REAL OPTIONS VALUATION OF INVESTMENT IN SOLAR PARABOLIC TROUGH TECHNOLOGY

ARJUN P. GUPTA

ESD 71 Application Portfolio

Special Thanks to:

Prof. Richard de Neufville

Michel A. Cardin

December 08, 2009

Cover Photo Credit:
Linvents Century Lab
http://www.centuryinventions.com/03_solar_fuel_producer/Images_Solar_Tech/Solar_Technologies_Review.htm

Real Options Valuation of Investment in Parabolic Trough Technology

This report compares the expected value of a conventional combined cycle (CC) power plant with that of a modified CC power plant which can be converted into an integrated solar combined cycle (ISCC) power plant using solar parabolic trough technology being developed at MIT. The ISCC plant generates electricity using a conventional gas turbine as well as solar parabolic troughs. Parabolic trough technology already exists (in the US and elsewhere) but the innovation in the technology being developed at MIT relates to the use of cheaper materials and improvements in design that enable cheaper shipping and lower maintenance costs (through improvements in mechanisms to clean the mirrors) while increasing the efficiency of converting heat from the sun into electricity. This new technology entails numerous uncertainties and thus offers numerous options to Eni for its development. The critical uncertainties examined in this report are: capital cost of the solar component, price of natural gas and carbon costs. This report treats the investment in the technology as an option and evaluates the value of this option using three approaches: decision analysis, lattice analysis and Monte-Carlo simulation. The two-stage decision analysis compares along multiple dimensions a situation in which Eni does not invest in the technology (and thus can only build a CC power plant) with one in which it does invest in the technology and thus has the option of building either a CC plant or an ISCC plant depending upon the way uncertainties unfold. The lattice analysis models natural gas prices over the lifetime of a power plant and compares the expected value of a conventional CC plant with a modified CC plant that can be transformed into an ISCC plant in year 5 depending upon future expectations of natural gas prices. Finally, the Monte-Carlo analysis compares the expected value of the case when the solar option is exercised in the beginning stages of the power generation project with that of a case when the decision makers have flexibility in exercising this option during any of the first ten years of the power plant's operation in reaction to the way the uncertainties unfold. The analysis in this report suggests that though the parabolic trough technology is currently not cost effective, there are realistic scenarios defined by combinations of outcomes of key uncertainties that make acquisition of the new technology desirable. It also suggests that there may be increasing expected net present value associated with waiting a few years before exercising the option of adding the solar component to the modified CC power plant.

Table of Contents

1. Introduction 6
    - 1.1. Combined-Cycle Plant: 6
    - 1.2. Integrated Solar Combined Cycle Plant: 7
2. Uncertainties 9
    - 2.1. Cost of Solar Power 10
    - 2.2. Oil and Gas Prices 11
    - 2.3. Regulations 12
3. Decision Analysis 13
4. Lattice Analysis 16
    - 4.1. Modeling Natural Gas Prices 16
    - 4.2. Valuation of the Fixed System 20
    - 4.3. Valuation of the Flexible Option 21
5. Valuation of Flexibility Using Monte-Carlo Simulation 25
6. Conclusions 28
7. Course Reflections 30
8. References 33
9. Appendix 35

List of Tables

Table 1: Combined Cycle Plant Input Values 7
Table 2: Parabolic Trough Costs from 8
Table 3: Values of uncertain variables in chance outcomes 13
Table 4: Multi-Dimensional Comparison of Fixed and Flexible Systems 14
Table 5: Values of Lattice Parameters (Brownian Motion Approach) 17
Table 6: Evolution of Gas Prices Over 30 Years 17
Table 7: Probability Lattice 18
Table 8: Final Input Values and Lattice Parameters 19
Table 9: Final Lattice of Gas Prices ($/MMBtu) 19
Table 10: Final Probability Lattice 20
Table 11: Fixed System Cost Components 20
Table 12: Folded Back Lattice for the Fixed System 21
Table 13: Flexible System Cost Components 22
Table 14: Folding Back Lattices for the Flexible Case 23
Table 15: The Decision Lattice 23
Table 16: Calculations of Power Plant Costs for Fixed and Flexible Systems 26
Table 17: Net Present Costs of the Option (Fixed and Flexible Cases) 26

List of Figures

Figure 1: ISCCS System Design 7
Figure 2: Experience Curve for SEGS plants 10
Figure 3: Projected Solar PV System Cost Decline 2008-30 ($/W) 11
Figure 4: Natural Gas Prices in the US 11
Figure 5: EUA Allowance Price Forecast under the EU ETS (Euro/tCO2) 12
Figure 6: Two-Stage Decision Tree 14
Figure 7: VARG Curve from Decision Analysis 15
Figure 8: Natural Gas Well-Head Price History 16
Figure 9: VARG Curve 27

1. Introduction

Eni, an Italian energy company, has decided to investigate investment options in renewable energy technologies. One such technology, Solar Parabolic Troughs, is being developed in the Mechanical Engineering Department at MIT. Eni plans to use the technology in conjunction with existing fossil-based power plants. Investment in solar parabolic trough technology will provide Eni with the ability but not the obligation to use this technology. Thus, it is an option. This report performs an analysis for evaluating this option by looking at the costs of a single 400 MW power plant. The exact definitions of the fixed and flexible systems are different for each analysis method, but follow the same theme in general; the fixed system is the situation where Eni does not invest in the solar technology and can only build a 400 MW conventional Combined-Cycle (CC) power plant (with no solar component) while the flexible system is the situation where it does invest in the solar technology and can choose whether or not to deploy it and when to do so depending upon the expected outcomes of uncertain parameters. The form of deployment of the option is an Integrated Solar Combined-Cycle (ISCC) plant which is capable of producing 25% of its electricity from the solar component.

In reality, incorporation of the solar component increases the electricity production capacity of the plant but the report examines a situation where the electricity produced by the solar component simply replaces that produced by gas such that the total amount of electricity generation remains constant. It adopts this approach to estimate the value of reduction in gas use since one of the main reasons for the development of the solar technology is to displace fossil fuel usage. The ISCC plant entails additional capital costs over the CC plant since the land requirement increases, the steam turbine needs to be oversized, and the engineering design costs increase. Such a plant would turn out to be cost effective if the additional capital costs were somehow offset by operational savings.

1.1. Combined-Cycle Plant:

Conventional combined cycle (CC) power plants are a very attractive configuration where a suitable fossil fuel (typically natural gas) is available due to excellent performance, cost and emission characteristics. The CC plant consists of a combustion (gas) turbine (GT), heat recovery steam generator (HRSG) and steam turbine (ST). Fuel is combusted in the gas turbine in the normal way, and the hot exhaust gases pass through the HRSG. Here the energy from the gases generates and superheats steam to be used in the ST bottoming Rankine cycle. Hence, the energy in the gas, or other fossil fuel, is used much more efficiently than in a GT alone. The carbon intensity of electricity production is much lower for such plants as compared to conventional coal- or oil-based plants at 0.4 kg per kilowatt-hour of electricity generated.

Combined cycle plants have lower capital costs than traditional coal-fired power plants. The values presented in Table 1 have been used for calculating the net discounted costs of CC plants based on data from 2002 provided by the Energy Information

Administration (EIA, 2002) and data on inflation in the United States (Inflation). The value for capacity factor has been taken from (Tester et al., 2005).

CC Plant	Value	Unit
Capital Cost	718	$/kW
O&M Fixed	18	$/kW/yr
O&M Variable	0.00063	$/kWh
Fuel Cost	4.50	$/MMBtu
Heat Rate	6800	Btu/kWh
Capacity Factor	60%	%

Table 1: Combined Cycle Plant Input Values (EIA, 2002; Inflation, 2009; Tester et al., 2005)

1.2.Integrated Solar Combined Cycle Plant:

Solar energy from a parabolic trough solar field can be integrated with a CC to increase the efficiency even further and to decrease the already low emissions. Given a particular level of electricity generation this efficiency improvement implies the displacement of gas use by the solar resource. This is accomplished in an integrated solar-combined cycle system (ISCCS). The ISCCS calls for part of the heat recovery steam generator (HRSG) to be either replaced or paralleled by equipment serviced by solar thermal energy to supplement turbine exhaust gases.

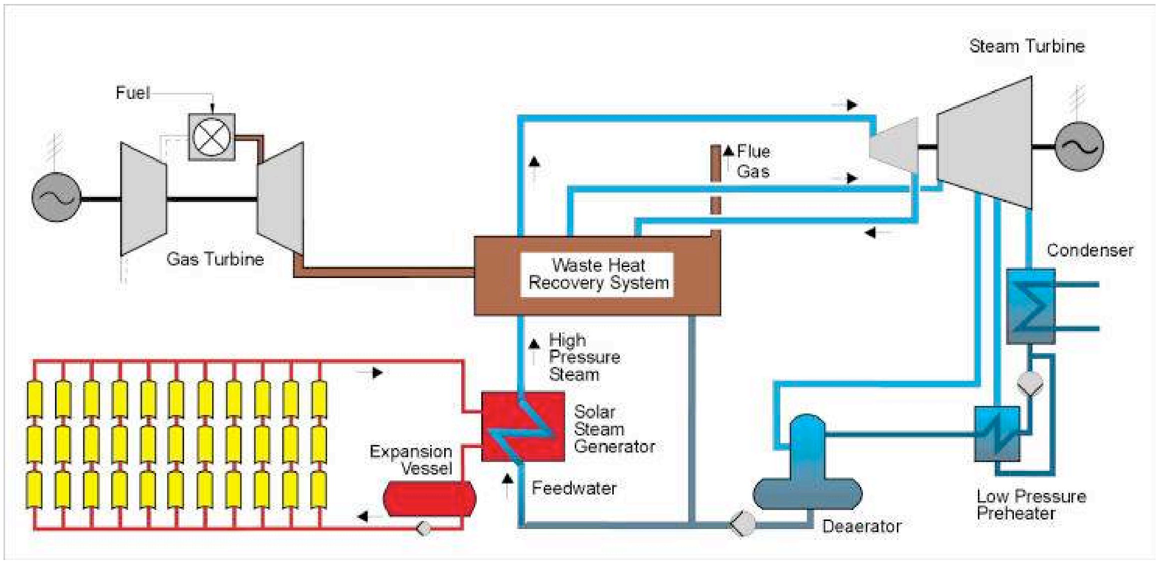

Figure 1: ISCCS System Design (Source: http://www.flagsol.com/ISCCS_tech.htm)

Data on the cost increments resulting from the addition of solar components to combined cycle plants are not readily available, but can be approximated from surveying the literature on costs of existing ISCCS plants. Though literature on this subject is limited, some sources provide valuable information. (Hosseini et al., 2005) for example, present some numbers from their experience with ISCCS plants in Iran. The Global Environment Facility (GEF) provides data on costs of a hybrid solar thermal power plant in Mexico

(World Bank, 2006). (Horn et al., 2004) provide similar data from a feasibility study of ISCCS power plants in Egypt. The most useful resource for the purposes of this report, however, is the data engrained in the Solar Advisor Model (SAM), which was prepared by the National Renewable Energy Laboratory in conjunction with Sandia National Laboratory and in partnership with the U.S. Department of Energy (DOE) Solar Energy Technologies Program (NREL, 2009). SAM uses the most up-to-data data based on current prices and industry status and presents a detailed break-up of the costs of Concentrated Solar Power stations. Access to these individual cost components is especially useful for the purposes of this report since it allows for the accounting of only those components that would actually be required in conjunction with CC plants and it allows for the freedom of conducting the analysis for different sizes of the solar component.

In addition to these costs, we assumed a 5% increase over the first (capital) costs of the CC plant to account for changes in the power plant design due to the incorporation of the solar component. The capacity (in MW) of the Solar component needed to be back-calculated based on the percentage of electricity of the ISCC plant to be provided by the solar component (25% in this case), the net solar heat to electricity conversion efficiency, which was assumed to be 16% (consistent with the high efficiencies estimated for new parabolic trough power plants (Estela Solar, 2009)), an estimate of direct normal solar insolation, which was assumed to be 2500 kWh/m^2/yr (consistent with conditions for which a parabolic trough would be considered) and the area requirement per kW of solar capacity, which was imbedded in SAM (8.5 m^2/kW). These values were used in conjunction with the values in Table 2 to estimate the total costs of the solar component after accounting for economies of scale (using a factor of 0.8 on a Cobb-Douglas function).

Solar Plant (100 MWe)	Value	Units
Direct Capital Costs		
Site Improvements	20	\$/m^2
Solar Field	350	\$/m^2
Heat Transfer Fluid System	50	\$/m^2
Indirect Capital Costs		
Engineer, Procure, Construct	15%	
Project, Land, Management	3.5%	
O&M Costs		
Fixed Cost by Capacity	80	\$/kW-yr
Variable Cost by Generation	3	\$/MWh

Table 2: Parabolic Trough Costs from (NREL, 2009)

For the base case scenario outlined above, the net discounted costs for the CC plant are less than \$900 million while those for the ISCC plant are almost \$1,500 million – 75% higher. This result is not surprising since almost all new technologies are initially more expensive than incumbents. The actual decision of whether or not to invest in the technology, however, rests on some critical assumptions about uncertain variables, some of which are discussed in the next section.

2. Uncertainties

As noted in the previous section, Eni faces a lot of uncertainties while deciding on building a power plant. The main uncertainties include:

- Discount Rates

The discount rate used in a standard NPV analysis represents the opportunity cost of capital for the investing entity. This rate varies according to the expected returns from the different projects available at any given point of time. It is standard practice to conduct a sensitivity analysis to this parameter.

- Cost of Solar Power

The capital costs of power plants using parabolic trough technology are currently prohibitively high. These costs vary from one location to the other since important inputs like labor and material costs may substantially differ from place to place. Moreover, these costs can fall substantially owing to technological innovation, learning curve effects, economies of scale and other mechanisms. If the costs fall substantially, this technology can become cost competitive (and even cheaper in the long run) with traditional fossil based power generation. This is indeed one of the objectives of the current research that is of interest to Eni and thus an important uncertainty to consider.

- Natural Gas Prices

Gas prices have been found to vary substantially in the past. Depletion of easily accessible gas fields and other changes in the industry may lead to an increase in gas prices in the future. Since the technology under examination displaces the use of natural gas for power production, it may become desirable if the price of gas rises to a certain degree. Thus, increases and decreases in gas prices merit consideration in our analysis of uncertainty.

- Regulations

International, regional, national and local policies exist in different areas to support renewable electricity in general and some to support solar-based implements in particular. These could take different forms including subsidies and mandates (for example, to meet renewable portfolio standards). Another form of regulatory support for renewables is pricing carbon emissions.

- Technology Performance

The standard analysis assumes based on current performance levels that the solar component converts 16% of the direct normal solar insolation into electricity. This level (a measure of technology performance) has been improving in the past and can be expected to improve further in future.

- Location (Solar Insolation)

The base case assumes that the location where an ISCC plant would be considered receives direct normal solar insolation of 2,500 kWh per square meter per year. The desirability of the technology increases with this number. In reality, this number varies from place to place (it can be higher or lower) and is an important candidate for uncertainty analysis.

Though each of the uncertainties presented above are important, it is very cumbersome to analyze them all in detail. It is thus important to isolate the most important ones based on professional judgment. The three key uncertainties chosen for this analysis are: cost of solar power, natural gas prices and regulation (carbon prices).

2.1.Cost of Solar Power

Costs of different parts of the solar component are highly uncertain given the new materials used in the technology and the rapidly evolving nature of solar parabolic trough technology in general. The cost of mirrors, efficiency of materials, choice of heat transfer fluid, and other design variables are susceptible to high levels of uncertainty. To keep the analyses simple, uncertainties will be associated with the total capital costs, not with each individual component in Table 2.

These costs can be realistically expected to drop. This would occur due to advances in technology, learning curve effects and economies of scale. For example, a study conducted by the World Bank shows that the levelized electricity cost for solar electricity generation stations (SEGS) dropped significantly as capacity was added in California (Mariyappan and Anderson, 2001). This experience curve is reproduced in Figure 2. Looking ahead, Figure 3 shows that the costs of solar PV systems are expected to fall by around 75% by 2030.

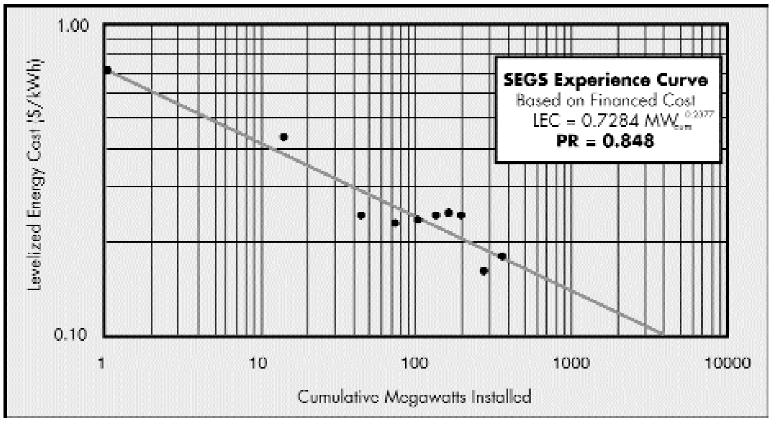

Figure 2: Experience Curve for SEGS plants (Mariyappan and Anderson, 2001)

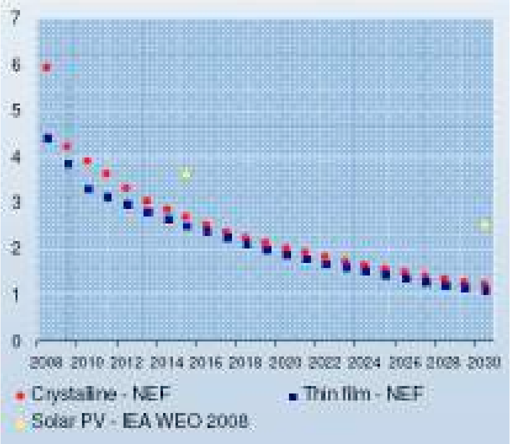

Figure 3: Projected Solar PV System Cost Decline 2008-30 ($/W) (Liebreich, 2009)

The extent to which prices will fall in future is highly uncertain and largely unknowable. However, a 20-30% reduction in cost per doubling of capacity is typical in this field and a reduction in capital costs of even 75% is reasonable (as Figure 3 shows) for the foreseeable future. The analysis thus considers a range of parabolic trough cost reduction between 0% and 75%.

2.2.Oil and Gas Prices

Rising/falling oil and gas prices would make the solar module more/less attractive. If the price of gas remains low, Eni may want to continue with the conventional combined cycle plant but if gas prices rise, it may want to utilize the solar technology's capabilities. Historic data on oil and gas prices are readily available (see Figure 4).

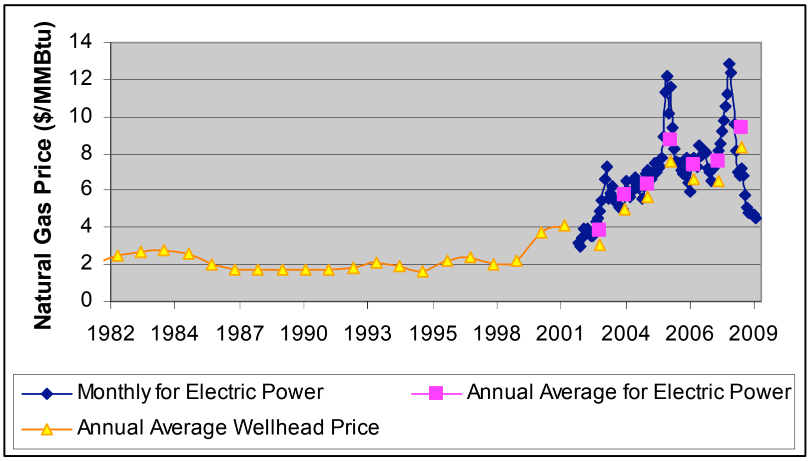

Figure 4: Natural Gas Prices in the US (EIA, 2009)

The maximum price over the past six years was $12.50/MMBtu in June 2008 while the minimum cost was $2.86/MMBtu in February 2002 (NEF, 2009). The latest available price of natural gas from (EIA, 2009) is $4.50/MMBtu (for July 2009). From Figure 4, we can see a rising trend in gas prices over the past 10 years and we can expect this trend to continue into the future, although not as aggressively as in the past owing to the recent rise in gas discoveries. We accept \$15/MMBtu as a reasonable limit on the gas price for the foreseeable future. The range of gas prices considered for the preliminary analysis is \$4.5-\$15/MMBtu.

2.3.Regulations

New agreements might be established during the global talks on climate change in Copenhagen in December (or in other climate treaties in future) to further support the development of this technology. Regulatory issues could thus change the economics that govern investment in this technology.

Expected regulations would likely improve the cost effectiveness of producing electricity using this technology in relation to others. Some current regulations supporting solar electricity in the US are:

a. 30% commercial investment tax credit (Federal government)
b. Exempt sales and property taxes on solar power plants – These exemptions will result in a 1-2¢/kWh price reduction.
c. Allowing longer-term Power Purchase Agreements (PPA) and setting equitable central station solar power price references – Encourage States to extend the allowed PPA term to 30 years. This provides the market stability needed for capital-intensive solar power development.

In this report, the effect of regulation is represented by a tax on carbon dioxide emissions. The Waxman-Markey climate bill introduced into the US Congress estimates that by 2015, carbon emissions will be priced between \$13 and \$26 per metric ton (Lomax, 2009). But the price in Europe has already reached a high of 30 Euros (approximately equal to US \$44) in July 2008 (Schiermeier, 2009). The Waxman-Markey estimate could thus be way off the mark, especially in the case of a global climate treaty or other environmental, social and political changes. For example, Figure 5 shows predictions that the value of emissions will skyrocket by 2020.

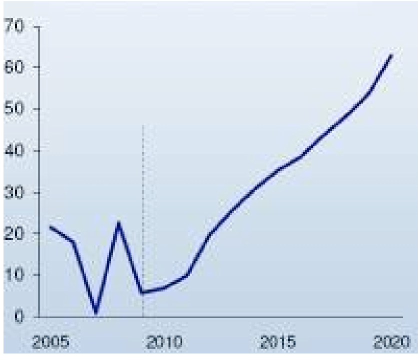

Figure 5: EUA Allowance Price Forecast under the EU ETS (Euro/tCO2) (Liebreich, 2009)

We can thus reasonably expect a carbon dioxide price in the range of \$100 per metric ton in the foreseeable future. The range considered for the analysis in this report is \$0-\$100/tonne. The next section performs a decision analysis based on these uncertainties.

3. Decision Analysis

A decision analysis helps to guide decision makers through the process of determining the option value of the investment. In this report, a two-stage decision analysis is described. The chance outcomes after each decision node are represented by combinations of outcomes of the uncertain variables discussed above. To keep the analysis simple, three possibilities are analyzed to represent the range of possible outcomes. The first scenario, "great," is when the outcome of each of the three uncertainties is as beneficial as possible for the solar technology. The second, "good," is when each uncertain variable takes on a value somewhere between the current scenario and the best case scenario. The third, "same," is when each uncertain variable sustains a value close to (slightly improved) that in the base case. The distribution of chance outcomes at the end of stage 2 is represented in Table 3.

Uncertainty/Outcome	Great	Good	Same
Solar Cost (% reduction over base-case)	75%	50%	25%
Gas Price ($/MMBtu)	15	10	5
CO_2 Price ($/tonne)	100	50	0

Table 3: Values of uncertain variables in chance outcomes

Owing to lack of historical data, uncertainties like cost reduction and CO_2 price cannot be easily predicted. Thus, for illustrative purposes, the probability of each chance outcome after the first decision node is assumed to be equal (=1/3). It is quite realistic to assume that for the second stage, the probability of the chance outcome from the first stage repeating itself would be high. For example, if the outcome was "great" in the first stage, representing a decrease in solar costs, an increase in the gas price and a price on carbon dioxide, the probability that the outcome would again be "great" for the second stage is high. The probability distribution for the second stage is modified to reflect this expectation. The outcome in the second stage that is a repeat of the outcome in the first stage has a probability of 2/3 with the rest shared equally between the other two possible outcomes.

The decision tree corresponding to the two-stage decision analysis is presented in Figure 6. C1, C2 and C(end) represent the net discounted costs of running the power plants over their lifetime of 30 years (in billions of US dollars). Thus, a lower value is preferred over a higher one. D1 and D2 represent the decisions made at stages 1 and 2 respectively while P1 and P2 represent the probability distributions of the chance outcomes. At decision stage 1 (time 0), Eni decides whether or not to invest in the technology. This decision dictates whether Eni is tied to a fixed system or open to a flexible system.

Fixed System

The fixed system for this analysis is the case where Eni does not invest in the solar technology. Therefore, regardless of the outcome of uncertainties, the decision makers are stuck with the decision of building a combined cycle plant with no solar capabilities. They are thus not able to react to the chance outcome after the first stage in any way.

Flexible System

In case the investment was made at time 0, Eni would have the option in stage 2 of either developing a CC plant or an ISCC plant. This decision would be informed by the outcome of the uncertain parameters in stage 1. Figure 6 shows, for example, that if the outcome in stage 1 is “great,” Eni would be wise to choose to invest in the ISCC plant in stage 2 expecting a “great” outcome again (which would result in a lower net discounted cost). In the other two cases, the decision to choose CC plants is optimal.

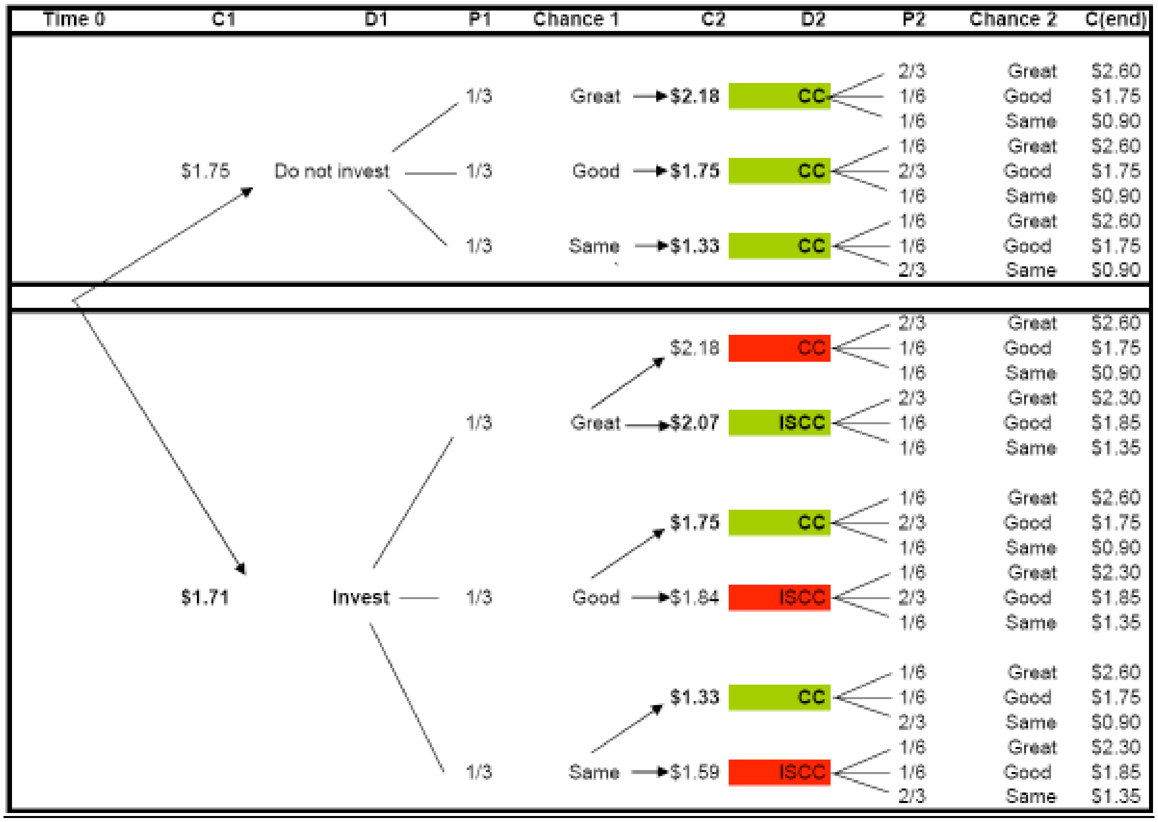

Figure 6: Two-Stage Decision Tree

The decision tree above shows the value of the option (investment in the solar technology) for Eni. This is precisely the difference between the expected values of the two decisions taken at time 0: $40 million. Based on these expected values (under the assumptions outlined above), it would make sense for Eni to invest in the solar technology if the investment cost was lower than $40 million. Table 4 compares the two alternatives across multiple dimensions:

In $ Billion	Fixed Option	Flexible Option	Which is Better?
Expected Value NPC	1.75	1.71	Flexible
Maximum NPC	2.6	2.3	Flexible
Minimum NPC	0.9	1.35	Fixed

Table 4: Multi-Dimensional Comparison of Fixed and Flexible Systems

Table 4 shows that the flexible system is preferable to the fixed system by two metrics: expected net present costs and maximum possible net present costs. However, the fixed system is preferred if one cares about the minimum possible net present costs.

The results of the decision analysis can be summarized using a Value at Risk-Gain (VARG) curve. The VARG curve is a plot of cumulative probability against a measure of value; in this case, net present costs over the lifetime of a power plant. The blue curve in Figure 7 represents the VARG curve for the case where Eni invests in the solar technology (flexible case) and the pink curve represents the VARG curves for the case where Eni does not invest in the solar technology. The curves shows that if the decision to invest in solar technology is taken, Eni will incur the same costs as it would if the decision not to invest was taken for the "good" and "same" cases. However, if the situation turns out to be "great" the net present costs in case Eni does invest in the technology are substantially lower than those if Eni does not invest in the technology. The pink vertical dotted line shows the expected value of net present costs for the inflexible case and the blue vertical dotted shows the net present costs for the flexible case. It is clear that the flexible case is more valuable.

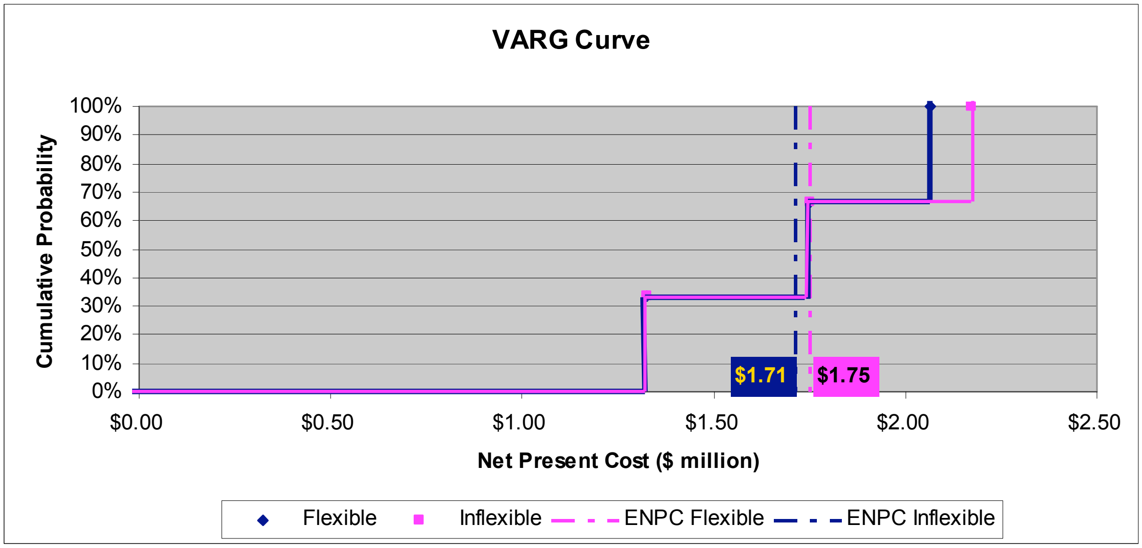

Figure 7: VARG Curve from Decision Analysis

The subsequent section performs a different evaluation of flexibility using the binomial lattice approach.

4. Lattice Analysis

This section employs the binomial lattice approach to estimate the value of flexibility by comparing the net present costs of a traditional CC plant (***fixed system***) with those of a modified CC plant that can be converted into an ISCC plant in year 5 (***flexible system***) depending on the outcome of a modeled uncertainty. Out of the three uncertainties considered for the analysis in this report, reliable historical data exists only for prices of natural gas. Thus, this uncertainty lends itself to a meaningful analysis using the binomial lattice approach.

4.1.Modeling Natural Gas Prices

As mentioned in the discussion of uncertainties in section 2, historical data on natural gas prices are readily available from the Energy Information Administration (EIA, 2009). Historical data beginning in 1985 and ending in 2008 were used for this analysis. An alternative choice for the time-period for which data were used for modeling would change the results somewhat. The model below has been developed using data going back to the first year for which data were available.

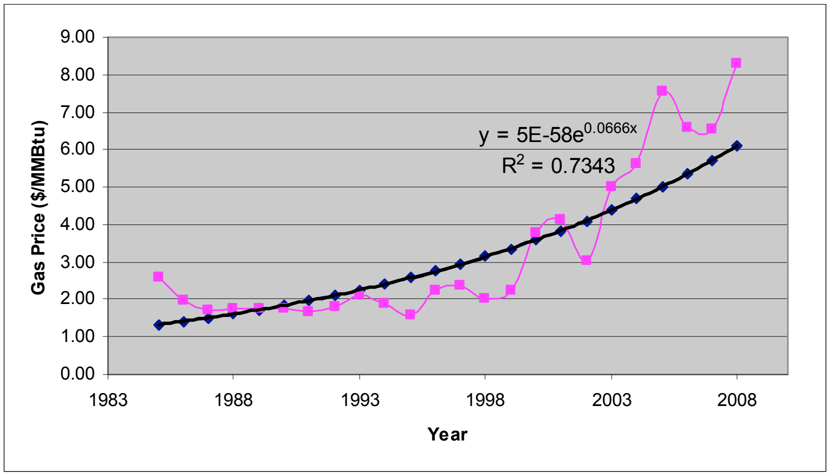

Figure 8: Natural Gas Well-Head Price History (EIA, 2009)

4.1.1. Brownian Motion Method

Natural gas prices can be modeled as a random walk. The black trend line in Figure 8 represents an exponential fit to the data. The equation that represents this fit is:

P(t) = P(0)*exp(r*t)

where,
P(t) = Price at time t
P(0) = Price at time 0
r = rate of growth

t = time in years since time 0

The trend-line equation identifies that the annual growth rate (ν) during 1985-2008 was 6.66%. The volatility associated with natural gas prices (σ) was almost 29%. These numbers, and a time-period of one year ($\Delta t=1$), form the basis upon which the lattice parameters (u, d, and p) are constructed. The relationships are given by the following formulae:

"Up" factor, u = exp(σ *sqrt(t))
"Down" factor, d = 1/u
Probability of the "Up" state, p = 0.5 + 0.5*(ν / σ)*sqrt(t)
The calculated outcomes are:

u	d	p
1.336	0.748	0.615

Table 5: Values of Lattice Parameters (Brownian Motion Approach)

The latest available price of natural gas (for July, 2009) is close to $4.50/MMBtu (EIA, 2009). This value is taken as the starting point for the analysis. Table 6 shows how the price of gas evolves over the 30-year life of the power plants and Table 7 shows the corresponding probabilities.

Year 0	5	10	15	20	25	29
4.50	19.16	81.54	347.09	1477.46	6289.13	20037.83
	10.73	45.68	194.45	827.72	3523.38	11225.88
	6.01	25.59	108.94	463.72	1973.92	6289.13
	3.37	14.34	61.03	259.79	1105.86	3523.38
	1.89	8.03	34.19	145.54	619.54	1973.92
	1.06	4.50	19.16	81.54	347.09	1105.86
		2.52	10.73	45.68	194.45	619.54
		1.41	6.01	25.59	108.94	347.09
		0.79	3.37	14.34	61.03	194.45
		0.44	1.89	8.03	34.19	108.94
		0.25	1.06	4.50	19.16	61.03
			0.59	2.52	10.73	34.19
			0.33	1.41	6.01	19.16
			0.19	0.79	3.37	10.73
			0.10	0.44	1.89	6.01
			0.06	0.25	1.06	3.37
				0.14	0.59	1.89
				0.08	0.33	1.06
				0.04	0.19	0.59
				0.02	0.10	0.33
				0.01	0.06	0.19
					0.03	0.10
					0.02	0.06
					0.01	0.03
					0.01	0.02
					0.00	0.01
						0.01
						0.00
						0.00
						0.00

Table 6: Evolution of Gas Prices Over 30 Years

Year 0	5	10	15	20	25	29
1.0000	0.0879	0.0077	0.0007	0.0001	0.0000	0.0000
	0.2753	0.0484	0.0064	0.0007	0.0001	0.0000
	0.3448	0.1364	0.0280	0.0045	0.0006	0.0001
	0.2159	0.2278	0.0760	0.0167	0.0030	0.0007
	0.0676	0.2496	0.1427	0.0445	0.0102	0.0027
	0.0085	0.1876	0.1966	0.0893	0.0269	0.0086
		0.0979	0.2051	0.1397	0.0561	0.0215
		0.0350	0.1652	0.1750	0.0954	0.0443
		0.0082	0.1034	0.1780	0.1344	0.0763
		0.0011	0.0504	0.1486	0.1590	0.1115
		0.0001	0.0189	0.1024	0.1593	0.1396
			0.0054	0.0583	0.1360	0.1510
			0.0011	0.0274	0.0993	0.1418
			0.0002	0.0105	0.0622	0.1161
			1.45E-05	0.0033	0.0334	0.0831
			6.06E-07	0.0008	0.0153	0.0520
				0.0002	0.0060	0.0285
				2.38E-05	0.0020	0.0136
				2.49E-06	0.0006	0.0057
				1.64E-07	0.0001	0.0021
				5.13E-09	2.40E-05	0.0006
					3.58E-06	0.0002
					4.07E-07	3.95E-05
					3.32E-08	7.53E-06
					1.73E-09	1.18E-06
					4.35E-11	1.48E-07
						1.42E-08
						9.89E-10
						4.42E-11
						9.55E-13

Table 7: Probability Lattice

The use of this approach on gas prices results in unreasonable predictions. For example, even though the associated probability is only 0.01%, Table 6 suggests that the gas price may reach $6,289/MMBtu. This observation points to the need of an alternative approach to modeling natural gas prices.

4.1.2. Prescriptive Approach

An alternative approach to the random walk approach considered above consists of making predictions of a maximum and an average gas price in a given number of years. Based on these inputs, u, d, and p are then calculated using the following relationships:

u = (Maximum Gas Price/Gas Price in Base Year) $^{(\text{duration-1})}$;
d = 1/u;
p = back-calculated using excel function “goal seek”

Table 8 shows the values of u, d and p that are used in the final price lattice and the associated inputs of maximum price in year 11 (12 years after the start of the project in year 0) and average gas price in year 10:

Maximum ($/MMBtu) in Year 11	30	u	1.188
Average ($/MMBtu) in Year 10	10	d	0.842
Starting ($/MMBtu)	4.5	p	0.697

Table 8: Final Input Values and Lattice Parameters

The resulting price and probability lattices are presented below:

Year 0	5	10	15	20	25	29
Price						
4.50	10.66	25.25	59.80	141.65	335.53	668.86
	7.55	17.88	42.36	100.33	237.65	473.73
	5.35	12.67	30.00	71.06	168.32	335.53
	3.79	8.97	21.25	50.33	119.21	237.65
	2.68	6.35	15.05	35.65	84.44	168.32
	1.90	4.50	10.66	25.25	59.80	119.21
		3.19	7.55	17.88	42.36	84.44
		2.26	5.35	12.67	30.00	59.80
		1.60	3.79	8.97	21.25	42.36
		1.13	2.68	6.35	15.05	30.00
		0.80	1.90	4.50	10.66	21.25
			1.35	3.19	7.55	15.05
			0.95	2.26	5.35	10.66
			0.68	1.60	3.79	7.55
			0.48	1.13	2.68	5.35
			0.34	0.80	1.90	3.79
				0.57	1.35	2.68
				0.40	0.95	1.90
				0.28	0.68	1.35
				0.20	0.48	0.95
				0.14	0.34	0.68
					0.24	0.48
					0.17	0.34
					0.12	0.24
					0.09	0.17
					0.06	0.12
						0.09
						0.06
						0.04
						0.03

Table 9: Final Lattice of Gas Prices ($/MMBtu)

Year 0	5	10	15	20	25	29
Probabilities						
1.0000	0.1643	0.0270	0.0044	0.0007	0.0001	0.0000
	0.3574	0.1175	0.0290	0.0063	0.0013	0.0004
	0.3110	0.2300	0.0882	0.0262	0.0068	0.0022
	0.1353	0.2668	0.1662	0.0684	0.0227	0.0085
	0.0294	0.2031	0.2169	0.1265	0.0543	0.0240
	0.0026	0.1060	0.2076	0.1761	0.0992	0.0523
		0.0384	0.1505	0.1915	0.1438	0.0910
		0.0096	0.0842	0.1667	0.1698	0.1300
		0.0016	0.0366	0.1178	0.1662	0.1555
		0.0002	0.0124	0.0683	0.1366	0.1579
		0.0000	0.0032	0.0327	0.0951	0.1374
			0.0006	0.0129	0.0564	0.1032
			0.0001	0.0042	0.0286	0.0674
			0.0000	0.0011	0.0125	0.0383
			5.79E-07	0.0002	0.0046	0.0190
			1.68E-08	0.0000	0.0015	0.0083
				0.0000	0.0004	0.0032
				5.95E-07	0.0001	0.0010
				4.31E-08	0.0000	0.0003
				1.97E-09	0.0000	0.0001
				4.30E-11	3.75E-07	0.0000
					3.88E-08	0.0000
					3.07E-09	4.92E-07
					1.74E-10	6.51E-08
					6.32E-12	7.08E-09
					1.10E-13	6.16E-10
						4.12E-11
						1.99E-12
						6.19E-14
						9.29E-16

Table 10: Final Probability Lattice

Though some values for the latter years are still unreasonable, the prescriptive approach still leads to a more realistic model for the development of gas prices. The analysis in the subsequent sub-sections thus uses the values from Table 9 and Table 10. In order to assess the value of flexibility, the next sub-sections compare the net present costs of a traditional CC plant against those of a modified CC plant which can be converted into an ISCC plant in year 5 depending upon the expected gas prices.

4.2. Valuation of the Fixed System

The fixed system is a 400 MW conventional combined cycle plant with no capability of accommodating a solar component over its lifetime. It has the same input profile as presented in Table 1. In addition, carbon dioxide emissions are valued at a price of $50 per metric ton. The major cost components of this plant with the exception of fuel costs then are:

CC Plant (Fixed System)	
Capital Cost ($)	287,034,764
Annual Carbon Costs ($, @$50/tonne)	42,048,000
Annual Operational Costs ($)	8,364,446

Table 11: Fixed System Cost Components

Fuel costs vary from year to year depending upon the price of natural gas (modeled in Table 9). Total costs for each year of the power plant's life are calculated corresponding to each possible price level of natural gas to produce a total cost lattice for the fixed design. This lattice is folded back starting from the final year of the plant's life to arrive at a net present cost for the fixed design of $2,366 million. The results for the first six years of the folded back lattice are presented in Table 12 below.

CC Lattice						
	Year 0	1	2	3	4	5
2,366,489,556		2.3E+09	2.6E+09	2.9E+09	3.3E+09	3.7E+09
		1.8E+09	2.0E+09	2.2E+09	2.5E+09	2.8E+09
			1.6E+09	1.7E+09	1.9E+09	2.1E+09
				1.4E+09	1.5E+09	1.6E+09
					1.2E+09	1.3E+09
						1.1E+09

Table 12: Folded Back Lattice for the Fixed System

4.3.Valuation of the Flexible Option

The flexible system is a modified CC plant, one that can be converted into an ISCC plant in year 5 depending on expectations of natural gas prices. The system is flexible since decision makers can choose whether or not to implement the option.

The lattice approach allows the analyst to estimate the value of flexible systems by implementing decision rules (do 'X' if 'Y') and estimating the expected NPV using dynamic programming (making decisions at the end of a stage considering expectations of what is coming later). This section presents a simple analysis using this approach.

Some up-front changes need to be made to the conventional CC (fixed system) to transform it into a modified CC plant. To this modified CC plant, we can later add solar troughs to transform it into an ISCC plant. The up-front changes involve costs that are termed here as 'design-in' costs.

- The 'design-in' cost: This is the cost of transforming a conventional CC plant into a modified CC plant. It includes site work and infrastructure costs (including land and labor) and systems costs (including over-sizing the steam turbine). This amounts to ~$46 million. The total capital cost in year 0 is thus $333 million.

For simplicity, the analysis presented here considers a single year (year 5) when the option of converting the modified CC plant into an ISCC plant can be exercised. Exercising this option requires large investments since it requires major modifications to the existing plant. These invests are referred to as 'decision costs.' The analysis in this section assumes that the values of the other two uncertainties - capital cost and carbon prices - correspond to the "good" scenario from the Decision Analysis section. Thus, the capital cost of the solar component is assumed to be 50% lower than in the base case and the carbon price is assumed to be $50 per metric ton.

- The 'decision' cost: This represents the costs of transforming the modified CC plant into an ISCC plant once the decision to do so is made. It includes the costs of mirrors, support structures, heat transfer fluids, etc. and additional engineering and construction costs. This amounts to ~$306 million (under the assumptions of a "good" scenario from the decision analysis section).

The decision on whether or not to exercise this option depends upon the expectations of gas prices since adding the solar component reduces the amount of electricity that is generated using gas. If the option is exercised, annual carbon costs reduce to less than $32 million since the solar component now produces a significant portion of the plant's total electricity. Also, total operational costs rise to almost $20 million since maintenance work is required on the solar troughs. Table 13 summarizes the cost components of the flexible case. The last two rows represent the annual costs after year 5 assuming that the option is exercised:

Enhanced CC Plant (Flexible System)	
Capital Cost ($)	332,727,051
Cost of Exercising Flexibility; 'Decision Cost' ($)	305,674,562
Annual Carbon Costs ($, @$50/tonne)	31,536,000
Annual Operational Costs ($)	20,670,791

Table 13: Flexible System Cost Components

Valuation of the flexible system requires the construction of the following lattices:

i. Lattice of annual costs for the flexible system assuming that the option is never exercised (just the modified CC plant). This lattice is identical to the cost lattice developed for the fixed scenario except for the additional capital costs incurred in year 0. This lattice is reproduced in the Appendix.

ii. Lattice of annual costs for the flexible system assuming that the option is exercised in year 5 regardless of the future evolution of gas prices. This lattice is identical to lattice (i) until year 5. In year 5, the 'decision cost' in incurred and for every year after year 5 (and including year 5), the annual carbon costs and operational costs correspond to the values in Table 13. This lattice is reproduced in the Appendix.

iii. Folded back lattice assuming that the option is never exercised to arrive at a net present cost for this case (see Table 14).

iv. Folded back lattice assuming that the option is always exercised in year 5 to arrive at a net present cost for this case (see Table 14).

v. Folded back lattice assuming that the option is only exercised in year 5 if it is profitable to do so considering expectations of the future evolution of gas prices (see Table 14). At the end of year 4, this lattice compares the net present costs in year 5 calculated in (iii) and (iv) above. For high gas prices, the expected value of net present costs in year 5 is lower for (iv) than for (iii). The situation is reversed for low gas prices. The decision rule, thus, is:

   Implement the solar option in year 5 if the expected net present costs in year 5 are lower in case (iv) than in case (iii).

> Thus, the option is exercised in case of expectations of high gas prices and not otherwise. This lattice calculates the expected net present costs under this decision rule.

The first six years for lattices (iii), (iv) and (v) are reproduced below:

Lattice (iii)					
Year 0	1	2	3	4	5
2,412,181,843	2.3E+09	2.6E+09	2.9E+09	3.3E+09	3.7E+09
	1.8E+09	2.0E+09	2.2E+09	2.5E+09	2.8E+09
		1.6E+09	1.7E+09	1.9E+09	2.1E+09
			1.4E+09	1.5E+09	1.6E+09
				1.2E+09	1.3E+09
					1.1E+09
Lattice (iv)					
Year 0	1	2	3	4	5
2,301,921,967	2.2E+09	2.4E+09	2.6E+09	2.9E+09	3.2E+09
	1.75E+09	1.9E+09	2.1E+09	2.3E+09	2.5E+09
		1.6E+09	1.7E+09	1.9E+09	2.0E+09
			1.4E+09	1.6E+09	1.7E+09
				1.3E+09	1.4E+09
					1.3E+09
Lattice for Flexible Case (v)					
Year 0	1	2	3	4	5
2,298,014,945	2.2E+09	2.4E+09	2.6E+09	2.9E+09	
	1.71E+09	1.9E+09	2.1E+09	2.3E+09	
		1.5E+09	1.7E+09	1.9E+09	
			1.4E+09	1.5E+09	
				1.2E+09	

Table 14: Folding Back Lattices for the Flexible Case

The expected net present cost of the flexible system is thus calculated as $2,298 million. The "yes" cases in decision lattice below represent the cases in which the option is exercised at the end of year 4.

Decision Lattice				
Year 0	1	2	3	4
				yes
				yes
				yes
				no
				no

Table 15: The Decision Lattice

The value of flexibility is the difference between this value and the expected net present costs calculated in lattice (v) and those calculated for the fixed system (in Table 12). The value of flexibility is thus:

$2,366 million - $2,298 million = **$68 million**

The lattice analysis shows that under the modeled distribution of natural gas prices and the assumptions discussed above, the flexible system is $68 million more valuable than the fixed system.

The subsequent section allows for a more meaningful analysis of flexibility as Monte-Carlo simulation allows for the modeling of a more realistic decision rule (one not restricted to exercising the option in a particular year) while keeping the analysis simple and transparent.

5. Valuation of Flexibility Using Monte-Carlo Simulation

In this section, a third way to value flexibility - Monte-Carlo simulation - is introduced. The kind of flexibility modeled in this section differs from the one modeled in the previous sections. The previous sections modeled the value of the flexibility gained from an investment in solar parabolic trough technology as they compared fixed systems in which Eni would not have the option of deploying the solar component with flexible systems in which Eni would have this option. This section assumes that investment in solar parabolic trough technology has already been made and models the value of flexibility gained from deferring the full commitment to build an ISCC plant to the future. Hence, the ***fixed system*** in this section is the modified CC plant from the lattice section above in which the decision to exercise the option is made in year 0 itself (this is simply an ISCC plant). The ***flexible system*** is one in which the decision to implement the solar component is exercised at any time during the first ten years of the plant's life depending upon an uncertain variable. As in the lattice model above, the uncertain variable considered for the analysis is the natural gas price.

The Lattice Analysis section above identified a trend-line for natural gas prices with an annual growth rate (ν) during 1985-2008 of 6.66% and volatility (σ) of almost 29%. For the Monte-Carlo analysis, these parameters are used as the mean and standard deviation of a normal distribution from which the percentage change in fuel costs in sampled for each year of the power plants' life.

The decision rule employed for this analysis is different from that used earlier. The new decision rule is:

> *Implement the option if gas prices for the previous two years have been observed to be higher than $8/MMBtu.*

This rule is exercised for the first ten years of the power plant's life. The rule effectively constrains the use of the option between years 2 and 9. If gas prices were higher than $8/MMBtu in year 0 and year 1, the option would be exercised in year 2. Beginning in year 10, the plant would remain the same as it was in the previous year. Table 16 shows some calculations for the fixed case and the flexible case:

Power Plant Costs	Units	**Flexible Case**			**Fixed Case**		
Time	year	0	5	10	0	5	10
Electricity (Gas)	GWh	2,102	2,102	1,577	1,577	1,577	1,577
Electricity (Solar)	GWh	0	0	526	526	526	526
Electricity (Total)	GWh	2,102	2,102	2,102	2,102	2,102	2,102
Capital Cost	$	332,727,051	305,674,562	0	638,401,613	0	0
Non Fuel O&M	$	8,364,446	8,364,446	21,003,206	21,003,206	21,003,206	21,003,206
Fuel Price	$/MMBtu	4.50	12.38	4.06	4.50	12.38	4.06
Fuel O&M	$	64,333,440	176,948,104	43,512,983	48,250,080	132,711,078	43,512,983
CO2 emissions	‘1000 tonnes	841	841	631	631	631	631
CO2 price	$/ton	50	50	50	50	50	50
CO2 total cost	$	42,048,000	42,048,000	31,536,000	31,536,000	31,536,000	31,536,000
Total Cost (nominal)	$	447,472,937	533,035,112	96,052,189	739,190,899	185,250,285	96,052,189
CRF	1/(1+r)^n	1.000	0.621	0.386	1.000	0.621	0.386
Total Cost (PV)	$	447,472,937	330,972,867	37,032,277	739,190,899	115,025,852	37,032,277

Table 16: Calculations of Power Plant Costs for Fixed and Flexible Systems

Table 16 presents a snap-shot of one scenario in a Monte-Carlo analysis. It compares the costs of a power plant under a flexible system (where the decision rule applies) and a fixed system (ISCC from the start). In this particular scenario, the price of natural gas was higher than $8/MMBtu in years 3 and 4 so the decision to exercise the option (to add the solar component) is made in year 5. Hence, there is an additional capital cost in year 5 in the flexible case. Subsequent to year 5, the O&M costs of the power plant increase (become equal to those in the fixed case), the fuel O&M costs decrease (for the same fuel price) and the CO_2 emissions decrease. These values are constant throughout the analysis timeframe for the fixed case.

The value of flexibility is the difference in the expected net present costs of the two systems given the same random distribution of gas prices. The results of Monte-Carlo simulations of the net present costs of the two systems are summarized in Table 17 along-with other metrics to compare among the two alternatives:

	Fixed System	**Flexible System**	**Which is Better?**
Expected NPC ($ million)	2,158	2,074	Flexible
Maximum NPC ($ million)	14,663	14,695	Fixed
Minimum NPC ($ million)	1,280	985	Flexible
Initial Capital Ex ($ million)	638	333	Flexible

Table 17: Net Present Costs of the Option (Fixed and Flexible Cases)

Table 17 shows that the expected net present cost is lower for the flexible system than for the fixed system. Thus, use of the decision rule increases the value of the project as compared to a full commitment in the beginning to implement the option. The value of the flexibility (= NP Cost of the plant with the solar component added in year 0 – NP Cost of the plant with the solar component added based on the decision rule) is $84 million.

Table 17 also shows that the flexible option is superior to the fixed option in terms of the best possible performance, represented by the minimum net present costs of the power plant and in terms of initial capital expenditure, which is much lower for the flexible case. However, it marginally under-performs when we compare the worst possible performance (maximum net present costs).

Figure 9 plots the difference in expected net present costs for the fixed and the flexible option. As before, the expected value of flexibility is calculated as the expected net present cost of the fixed system minus the expected net present cost of the flexible system.

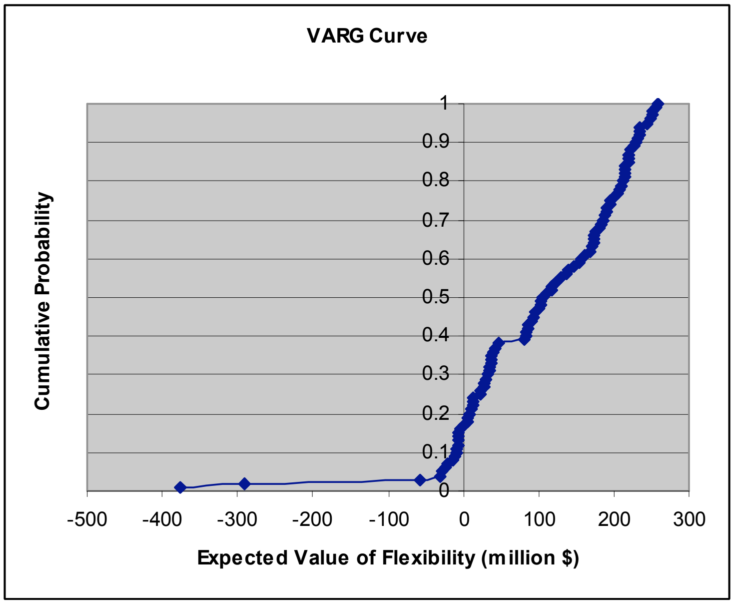

Figure 9: VARG Curve

Figure 9 shows that the probability of the fixed system performing better than the flexible system is lower than 20% when the metric of performance is expected net present cost. These situations correspond to cases where the cost of natural gas rises dramatically in the later stages of the life of the power plant (after 10 years), after the flexible option has expired.

6. Conclusions

This report studied investment in solar parabolic trough technology as an option available to Italian oil and gas company Eni. It compared two alternative types of power plants – combined cycle and integrated solar combined cycle – to approximate the value of this option.

The systems studied in this report were:

- Conventional Combined Cycle (CC) Power Plant: A 400 MW power plant using natural gas as the primary fuel.
- Modified CC Plant: A 400 MW CC power plant with the option of conversion into an ISCC power plant producing 25% of its electricity from the solar component.
- Integrated Solar Combined Cycle (ISCC) Power Plant: A 400 MW power plant producing 25% of its electricity from the solar component.

The base case analysis showed that an ISCC plant is approximately 75% more expensive than a CC plant over the 30-year lifetime of a power plant. Realistic ranges of the three major uncertainties considered in this report suggested that this technology may actually become cost competitive in future. Three different approaches were employed to account for these uncertainties: decision analysis, lattice analysis, and Monte-Carlo simulation.

A two-stage decision tree was constructed representing three different outcomes of the combinations of uncertainties. Under the assumptions of this simple decision analysis, investment in the solar parabolic trough technology was found to be justified for Eni if the investment cost of acquiring the option was less than $40 million.

The second approach to evaluate the value of the option modeled natural gas prices using a binomial lattice. This analysis showed under the assumptions of a 50% reduction in capital costs of solar parabolic troughs and a $50 per metric ton cost on carbon emissions, a modified CC power plant that can be converted into an ISCC plant is more valuable than a simple CC plant even though it has higher capital costs. The value of flexibility for a one-time-only decision rule (in year 5) was found to be around $68 million. Computational difficulty using this approach necessitated the use of Monte-Carlo simulation to model the value of flexibility under a more realistic decision rule.

The Monte-Carlo approach modeled the natural gas price as a random variable with the mean and standard deviation derived from actual natural gas price data for the US. This analysis was conducted assuming decision makers could decide to add the solar component to the modified CC plant in any of the first ten years of the plant's life depending on past gas prices. This analysis found the value of flexibility to be around $84 million. Comparisons of the fixed and the flexible system across multiple metrics showed that the flexible system was preferred for most metrics.

The analysis presented in this report is not meant to be comprehensive in order to aid Eni to make an investment decision on solar parabolic troughs. Rather, it is meant to illustrate ways to account for major uncertainties in valuing new technologies.

7. Course Reflections

The course has clearly and convincingly highlighted the potential value of flexibility in the design of engineering systems and has taught students multiple methods to determine the value of this flexibility. In this section, I summarize the main lessons that I have learnt from this course.

1. Traditional Methods of Project Evaluation

The course has provided a good and thorough review of traditional methods of project evaluation like net present value (NPV), benefit-cost ratio, internal rate of return and pay back period. The discussions have highlighted the strengths and weaknesses of each method and cases in which one of the methods is preferred over others. The fact that several criteria should be ideally used to compare across investment alternatives has been emphasized.

2. Uncertainty in inevitable and forecasts are always wrong

The course has throughout emphasized the fact that we live in an uncertain world. Some systems are associated with large uncertainties while some with smaller uncertainties, but necessarily all systems are associated with at-least some uncertainty that we cannot realistically hope to avoid with any statistical technique. Thus, we need to account for these uncertainties in our designs in order to improve them. The "flaw of averages" highlights the importance of accounting for uncertainties and drives home the point that designing to predictions of the average expectations can be misleading.

3. Uncertainty implies risk as well as opportunity

Perhaps the most fundamental realization from this class has been that the way we traditionally think about uncertainties is highly myopic; uncertainties do not only present risks but also opportunities. We are usually concerned with insuring our systems against the downsides but rarely think about positioning our systems to take advantage of upsides. This realization fundamentally changes the way we design engineering systems.

4. A (very good) way to deal with uncertainty in engineering systems is designing flexibility into the system

The realizations that uncertainties are inevitable and that they present opportunities as well as risks necessitate the methods to effectively deal with them. The course has concentrated on designing flexibility into engineering systems as a way to do so. Examples of flexibility include deferring investments, skipping investments, building smaller initially and so on. Such flexibility can provide insurance against risks as well as enable designers to take advantage of unforeseen upside opportunities. In fact, such an approach to design has been found to increase the expected value of projects consistently. The emphasis is on expected costs since we cannot predict what will happen but we can average over realistic expectations of the future. In addition, this approach usually involves lower up-front costs and thus presents win-win situations – a major selling point for decision makers.

5. There are advantages and limitations of different approaches to analyze the value of this flexibility

The course introduced three main methods suitable for the valuation of flexibility: decision analysis, lattice analysis and Monte-Carlo simulation. It stressed that each method has its strengths and weaknesses and is more or less appropriate depending upon the details of the system and the kind of analysis that one hopes to perform. At the end of the day, the choice of approach depends upon the nature of the system and the uncertainties, and the available information. Specifically,

- Decision analysis allows for easy and flexible modeling of decision and outcomes but can easily get out of hand in terms of computations complexity in case a significant number of stages and decisions need to be modeled. A big advantage of using decision analysis is that it is not limited by static probabilities, unlike lattice analysis which assumes that the diffusion process is static. This method is the preferred option to deal with abrupt (step) changes and multiple decision points.

- Binomial lattice analysis simplifies the computations problem by restricting the number of possibilities of future outcomes to an “up” and a “down” scenario. This approach has great difficulty in dealing with decisions since it implicitly assumes path independence. This is not a very realistic assumption for engineering systems for which the processes and decisions are usually path dependent. However, this approach is the preferred option to deal with steady changes and one-time decisions.

- Monte Carlo simulation is an easy and transparent approach that allows for the modeling of uncertainties as random variables whose mean values and standard deviations can be obtained from historic data or other means. For my application portfolio, I found this method to be the most effective as it did not restrict my decision rule to a particular year (like the lattice approach) and allowed for a more comprehensive analysis than the decision analysis without getting out of control.

6. Implementation Procedures

There is a temptation to get carried away with the concept of flexibility and its magic in increasing expected value. The later stages of the course served as a reminder that it is not enough to have a good idea and that flexibility plans that we create as designers may face serious implementation issues and thus be practically worthless. Some obstacles to implementation of options include inattention to system operators, failure to plan ahead in terms of expected regulations, and resistance from stakeholders. This discussion urged me to truly think from a systems perspective. Some ways to keep options “alive” are:

- Use of Integrated Project Delivery

This approach involves all stakeholders in the initial stages of the project, thereby reducing the likelihood problems like inattention to operations and stakeholder block.

- Development of a Game Plan

If designs lay out the steps that managers should take in order to implement any form of flexibility that they design into the system, it makes the task much easier.

- Anticipating Developments

In certain cases, some non-design actions may be required in order to enable the exercising of the flexibility. These actions involve obtaining permits and taking other legal or financial measures.

- Operational Actions like maintaining the right and the knowledge to implement the flexibility

If the flexibility option is not implemented for a considerable period of time, the organization may lose the human expertise needed for the implementation. In addition, the rights to implement the flexibility may expire. Operational actions need to be taken to guard against these possibilities.

My future with flexibility and options

I believe that the thinking that I have developed and the methods I have learnt will have great utility for me in future. My interest in the planning of major civil infrastructure systems will undoubtedly benefit from this learning. If I choose to go down the policy track, I will still use these tools to evaluate the impacts of various kinds of policies and design flexibility into policies so that they are able to take advantage of technological and other opportunities as they arise. Now that I know how to value a particular type of flexibility, I wish to develop a better understanding of how to pick from the various flexibility alternatives available to a designer or planner.

8. References

Energy Information Administration (EIA) 2002, *Derivatives and Risk Management in the Petroleum, Natural Gas, and Electricity Industries*, Available at http://www.eia.doe.gov/oiaf/servicerpt/derivative/pdf/appb_tbls.pdf, accessed November 03, 2009.

Energy Information Administration (EIA) 2009, *Gas Prices in the US*, Available at http://tonto.eia.doe.gov/dnav/ng/hist/n3045us3A.htm, accessed October 13, 2009.

Estela Solar 2009, *Andasol Powerplant*, Available at http://www.estelasolar.eu/index.php?id=22, accessed October 13, 2009.

Inflation 2009, *The United States Inflation Rate by Year*, Available at http://www.miseryindex.us/irbyyear.asp, accessed November 03, 2009.

Liebreich, M. 2009, ‘Global Futures 2009: Clean Energy Investment Not On Track To Prevent Climate Change’, *New Energy Finance*, Barcelona, Spain, 21st April 2009.

Lomax, S. 2009 ‘US Prices Carbon Dioxide at More Than $13 a Ton in Draft Plan’, *Bloomberg,* 22 April, 2009, Available at http://www.bloomberg.com/apps/news?pid=20601130&sid=an3CLLybVe8A, accessed November 4, 2009.

Mariyappan, J. and Dennis Anderson 2001, ‘Thematic Review of GEF-Financed Solar Thermal Projects’, *Global Environment Facility*, Available at http://www.thegef.org/uploadedFiles/Evaluation_Office/Publications__(PDF_DOC)/Focal_Area_Studies/Climate%20Change%20-%20Thematic%20Review%20of%20GEF-Financed%20Solar%20Thermal%20Projects%202002.pdf, accessed October 16, 2009.

Horn, M. et al. 2004, ‘Economic analysis of integrated solar combined cycle power plants: A sample case: The economic feasibility of an ISCCS power plant in Egypt’, *Energy*, Volume 29, Issues 5-6, pp. 935-945.

National Renewable Energy Laboratory (NREL) 2009, ‘Solar Advisor Model (SAM) Version 2009.10.13’, Available at https://www.nrel.gov/analysis/sam/, accessed October 15, 2009.

New Energy Finance (NEF) 2009, ‘New Energy Finance Summit Book 2009’, Available at http://www.newenergyfinance.com/free-publications/white-papers/, accessed October 25, 2009.

Hosseini, R. et al. 2005, ‘Technical and economic assessment of the integrated solar combined cycle power plants in Iran’, *Renewable Energy*, Volume 30, Issue 10, pp. 1541-1555.

Schiermeier, Q. 2009, ‘Prices Plummet on Carbon Market’, *Nature*, 20 January 2009, Available at http://www.nature.com/news/2009/090120/full/457365a.html, accessed November 04, 2009.

Tester, J. W. et al. Sustainable Energy: Choosing Among Options. Cambridge: MIT Press, 2005.

World Bank 2006, ‘Solar Thermal Project Agua Prieta Project for Mexico’, Available at http://web.worldbank.org/external/projects/main?Projectid=P066426&theSitePK=40941&pagePK=64283627&menuPK=228424&piPK=73230, accessed October 20, 2009.

9. Appendix

Fixed System: Total Costs by Year Combined Cycle Plant

Year						
0	5	10	15	20	25	29
401,780,650	2.0E+08	4.1E+08	9.1E+08	2.1E+09	4.8E+09	9.6E+09
	1.6E+08	3.1E+08	6.6E+08	1.5E+09	3.4E+09	6.8E+09
	1.3E+08	2.3E+08	4.8E+08	1.1E+09	2.5E+09	4.8E+09
	1.0E+08	1.8E+08	3.5E+08	7.7E+08	1.8E+09	3.4E+09
	8.9E+07	1.4E+08	2.7E+08	5.6E+08	1.3E+09	2.5E+09
	7.8E+07	1.1E+08	2.0E+08	4.1E+08	9.1E+08	1.8E+09
		9.6E+07	1.6E+08	3.1E+08	6.6E+08	1.3E+09
		8.3E+07	1.3E+08	2.3E+08	4.8E+08	9.1E+08
		7.3E+07	1.0E+08	1.8E+08	3.5E+08	6.6E+08
		6.7E+07	8.9E+07	1.4E+08	2.7E+08	4.8E+08
		6.2E+07	7.8E+07	1.1E+08	2.0E+08	3.5E+08
			7.0E+07	9.6E+07	1.6E+08	2.7E+08
			6.4E+07	8.3E+07	1.3E+08	2.0E+08
			6.0E+07	7.3E+07	1.0E+08	1.6E+08
			5.7E+07	6.7E+07	8.9E+07	1.3E+08
			5.5E+07	6.2E+07	7.8E+07	1.0E+08
				5.9E+07	7.0E+07	8.9E+07
				5.6E+07	6.4E+07	7.8E+07
				5.4E+07	6.0E+07	7.0E+07
				5.3E+07	5.7E+07	6.4E+07
				5.2E+07	5.5E+07	6.0E+07
					5.4E+07	5.7E+07
					5.3E+07	5.5E+07
					5.2E+07	5.4E+07
					5.2E+07	5.3E+07
					5.1E+07	5.2E+07
						5.2E+07
						5.1E+07
						5.1E+07
						5.1E+07

Flexible System: Lattice (i)

Year 0	5	10	15	20	25	29
447,472,937	2.0E+08	4.1E+08	9.1E+08	2.1E+09	4.8E+09	9.6E+09
	1.6E+08	3.1E+08	6.6E+08	1.5E+09	3.4E+09	6.8E+09
	1.3E+08	2.3E+08	4.8E+08	1.1E+09	2.5E+09	4.8E+09
	1.0E+08	1.8E+08	3.5E+08	7.7E+08	1.8E+09	3.4E+09
	8.9E+07	1.4E+08	2.7E+08	5.6E+08	1.3E+09	2.5E+09
	7.8E+07	1.1E+08	2.0E+08	4.1E+08	9.1E+08	1.8E+09
		9.6E+07	1.6E+08	3.1E+08	6.6E+08	1.3E+09
		8.3E+07	1.3E+08	2.3E+08	4.8E+08	9.1E+08
		7.3E+07	1.0E+08	1.8E+08	3.5E+08	6.6E+08
		6.7E+07	8.9E+07	1.4E+08	2.7E+08	4.8E+08

6.2E+07	7.8E+07	1.1E+08	2.0E+08	3.5E+08
	7.0E+07	9.6E+07	1.6E+08	2.7E+08
	6.4E+07	8.3E+07	1.3E+08	2.0E+08
	6.0E+07	7.3E+07	1.0E+08	1.6E+08
	5.7E+07	6.7E+07	8.9E+07	1.3E+08
	5.5E+07	6.2E+07	7.8E+07	1.0E+08
		5.9E+07	7.0E+07	8.9E+07
		5.6E+07	6.4E+07	7.8E+07
		5.4E+07	6.0E+07	7.0E+07
		5.3E+07	5.7E+07	6.4E+07
		5.2E+07	5.5E+07	6.0E+07
			5.4E+07	5.7E+07
			5.3E+07	5.5E+07
			5.2E+07	5.4E+07
			5.2E+07	5.3E+07
			5.1E+07	5.2E+07
				5.2E+07
				5.1E+07
				5.1E+07
				5.1E+07

Flexible System: Lattice (ii)

Year 0	5	10	15	20	25	29
447,472,937	4.7E+08	3.2E+08	6.9E+08	1.6E+09	3.6E+09	7.2E+09
	4.4E+08	2.4E+08	5.1E+08	1.1E+09	2.6E+09	5.1E+09
	4.2E+08	1.9E+08	3.7E+08	8.1E+08	1.9E+09	3.6E+09
	4.0E+08	1.5E+08	2.8E+08	5.9E+08	1.3E+09	2.6E+09
	3.9E+08	1.2E+08	2.1E+08	4.3E+08	9.6E+08	1.9E+09
	3.8E+08	1.0E+08	1.7E+08	3.2E+08	6.9E+08	1.3E+09
		8.6E+07	1.3E+08	2.4E+08	5.1E+08	9.6E+08
		7.6E+07	1.1E+08	1.9E+08	3.7E+08	6.9E+08
		6.9E+07	9.3E+07	1.5E+08	2.8E+08	5.1E+08
		6.4E+07	8.1E+07	1.2E+08	2.1E+08	3.7E+08
		6.1E+07	7.3E+07	1.0E+08	1.7E+08	2.8E+08
			6.7E+07	8.6E+07	1.3E+08	2.1E+08
			6.2E+07	7.6E+07	1.1E+08	1.7E+08
			5.9E+07	6.9E+07	9.3E+07	1.3E+08
			5.7E+07	6.4E+07	8.1E+07	1.1E+08
			5.6E+07	6.1E+07	7.3E+07	9.3E+07
				5.8E+07	6.7E+07	8.1E+07
				5.7E+07	6.2E+07	7.3E+07
				5.5E+07	5.9E+07	6.7E+07
				5.4E+07	5.7E+07	6.2E+07
				5.4E+07	5.6E+07	5.9E+07
					5.5E+07	5.7E+07
					5.4E+07	5.6E+07
					5.3E+07	5.5E+07
					5.3E+07	5.4E+07
					5.3E+07	5.3E+07
						5.3E+07
						5.3E+07
						5.3E+07
						5.3E+07