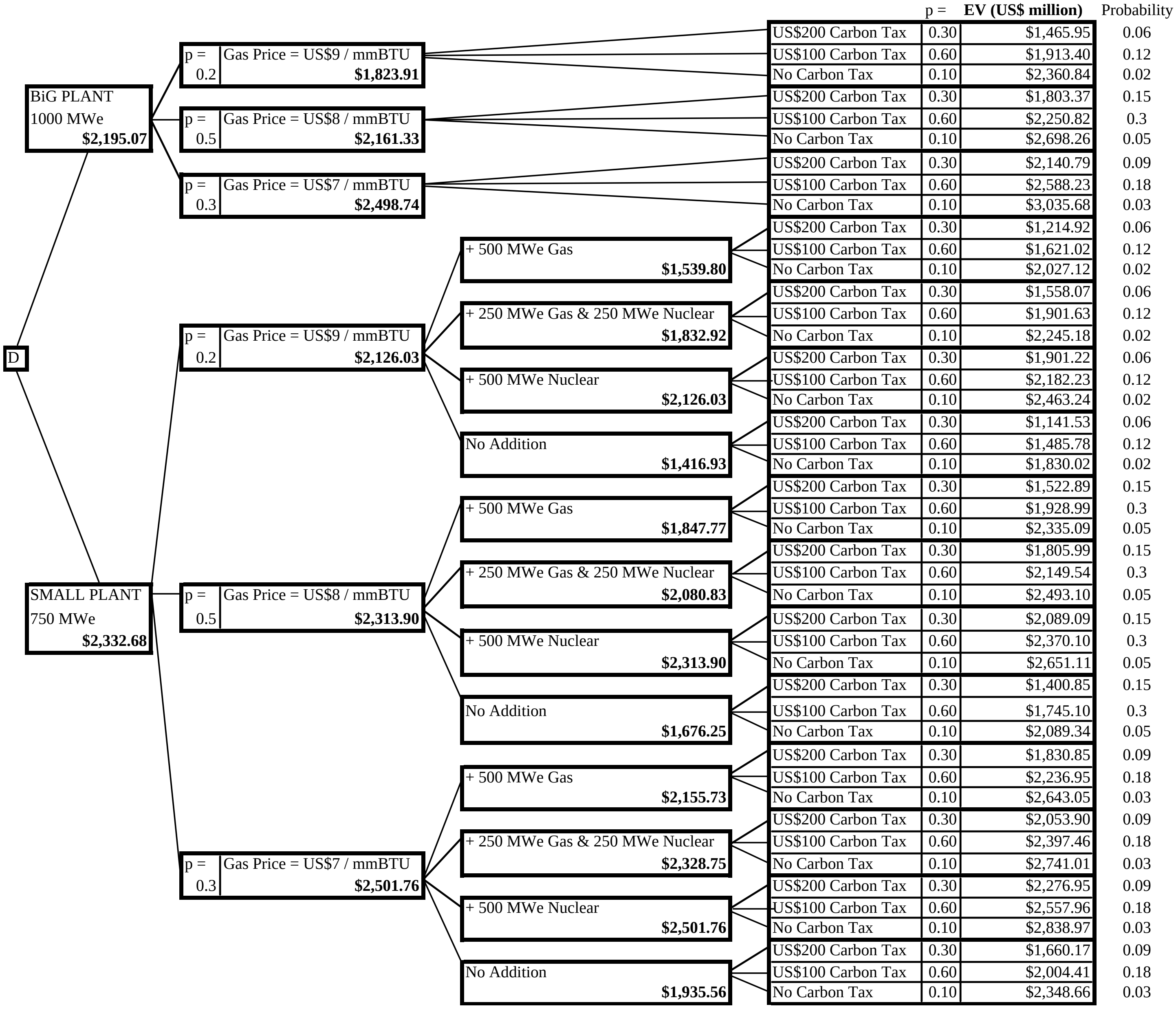
Carbon Tax (US$ / C-tonne)	Probability
0	0.1
100	0.6
200	0.3

Table 4.2: Probability of Future Carbon Taxes

The decision analysis tree is presented in Figure 4.1. The expected value of the flexible alternative is higher than that of the fixed alternative (US$ 2,333 million compared with US$ 2,195 million, respectively). The best strategy, then, is to build a small NGCC plant of 750 MWe with the potential to expand at a later time.

The decision analysis tree shows that regardless of the evolution of natural gas prices, the best strategy is to expand the small NGCC plant by adding a nuclear power production potential of 500 MWe, given the possibility and uncertainty of a future implementation of carbon taxes. If the price of natural gas remains at US$ 7 per mmBTU, the highest expected value of the four alternatives for expansion considered in this exercise is that of adding 500 MWe of Nuclear Power, which is of US$ 2,502 million. If the price of natural gas increases to US$ 8 per mmBTU or US$ 9 per mmBTU, the highest expected value is still that of adding 500 MWe nuclear power generation potential to the NGCC plant, obtaining US$ 2,314 million and US$ 2,126.03 million, respectively.

We can observe that once the decision to develop a flexible system is made, the implementation of a carbon tax does not affect which is the best strategy. This is because all alternatives are affected by the tax in similar proportions. In other words, the carbon tax does not make the NGCC expansion alternative significantly more competitive with respect to the hybrid or nuclear expansion alternatives, or vice versa. In neither case does the carbon tax lead to money losses.



	p =	**EV (US$ million)**	Probability
US$200 Carbon Tax	0.30	$1,465.95	0.06
US$100 Carbon Tax	0.60	$1,913.40	0.12
No Carbon Tax	0.10	$2,360.84	0.02
US$200 Carbon Tax	0.30	$1,803.37	0.15
US$100 Carbon Tax	0.60	$2,250.82	0.3
No Carbon Tax	0.10	$2,698.26	0.05
US$200 Carbon Tax	0.30	$2,140.79	0.09
US$100 Carbon Tax	0.60	$2,588.23	0.18
No Carbon Tax	0.10	$3,035.68	0.03
US$200 Carbon Tax	0.30	$1,214.92	0.06
US$100 Carbon Tax	0.60	$1,621.02	0.12
No Carbon Tax	0.10	$2,027.12	0.02
US$200 Carbon Tax	0.30	$1,558.07	0.06
US$100 Carbon Tax	0.60	$1,901.63	0.12
No Carbon Tax	0.10	$2,245.18	0.02
US$200 Carbon Tax	0.30	$1,901.22	0.06
US$100 Carbon Tax	0.60	$2,182.23	0.12
No Carbon Tax	0.10	$2,463.24	0.02
US$200 Carbon Tax	0.30	$1,141.53	0.06
US$100 Carbon Tax	0.60	$1,485.78	0.12
No Carbon Tax	0.10	$1,830.02	0.02
US$200 Carbon Tax	0.30	$1,522.89	0.15
US$100 Carbon Tax	0.60	$1,928.99	0.3
No Carbon Tax	0.10	$2,335.09	0.05
US$200 Carbon Tax	0.30	$1,805.99	0.15
US$100 Carbon Tax	0.60	$2,149.54	0.3
No Carbon Tax	0.10	$2,493.10	0.05
US$200 Carbon Tax	0.30	$2,089.09	0.15
US$100 Carbon Tax	0.60	$2,370.10	0.3
No Carbon Tax	0.10	$2,651.11	0.05
US$200 Carbon Tax	0.30	$1,400.85	0.15
US$100 Carbon Tax	0.60	$1,745.10	0.3
No Carbon Tax	0.10	$2,089.34	0.05
US$200 Carbon Tax	0.30	$1,830.85	0.09
US$100 Carbon Tax	0.60	$2,236.95	0.18
No Carbon Tax	0.10	$2,643.05	0.03
US$200 Carbon Tax	0.30	$2,053.90	0.09
US$100 Carbon Tax	0.60	$2,397.46	0.18
No Carbon Tax	0.10	$2,741.01	0.03
US$200 Carbon Tax	0.30	$2,276.95	0.09
US$100 Carbon Tax	0.60	$2,557.96	0.18
No Carbon Tax	0.10	$2,838.97	0.03
US$200 Carbon Tax	0.30	$1,660.17	0.09
US$100 Carbon Tax	0.60	$2,004.41	0.18
No Carbon Tax	0.10	$2,348.66	0.03

Figure 4.1: Decision Analysis Tree

The carbon tax does make a difference in the expected value of the fixed and flexible alternatives, however. If no carbon tax is implemented, then the fixed alternative – developing a 1000 MWe NGCC plant – is more attractive than the flexible alternative for natural gas prices of US$ 7 per mmBTU and US$8 per mmBTU. If we knew, then, that no carbon taxes are going to be introduced in the next 10 years, the better choice would be the development of a fixed 1000 MWe NGCC plant (this choice would have an expected value of US$ 2,732 million compared to US$ 2,417 million for the flexible alternative). Alternatively, if we know carbon taxes will be introduced to account for any negative environmental externalities, then the better strategy, as mentioned earlier, is to go for the flexible design.

Table 4.3 shows the NPV obtained for different scenarios and the five different system design alternatives. It is useful in identifying the best choice given a set taxation environment and natural gas prices.

Price of Natural Gas *US$ / mmBTU*	**Carbon Tax** *US$ / tonne-C*	**NPV** *US$ million*				
		1000 MWe NGCC	750 MWe NGCC + 500 MWe NGCC	750 MWe NGCC + 250 MWe NGCC + 250 MWe Nuclear	750 MWe NGCC + 500 MWe Nuclear	750 MWe NGCC
7	0	**3,035.68**	2,643.05	2,741.01	2,838.97	2,348.66
	100	**2,588.23**	2,236.95	2,397.46	2,557.96	2,004.41
	200	2,140.79	1,830.85	2,053.90	**2,276.95**	1,660.17
8	0	**2,698.26**	2,335.09	2,493.10	2,651.11	2,089.34
	100	2,250.82	1,928.99	2,149.54	**2,370.10**	1,745.10
	200	1,803.37	1,522.89	1,805.99	**2,089.09**	1,400.85
9	0	2,360.84	2,027.12	2,245.18	**2,463.24**	1,830.02
	100	1,913.40	1,621.02	1,901.63	**2,182.23**	1,485.78
	200	1,465.95	1,214.92	1,558.07	**1,901.22**	1,141.53

Table 4.3: Calculated NPVs for different alternatives in differing taxation environments and varying natural gas prices. The values in bold indicate the highest NPV for a particular situation.

5. DECISION ANALYSIS USING LATTICE

In this section, I use a lattice analysis to model the development of the price of natural gas, which is a principal uncertainty affecting the system under consideration.[14] By examining the price of natural gas more closely one can better understand the effect its uncertainty has on the profitability and viability of the system. I only account for one uncertainty in this section, and have therefore assumed a carbon tax of US$100 per tonne-C. This is a realistic assumption given the present political environment, as carbon taxes will likely be introduced in the future. As previously mentioned, I also assume that there is always sufficient electricity demand for the supply produced by the system.

I consider two different scenarios in this section. In the first scenario, the lattice analysis is carried out assuming that investors have opted for the fixed system. In this case, I consider the put option on the system of shutting down the plant. A put option is the right to limit losses in a bad situation. In the second scenario, the lattice analysis is carried out assuming that investors have opted for the flexible system. In this second case, I consider the call option in the system of expanding the plant. A call option is the right, but not the obligation, to take advantage of an opportunity. Instead of taking into account three different alternatives for expansion as in the previous section, however, I only consider expanding by creating a hybrid system with an additional 500MWe of nuclear potential. I showed in Section 4 how this is the best alternative for expansion, based on the calculated NPV, among the three available expansion choices.

5.1 Lattice Parameters

Natural gas prices have varied between US$ 3 per mmBTU to the present US$ 7 per mmBTU during the period between 1997 and 2005 (Section 2.3). While there has been an increasing trend in the cost of this fossil fuel in recent years, it is still difficult to predict what the future price of natural gas will be. The lattice was therefore developed using an average annual growth rate equivalent to Portugal's rate of inflation for 2005, which the United States Central Intelligence Agency quotes as 2.3%.[15]

The volatility of the price of natural gas is calculated based on the standard deviation σ_x of its price during a period of 5 years. I used approximate natural gas price values from 2001 to 2005, the most recent time period, to calculate the volatility of this uncertainty. The cost of natural gas varied from US$ 3 per mmBTU to the present value of US$ 7 per mmBTU during the chosen five-year period (Section 2.3). Therefore, the volatility of natural gas prices is considered to be of 1.52%. The calculation of this standard deviation, which is shown below, was done using Equation 5.1 and the depicted values in Table 5.1, which are approximations based on Figure 2.3.

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[14] This lattice analysis is based on the Binomial Tree Model Spreadsheet that is available on the website of ESD.71 – Engineering Systems Analysis for Design.
[http://ardent.mit.edu/real_options/Common_course_materials/spreadsheets.html, last viewed 12/14/2006]

[15] The CIA World Factbook. "Field Listing – Inflation Rate (consumer prices)".
[https://www.cia.gov/cia/publications/factbook/fields/2092.html, last viewed 12/11/06]

$$\sigma_x = \sqrt{\frac{1}{N-1}\sum d_1^{\,2}} \tag{5.1}$$

$$\sigma_x = \sqrt{\frac{9.2}{4}} = 1.52$$

Year	Trial number I	Measured Value x_i	Deviation $d_i = x_i - x_{avg}$	Deviation Squared d_i^2
2001	1	4	-0.4	0.16
2002	2	3	-1.4	1.96
2003	3	4	-0.4	0.16
2004	4	4	-0.4	0.16
2005	5	7	2.6	6.76

Table 5.1: Values used in the calculation of the standard deviation.

Using these values for the average annual growth rate and the volatility of natural gas prices, along with equations 5.2, 5.3 and 5.4, one can calibrate the values of the probability up *p*, the probability down *(1 – p)*, the upside factor *u*, and the downside path *d*. It is obvious from Equation 5.4 that the ratio of appreciation v to the volatility σ must be smaller than 1. We therefore use a time period Δt of six months or half a year. Because of this, we calculate the rate of appreciation v by dividing the annual growth rate by 2, to obtain a semi-annual growth rate of 1.15%. The values of all these variables are shown in Table 5.2.

$$u = e^{\sigma\sqrt{\Delta t}} \tag{5.2}$$

$$d = e^{-\sigma\sqrt{\Delta t}} \tag{5.3}$$

$$p = 0.5 + 0.5\left(\frac{v}{\sigma}\right)\sqrt{\Delta t} \tag{5.4}$$

Variable		Value
Rate of Appreciation	v	1.15%
Volatility	σ	1.52%
Time Period	Δt	1/2 year
Upside Factor	u	1.0108
Downside Factor	d	0.9893
Probability Up	p	0.7675
Probability Down	$1 - p$	0.2325
Discount Rate	r	15%

Table 5.2: Values of Variables used in Lattice Model of System Evolution

5.2 Modeling Uncertainty: Natural Gas Price Evolution – States and Probabilities

One can develop a lattice model using Excel spreadsheets. The lattice begins with the initial price of natural gas (US$ 7 per mmBTU) and is developed for a period of 10 years in intervals, or stages, of 6 months each. Table 5.3 shows the equations used to calculate the natural gas price outcomes in the lattice, while Table 5.4 shows the formulas used to calculate the node probabilities in the lattice.

Year t	**Year $t + \Delta t$**	**Year $t + 2\Delta t$**
Start Price, P_t	$P_{t + \Delta t, 1} = P_t * u$	$P_{t + 2\Delta t, 1} = P_{t + \Delta t, 1} * u$
	$P_{t + \Delta t, 2} = P_t * d$	$P_{t + 2\Delta t, 2} = P_{t + \Delta t, 1} * d$
		$P_{t + 2\Delta t, 3} = P_{t + \Delta t, 2} * d$

Table 5.3: Equations used to calculate the Natural Gas Price Outcome Lattice

Year t	**Year $t + \Delta t$**	**Year $t + 2\Delta t$**
Start Probability, p_t	$p_{t + \Delta t, 1} = p_t * p$	$p_{t + 2\Delta t, 1} = p_{t + \Delta t, 1} * p$
	$p_{t + \Delta t, 2} = p_t * (1 - p)$	$p_{t + 2\Delta t, 2} = p_{t + \Delta t, 1} * (1 - p) + p_{t + \Delta t, 2} * p$
		$p_{t + 2\Delta t, 2} = p_t * (1 - p)$

Table 5.4: Equations used to calculate the Node Probability Lattice

With these equations, I developed a lattice model for the natural gas price variations for the 10-year period, along with the probabilities for each stage. Tables 5.5 and 5.6 present a sample of the calculated values, and Figure 5.1 presents the probability distribution function of the possible costs of natural gas and associated probabilities in the future 2, 4, 6, 8 and 10 years.

The probability distribution function shows that natural gas prices will experience a general increase in the future. Natural gas prices are highly volatile, so one can expect variability from year to year. One can see, however, that it is highly unlikely that in 10 years the cost of natural gas will continue to be US$ 7 per mmBTU, and that it will most likely have increased to about US$8 per mmBTU.

YEAR	**t = 0**	**t = 0.5**	**t = 1**	**t = 1.5**	**t = 2**	**t = 4**	**t = 6**	**t = 8**	**t = 10**	**STEP**
PRICE OF NATURAL GAS	7.00	7.06	7.11	7.17	7.23	7.47	7.72	7.97	8.24	20
		6.93	6.98	7.04	7.10	7.33	7.57	7.82	8.08	19
			6.85	6.91	6.96	7.19	7.43	7.68	7.93	18
				6.78	6.83	7.06	7.29	7.53	7.78	17
					6.71	6.93	7.16	7.39	7.64	16
						6.80	7.02	7.25	7.49	15
						6.67	6.89	7.12	7.35	14
						6.55	6.76	6.99	7.22	13
						6.42	6.64	6.86	7.08	12
							6.51	6.73	6.95	11
							6.39	6.60	6.82	10
							6.27	6.48	6.69	9
							6.15	6.36	6.57	8
								6.24	6.44	7
								6.12	6.32	6
								6.01	6.20	5
								5.89	6.09	4
									5.98	3
									5.86	2
									5.75	1
									5.65	0

Table 5.5: Outcome Lattice for the Price of Natural Gas

YEAR	t = 0	t = 0.5	t = 1	t = 1.5	t = 2	t = 4	t = 6	t = 8	t = 10	STEP
PROBABILITY NODES	1.00	0.77	0.59	0.45	0.35	0.12	0.04	0.01	0.01	20
		0.23	0.36	0.41	0.42	0.29	0.15	0.07	0.03	19
			0.05	0.12	0.19	0.31	0.25	0.16	0.09	18
				0.01	0.04	0.19	0.26	0.23	0.16	17
					0.00	0.07	0.17	0.22	0.21	16
						0.02	0.08	0.16	0.20	15
						0.00	0.03	0.09	0.15	14
						0.00	0.01	0.04	0.09	13
						0.00	0.00	0.01	0.04	12
							0.00	0.00	0.02	11
							0.00	0.00	0.01	10
							0.00	0.00	0.00	9
							0.00	0.00	0.00	8
								0.00	0.00	7
								0.00	0.00	6
								0.00	0.00	5
								0.00	0.00	4
									0.00	3
									0.00	2
									0.00	1
									0.00	0

Table 5.6: Probability Lattice

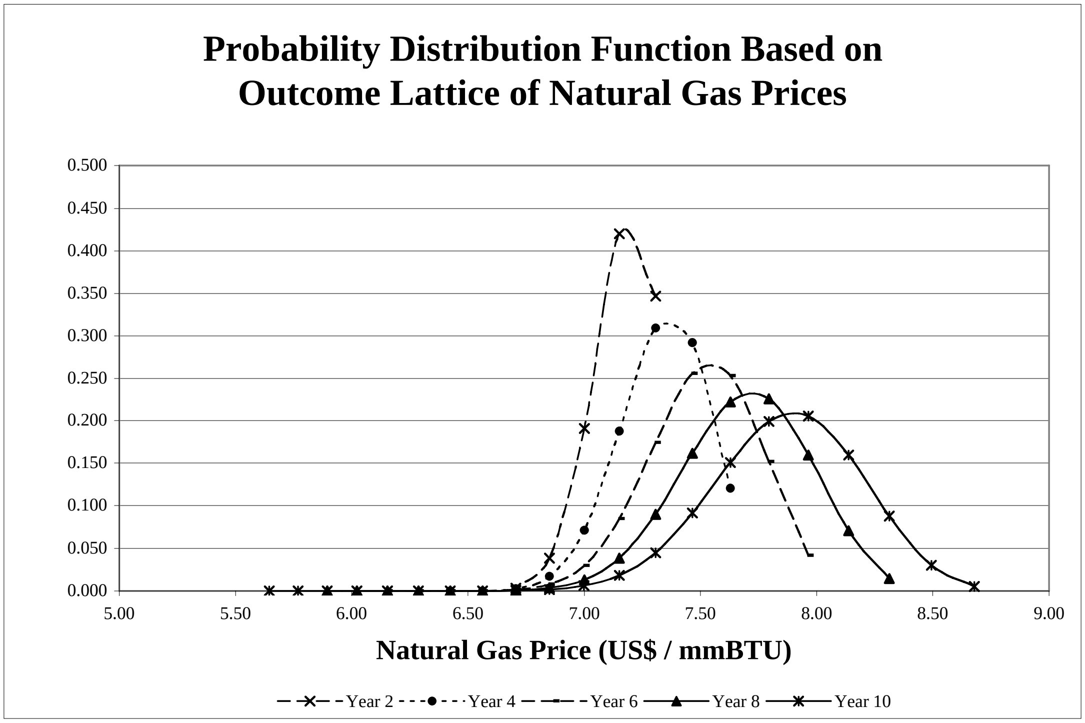

Figure 5.1: Probability Distribution Function of future Natural Gas Prices

5.3 Analysis Recognising Uncertainty

Scenario 1 – Fixed 1000 MWe NGCC Plant with Put (Shut Down) Option

In the first scenario, the lattice analysis is carried out assuming that investors have opted for the fixed system. In this case, I consider the put option on the system of shutting down the plant.

Equations 5.5, 5.6, and 5.7 were used to carry out the calculation of the system's net revenue for each state of the lattice. Table 5.7 shows the values used in this calculation. These values are taken directly from the NPV financial model introduced in Section 3 and used previously in this paper. Note that the price of natural gas is taken directly from the Outcome Lattice.

$$\text{Net Revenue} = \text{Income} - (\text{Total Annual Expenses} + \text{NGCC Fuel Cost Constant} * \text{Price of Natural Gas}) \tag{5.5}$$

$$\text{Income} = \text{Annual Production} * \text{Price of Electricity} \tag{5.6}$$

$$\text{Total Annual Expenses} = \text{NGCC Fixed Cost} + \text{NGCC Variable Cost} + \text{Total Carbon Emissions Tax} \tag{5.7}$$

Income	**1226.40**	**US$ million / year**
Annual Production	8.76	TWh / year
Total Capacity	1000.00	MWe
Price of Electricity	0.14	US$ / kWh
Total Annual Expenses	**212.01**	**US$ million / year**
NGCC Fixed Cost	16.00	US$ million / year
NGCC Variable Cost	4.56	US$ million / year
NGCC Fuel Cost Constant	63.07	US$ million / year
Carbon Emissions Tax	100.00	US$ / tonne-C
Total Carbon Emissions Tax	91.45	US$ million / year
Overnight Cost	**500.00**	**US$ million**

Table 5.7: Input Values for Net Revenue Calculation in Scenario 1

The impact of uncertainty on the system is illustrated in Tables 5.8 and 5.9, which show the Net Revenue Lattice and the Probability Weighted Net Revenue Lattice for the 1000 MWe NGCC plant, respectively. One can immediately see that given a starting natural gas price of US$ 7 per mmBTU, the 1000 MWe NGCC plant is a profitable and attractive investment.

YEAR	t = 0	t = 0.5	t = 1	t = 1.5	t = 2	t = 4	t = 6	t = 8	t = 10	STEP
NET REVENUE LATTICE FOR 1000 MWe NGCC (US$ million)	0.00	569.28	565.65	561.98	558.29	543.21	527.63	511.54	494.91	20
		577.61	574.04	570.44	566.82	552.02	536.74	520.94	504.63	19
			582.28	578.75	575.19	560.67	545.67	530.17	514.16	18
				586.90	583.40	569.16	554.44	539.23	523.52	17
					591.47	577.48	563.04	548.12	532.70	16
						585.65	571.48	556.84	541.71	15
						593.67	579.76	565.39	550.55	14
						601.54	587.89	573.79	559.22	13
						609.26	595.87	582.03	567.74	12
							603.70	590.12	576.09	11
							611.38	598.05	584.29	10
							618.91	605.84	592.33	9
							626.31	613.48	600.23	8
								620.98	607.97	7
								628.34	615.57	6
								635.56	623.03	5
								642.64	630.35	4
									637.53	3
									644.58	2
									651.50	1
									658.29	0

Table 5.8: Net Revenue Lattice for 1000 MWe NGCC (US$ million)

YEAR	t = 0	t = 0.5	t = 1	t = 1.5	t = 2	t = 4	t = 6	t = 8	t = 10	STEP
PROBABILITY WEIGHTED NET REVENUE LATTICE FOR 1000 MWe NGCC (US$ million)	0.00	436.92	333.19	254.06	193.71	65.40	22.04	7.41	2.49	20
		134.30	204.87	234.38	238.32	161.06	81.51	36.60	15.38	19
			31.48	72.04	109.90	173.45	138.07	84.63	45.09	18
				7.38	22.51	106.69	141.66	121.68	83.45	17
					1.73	40.99	98.06	121.78	109.32	16
						10.08	48.24	89.95	107.77	15
						1.55	17.30	50.73	82.96	14
						0.14	4.55	22.28	51.05	13
						0.01	0.87	7.70	25.52	12
							0.12	2.10	10.46	11
							0.01	0.45	3.53	10
							0.00	0.08	0.99	9
							0.00	0.01	0.23	8
								0.00	0.04	7
								0.00	0.01	6
								0.00	0.00	5
								0.00	0.00	4
									0.00	3
									0.00	2
									0.00	1
									0.00	0

Table 5.9: Probability Weighted Net Revenue Lattice for 1000 MWe NGCC (US$ million)

I used the Probability Weighted Net Revenue Lattice to calculate the expected value of the net revenue at each stage. Each of the expected values is discounted using a discount rate of 15% (Table 5.2) to calculate the present value of each stage, and these are added to get the NPV for the system without an option. Table 5.10 illustrates this process.

YEAR	t = 0	t = 0.5	t = 1	t = 1.5	t = 2	t = 4	t = 6	t = 8	t = 10
EV	0.00	571.22	569.54	567.86	566.17	559.35	552.43	545.41	538.27
PV(EV)	0.00	532.66	495.25	460.46	428.11	319.81	238.83	178.29	133.05
NPV	5812.26								

Table 5.10: Net Present Value for 1000 MWe NGCC (US$ million)

In order to calculate the value of the option to close the plant in case money is being lost, I developed a lattice of the net revenue with the option to close, and based on this created a Lattice of the Present Value of the Net Revenue with the Option to Close, which is illustrated in Table 5.11. The strike price of the option is equivalent to the fixed operational costs of the system, indicated to be US$ 16 million (Table 5.7).

YEAR	t = 0	t = 0.5	t = 1	t = 1.5	t = 2	t = 4	t = 6	t = 8	t = 10	STEP
PRESENT VALUE (NET REVENUE) FOR 1000 MWe NGCC WITH OPTION TO CLOSE (US$ million)	3518.23	4031.74	3967.64	3898.16	3822.55	3439.80	2863.82	1959.30	494.91	20
		4092.90	4028.67	3958.95	3882.99	3497.28	2914.36	1995.79	504.63	19
			4088.55	4018.60	3942.30	3553.68	2963.96	2031.60	514.16	18
				4077.14	4000.50	3609.03	3012.63	2066.74	523.52	17
					4057.62	3663.34	3060.39	2101.22	532.70	16
						3716.64	3107.26	2135.06	541.71	15
						3768.94	3153.25	2168.27	550.55	14
						3820.26	3198.38	2200.85	559.22	13
						3870.62	3242.66	2232.82	567.74	12
							3286.12	2264.20	576.09	11
							3328.77	2294.99	584.29	10
							3370.61	2325.20	592.33	9
							3411.68	2354.85	600.23	8
								2383.94	607.97	7
								2412.49	615.57	6
								2440.51	623.03	5
								2468.00	630.35	4
									637.53	3
									644.58	2
									651.50	1
									658.29	0

Table 5.11: Present Value (Net Revenue) for 1000 MWe NGCC with Option to Close (US$ million)

Valuation of Option to Close

The value of the put option in this case, then, is US$ 0 (it is actually a negative value, but to us it is worth nothing because it does not make sense to exercise the option). The value of the plant without the option to close is of US$ 5,812 (Table 5.10), which is greater than the estimated NPV of the plant with the option to close, which is US$ 3,518 million (Table 5.11).

Given the modelled uncertainty of natural gas prices and its impact on the system, the 1000 MWe NGCC will always be more profitable during the 10 year time period evaluated in this analysis. The decision made at each state of whether to exercise the option or not is illustrated in the Decision Lattice shown in Table 5.12.

YEAR	**t = 0**	**t = 0.5**	**t = 1**	**t = 1.5**	**t = 2**	**t = 4**	**t = 6**	**t = 8**	**t = 10**	**STEP**
EXERCISE PUT (SHUT DOWN) OPTION?	NO	NO	NO	NO	NO	NO	NO	NO	-	20
		NO	NO	NO	NO	NO	NO	NO	-	19
			NO	NO	NO	NO	NO	NO	-	18
				NO	NO	NO	NO	NO	-	17
					NO	NO	NO	NO	-	16
						NO	NO	NO	-	15
						NO	NO	NO	-	14
						NO	NO	NO	-	13
						NO	NO	NO	-	12
							NO	NO	-	11
							NO	NO	-	10
							NO	NO	-	9
							NO	NO	-	8
								NO	-	7
								NO	-	6
								NO	-	5
								NO	-	4
									-	3
									-	2
									-	1
									-	0

Table 5.12: Decision Lattice – Exercising Put Option?

As a mere exercise, and to illustrate the power of this type of analysis, I consider the possibility of the starting price of natural gas being US$ 16 per mmBTU. This significant increase in price could be the result of some sort of political crisis, for example. The analysis carried out is exactly the same as that detailed above, and I only show the final Decision Lattice. Table 5.13 shows when one would choose to exercise the put option in this case, given the uncertainty in natural gas prices modelled in the outcome lattice. In this case the option is worth US$ 277 million, because the NPV of the plant without the option to close results in losses of negative US$ 279 million, while the present value of the plant with the option to close results in a loss of only negative US$ 2 million.

YEAR	t = 0	t = 0.5	t = 1	t = 1.5	t = 2	t = 4	t = 6	t = 8	t = 10	STEP
EXERCISE PUT (SHUT DOWN) OPTION?	NO	YES	YES	YES	YES	YES	YES	YES	-	20
		NO	NO	NO	YES	YES	YES	YES	-	19
			NO	NO	NO	YES	YES	YES	-	18
				NO	NO	YES	YES	YES	-	17
					NO	NO	YES	YES	-	16
						NO	NO	YES	-	15
						NO	NO	YES	-	14
						NO	NO	NO	-	13
						NO	NO	NO	-	12
							NO	NO	-	11
							NO	NO	-	10
							NO	NO	-	9
							NO	NO	-	8
								NO	-	7
								NO	-	6
								NO	-	5
								NO	-	4
									-	3
									-	2
									-	1
									-	0

Table 5.12: Decision Lattice – Exercising Put Option? (Starting natural gas price of US$ 16 per mmBTU)

Scenario 2 – Flexible 750 MWe NGCC Plant with Call (Expand) Option

In the second scenario, the lattice analysis is carried out assuming that investors have opted for the flexible system. In this second case, I consider the call option in the system of expanding the plant. Instead of taking into account three different alternatives for expansion as I did in Section 4, however, I only consider the option of expanding by creating a hybrid system with an additional 500MWe of nuclear potential. In Section 4, I showed, based on NPV calculations, how this is the best alternative for expansion among the three available expansion choices.

Equations 5.5, 5.6, and 5.8 were used to carry out the calculation of the system's net revenue for each state of the lattice. Table 5.13 shows the values used in this calculation. These values are taken directly from the NPV financial model introduced in Section 3 and used previously in this exercise. Note that the price of natural gas is taken directly from the outcome lattice.

$$\textit{Total Annual Expenses} = \textit{NGCC Fixed Cost} + \textit{NGCC Variable Cost} + \textit{Total Carbon Emissions Tax} + \textit{Nuclear Fixed Cost} + \textit{Nuclear Variable Cost} + \textit{Nuclear Fuel Cost} \tag{5.8}$$

Income	**1533.00**	**US$ million / year**
Annual Production	10.95	TWh / year
Total Capacity NGCC	750.00	MWe
Total Capacity Nuclear	500	MWe
Price of Electricity	0.14	US$ / kWh
Total Annual Expenses	**138.98**	**US$ million / year**
NGCC Fixed Cost	12.00	US$ million / year
NGCC Variable Cost	3.42	US$ million / year
NGCC Fuel Cost Constant	47.30	US$ million / year
Carbon Emissions Tax	100.00	US$ / tonne-C
Total Carbon Emissions Tax	68.59	US$ million / year
Nuclear Fixed Cost	31.5	US$ million / year
Nuclear Variable Cost	2.0586	US$ million / year
Nuclear Fuel Cost	21.41	US$ million / year
Overnight Cost	**1000**	**US$ million**

Table 5.13: Input Values for Net Revenue Calculation in Scenario 1

The impact of uncertainty on the system is illustrated in Tables 5.14 and 5.15, which show the Net Revenue Lattice and the Probability Weighted Net Revenue Lattice for the smaller 750 MWe NGCC plant, respectively. One can immediately see that given a starting natural gas price of US$ 7 per mmBTU, the 750 MWe NGCC plant is a profitable and attractive investment. In addition, Table 5.16 shows the Net Revenue Lattice for the 750 MWe NGCC plant with the option to expand the plant with 500 MWe of nuclear energy production potential. Table 5.17, in turn, shows the Probability Weighted Net Revenue Lattice for the 750 MWe NGCC plant with the option to expand with 500 MWe of nuclear energy production potential.

YEAR	**t = 0**	**t = 0.5**	**t = 1**	**t = 1.5**	**t = 2**	**t = 4**	**t = 6**	**t = 8**	**t = 10**	**STEP**
NET REVENUE LATTICE FOR 750 MWe NGCC (US$ million)	0.00	501.96	499.24	496.49	493.72	482.41	470.72	458.65	446.19	20
		508.20	505.53	502.83	500.11	489.02	477.55	465.71	453.47	19
			511.71	509.06	506.39	495.50	484.25	472.63	460.62	18
				515.17	512.55	501.87	490.83	479.42	467.64	17
					518.60	508.11	497.28	486.09	474.52	16
						514.24	503.61	492.63	481.28	15
						520.25	509.82	499.05	487.91	14
						526.16	515.92	505.34	494.42	13
						531.95	521.90	511.52	500.80	12
							527.77	517.59	507.07	11
							533.53	523.54	513.22	10
							539.19	529.38	519.25	9
							544.73	535.11	525.17	8
								540.73	530.98	7
								546.25	536.68	6
								551.67	542.27	5
								556.98	547.76	4
									553.15	3
									558.44	2
									563.62	1
									568.71	0

Table 5.14: Net Revenue Lattice for 750 MWe NGCC (US$ million)

YEAR	t = 0	t = 0.5	t = 1	t = 1.5	t = 2	t = 4	t = 6	t = 8	t = 10	STEP
PROBABILITY WEIGHTED NET REVENUE LATTICE FOR 750 MWe NGCC (US$ million)	0.00	385.25	294.07	224.45	171.31	58.08	19.66	6.65	2.24	20
		118.16	180.42	206.60	210.28	142.68	72.52	32.72	13.82	19
			27.66	63.36	96.75	153.29	122.53	75.44	40.39	18
				6.48	19.78	94.07	125.41	108.19	74.54	17
					1.52	36.07	86.61	108.00	97.38	16
						8.85	42.51	79.58	95.75	15
						1.36	15.21	44.77	73.52	14
						0.12	4.00	19.62	45.14	13
						0.00	0.77	6.77	22.51	12
							0.10	1.84	9.21	11
							0.01	0.40	3.10	10
							0.00	0.07	0.87	9
							0.00	0.01	0.20	8
								0.00	0.04	7
								0.00	0.01	6
								0.00	0.00	5
								0.00	0.00	4
									0.00	3
									0.00	2
									0.00	1
									0.00	0

Table 5.15: Probability Weighted Net Revenue Lattice for 750 MWe NGCC (US$ million)

YEAR	t = 0	t = 0.5	t = 1	t = 1.5	t = 2	t = 4	t = 6	t = 8	t = 10	STEP
NET REVENUE LATTICE FOR 750 MWe NGCC WITH OPTION TO EXPAND WITH 500 MWe NUCLEAR (US$ million)	0.00	1060.19	1057.47	1054.72	1051.95	1040.64	1028.96	1016.89	1004.42	20
		1066.44	1063.76	1061.07	1058.35	1047.25	1035.78	1023.94	1011.70	19
			1069.94	1067.29	1064.62	1053.73	1042.48	1030.86	1018.85	18
				1073.40	1070.79	1060.10	1049.06	1037.65	1025.87	17
					1076.83	1066.34	1055.51	1044.32	1032.76	16
						1072.47	1061.84	1050.86	1039.51	15
						1078.49	1068.05	1057.28	1046.14	14
						1084.39	1074.15	1063.58	1052.65	13
						1090.18	1080.13	1069.76	1059.03	12
							1086.00	1075.82	1065.30	11
							1091.76	1081.77	1071.45	10
							1097.42	1087.61	1077.48	9
							1102.96	1093.34	1083.40	8
								1098.97	1089.21	7
								1104.48	1094.91	6
								1109.90	1100.51	5
								1115.21	1106.00	4
									1111.38	3
									1116.67	2
									1121.86	1
									1126.95	0

Table 5.16: Net Revenue Lattice for 750 MWe NGCC
with Option to Expand with 500 MWe Nuclear (US$ million)

YEAR	t = 0	t = 0.5	t = 1	t = 1.5	t = 2	t = 4	t = 6	t = 8	t = 10	STEP
PROBABILITY WEIGHTED NET REVENUE LATTICE FOR 750 MWe NGCC WITH OPTION TO EXPAND WITH 500 MWe NUCLEAR (US$ million)	0.00	813.69	622.89	476.82	365.00	125.28	42.98	14.74	5.05	20
		247.96	379.65	435.96	444.99	305.56	157.29	71.93	30.83	19
			57.84	132.85	203.41	325.99	263.77	164.55	89.34	18
				13.49	41.32	198.71	268.04	234.16	163.52	17
					3.15	75.69	183.83	232.03	211.95	16
						18.45	89.64	169.76	206.81	15
						2.81	31.87	94.86	157.63	14
						0.24	8.32	41.30	96.10	13
						0.01	1.58	14.16	47.60	12
							0.21	3.83	19.34	11
							0.02	0.82	6.48	10
							0.00	0.14	1.80	9
							0.00	0.02	0.41	8
								0.00	0.08	7
								0.00	0.01	6
								0.00	0.00	5
								0.00	0.00	4
									0.00	3
									0.00	2
									0.00	1
									0.00	0

Table 5.17: Probability Weighted Net Revenue Lattice for 750 MWe NGCC with Option to Expand with 500 MWe Nuclear (US$ million)

I used the Probability Weighted Net Revenue Lattices to calculate the expected value of the net revenue at each stage, both for the 750 MWe NGCC plant and the 750 MWe NGCC plant with the option to expand with 500 MWe of nuclear power potential. Each of the expected values is discounted using a discount rate of 15% (Table 5.2) to calculate the present value of each stage, and these are added to get the NPV for the system with and without the call option. Tables 5.18 and 5.19 illustrate this process.

YEAR	t = 0	t = 0.5	t = 1	t = 1.5	t = 2	t = 4	t = 6	t = 8	t = 10
EV	0.00	503.41	502.16	500.89	499.63	494.52	489.33	484.06	478.71
PV(EV)	0.00	469.43	436.66	406.16	377.79	282.74	211.55	158.24	118.33
NPV	5139.25								

Table 5.18: Net Present Value for 750 MWe NGCC (US$ million)

YEAR	t = 0	t = 0.5	t = 1	t = 1.5	t = 2	t = 4	t = 6	t = 8	t = 10
EV	0.00	1061.64	1060.39	1059.13	1057.86	1052.75	1047.56	1042.29	1036.94
PV(EV)	0.00	989.99	922.08	858.82	799.89	601.91	452.89	340.73	256.32
NPV	10945.31								

Table 5.19: Net Present Value for 750 MWe NGCC with Option to Expand with 500 MWe Nuclear (US$ million)

Valuation of Option to Expand

The value of the call option is calculated using Equation 5.9 and the NPVs in Tables 5.18 and 5.19. The value of this call option is of US$ 5,806 million. The value of this option to expand is greater than its strike price, since the latter is equivalent to the overnight cost of the expansion itself, which in this case is of US$ 1,000 million (Table 5.13).

$$\text{Value of Option} = \text{NPV with Option} - \text{NPV without Option} \qquad (5.9)$$

In order to construct the Decision Lattice, I first developed the Present Value Net Revenue Lattice for the 750 MWe NGCC plant with the call option. This is shown in Table 5.20. By comparing these obtained values to the net revenue of the same system without the expansion option, I formulated the Decision Lattice shown in Table 5.21. The call option can be exercised anytime the expected revenue of the expanded system minus the overnight cost of the expansion (the option's strike price) is greater than the expected revenue of the original smaller system. Given the assumptions I made (in particular, that there is sufficient demand for any level of electricity production, that the cost of electricity is constant in time, and what the cost of the strike price is) it seems that exercising the call option is immediately desirable. Changing these assumptions would certainly affect the results presented here, and this could be studied in future work.

YEAR	t = 0	t = 0.5	t = 1	t = 1.5	t = 2	t = 4	t = 6	t = 8	t = 10	STEP
PRESENT VALUE (NET REVENUE) FOR 750 MWe NGCC WITH OPTION TO EXPAND WITH 500 MWe NUCLEAR (US$ million)	437.75	937.35	932.25	927.10	921.91	900.73	878.85	856.24	446.19	20
		949.04	944.04	938.99	933.89	913.11	891.64	869.45	453.47	19
			955.60	950.65	945.65	925.26	904.18	882.42	460.62	18
				962.09	957.19	937.17	916.50	895.14	467.64	17
					968.51	948.87	928.58	907.62	474.52	16
						960.35	940.44	919.87	481.28	15
						971.61	952.07	931.89	487.91	14
						982.66	963.49	943.69	494.42	13
						993.51	974.70	955.26	500.80	12
							985.69	966.62	507.07	11
							996.48	977.76	513.22	10
							1007.07	988.70	519.25	9
							1017.46	999.43	525.17	8
								1009.97	530.98	7
								1020.30	536.68	6
								1030.44	542.27	5
								1040.40	547.76	4
									553.15	3
									558.44	2
									563.62	1
									568.71	0

Table 5.20: Present Value (Net Revenue) for 750 MWe NGCC with Option to Expand with 500 MWe Nuclear (US$ million)

YEAR	t = 0	t = 0.5	t = 1	t = 1.5	t = 2	t = 4	t = 6	t = 8	t = 10	STEP
EXERCISE CALL (EXPAND) OPTION?	YES	YES	YES	YES	YES	YES	YES	YES	-	20
		YES	YES	YES	YES	YES	YES	YES	-	19
			YES	YES	YES	YES	YES	YES	-	18
				YES	YES	YES	YES	YES	-	17
					YES	YES	YES	YES	-	16
						YES	YES	YES	-	15
						YES	YES	YES	-	14
						YES	YES	YES	-	13
						YES	YES	YES	-	12
							YES	YES	-	11
							YES	YES	-	10
							YES	YES	-	9
							YES	YES	-	8
								YES	-	7
								YES	-	6
								YES	-	5
								YES	-	4
									-	3
									-	2
									-	1
									-	0

Table 5.21: Decision Lattice – Exercising Call Option?

6. CONCLUSION

The alternative designs considered in this project were evaluated by using a two-stage decision analysis and a lattice analysis. These two types of analyses allowed me to examine the effect on the systems of the uncertainty of the price of natural gas and the potential implementation of carbon taxes. I found that, given the assumptions made for the purposes of this exercise, the flexible design – that of a 750 MWe NGCC plant with potential for expansion – is desirable over the fixed 1000 MWe NGCC plant.

The two-stage decision analysis showed that flexibility helps downsize the negative effect of carbon taxes in the NGCC plant, and that it also enables a response towards variability in natural gas prices. The lattice analysis showed that the value of a put or shut down option for the flexible NGCC plant with no potential for expansion is dependent on the price of natural gas. At present values, the put option offers no value to the system. If the price of natural gas were to considerably increase, however, the put option would be a desired characteristic of the system. In addition, the decision analysis showed that the call or expand option in the system is desirable if one is to take advantage of upside potential.

The value of having flexibility in a system was apparent in both types of analysis. Future work for this particular project could focus on the effect of the uncertainty in the price of electricity and in the demand for electricity produced by the proposed systems.

7. REMARKS

The main goal of this project was to explore different approaches to valuing flexibility in the design of a system. This was achieved by using both the two-stage decision analysis and the lattice analysis to evaluate the various design alternatives. The results show that flexibility is generally a desired characteristic in the system, for it allows both to avoid downside risk and to take advantage of upside potential. The exercise was also useful in identifying the strengths and weaknesses of these two types of analyses.

Using a flexible approach to design is important in that it gives you the opportunity to effectively respond to unforeseen circumstances. In this case, for example, it was good to see how different situations, such as the taxation environment and an increase in the price of natural gas, would affect the profitability of the system under consideration. This type of approach enables a more structured thinking methodology towards problems dealing with uncertainty. Nevertheless, it forces you to make some assumptions along the way, which may result in a significant simplification of the problem.

The process of developing this application portfolio has helped me understand the complexities involved in designing a particular system without knowing what the future holds. It has also helped me learn how one can try to deal with these uncertainties. It has been a challenging exercise on how to define a system and how to think about its potential for growth. Compared to other exercises done in class, the application portfolio forces you to think more about how the tools in class can be applied to problems that might not necessarily fit the models, and how to make the best of them.