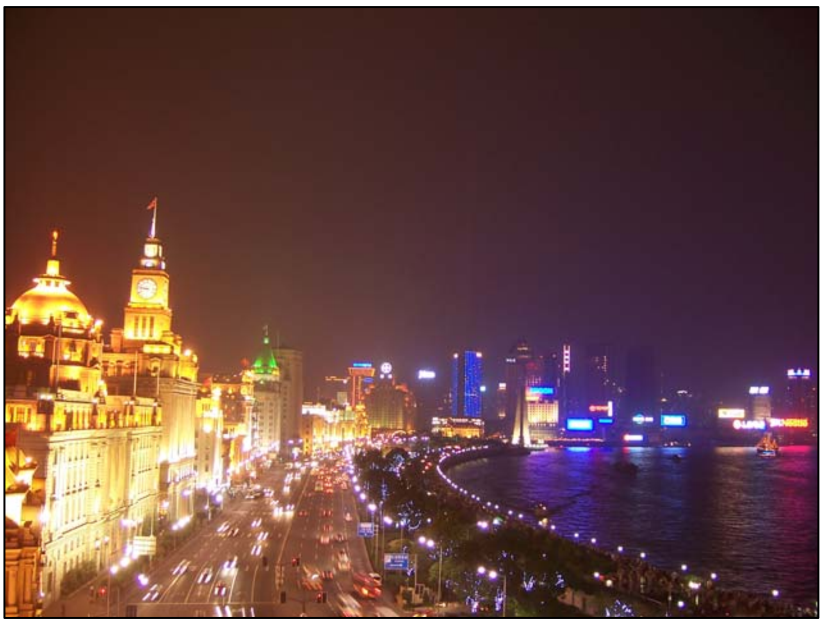
The Value of Flexibility in New Power Plant Construction for Municipal Shanghai, P.R. China



Valerie J. Karplus

ESD.71

Prof. Richard de Neufville
Michel Alexandre-Cardin

December 17, 2007

Table of Contents

Preface

This report was prepared for the Massachusetts Institute of Technology course ESD.71 Engineering Systems Analysis for Design (or Real Options), taught by Prof. Richard de Neufville and Michel-Alexandre Cardin. In this project, explore the value of flexibility in planning for new power generation capacity in municipal Shanghai, using several stylized examples to capture the relevant dimensions of choices faced by city planners and plant managers. In particular, the project examines potential trade-offs inherent in the choices among gas- and coal-fired power plants to meet Shanghai's rapidly growing demand for electric power. I hope that this report will provide a basis for future inquiries into how an options approach can be usefully employed in planning efforts, given uncertainties in mainland China's economic and regulatory environment that bear on the viability of new plant designs and fuel choices. My gratitude belongs to the instructors, Prof. Richard de Neufville and Michel-Alexandre Cardin, for their instruction, patience, and encouragement throughout the project.

Valerie J. Karplus
December 2007

Abstract

This application portfolio explores the value of incorporating flexibility into power infrastructure investments in municipal Shanghai, P. R. China. Specifically, the value of the "call-like" option to expand capacity by employing a staged design for a natural gas power plant and the value of a "put-like" option to shut down a coal power plant in response to changing demand and regulatory environment are explored. This analysis is based on a simple cost models for power production from coal and natural gas, and employs decision analysis and binomial lattice analysis to calculate the value of each option. In the natural gas and coal cases, the option to expand or shut down, respectively, offers financial benefits, which are significant especially in the case of the "call-like" option in the natural gas plant design.

I. Introduction

1.1 Background

The last decade has seen unprecedented expansion of electric power generation capacity in the People's Republic of China (hereafter referred to as "China" or "the mainland"). This growth has been especially strong in large urban centers, such as Shanghai, the major economic hub on the country's eastern coast, Shanghai. This expansion has paralleled—and indeed, driven by—the steady growth of the Chinese economy, which has averaged around nine percent per year over the last several decades.

Shanghai was the first city in China to produce electricity, and also the first to produce and use natural gas for electricity and heating purposes.[1] Nevertheless, as of 2002, over 90 percent of the city's electric power relied on coal-fired generation.[2] Recognizing the health and environmental consequences of extensive and growing reliance on coal (see Figure 1.1), the municipal government has grown increasingly keen on increasing the fraction of electricity generation provided from cleaner natural gas, as well as renewable sources such as solar and wind. However,

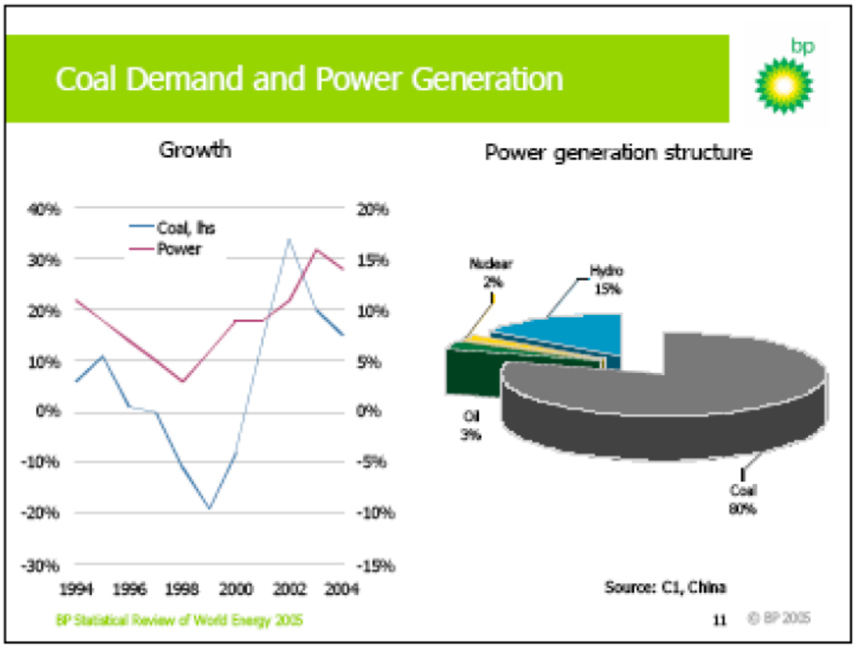


Fig. 1.1 Coal-fired generation capacity provides most of China's electricity needs (BP, 2005).

[1] Luo, Y. (2007). Shanghai Jiaotong University, *Development of Shanghai's Energy Industry: Status Quo and Prediction*.
[2] *Ibid*.

natural gas has remained the favored option after coal, given its low cost capital costs, scalability, and low emissions per kilowatt hour. The main concern with natural gas remains the availability of supply and price volatility. With the construction of the country's West-to-East pipeline to deliver domestic natural gas to urban centers in the East, and the signing of several major natural gas import contracts, concerns about price and supply have been mitigated to some extent in the near term. However, if demand for natural gas grows as projected, these concerns are likely to once again intensify (see Figure 1.2).

The national and municipal governments in China have taken various measures to incentivize the construction of cleaner generation capacity. In 2006, Shanghai instituted a ban on construction of new coal-fired power plants within the city limits in order to promote construction of natural-gas fired generation and renewable alternatives. However, the government had to rescind the ban and allow new construction due to uncertainties in natural gas supply and price.[3]

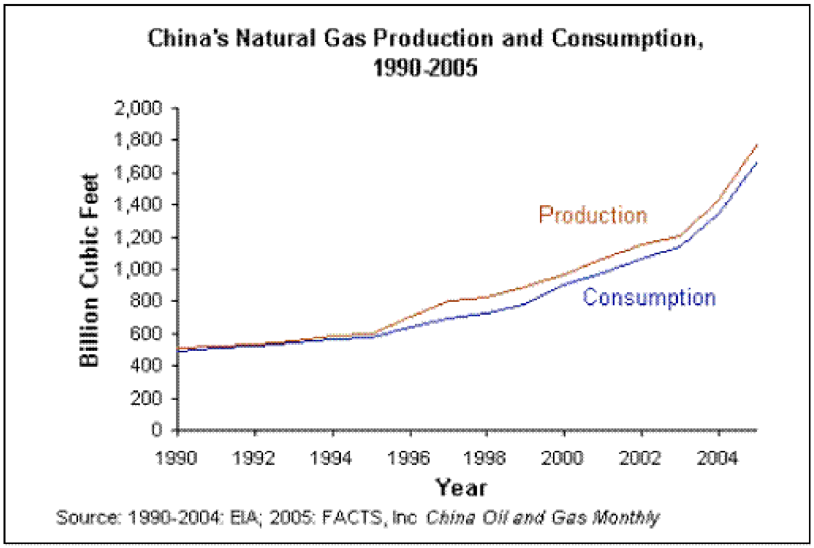


Fig. 1.2 Domestic natural gas production kept pace with consumption through 2004, but since then, imports have been needed to bridge the gap (not shown) (EIA, 2005).

However, the concerns that led to the implementation of the ban—urban air pollution and the associated environmental and health costs—are likely to worsen as reliance on coal grows. Also, international pressure to reduce carbon dioxide emissions in the power sector in order to mitigate the potential adverse impacts of global climate change is likely to increase as well. Indeed, coal is the most carbon dioxide emissions-intensive source of electric power generation in China, which contributes to coal's overall large contribution to China's growing emissions of this prominent greenhouse gas (see Figure 1.3).

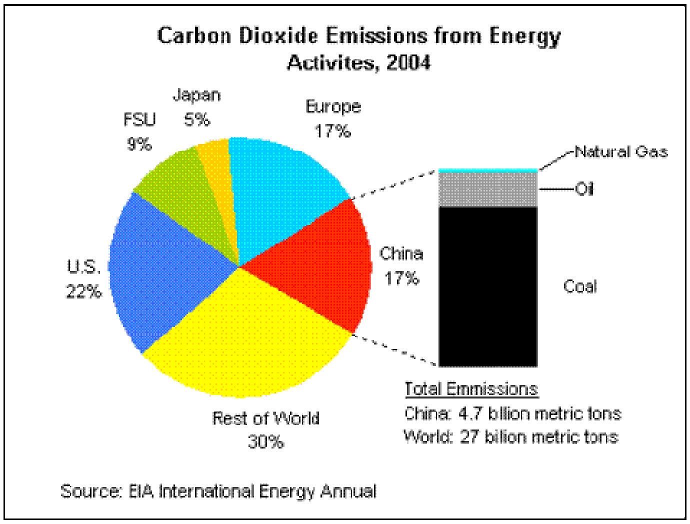


Fig. 1.3 Coal use was the largest contributor to China's carbon dioxide emissions from energy activities in 2004 (EIA, 2005).

[3] Researcher at Shanghai Jiaotong University, personal communication (2006).

Despite greener intentions, urban planners and energy policy makers in China may exercise only limited influence over local design choices.[4] In practice, policy efforts to induce cleaner plant construction often confront entrenched interests eager for the least expensive and readily available capacity additions to power booming local economies. It is my hypothesis that hurried plant design decisions may not take stock of available opportunities to introduce flexibility in ways that may increase the value of investments, given fluctuations in price, demand, and the regulatory environment. This project attempts to analyze, through stylized examples, the value of incorporating flexibility into future investments in gas- and coal-fired power generation infrastructure.

1.2 Scope of Analysis

Although the number of medium- and large-size cities in China that are rapidly building power generation capacity reaches into the hundreds, this project will focus on an example case involving the addition of capacity in a localized area of municipal Shanghai. Aside from the major uncertainties examined in this project (demand, price of natural gas, and regulation of coal-fired power plants), all other possible factors influencing design decisions are assumed to remain constant over the period examined. Also, I assume that all energy infrastructure investment decisions aim to maximize net present value (NPV), and NPV is the main dimension along which projects are compared. In reality, other considerations not reflected in capital and operating costs might influence design choices, such as political factors or payback period (given the uncertainties present in China's market of electricity, which is growing rapidly while at the same time undergoing significant reforms).

The sources for the estimates used in this study are described in the relevant sections. I have tried to provide detailed information about sources as well as the equations used in the cost model so that future work might improve on this initial attempt.

1.3 Tools and Methods

This study employs the techniques of options analysis applied to real engineering systems (also known as "Real Options") as presented in MIT's ESD.71 Engineering Systems Analysis for Design course. The main tools and techniques demonstrated in this portfolio include:

- A simplified cost model for natural gas- and coal-fired power generation
- Net present value calculation
- Decision analysis
- Binomial lattice model to assess value of "call"-like and "put"-like options

Each of these tools and techniques will be explained in the chapters that follow. Although the tools were learned in the ESD.71 course, the material for this example is the result of the author's research and estimates; thus any errors are the author's sole responsibility.

[4] Steinfeld, E. & Lester, R. (2007). Chapter 5: Coal Consumption in China and India. *The Future of Coal*. Cambridge, MA: Massachusetts Institute of Technology.

II. Defining the System

2.1 Overview

I have chosen to examine several design options for new power generation capacity to meet growing demand for electricity in municipal Shanghai. Since the early 1990s, Shanghai's demand for electric power has grown rapidly, with demand for additional production equivalent to what several new large (500 MW or more) power plants could supply every year (see Figure 2.1).

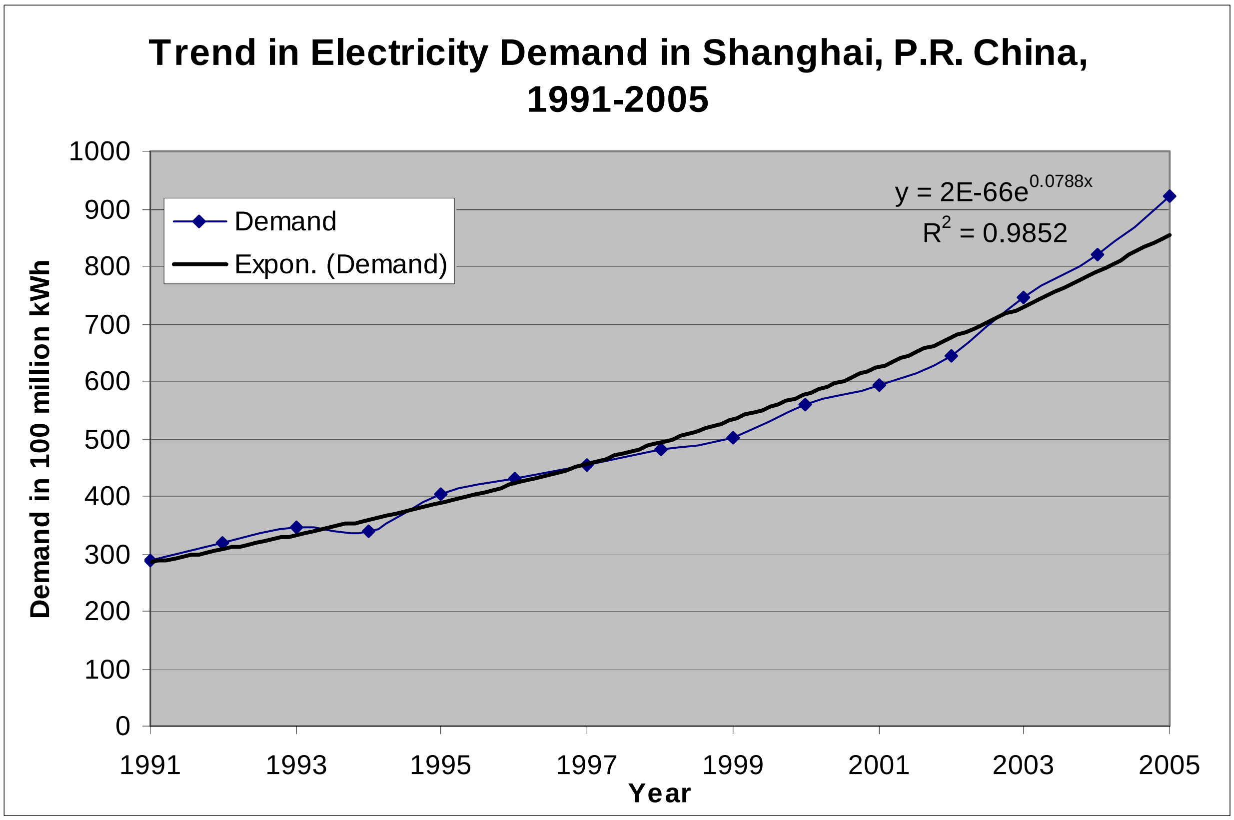


Fig. 2.1 Electricity consumption in Shanghai has tripled between 1991 and 2005, with growth accelerating in 2005 in particular. Source: *Shanghai Statistical Yearbook* (2006).

The most common response to the rising demand has been the construction of new electricity generation capacity (as opposed to measures to encourage efficiency, such as price increases). The typical design choice is to construct a new, large coal-fired power plant, since China has a cheap and abundant domestic coal supply, and Chinese plant designs can be constructed at relatively low capital cost, according to recent estimates.[5] However, natural gas has increasingly become attractive for its modularity, ability to inexpensively adjust output to

[5] Jiang, B. B. (2007). The Future of Natural Gas vs. Coal Consumption in Beijing, Guangdong and Shanghai: An assessment utilizing MARKAL. Working Paper #62. Stanford University: Program on Energy and Sustainable Development.

meet demand, and lower emissions per kWh. Natural gas plants also typically have lower capital costs than coal-fired plants.

This project considers a plant investment decision designed to meet rising local demand beginning in 2010 and continuing through 2020.[6] Three technology choices for meeting this demand are considered as follows:

- **Plan 1:** Construct **one 500 MW coal-fired power plant** to meet demand through 2020, which must operate at full capacity, may be subject to a per kWh tax on emissions post-2016, and if desirable, can be closed anytime during the second period (2016 to 2020);
- **Plan 2:** Construct **one 500 MW natural gas-fired power plant** to meet demand through 2020, which will not subject to emissions regulations; and for which output can be adjusted to meet demand (up to capacity).
- **Plan 3:** Construct one **300 MW natural gas-fired power plant**, which can be expanded if necessary by an **additional 300 MW** to meet demand through 2020, is not subject to regulations, and for which output can be adjusted to meet demand (up to capacity).

The relative favorability of these three possible plans will be explored in the remainder of this project.

2.2 Defining the Uncertainties

Demand is the first major source of uncertainty I will consider in this project. Since the rapid demand growth each year cannot be met by a single power plant, I have divided the historical annual incremental demand growth by 20 to yield a plausible local demand growth scenario that could be met by the construction of one 300 to 600 MW power system. I have modeled the historical incremental demand growth in Figure 2.2.[7] This demand profile was used in projecting demand growth for the binomial lattice analysis; the decision analysis relies on either a simplified "high" demand projection of 4.5 million kWh per year or "low" demand projection of 3.5 million kWh per year, while the lattice analysis models the evolution of demand over the lifetime of the project using historical data to calibrate the lattice.

There is no guarantee that such rapid growth in incremental demand will continue; the decision analysis in particular is highly vulnerable to fluctuations in actual demand that deviate from the unprecedented growth patterns witnessed over the previous decade. Therefore, demand forms a significant source of uncertainty that will bear directly on the value of plant design. To make calculations more manageable in the decision analysis, I have assumed that demand is correlated, that is, if demand is high in the first period, it will also be high in the second period, and similarly if it is low in the first period, it will be low in the second period. The lattice also assumes a certain degree of path dependence as well.

---

[6] Although ten years may be considered short for the lifetime of a power plant, I assume that the municipal government evaluates most investments on ten-year time horizons, given the large opportunity costs associated with investments in China's currently rapidly expanding market and the potential long term uncertainties in demand and fuel supply costs which preclude confidence in long term predictions of NPV.

[7] For the third year, 1994, the demand growth was very slightly negative. I changed this value to a small positive number (0.01) so that an exponential regression could be calculated and used in later analysis.

The second source of uncertainty is in the **price of natural gas**. The price of coal, on the other hand, remains stable over the period considered in this project at $1.05/MMBTU, given abundant reserves and inexpensive supply. Natural gas, on the other hand, is guaranteed at a price of $6.05/MMBTU in the first period, but in the second period, new contracts with exporting countries will have to be negotiated, resulting in either the same fixed price of $6.05/MMBTU ("low" scenario) or $7.05/MMBTU ("high" scenario). The price of natural gas will, in turn, affect the value of the investment.

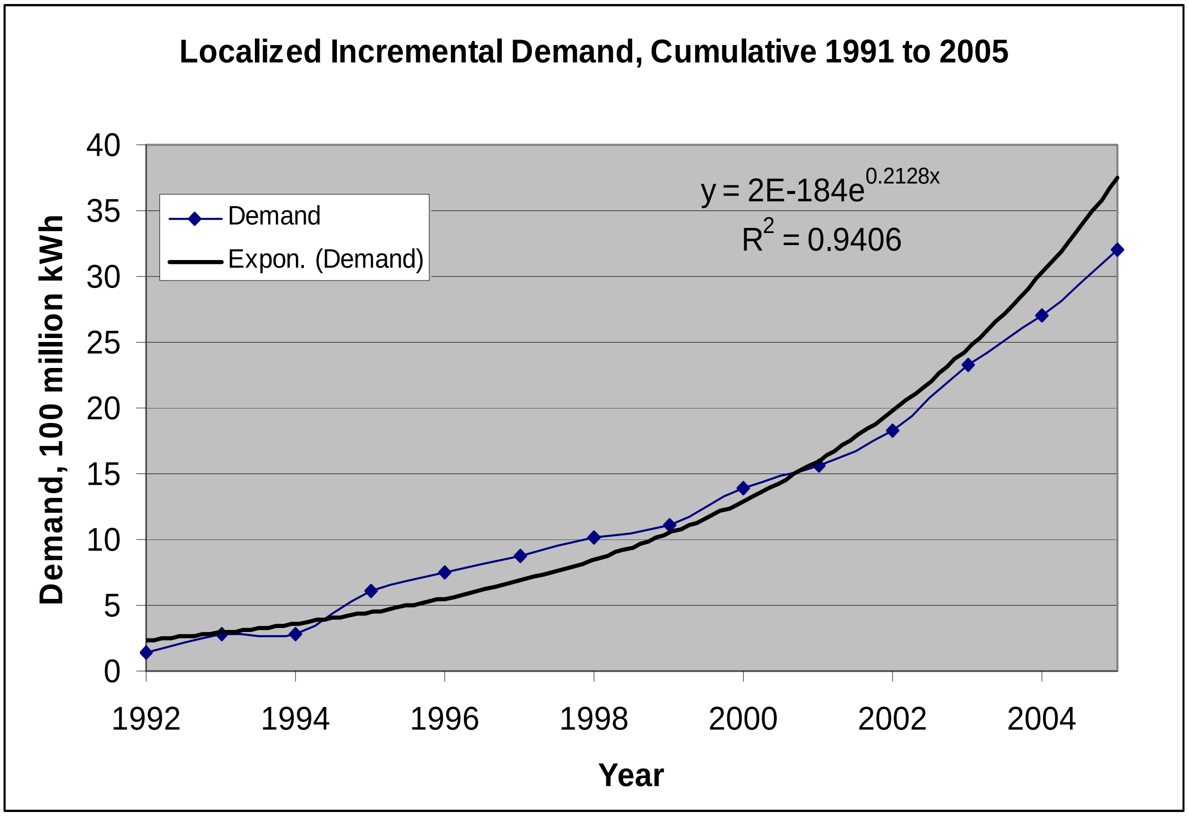


Fig. 2.2 Projected localized incremental demand growth for municipal Shanghai. Source: *Shanghai Statistical Yearbook* (2006).

The third source of uncertainty is in the **regulation of coal-fired power plants**. Instead of a ban on the operation of coal-fired power plants, as has been considered in Shanghai in the past, I assume that a per kWh tax is imposed on coal-fired power plants in the amount of two cents/kWh produced. This regulation would not affect natural gas-fired generation at all, but may significantly change the economics of coal-fired generation. Such a regulation is very plausible and could be interpreted as an attempt to value the health and environmental externalities associated with coal-fired generation. Since these regulatory costs cannot be passed along to consumers due to fixed end-user pricing schemes in most of China, the producer is assumed to bear the full amount of the regulatory cost.

The probabilities for each of the uncertainties (Table 2.1) were chosen based on past observation and intuition about expectations for the future; they are indeed very rough and subject to inaccuracy. Given past trends in demand growth, I selected both a high growth and a low growth scenario for the decision analysis. In the high growth scenario, demand grew by 4.5

100 million kWh per year. In the low growth scenario, demand grew by 3.5 100 million kWh per year. I assigned a probability of 0.5 to both the low growth and the high growth scenarios, since they were well within the range of demand growth in the last five years. In choosing the natural gas price forecasts for the analysis, I used the 2005 natural gas price ($6.05/MMBTU) for the low estimate and added an extra dollar to reflect the approximate growth through 2006 ($7.05/MMBTU).[8] However, the future price is highly uncertain, and since I do not have good information with which to predict the future, I base estimates of natural gas costs for the second period (2016-2020) on the 2005 and 2006 price range. I assume that the likelihood of high or low prices in the second period is equal, since the Chinese purchasers maybe somewhat unlikely to accept a future contract price that is much higher than the earlier agreed option. Finally, I estimated 0.2 as the probability of a regulation based crudely on the fact that Shanghai has shown hesitancy in the past in adopting regulatory standards, but the growing interest in improving air quality may lead to some modest public policy action in the future.

Table 2.1 Sources of uncertainty affecting power infrastructure construction decisions.

Source of Uncertainty	Probability	Plant Affected
Electricity demand	0.5 – High in first/second period 0.5 – Low in first/second period	Gas and Coal
Price of natural gas	0.5 – High in second period 0.5 – Low in second period	Gas
Regulation of 2 cents/kWh	0.8 – Regulations imposed in second period 0.2 – Regulations not imposed in second period	Coal

The choice of probabilities will be explained in more detail in the decision analysis.

2.3 Power Plant Specifications and Cost Models

Here I present the cost model for the coal-fired power plant. For simplicity’s sake, I focus on several main parameters that comprise the net cash flows (profits) of the plant, which is calculated from the discounted value of the revenues minus capital and operating costs. I assume that the plant is paid for at the end of the year it is built, and begins operating immediately in the following year. The technical specifications for the plant were borrowed from cost models presented in another MIT course, 1.149 Applications of Technology in Energy and the Environment. Both the cost and technical specifications are summarized in Table 2.2 below:

Table 2.2 Relevant technical and economic parameters

Plant Capacity	Value	Units
Large Plant (1 & 2)	500	MW
Small Plant (3)	300	MW
Small Plant – Added Cap (3)	300	MW
Capital Cost		
Large plant – Coal	500	million $
Large plant – Natural Gas	400	million $
Small plant	300	million $
Small plant expansion	180	million $

[8] Heren Energy Ltd. (2006). *Natural Gas Week*. Reprinted in the BP Statistical Review of World Energy, 2006.

Fuel Cost		
Heat Rate, Natural Gas Plant	5687	BTU/kWh
Price of Natural Gas – Low	6.05	$/MMBTU
Price of Natural Gas – High	7.05	$/MMBTU
Price of Coal	1.05	$/MMBTU
Heat Rate, Coal Plant	10,900	BTU/kWh
O&M Costs		
Large plant – Coal	10	million $/year
Large plant – Natural Gas	10	million $/year
Small plant	6	million $/year
Small plant + added cap	12	million $/year
Regulatory Costs		
Coal-fired power plant	2	cents/kWh
Demand		
High	4.5	hundred million kWh per year
Low	3.5	hundred million kWh per year
Max Output - Large Gas or Coal Plant	37	hundred million kWh per year
Max Output - Small Plant	22	hundred million kWh per year
Max Output - Small Plant with Addition	44	hundred million kWh per year

The importance of the above-mentioned parameters will become apparent in the cost model below, but will be summarized here for clarity's sake. The capital costs for the construction of the plants are based on a very rough estimate of the cost of constructing new generation capacity in the United States, and include all regulatory and other one-time start-up costs in addition to the new equipment itself. Since the natural gas plant does not exhibit economies of scale, it is a good candidate for a staged design. The capital expenditures associated with expansion are less than proportional to the original cost of capacity, since there is no need to reapply for site permissions or install redundant control architecture. Plant capacity is a measure of the total output a plant is capable of at any given moment and measured in megawatts (MW); energy produced (output) is measured in kilowatt-hours (kWh). The heat rate is a measure of the efficiency of a power plant's conversion of feedstock into usable energy, which is important in determining the cost of fuel needed to supply a given level of demand (capped at the level of maximum plant output). The maximum output of each of the plants is calculated in the bottom three rows of the table. The plants are (unrealistically) assumed to operate at full capacity around the clock in all cases to simplify the calculations. The operating and maintenance (O&M) costs for the plant were estimated as fixed for both of the larger plants, while O&M costs are lower for the small plant but double with the expansion of capacity from 300 MW to 600 MW.

These variables were used to develop cost models for each of the three options. The main formulas of interest include the calculation of fuel cost:

Fuel Cost = Fuel Price * Heat Rate * Plant Output * Unit Conversion Factors

The Fuel Cost was then one of the inputs into the equation for calculating cash flow, as follows:

Cash Flow = Revenues – (Capital Cost + Fuel Cost + O&M Cost + Regulatory Cost)

In this equation, Revenues is calculated as follows. The fixed retail price of electricity in China was 8.2 cents/kWh in 2007.[9] The revenues are calculated by multiplying the demand for electricity in any given year times this electricity price, ignoring all taxes and fees. The net present value of the cash flow is then calculated and summed across all periods to find the value of the investment.

Below I include several example spreadsheets showing the NPV calculation for each one of the three possible plans:

Table 2.3 (Plan 1) 500 MW Coal Plant, Demand High, with Regulations in 2016

	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Year	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Capital Cost ($ millions)	500.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Price of Coal ($/MMBTU)		1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Fuel Cost ($ millions)		42.35	42.35	42.35	42.35	42.35	42.35	42.35	42.35	42.35	42.35
O&M Cost ($ millions)		10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Regulations ($ millions)							74.00	74.00	74.00	74.00	74.00
Price of Electricity (cents/kWh)		8.20	8.20	8.20	8.20	8.20	8.20	8.20	8.20	8.20	8.20
Demand (100 m kWh)		4.50	9.00	13.50	18.00	22.50	27.00	31.50	36.00	37.00	37.00
Revenues ($ millions)		36.90	73.80	110.70	147.60	184.50	221.40	258.30	295.20	303.40	303.40
Net Income ($ millions)	-500.00	-15.45	21.45	58.35	95.25	132.15	95.05	131.95	168.85	177.05	177.05
Discount Rate	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Discount Factor	1.00	1.10	1.21	1.33	1.46	1.61	1.77	1.95	2.14	2.36	2.59
Annual Discounted Cash Flow	-500.00	-14.04	17.73	43.84	65.06	82.06	53.66	67.71	78.77	75.09	68.26
NPV	-500.00	-514.04	-496.31	-452.47	-387.41	-305.35	-251.70	-183.99	-105.21	-30.13	**38.14**

[9] The price of electricity in Shanghai was reported by the Shanghai Foreign Economic Relation and Trade in early November 2007. The price of Electricity in Shanghai was quoted as 0.61 RMB/kWh.

Table 2.4 (Plan 2) 500 MW Natural Gas-Fired Power Plant, Demand High, Price High

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Year	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Capital Cost ($ millions)	400.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Price of Gas ($/MMBTU)		6.05	6.05	6.05	6.05	6.05	7.05	7.05	7.05	7.05	7.05
Fuel Cost ($ millions)		15.48	30.97	46.45	61.93	77.41	108.25	126.29	144.34	148.35	148.35
O&M Cost ($ millions)		10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Price of Electricity (cents/kWh)		8.20	8.20	8.20	8.20	8.20	8.20	8.20	8.20	8.20	8.20
Demand (million kWh)		4.50	9.00	13.50	18.00	22.50	27.00	31.50	36.00	37.00	37.00
Revenues ($ millions)		36.90	73.80	110.70	147.60	184.50	221.40	258.30	295.20	303.40	303.40
Net Income, NI = R - C(Cap) - C(Fuel) - C(O&M)	-400.00	11.42	32.83	54.25	75.67	97.09	103.15	122.01	140.86	145.05	145.05
Discount Rate	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Discount Factor	1.00	1.10	1.21	1.33	1.46	1.61	1.77	1.95	2.14	2.36	2.59
Annual Discounted Cash Flow	-400.00	10.38	27.14	40.76	51.68	60.28	58.22	62.61	65.71	61.52	55.92
NPV	-400.00	-389.62	-362.49	-321.73	-270.04	-209.76	-151.54	-88.93	-23.21	38.30	**94.23**

Table 2.3 (Plan 3) 300 MW Natural Gas-Fired Power Plant, Demand High, Price High, New Plant Constructed in 2015

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Year	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Capital Cost ($ millions)	300.00	0.00	0.00	0.00	0.00	180.00	0.00	0.00	0.00	0.00	0.00
Price of Gas ($/MMBTU)		6.05	6.05	6.05	6.05	6.05	7.05	7.05	7.05	7.05	7.05
Fuel Cost ($ millions)		15.48	30.97	46.45	61.93	75.69	106.25	124.29	142.33	160.37	176.41
O&M Cost ($ millions)		10.00	10.00	10.00	10.00	10.00	15.00	15.00	15.00	15.00	15.00
Price of Electricity (cents/kWh)		8.20	8.20	8.20	8.20	8.20	8.20	8.20	8.20	8.20	8.20
Demand (100 million kWh)		4.50	9.00	13.50	18.00	22.00	26.50	31.00	35.50	40.00	44.00
Revenues ($ millions)		36.90	73.80	110.70	147.60	180.40	217.30	254.20	291.10	328.00	360.80
Net Income, NI = R - C(Cap) - C(Fuel) - C(O&M)	-300.00	11.42	32.83	54.25	75.67	-85.29	96.05	114.91	133.77	152.63	169.39
Discount Rate	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Discount Factor	1.00	1.10	1.21	1.33	1.46	1.61	1.77	1.95	2.14	2.36	2.59
Annual Discounted Cash Flow	-300.00	10.38	27.14	40.76	51.68	-52.96	54.22	58.97	62.40	64.73	65.31
NPV	-300.00	-289.62	-262.49	-221.73	-170.04	-223.00	-168.78	-109.82	-47.41	17.32	**82.62**

2.4 Summary

This section has explained the three different plans that will be considered in the following sections as well as the uncertainties that affect their value, and has reviewed the cost model that will underpin all of the subsequent analysis. Only a few of the relevant spreadsheets were presented in full at the close of the section to illustrate the results of the cost model for three relevant cases.

III. Decision Analysis

3.1 Introduction

Now that the potential plans under consideration and relevant uncertainties have been described, I begin my analysis of value of the different options *in* and *on* particular designs by developing a decision model that depicts a simplified version of the relevant uncertainties and possible outcomes. The decision analysis approach is valuable because it allows for the evaluation of many alternatives to a single fixed decision. It also allows one to develop a strategy for altering choices as new information becomes available, as will be the case for the system under consideration. Finally, decision analysis offers the chance to identify "second best" alternatives that will allow for exploitation of the upside and/or minimization of downside risks.

3.2 Decision Trees

The decisions and uncertainties facing developers for each of the three options were mapped out using decision trees. Each individual tree represents a branch of a larger initial decision over which option to pursue. The intuition behind the probabilities was presented earlier in Section 2.2.

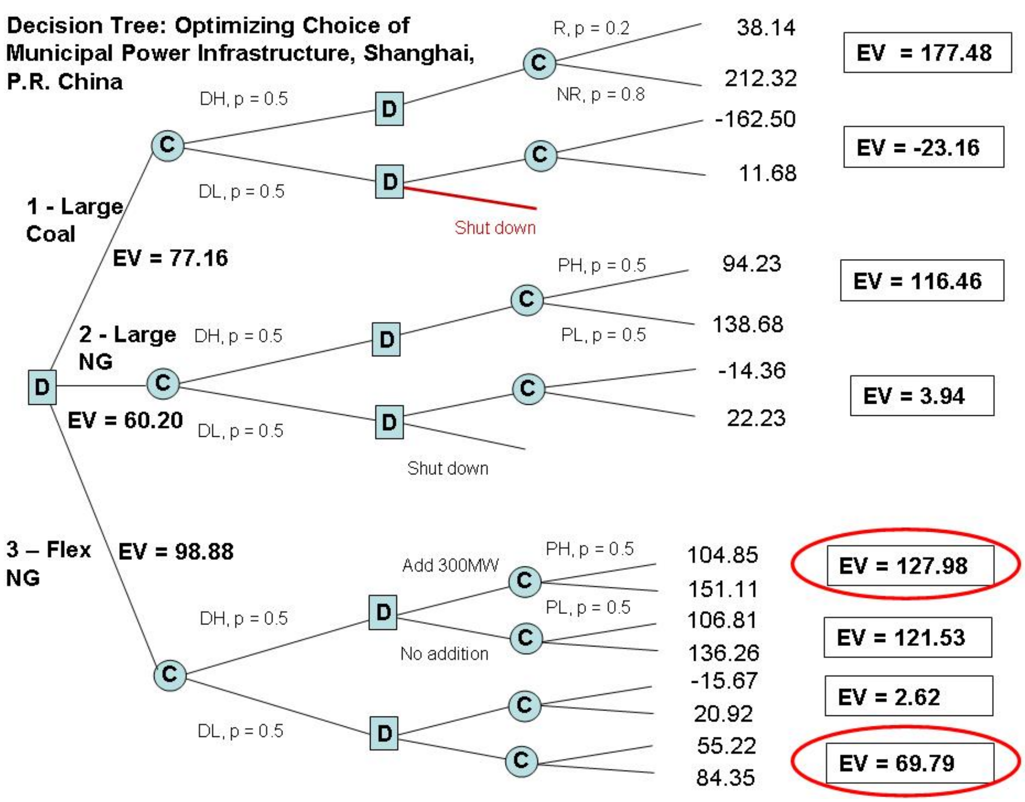


Fig. 3.1 The decision tree helps to illuminate optimal strategies in response to variation in demand during the first period, and incorporates uncertainty in price and regulation in the second period where applicable. **EV – Expected Value, NG – Natural Gas, DH – Demand High, DL – Demand Low, PH – Price High, PL – Price Low.** All expected values are in dollars.

The decision analysis indicates that the coal plant (Plan 1) is, in terms of expected net present value, the most favorable decision. However, the economic viability of the plant is still dependent on demand growth. If demand grows rapidly and the plant reaches full capacity several years before the end of the period, then the net present value is positive, even if regulations are imposed. However, if demand grows more slowly than expected in the “low” scenario, the expected net present value becomes negative, leaving power producers vulnerable to losses, since it assumed that output cannot be adjusted downward to match demand without assuming prohibitive costs.

In the case of Plan 2, the power plant investment is on balance less valuable in expected net present value terms, but the chances that expected net present value would be negative are very low, minimizing losses compared to the coal plant case. This comparison serves to illustrate the potential complications of relying solely on net present value to evaluate investments.

Finally, in the case of Plan 3, the plan has built-in flexibility that allows producers to revisit the optimal capacity decision at the start of 2015. With knowledge of demand growth trends, managers can make an informed decision as to whether or not to expand the initial plant. Although capacity is more expensive per megawatt to built the 300MW generating facility up front, the remaining 300 MW capacity can be added more cost-effectively that the per MW cost of building the large natural gas plant.

The relative attractiveness of the three plans in terms of expected net present value is shown below in a Value-at-Risk and Gain chart. It shows how the upside and downside are quite large in the case of the coal plant (Plan 1), as well as how a staged approach allows for the reduction of downside losses and the capture of upside possibilities.

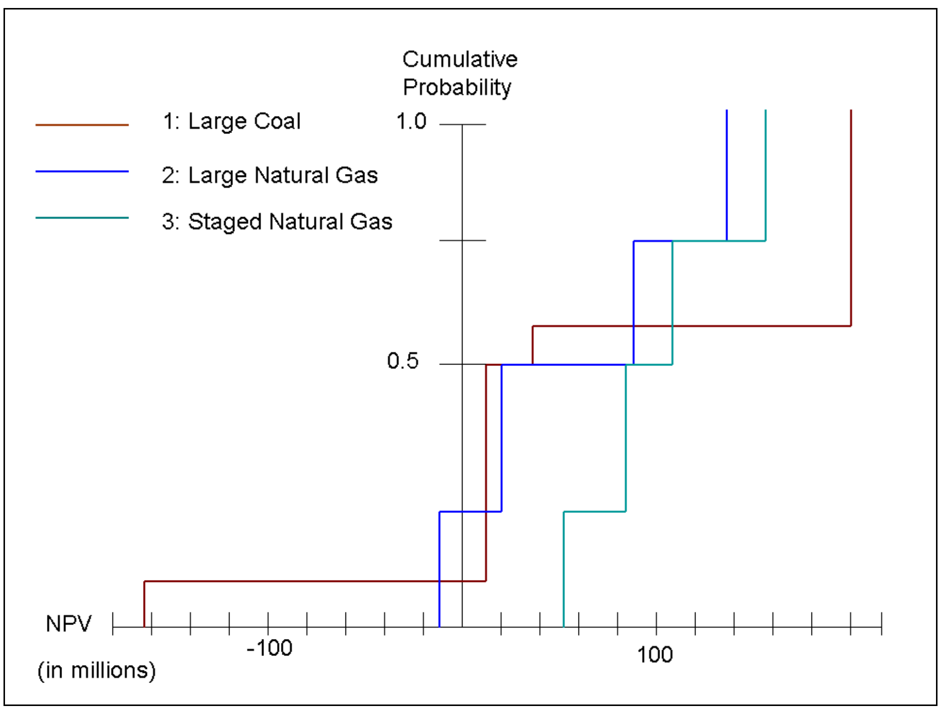


Fig. 3.2 The **Value-at-Risk and Gain** chart compares the three possible options for power plant construction. The downside of building a natural gas plant is significantly reduced by the addition of flexibility, and the upside slightly increased. **NPV** – Net Present Value

As mentioned above, the fact that the total plant capacity with expansion is larger than the total base case capacity makes expected NPV an imperfect basis upon which to compare the three plant designs. In order to improve on the NPV measure of the value of flexibility, I summarize the performance of these two investments using the benefit-cost ratio, which is useful for ranking because it places all projects on a common scale. The benefit-cost ratio is simply the sum of the present value of all benefits divided by the sum of the present value of all costs. For purposes examined here, I use only the capital expenditures, since it is directly proportional to plant capacity. Benefits are expressed in terms of the present value of net revenues. Ranked on this basis, the relative attractiveness of the different investments can be depicted as follows in Table 3.1.

Table 3.1 Summary of measures of value for three projects (in millions) and calculation of Benefit-Cost Ratio.

Project	Expected NPV	NPV of Cap Ex	Benefit-Cost Ratio
Plan 1 – Large Coal (500 MW)	$77.16	$500	0.1543
Plan 2 – Large Gas (500 MW)	$60.20	$400	0.1505
Plan 3 – Phased Gas (300 MW or 600 MW)	$98.88	$300 (+$112*0.5) E = $356	0.2778

* E = probability weighted capital expenditures for phased gas plant based on decision analysis.

The phased gas plant design (Plant 3) again emerges as superior among the three options, with the large coal and large gas plants roughly equally attractive on the basis of the cost-benefit ranking.

3.3 Summary of Results

The above analysis has shown that by using several assumptions and a simple cost model, it is possible to explore the relationship between flexibility and added value in net present value terms for power plant investment decisions in Shanghai. Based on the above decision analysis, and ranking on the basis of NPV, the most attractive investment would be the coal plant, with an expected value of $77.16 million, followed by the fixed natural gas plan with an expected value of $60.20 million. However, the flexible natural gas plant offers an expected value of $98.88 million. While this value should not be directly compared to the others because it represents a 20 percent larger capacity plant under certain demand conditions, among the three plans defined here it is the most attractive investment. Ranking on the basis of the benefit-cost ratio is in agreement with the NPV-based ranking, and allows for a more meaningful comparison among the three plans. Future analysis could consider the comparable viability of other designs. In this case, an upper bound on the value of the option to expand capacity can be estimated by the difference in net present value of the fixed (500 MW) and flexible natural gas plant (300 MW + possible 300 MW) at $30.68 million.

IV. Application of Binomial Lattice

4.1 Rationale for Binomial Lattice Approach

In this section, I use a lattice model to more accurately represent uncertainty in the **demand** projection to improve on my earlier evaluation of the best plant design. A binomial lattice model allows for the modeling of two important questions in the construction of new power infrastructure for municipal Shanghai:

- What is the value of a "call-like" option to expand the natural gas plant in the event of high demand?
- What is the value of the "put-like" option to close the coal-fired power plant in the event of low demand (and potentially also regulations)?

4.2 Estimating Parameters for Lattice Model

Parameters for the lattice model were estimated from the annual localized demand growth data presented above for municipal Shanghai in Figure 2.2. Parameters needed for the lattice model include the average growth rate per period (one year for this system) and the standard deviation (volatility or sigma) around that growth trend. We use the growth of annual localized demand between 1992 and 2005 as a model for how growth in demand would be expected to evolve in the neighborhoods served by the new power plant investment. First, I modeled the annual growth that occurred in each year and performed an exponential regression as follows:[10]

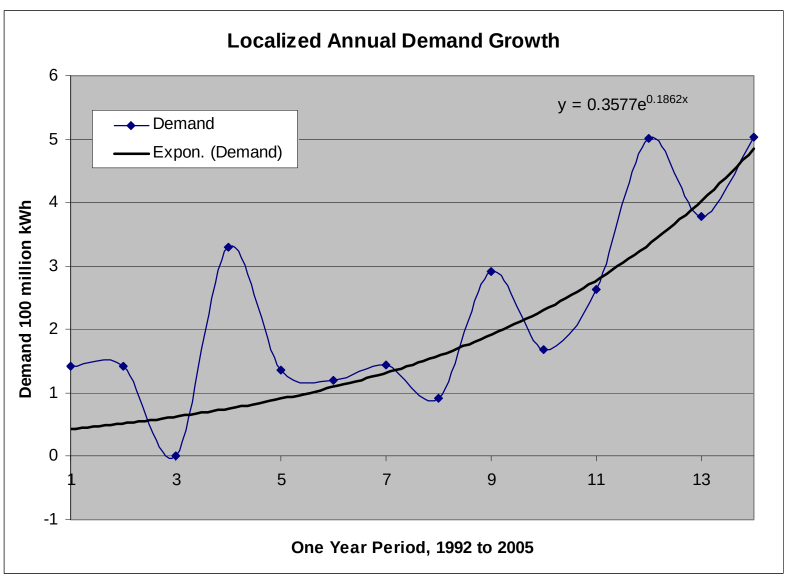


Fig. 4.1 Incremental annual growth in electricity consumption between 1992 and 2005 was highly volatile. Source: *Shanghai Statistical Yearbook* (2006).

[10] In the third period, demand growth was very slightly negative. This value was changed to 0.01 in order to facilitate the calculation of the exponential regression. Also, the negative value may be an artifact of the shortages of capacity that were taking place in the 1990s, since it is anomalous in light of the growth experienced in neighboring years. This value was also left out of the calculation of the volatility to prevent large bias in the result.

Parameters for analysis (based on historical data)
Growth rate = 18.62%
Volatility = Square Root (Average (Demand – Trend line)) = 44.12%

These parameters were used to calculate the binomial lattice inputs:

u	1.55
d	0.64
p	0.71

These inputs enabled the calculation of a lattice of probabilities, along with the evolution of demand over the ten-year period. The starting value for the lattice was assumed to be 3.0 hundred million kWh, the average of the values of the annual increases observed over the five years prior to 2006. It should be noted that all subsequent results are very sensitive to this choice of initial value, and evaluating the sensitivity of results to this parameter would be a useful area for future work.

Table 4.1 Lattice of Probabilities

PROBABILITY LATTICE										
2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
1.00	0.71	0.51	0.36	0.26	0.18	0.13	0.09	0.07	0.05	0.03
	0.29	0.41	0.44	0.42	0.37	0.32	0.26	0.21	0.17	0.13
		0.08	0.18	0.25	0.30	0.32	0.32	0.30	0.28	0.25
			0.02	0.07	0.12	0.17	0.22	0.25	0.26	0.27
				0.01	0.02	0.05	0.09	0.12	0.16	0.19
					0.00	0.01	0.02	0.04	0.06	0.09
						0.00	0.00	0.01	0.02	0.03
							0.00	0.00	0.00	0.01
								0.00	0.00	0.00
									0.00	0.00
										0.00

Graphically, the evolution of probabilities above can be depicted as follows in Figure 4.2.

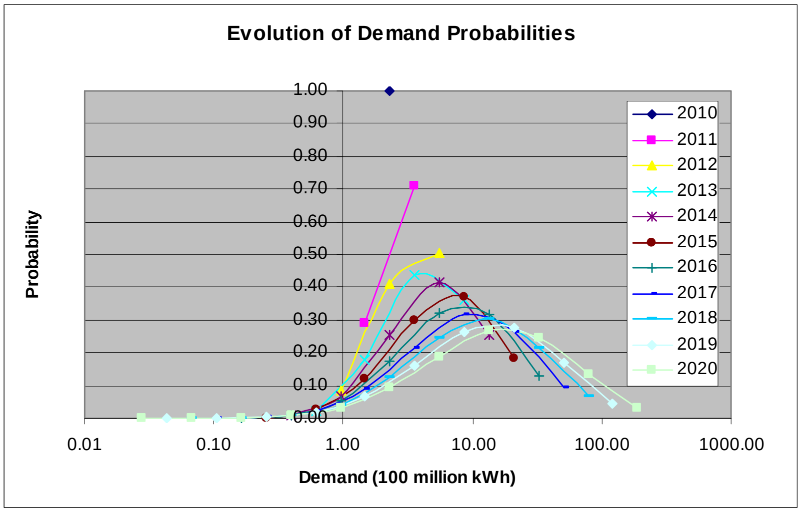


Fig. 4.2 Graphical depiction of the evolution of probabilities of different demand predictions is based on the lattice model shown above.

Table 4.2 Evolution of Demand

OUTCOME LATTICE										
2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
3.00	4.66	7.25	11.27	17.52	27.24	42.34	65.83	102.33	159.08	247.30
	1.93	3.00	4.66	7.25	11.27	17.52	27.24	42.34	65.83	102.33
		1.24	1.93	3.00	4.66	7.25	11.27	17.52	27.24	42.34
			0.80	1.24	1.93	3.00	4.66	7.25	11.27	17.52
				0.51	0.80	1.24	1.93	3.00	4.66	7.25
					0.33	0.51	0.80	1.24	1.93	3.00
						0.21	0.33	0.51	0.80	1.24
							0.14	0.21	0.33	0.51
								0.09	0.14	0.21
									0.06	0.09
										0.04

In the final year, the range of potential annual demand growth projections is very wide, with non-zero probability outcomes ranging from 0.04 to 247.30 hundred million kWh. However, these possible outcomes are skewed by the probabilities, which suggest annual (year-on-year) demand growth will increase from 3.00 to between 7.25 and 102.33 hundred million kWh in the localized area considered. This projection was then used to calculate the cumulative demand that would have to be met by expanded power infrastructure. In the case that the cumulative demand (shown in Table 4.3) grows beyond 44 hundred million kWh, neither plant design can handle the total demand growth. Therefore demand as an input for subsequent lattices is capped for these states.

Table 4.3 Lattice of cumulative demand growth

CUMULATIVE DEMAND EVOLUTION										
2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
3.00	7.66	14.91	26.18	43.71	70.94	113.29	179.11	281.44	440.52	687.83
	4.93	7.93	12.59	19.84	31.11	48.64	75.87	115.22	184.04	286.37
		6.17	8.10	11.10	15.76	23.01	34.29	51.81	79.04	121.39
			6.97	8.21	10.14	13.14	17.80	25.05	36.33	53.85
				7.48	8.28	9.13	11.45	14.45	19.12	26.37
					7.81	8.36	9.13	10.37	12.30	15.30
						8.03	8.36	8.87	9.67	10.91
							8.16	8.38	8.71	9.22
								8.25	8.39	8.60
									8.31	8.40
										8.34

4.3 Value of "Call" Option to Expand Natural Gas Plant Capacity

In order to calculate the value of the "call-like" option to expand the natural gas plant and take advantage of the upside of rapid demand growth, I employed a binomial lattice model and dynamic programming to evaluate the expected net present value of profits in the presence and absence of the option to expand. The binomial lattice model is a tractable way of exploring how a project will perform in response to the evolution of a particular important parameter (in this case, demand). The fact that each state leads only to two additional states, that paths coincide (i.e. down than up is the same as up than down), and that each state is a multiple of an earlier state. Dynamic programming then starts from the end-state value of interest and works backwards to calculate the cumulative discounted expected value of the project (in revenues, profits, etc.).

The value of a "call-like" option to expand the plant in Year 5 (with expanded production beginning in Year 6) is explored below. First, the evolution of demand lattice shown in Table 4.2 was used to calculate a lattice showing cumulative demand at the beginning of each of the eleven periods (Table 4.3). The lattices of electricity output were then created to represent two alternative base cases: forced expansion (to 44 hundred million kWh) and no expansion (remain at 22 hundred million kWh). These lattices are shown in Tables 4.4 and 4.5, respectively. These results are then later compared to the case of the large natural gas power plant.

Table 4.4 Evolution of electricity output for no expansion case (22 hundred million kWh is maximum annual output)

CUMULATIVE DEMAND EVOLUTION – FLEX, NO EXPANSION										
2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
3.00	7.66	14.91	22.00	22.00	22.00	22.00	22.00	22.00	22.00	22.00
	4.93	7.93	12.59	19.84	22.00	22.00	22.00	22.00	22.00	22.00
		6.17	8.10	11.10	15.76	22.00	22.00	22.00	22.00	22.00
			6.97	8.21	10.14	13.14	17.80	22.00	22.00	22.00
				7.48	8.28	9.13	11.45	14.45	19.12	22.00
					7.81	8.36	9.13	10.37	12.30	15.30
						8.03	8.36	8.87	9.67	10.91
							8.16	8.38	8.71	9.22
								8.25	8.39	8.60
									8.31	8.40
										8.34

Table 4.5 Evolution of electricity output for expansion case (22 hundred million kWh is maximum annual output in years 2011 to 2015; 44 hundred million kWh is maximum in years 2016 to 2020)

CUMULATIVE DEMAND EVOLUTION – FLEX, EXPANSION										
2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
3.00	7.66	14.91	22.00	22.00	22.00	44.00	44.00	44.00	44.00	44.00
	4.93	7.93	12.59	19.84	22.00	44.00	44.00	44.00	44.00	44.00
		6.17	8.10	11.10	15.76	23.01	34.29	44.00	44.00	44.00
			6.97	8.21	10.14	13.14	17.80	25.05	36.33	44.00
				7.48	8.28	9.13	11.45	14.45	19.12	26.37
					7.81	8.36	9.13	10.37	12.30	15.30
						8.03	8.36	8.87	9.67	10.91
							8.16	8.38	8.71	9.22
								8.25	8.39	8.60
									8.31	8.40
										8.34

These lattices were then used as inputs for the cost model, and corresponding lattices of profits (equal to revenues minus O&M costs minus fuel costs) were calculated using the simple cost model detailed above. The value of being in any particular state was then calculated using dynamic programming. Capital costs were initially ignored, but later incorporated in the NPV comparison. Fuel prices were assumed to be in the “low” state throughout this analysis.

Table 4.6 Lattice of cumulative profits for no expansion case (before capital costs)

CUMULATIVE PROFITS – FLEXBILE PLAN, NO EXPANSION										
2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
428.52	506.81	559.98	571.16	527.96	473.15	412.00	344.62	270.51	188.98	99.31
	384.19	435.37	478.91	499.38	469.80	411.60	344.62	270.51	188.98	99.31
		324.74	358.07	388.94	408.32	399.85	343.10	270.51	188.98	99.31
			266.15	282.12	297.57	307.68	302.15	264.70	188.98	99.31
				215.54	215.81	214.81	212.53	199.11	166.88	99.31
					176.74	165.77	152.26	134.43	108.32	67.40
						146.19	127.79	106.35	80.20	46.53
							119.46	96.21	69.64	38.48
								92.96	65.97	35.53
									64.89	34.56
										34.31

Table 4.7 Lattice of cumulative profits for forced expansion case (before capital costs)

CUMULATIVE PROFITS – FLEXBILE PLAN, FORCED EXPANSION										
2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
558.19	673.32	769.95	830.50	840.52	838.49	822.12	688.35	540.03	376.88	197.41
	468.06	552.58	640.06	717.54	760.64	793.19	684.30	540.03	376.88	197.41
		355.61	407.77	465.60	523.14	568.05	584.14	524.64	376.88	197.41
			261.38	282.67	306.86	330.91	353.78	357.21	318.30	197.41
				196.04	195.04	193.01	196.77	190.89	168.31	113.49
					153.62	140.34	130.89	117.52	96.32	60.80
						120.76	106.42	89.44	68.20	39.93
							98.09	79.30	57.64	31.88
								76.05	53.97	28.93
									52.89	27.96
										27.71

Table 4.8 Expected value of cumulative profits after capital costs for different plant options

(1) No expansion case (300 MW)	$ 129 million
(2) Forced expansion case (600 MW)	$ 146 million
(3) Fixed plant case (500 MW, no expansion)	$ 144 million
(4) Flexible expansion case (300 MW + 300 MW if needed)	$ 206 million
Value of option (4) to expand compared to (1)	$ 77 million
Value of option (4) to expand compared to (2)	$ 60 million
Value of option (4) to expand compared to (3)	$ 62 million

The cumulative value lattices (Tables 4.6 and 4.7) allow for a comparison between value of the project given deterministic decisions either to add capacity or not at the outset. After incorporating capital costs (see Table 4.8) ($300m for the plant in Year 1 plus an additional

$180m in the expansion case in Year 5, equivalent to $112m when discounted to present value terms), I then examine the value of flexibility by taking the maximum of the expected value in Year 5 in the no expansion case and the expected value (including capital costs of expansion) of the forced expansion case in Year 5. I also compare the NPV in the expanded case to the fixed natural gas plant case. The result is as follows:

Table 4.9 Lattice of cumulative profits for case **with option** to expand (including capital costs for expansion when appropriate)

PROFITS – FLEXBILE PLAN, EXPANSION										
2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
205.97	608.94	692.86	740.83	738.91	**726.72**	412.00	344.62	270.51	188.98	99.31
	427.69	497.19	567.23	626.20	**648.88**	411.60	344.62	270.51	188.98	99.31
		338.22	376.11	413.11	**411.37**	399.85	343.10	270.51	188.98	99.31
			273.09	291.30	**297.57**	307.68	302.15	264.70	188.98	99.31
				219.34	**215.81**	214.81	212.53	199.11	166.88	99.31
					176.74	165.77	152.26	134.43	108.32	67.40
						146.19	127.79	106.35	80.20	46.53
							119.46	96.21	69.64	38.48
								92.96	65.97	35.53
									64.89	34.56
										34.31

As the above analysis shows, the ability to decide whether or not to expand in Year 5 is a very valuable "call-like" option in the system, worth $77 million compared to the case in which no expansion is allowed. The option to expand is worth less ($62 million) if the alternative considered is the fixed case of a single 500 MW plant in Year 1, or the other base case in which expansion to 600 MW is forced under all demand conditions ($60 million). The main reason for the observed value of the option is the high likelihood that year-on-year demand will continue to grow to the extent that the option will almost certainly be valuable. Indeed, flexibility allows plant managers to take advantage of the upside when demand is high, without maintaining excess capacity if demand proves low. In the case of flexible plant, the decision profile that results for Year 5 (2015) shown in Table 4.10.

Table 4.10 Optimal Decisions in Given States of the World in Year 5

Probability	**Demand**	**2015**
0.18	70.94	EXPAND
0.37	31.11	EXPAND
0.30	15.76	EXPAND
0.12	10.14	NO CHANGE
0.02	8.28	NO CHANGE
0.00	7.81	NO CHANGE

The fact that the probabilities are skewed towards expected expansion suggests that it is almost certain that additional capacity will be needed. It also suggests that under the assumptions that emerge from the published demand trend data cited above, it may be worth considering other configurations of capacity that would allow for most advantageous design of expansion options. For instance, building capacity increments larger than 300 MW would be worth exploring.

4.4 Value of "Put" Option to Close Coal-Fired Power Plant

The coal-fired power plant is extremely sensitive to demand, and therefore retaining the ability to close the plant at any time may be a valuable "put-like" option to have available. Here I explore the value of the option to close the plant at any point at which the plant is no longer expected to be profitable. I assume that fuel costs are low, that demand evolves as described above, and regulatory costs are expected starting at the beginning of 2016. The closure costs associated with shutting down the plant are $4.5 million. I use dynamic programming (Tables 4.11 and 4.12) in a manner similar to that employed above to calculate the value of the coal plant with and without the option to close.

Table 4.11 Expected profit of Coal Plant with No Option to Close as Viewed from the N-1 State (capital cost ignored)*

COAL PLANT – PROFITS WITH REGULATIONS – NO FLEXIBILITY										
2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
520.41	713.83	897.91	1033.54	1051.07	916.39	737.77	617.36	484.34	338.01	177.05
	330.22	467.98	608.67	730.01	790.54	717.35	615.40	484.34	338.01	177.05
		150.92	235.51	326.93	413.58	472.28	542.47	476.87	338.01	177.05
			1.67	38.47	79.63	119.47	225.57	302.39	309.57	177.05
				-106.59	-106.55	-108.10	-29.45	39.81	88.26	89.86
					-177.91	-198.85	-142.94	-86.60	-35.79	-0.91
						-232.58	-185.11	-134.96	-84.23	-36.88
							-199.47	-152.44	-102.42	-50.75
								-158.05	-108.76	-55.82
									-110.61	-57.50
										-57.93

Table 4.12 Expected profit of Coal Plant with Option to Close as Viewed from the N-1 State (capital cost ignored)*

COAL PLANT – PROFITS WITH REGULATIONS – FLEXIBILITY										
2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
523.86	715.32	898.34	1033.62	1051.08	916.39	737.77	617.36	484.34	338.01	177.05
	339.68	472.59	610.12	730.28	790.57	717.35	615.40	484.34	338.01	177.05
		175.61	249.48	331.75	414.54	472.39	542.47	476.87	338.01	177.05
			61.23	79.80	95.62	122.87	225.99	302.39	309.57	177.05
				18.44	11.47	-55.60	-17.58	41.44	88.26	89.86
					7.64	-61.91	-55.60	-45.43	-29.60	-0.91
						-64.62	-61.91	-57.70	-51.15	-36.88
							-63.50	-61.76	-59.05	-50.75
								-62.78	-61.66	-55.82
									-62.32	-57.50
										-57.93

*In both cases, the 2020 column indicates the NPV of the final year of operation, and is used as a basis for the expected value calculations.

By comparing the expected profits, the value of the option of close is calculated as $523.86 million minus $520.41 million, or $3.45 million. Capital costs are ignored here because their contribution is the same regardless of whether or not the option is exercised, and thus does not affect the final calculation of the value of the option. In Table 4.12, the cells where NPV is negative indicate points at which money would be saved by closing the plant starting the following year because the expected NPV of operating that year is less than the closure costs, which are incurred at the end of the following year after the plant has been fully decommissioned and are thus discounted over this period. Plant closure is only possible starting at the beginning of 2016, according to the terms of the assumed contract described above. The following strategy indicating when plant closure would be desirable *and* feasible is presented below in Table 4.13.

Table 4.13 Strategy for Operation or Closure of Coal-fired Power Plant at Start of Subsequent Year

CONTINUE OPERATING PLANT?									
2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
	NO	NO	NO	NO	NO	NO	NO	NO	NO
		NO	NO	NO	NO	NO	NO	NO	NO
			NO	NO	NO	NO	NO	NO	NO
				NO	NO	YES	YES	NO	NO
					NO	YES	YES	YES	YES
						YES	YES	YES	YES
							YES	YES	YES
								YES	YES
									YES

The decision path described gives the plant manager a degree of "insurance" against the downside financial risks associated with lower-than-expected demand in the second half of the project. The value of this option, estimated at $3.45 million, is substantial in absolute terms. However, since it depends on the initial demand projection and subsequent growth pattern depicted in the lattice, small changes in the latter could greatly increase or decrease *a priori* estimates of the option value, and would be worth exploring in future studies.

V. Conclusions and Discussion

5.1 Value of Flexibility in Shanghai Power Planning

The above analysis has shown that flexibility may have the potential to add significant value to investments in power generation capacity to meet Shanghai's rapidly rising demand for electricity. These investments can take the form of either a "call-like" option in a plant's design, for example, the ability to expand plant capacity in response to rising demand. Conversely, a "put-like" option would allow the manager to minimize losses. Both of these types of options may prove important in the context of Shanghai's rapidly growing market where volatility of both demand and prices is high. The regulatory environment for new power infrastructure investments is likewise in a state of transformation, adding to the uncertainties involved.

The two options investigated here—the option to expand a natural gas fired power plant to meet growing demand and to close down an unprofitable coal plant—were shown to offer potential value under the assumptions in this work. First, decision analysis was used to value the option to expand. The value of the option to expand from 300MW to 600MW was found to be around $30.68 million, given plausible assumptions for the two demand and price scenarios, compared to the fixed 500MW natural gas plant investment. Cost-benefit ranking of all three cases analyzed in the decision analysis model likewise showed that the flexible natural gas plant design was likely to be the most favorable. The value-at-risk and gain chart showed how the flexible natural gas configuration minimizes potential losses and maximizes gains under conditions of uncertain demand. The favorability of the three options is affected in the second period by uncertainty in the natural gas price and regulatory environment.

A binomial lattice model was applied to calculate the difference in NPV that resulted in the expansion versus base cases. Again, the flexible natural gas plant design (Plan 3) proved to be the best of the natural gas configurations with equal capacity, compared in net present value terms. The value of the option ranged from \$60 to \$77 million, depending on the base case assumed. In comparing these results to the decision analysis, it must be recognized that the binomial lattice model assumes much more rapid demand growth than the simple model underlying the decision analysis, due to the improved resolution of demand growth projections. It should come as no surprise that when demand growth is higher than expected, the flexible design performs better, and thus the option will appear more valuable.

I then applied the binomial lattice model to examine the value of the "put"-like option to close the coal-fired power plant. According to the decision analysis model, the coal plant was the attractive relative to the large natural gas plant (Plan 2). Also, the maximum potential gains in NPV terms were possible with the coal plant, and designers who do not consider other measures of project value and assume very high demand may be misled to invest on this basis. This fact may help to explain why coal is still the preferred electricity generation option in Shanghai. However, a significant downside is associated with the low demand and the imposition of regulations, according to the decision analysis. Binomial lattice analysis provided a framework to evaluate the value of the option to close the plant in the second period, in response to the imposition of costly regulations or other unfavorable conditions. Under the high demand conditions assumed, the option to close the plant was modestly valuable at \$3.45 million. However, sensitivity of the optimal decision path to changes in the assumed initial demand could help to develop a more complete picture of the value of this option under a variety of conditions.

5.2 Directions for Future Work

This work has only scratched the surface of potential applications of options to design problems in the electric power industry. In particular, these techniques may be particularly valuable in markets such as Shanghai where demand is high and volatile, and there is a great deal of uncertainty in the regulatory environment. This project has opened a new realm of interesting research prospects, not least among them the improvement on underlying assumptions and data projections used here. Beyond simply improving on the model used here, a more sophisticated options analysis could examine the effects of uncertainties in demand and price simultaneously on optimal investments in natural gas plants. Uncertainties in coal supply and prices—though far less pronounced than for natural gas—might also be worth exploring in the Chinese context. An important application mentioned above could involve a sensitivity analysis to explore how various regulation scenarios would change optimal plant design configurations, and how introducing flexibility at the outset might provide more room for environmental commitments to be met later if regulations are introduced. Finally, an options analysis of energy investment in China's rapidly changing market should be preceded by a broader investigation into the criteria investors and plant managers use to inform their design choices. Net present value is often assumed to be universal, but social, political, or temporal factors may account for deviations from this assumption in the Chinese context.

5.3 Comments on Application Portfolio Assignment

This exercise and the ESD.71 course have provided very valuable learning experiences. I enjoyed developing a project that enabled me to apply real options techniques to a problem in which I already had prior interest. Although challenging at times, distilling a complex design issue into a case study focusing on several important sources of uncertainty was a very worthwhile undertaking, and reinforced most of the course concepts to the extent that I will be able to apply them with proficiency to future design problems.

Suggestions for improving the overall process are minor and procedural. At the outset of the project and the course, I would have liked to have a clearer vision of the end product of the application portfolio in mind, so that I could have more realistically tailored my chosen uncertainties and options under consideration to the scope and techniques expected. Perhaps one suggestion would be to group projects into categories, or provide some previously developed cost models, for students to adapt to their particular application. Also, the Excel mini-course is very valuable, and instructors should underscore that all students participate if possible.

Overall, I am extremely pleased with all that I have learned in the ESD.71 course. I am very grateful to Prof. de Neufville and Michel-Alexandre Cardin for their patience and efforts in supporting our learning throughout the semester.

Works Cited

Jiang, B. B. (2007). The Future of Natural Gas vs. Coal Consumption in Beijing, Guangdong and Shanghai: An assessment utilizing MARKAL. Working Paper #62. Stanford University: Program on Energy and Sustainable Development.

Luo, Y. (2007). Shanghai Jiaotong University, *Development of Shanghai's Energy Industry: Status Quo and Prediction*. Prepared for Workshop on Natural Gas Markets in Beijing, Shanghai, and Guangdong. Retrieved December 18, 2007, from http://iis-db.stanford.edu/evnts/4164/Shanghai,_gas_overview.pdf.

Steinfeld, E. & Lester, R. (2007). Chapter 5: Coal Consumption in China and India. *The Future of Coal*. Cambridge, MA: Massachusetts Institute of Technology.

.

Shanghai Foreign Economic Relation and Trade Web Site. (2007). Price of electricity in Shanghai (Unitary System). Retrieved December 18, 2007, from http://www.smert.gov.cn/gb/2/node498/node580/node582/node640/userobject1ai10902.html.

Shanghai Statistical Yearbook. (2006). Retrieved December 18, 2007, from www.ChinaDataOnline.org.

Gas: Prices. (2007). *BP Statistical Review of World Energy*. London, England: BP. Retrieved December 18, 2007, from http://www.bp.com/productlanding.do?categoryId=6848&contentId=7033471.