Power Plant Investment Appraisal: Electric Industry and Economic Growth Nexus

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by

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DEDICATION

This thesis is dedicated to my parents

for their

pure and unconditional love to me

ACKNOWLEDGEMENT

I would like to express my deepest and sincere gratitude to my supervisor, Professor K. L. Lo, Head of the Power Systems Research Group (PSRG), University of Strathclyde, for his supervision and most valuable guidance throughout the period of my research work. His encouragement and help greatly contributed in my current achievement.

Declaration of Author's Right

Signed: ______________________ Date: ______________________

ABSTRACT

Electric power industries are undergoing restructuring around the world. Under deregulation, the non-utility, independent power producers (IPP) are allowed to invest in the power system. Each year, many new investments in different types of power plants are proposed by generators all over the world. However, investment in generation projects involves large amounts of capital with a long payback period, comparable with the lifetime of the plant. Moreover, macroscopic situation of electrical industry and economic environment also need to be taken into account. Therefore, how to make an investment decision is a complex problem.

This thesis considers the power plant investment issues in UK and China from microscopic and macroscopic viewpoint. The microscopic viewpoint focuses on investment appraisal approaches, different types of generation technologies, and levelised cost of generation. The macroscopic viewpoint focuses on investment environment in UK and China, such as the relationship among electricity consumption, installed capacity and GDP.

The thesis begins by presenting the current situation of electricity generation in UK and China. It continues to introduce some classic and practical investment theories and project analysis tools. Then, the applications of these approaches on the investment of eight types of electricity generation technologies in the UK and pulverised coal plant in China are given. The analysis results show evidences for several investment advices on microscopic viewpoint. These advices could help investors to more clearly make their investment decision on different types of power plant.

From macroscopic viewpoint, the relationship among electricity consumption, economic growth and installed capacity in the UK and China are found by applying econometric approaches. The forecast of electricity consumption and GDP of China

are also given. After this, the thesis takes into account the differences of economic growth and environment in different regions of China, and classifies China's provinces into four parts: Northeast, Coastal, Central and West. The relationship between electricity consumption and economic growth in China are determined based on provincial data and panel time series approaches. These results can help investors to fully understand the electric industry investment environment of China, which lead to some policy suggestions.

GLOSSARY

ADF	**Augmented Dickey-Fuller**
AIC	**Akaike Information Criterion**
AR	**Autoregression**
BEP	**Break-even point**
BIC	**Bayesian information criterion**
CCGT	**Combined Cycle Gas Turbine**
CCS	**Carbon Capture and Storage**
CPI	**Consumer price index**
DCF	**Discount cash flow**
DF	**Dickey-Fuller**
EC	**Electricity Consumption**
ECM	**Error correction model**
EG	**Engle-Granger test**
FV	**Future value**
GDP	**Gross domestic product**
HRSG	**Heat recovery steam generator**
IGCC	**Integrated Gasification Combined Cycle**
IRR	**Internal rate of return**
LC $_A$	**Levelised cost by "annuity" approach**

$$LC_A = \frac{Annual(Costs)}{Average(Output)} = \frac{(\sum_{t=0}^{n} C_t / (1+r)^t) \times (r / (1-(1+r)^{-n}))}{(\sum_{t=1}^{n} O_t) / n}$$

LC $_D$	**Levelised cost by "discounting" approach**

$$LC_D = \frac{PV(Total\ Costs)}{PV(Total\ Outputs)} = \frac{\sum_{t=0}^{n} C_t / (1+r)^t}{\sum_{t=0}^{n} O_t / (1+r)^t}$$

NPV	**Net present value**
PP	**Phillips-Perron**
PV	**Present value**
ROC	**Renewable Obligation Certificate**
RSS	**Residual sum of squares**
RWM	**Random Walk Model**
SCPC	**Supercritical pulverised coal**
SubCPC	**Subcritical pulverised coal**
USCPC	**Ultra-supercritical pulverised coal**
VAR	**Vector autoregression**
VECM	**Vector error correction model**

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Chapter 1: Introduction

The electricity supply is a fundamental infrastructure in developed societies on which electric power supply is assumed to be readily available. The electricity industry consists of four parts:

Generation the production of electricity at power plants in which energy stored in different kinds of fuels (coal, gas, oil, nuclear, hydraulic, wind, etc.) is converted to electric energy.

Transmission the bulk transfer of generated electricity from the generation side to local networks through high voltage transmission lines (the grid).

Distribution the process by which electricity received from the grid is delivered to consumers through lower voltage power lines.

Supply the purchase of electricity from generators and its sale to end-users.

Each year, many new investments in different types of power plants are proposed by generators all over the world. However, investment in generation projects involves large amounts of capital and long payback periods and it thought of as long term investment, comparable with the lifetime of the plant. Therefore, how to make the decision is a problem for investors. This thesis investigates the project evaluation of electricity generation investment, and gives the nexus of electric industry and economic growth in **UK** and **China** respectively.

1.1 What is the investment appraisal?

Investment appraisal (or capital budgeting) is the planning process used to determine whether an organization's long term investments such as new machinery, replacement machinery, new plants, new products, and research development projects are worth pursuing. It is budget for major capital, or investment, expenditures. [1]

Many formal methods are used in capital budgeting, including the techniques such as:

- Accounting rate of return
- Payback period
- Net present value
- Profitability index
- Internal rate of return
- Modified internal rate of return
- Equivalent annuity

These methods use the incremental cash flows from each potential investment, or project. Techniques based on accounting earnings and accounting rules are sometimes used - though economists consider this to be improper - such as the accounting rate of return, and "return on investment." Simplified and hybrid methods are used as well, such as payback period and discounted payback period.

1.2 What is Electric Industry & Economic Growth Nexus?

The *Electric Industry* in the title is mainly refers to electricity consumption. The *Electric Industry & Economic Growth Nexus* chiefly means the relationship between electricity consumption and economic growth. The reason of using *Electric Industry* is because some parts of this thesis take account of the relationship between installed capacity and economic growth.

It is widely understood that electricity plays a vital role in both the production and consumption of goods and services within an economy. In a study of over 100 countries, Ferguson et al.[2] find a strong correlation between electricity usage and the level of economic development and growth. However, the presence of a strong correlation does not necessarily imply a causal relationship. The causal relationship may be one from electricity consumption to economic growth, economic growth to electricity consumption, in both directions, or the absence of causality entirely. Indeed, understanding the causal relationship between electricity consumption and economic growth is important in the design and implementation of electricity and energy policies.[3]

The causal relationship between electricity consumption and economic growth has been synthesized into four testable hypothesizes by Ozturk.[4]

1) *No causality*: No causality between electricity consumption and GDP is referred to as "neutrality hypothesis". It implies that electricity consumption is not correlated with GDP, which means that neither conservative nor expansive policies in relation to electricity consumption have any effect on economic growth. Thus, the neutrality hypothesis is supported by the absence of a causal relationship between electricity consumption and real GDP.

2) The *unidirectional causality* running from economic growth to electricity consumption. It is also called "conservation hypothesis". It suggests that the policy of conserving electricity consumption may be implemented with little or no adverse effect on economic growth, such as in a less electricity-dependent economy. The conservation hypothesis is supported if an increase in real GDP causes an increase in electricity consumption.

3) The *unidirectional causality* running from electricity consumption to economic growth. It is also called "growth hypothesis". It implies that restrictions on the use of electricity may adversely affect economic growth while increases in

electricity consumption may contribute to economic growth. The growth hypothesis suggests that electricity consumption plays an important role in economic growth both directly and indirectly in the production process as a complement to labour and capital. Consequently, the electricity is a limiting factor to economic growth and, hence, shocks to electricity supply will have a negative impact on economic growth.

4) *Bidirectional causality* between electricity consumption and economic growth. It is also called “feedback hypothesis”. It implies that electricity consumption and economic growth are jointly determined and affected at the same time.

1.3 Research Motivation and Innovation

1.3.1 The motivation of the study

Firstly, traditional researches did not point out the importance of studying electricity consumption and economic growth nexus on power plant investment. The coordination of electricity consumption and economy is crucial to sustain economic growth and, therefore, research on the relationship and causality between electricity consumption and economic growth has a positive significance on policy making and power plant investments. In China, because regional differences in the relationship between electricity consumption and economic growth are significant, the ultimate decision on the power generation investment strategy of a region should take account of the electricity elasticity and causality direction of that region. In one word, the relationship between electricity consumption and economic growth is the investment environment for power plant investment, and it will help investors to decide the investment timing, scale and location.

Secondly, traditional investment appraisal always focuses on project net present value, payback period and rate of return.[5] In a power plant project, the profitability is based on the electricity price and the cost of electricity generation. Because the electricity price is uncontrollable for power plant, the analysis of cost of electricity generation plays an important role on investment evaluation. The author believes the investigation on the cost of electricity generation, especially by different generation technologies, is necessary.

Thirdly, some researches did not consider the differences of economic growth and environment in different regions of China when they studied the relationship between electricity consumption and economic growth. Moreover, the sample size and time period of aggregate data of China is too small to ensure accurate results. For instance, Shiu and Lam[6] analyzed the electricity data during 1971-2000. They asserted that there was a unidirectional causality running from electricity consumption to economic growth in China. Yuan, et al.[7] got the same result by using the data for the 1963-2005 period. Some researchers were aware of such weakness, so they tried to sub-divide China into two or three parts and applied panel methods to embody the differences. Li, et al.[8] classified 30 China provinces into two parts. A number of researchers employ conventional classification. They divided China into three parts: east, central and west parts, to investigate the relationship between energy consumption and economic growth, like Wu, et al.[9]. The authors of this thesis think these classifications are not proper.

1.3.2 The innovation of this thesis

Firstly, in order to combine the study of electricity consumption and economic growth nexus with power plant investment appraisal, this thesis considers power plant investment from microscopic and macroscopic viewpoint.

Microscopic viewpoint is from the point of operation and profit return angle. It forces on project net present value, payback period, internal rate of return, sensitivity of main factors (tornado diagram), and levelised cost of generation. Net present value, payback period and internal rate of return are classical investment appraisal methods. Tornado diagram is a useful graphical tool which is used to illustrate the relative sensitivity and influence of the project's net present value to its variables.

Levelised cost is the "ratio of total lifetime expenses versus total expected outputs, expressed in terms of the present value equivalent".[10] The levelised cost in this thesis consists of:

1) Construction cost (Capital cost),
2) Fixed O&M cost,
3) Variable O&M cost,
4) Operational fuel cost,
5) Fuel delivery cost,
6) Carbon tax cost,
7) Additional cost for carbon capture and storage.

The macroscopic viewpoint of power plant investment focus on investment environment in a country, such as the relationship among electricity consumption, installed capacity and economic growth, long-run and short-run causality direction between electricity consumption and GDP, and the electricity elasticity on GDP. Such research may give investors advices on power plant investment timing, scale and location. The research contains two parts.

- The country-specific study

The country-specific study looks at a country as a whole, and applies single time series econometric methods on electric and economic data of UK and China respectively.

- The panel-based study

The panel-based study in this thesis analyzes the electricity consumption and economic growth in China by provincial panel data. This method considers the differences of economic growth and environment in different regions of China.

In this thesis, chapter 2 & 3 discuss the power plant investment from microscopic viewpoint, and chapter 4 & 5 discuss the power plant investment from macroscopic viewpoint.

Secondly, this thesis analyses the profitability and levelised cost of eight types of electricity generation projects in UK but only pulverised coal plant in China. These projects are:

1) CCGT (Combined Cycle Gas Turbine),
2) CCGT with CCS (Carbon capture and storage),
3) Pulverised coal,
4) Pulverised coal with CCS,
5) IGCC (Integrated Gasification Combined Cycle),
6) IGCC with CCS,
7) Onshore wind power,
8) Offshore wind power.

In order to investigate the performance of projects under fluctuation of costs, this thesis sets three scenarios for each project to calculate the levelised costs, which involves high scenario, base scenario and low scenario. Each scenario has a combination of different costs level. The levelised costs of three scenarios reflect the profitability and risk resistance capability of a project.

Thirdly, unlike the published articles, this thesis researches electricity consumption – economic growth nexus in China and classifies China’s provinces into four parts: Northeast, Coastal, Central and West. The classification is based on GDP per head, industry production per head and industrial structure. Comprehensively considering the location of each province, the under-developed ones will be grouped into the west panel, since most of them are located in the west region of China. Similarly, the better-developed provinces and the less-developed ones will be named coastal panel and central panel respectively. In this thesis, the three northeast provinces are treated as a separate group because this area has always been seen as the original base of China’s industry, especially heavy industry. Their demand of electricity is huge and it plays an important role in economic development in the northeast region.

1.4 Current situation of electricity generation

1.4.1 Current situation of UK electricity generation

In UK, the total electricity supply is 377.98 TWh in 2010. The energy sources for electricity generation mainly come from coal, natural gas, nuclear, renewable, oil and others including the inter-countries connection. Figure 1.1 gives the electricity generated by fuel type in UK from the first quarter of 2008 to the third quarter of 2011.[11]

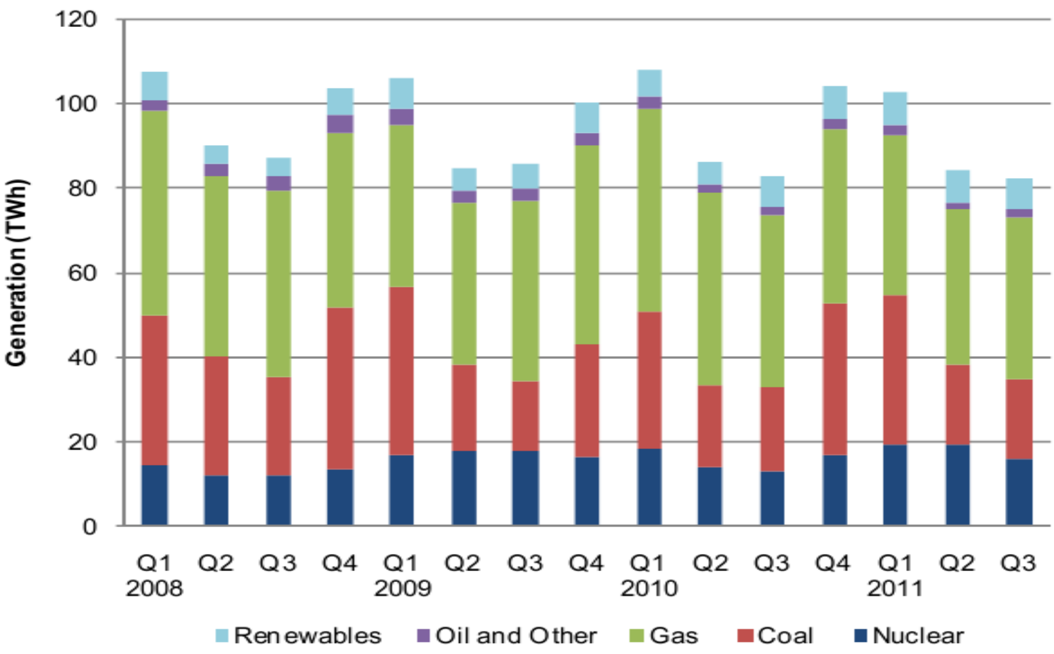

Figure 1.1: Electricity generated by fuel type in UK

In the third quarter (Q3) of 2011, total electricity generated fell 0.2% from 82.6 TWh in 2010 Q3 to 82.5 TWh, and the lowest level since prior to 1998 Q1. Coal fired generation fell by 3.8% from 19.8 TWh to 19.1 TWh, its lowest level for two years. Gas fired generation fell 5.7% from 40.6 TWh to 38.3 TWh due to high gas prices, with several stations being run at very minimal (or near zero) levels as a result. In 2011 Q3, nuclear generation rose 21.2% from 13.0 TWh to 15.8 TWh, due to increased availability compared to a year ago. Several stations had returned from maintenance outages including Sizewell B, which, unplanned, was offline for six months in 2010. However, due to planned outages on a smaller scale in 2011 Q3, nuclear generation fell by 17.9 per cent on 2011 Q2's 19.2 TWh. In 2011 Q3, wind generation rose 8.8% from 2.7 TWh to 3.0 TWh, due to increased installed capacity. Hydro generation rose 41.3% from 0.9 TWh to 1.2 TWh, due to much higher rainfall in 2011 as a whole.

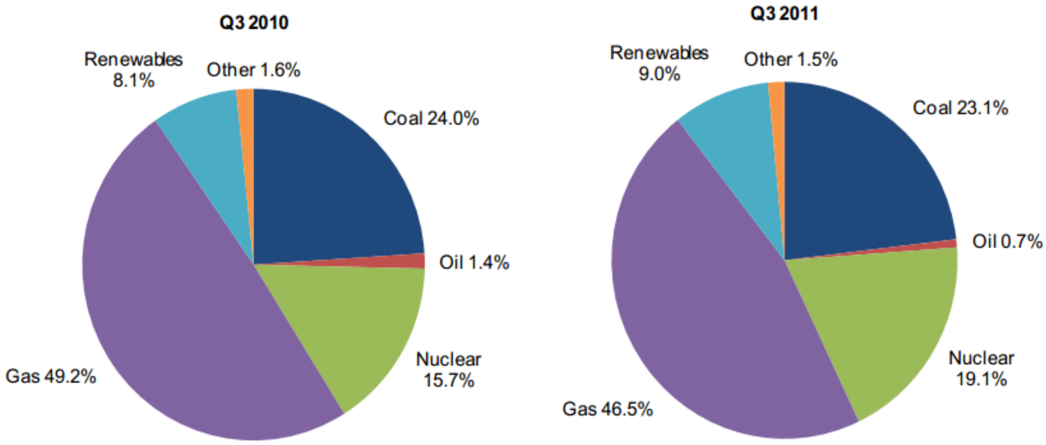

Figure 1.2: Shares of electricity generation in UK

Figure 1.2 shows the shares of electricity generation in 2010 Q3 and 2011 Q3.[11] The percentage of generation from coal decreased from 24.0% in 2010 Q3 to 23.1% in 2011 Q3. Gas's percentage of generation decreased from 49.2% in 2010 Q3 to 46.5% in 2011 Q3. Nuclear share of generation increased from 15.7% in 2010 Q3 to 19.1% in 2011 Q3, due to increased availability. The share of renewable (hydro, wind and other renewable) increased from 8.1% in 2010 Q3 to 9.0% in 2011 Q3.

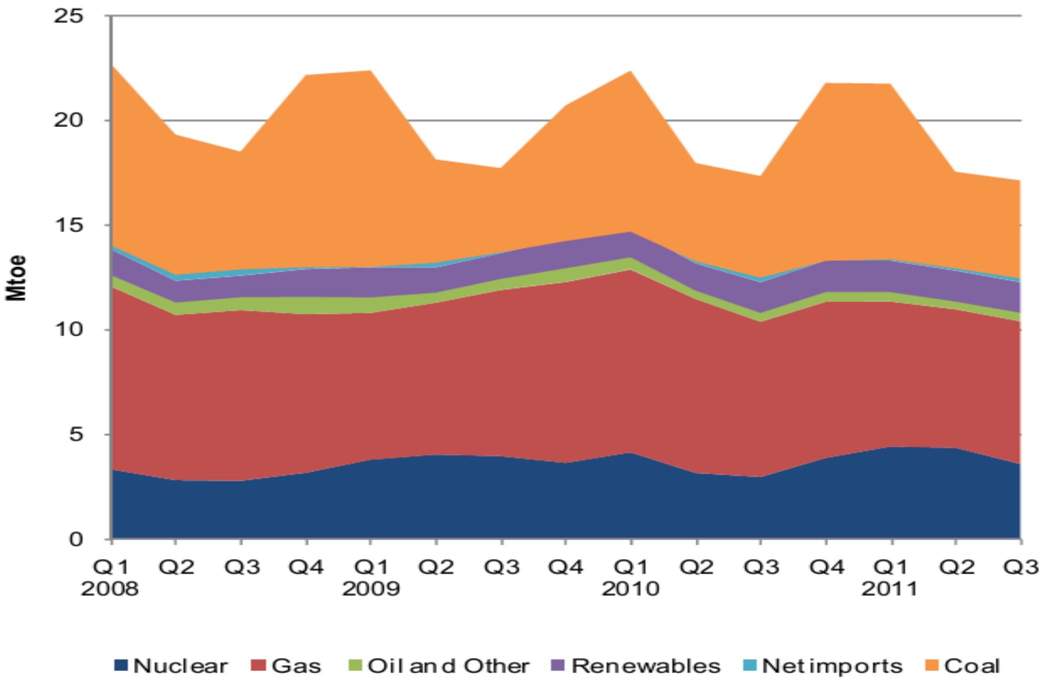

Figure 1.3: Fuel used for electricity generation

Figure 1.3 gives the fuel used for electricity generation from Q1 of 2008 to Q3 of 2011. Where the unit Mtoe is million tonnes of oil equivalent. The tonne of oil equivalent is a unit of energy: the amount of energy released by burning one tonne of crude oil. The IEA (International Energy Agency) defines one toe to be equal to 41.868 GJ or 11.63 MWh.[12] Fuel used by generators in 2011 Q3 fell 1.2%, from 17.3 Mtoe in 2010 Q3 to 17.1 Mtoe, the lowest level since 1998 Q1. In 2011 Q3, gas use was 8.0% lower than in 2010 Q3, due to high gas prices. Coal use during the 2011 Q3 was 3.6% lower than a year earlier, while nuclear sources were 21.2% higher.

1.4.2 Current situation of China electricity generation

The total electricity generation of China is 4721.7 TWh in 2011, an increase of 11.68% over that in 2010.[13]

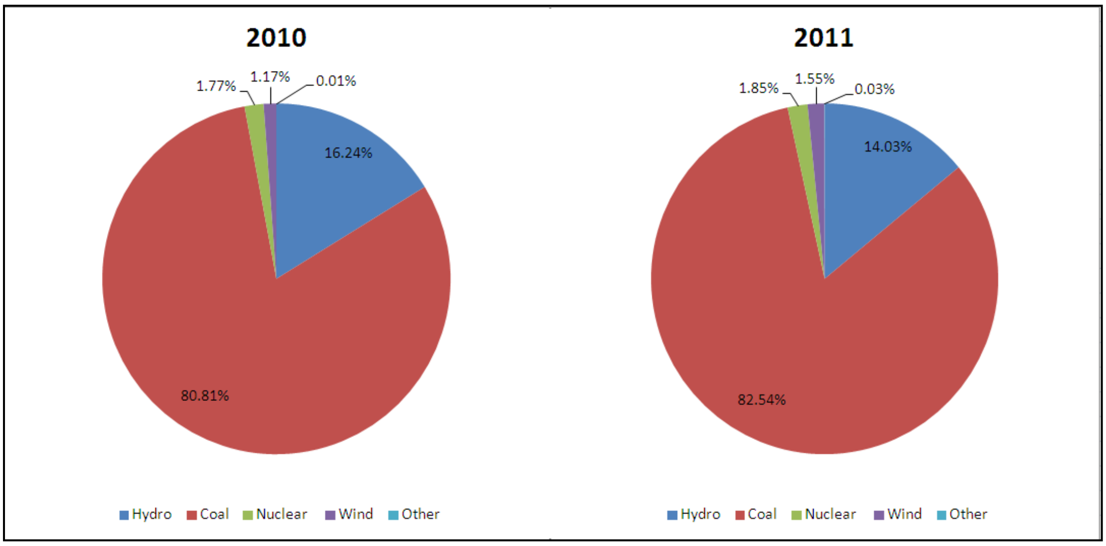

Figure 1.4: China energy sources for electricity generation and their percentage

Figure 1.4 indicates the percentage of electricity generation by energy sources in 2010 and 2011.[14] The figure shows that coal plant dominates the China's electricity generation. The shares of generation from coal increased from 80.81% in 2010 to 82.54% in 2011. Hydro's percentage decreased from 16.24% in 2010 to 14.03% in 2011. Nuclear and wind power occupied 1.85% and 1.55% of total electricity generation in 2011, which increased by 0.08% and 0.38% of 2010's percentages respectively.

The relationship between electricity supply and economic growth has never been fully studied in China. Historically there was a widespread shortage of electricity since 1960. In 1997 with the slow down of economic growth rate there emerged electricity surplus for the first time. However electricity shortage appears again since 2002 and worsened in 2004. In 2004, the number of provinces with shortage in electric power amounted to 24 and the total gap is 31 GW in China.[15] Following the outbreak of global economic crisis in 2008, many factories along the coastal provinces were either faced with reduced production or in some cases economic loss or bankruptcy, demand for power has slowed. The massive investments in power plants in earlier years are beginning to come on stream and create a saturating phenomenon of generating capacity. Power industry is a typical periodic industry in China.

1.5 Objective and Scope

It is mentioned in previous section that this thesis investigates the project evaluation of electricity generation investment, and gives the nexus of electric industry and economic growth. Therefore, the objectives of this thesis include:

- To apply investment appraisal approaches for analyzing the investment of different types of electricity generation projects and finding the profitability and cost structure of each generation technologies.

- To investigate the relationship and prediction of electricity consumption, installed capacity and economic growth in UK and China.

- To find the nexus between electricity consumption and economic growth in China by using the provincial panel data approach.

The scope of this thesis can be summarized as follows:

- To review the investment theories and project analysis methods, which include discounted cash flow approaches, sensitivity and scenario analysis and levelised cost analysis.

- To apply investment appraisal approaches for analyzing the investment of eight types of electricity generation projects in the UK and coal-fired plant in China.

- To review literatures of the relationship between energy and electricity consumption and economic growth, which is classified by country-specific studies and multi-country studies.

- To review the econometric analysis methods, which include single and panel time series approaches.

- To investigate the relationship and prediction of electricity consumption, installed capacity and economic growth in the UK and China by single time series analysis methods.

- To investigate the relationship between electricity consumption and economic growth in China based on provincial panel data analysis methods.

1.6 Original Contributions of the Thesis

Based on the above objectives, the research in this thesis has achieved the following original contributions:

1. Eight types of electricity generation technologies in UK and pulverised coal project in China are analysed by discounted cash flow approach and levelised cost approach. The analysis results show evidences for several investment advices. These advices could help investors to be more informed prior in making investment decision on different types of power plant.

2. The relationship among electricity consumption, economic growth and installed capacity in UK and China are discussed in this thesis. The forecast of electricity consumption and GDP of China are also given. These results can help investors to understand the electric industry investment environment of the UK and China. These results also lead to some policy suggestions to the government.

3. The relationship between electricity consumption and economic growth in China are found by provincial panel data methods. The study takes into account the differences of economic growth and environment in different

regions of China, and classifies China's provinces into four parts: Northeast, Coastal, Central and West. To the best of the author's knowledge, there is no published article to discuss and analyse the relationships between electricity consumption and economic growth in China by provincial data and panel methods.

1.7 Thesis Organization

This thesis is made up of six chapters. The organization is as follows:

Chapter 1 presents an introduction of the whole thesis. It includes the current situation of UK and China's electricity generation, and the historical statistic for UK and China electric industry. The objectives and scope of this thesis and main original contributions of the thesis are presented.

Chapter 2 introduced the main investment concepts and project appraisal approaches, which include the time value of money, the discounted cash flow approach, and project analysis methods. Firstly, the time value of money includes future and present values, perpetuities and annuities, and inflation. The discounted cash flow approach covers net present value, payback period and internal rate of return. Finally, project analysis methods section covers tornado diagram, scenario analysis and levelised cost of generation.

Chapter 3 analysed the investment of eight types of electricity generation technologies in the UK but only pulverised coal plant in China by the approaches introduced in chapter 2. Firstly, this chapter introduced some electricity generation technologies briefly. These technologies include combined cycle gas turbine (CCGT), pulverised coal, integrated gasification combined cycle (IGCC) and carbon capture and storage (CCS). Secondly, eight types of electricity generation technologies in UK are analysed one by one by discounted cash flow approach and levelised cost approach. Thirdly, pulverised coal project in China is also analysed by these approaches.

Chapter 4 studies the relationship between electricity consumption, economic growth and installed capacity in the UK and China respectively. Firstly, the literature review summarizes this kind of study and lists the recent papers of country-specific studies on energy or electricity economics. Secondly, chapter 4 also introduces the econometric analysis methods such as unit root test, cointegration test and causality test.

Then, all of these econometric approaches are applied to the UK and China's data respectively. The unit root test results of UK show that the logarithmic form of real GDP, electricity consumption and installed capacity in UK are all 1^{st} order process. The cointegration test results show that there is no cointegration relationship among real GDP, electricity consumption and installed capacity in UK. After creating a VAR model, the causality test does not find any causality among these three variables. The unit root test results of China state that logarithmic form of real GDP and electricity consumption are I(1) process, and the log installed capacity is I(2) process. Then, a cointegration relationship has found between real GDP and electricity consumption. Hence, these two variables build a VECM (vector error correction model) and tested short-run, long-run and joint causality. The test results indicate that there is no causality between these two variable in the short-run but has unidirectional causality running from electricity consumption to economic growth in the long-run and also in the joint test. After causality test, the forecast based on VECM gives the predicted value of electricity consumption and the real GDP from 2011 to 2015.

Chapter 5 examines the relationship and direction of causality between electricity consumption and economic growth in China by provincial panel data. The chapter applies the panel data for log electricity consumption and log GDP for 28 provinces from 1985 to 2009 and classifies them into four groups: northeast, coastal, central and west. Panel-based methods are employed for the following: whole China panel, northeast provinces panel, coastal provinces panel, central provinces panel and west provinces panel. The results of panel unit root tests and panel cointegration tests show that electricity consumption and economic growth are I(1) process and co-integrated in each panel. The directions of causality of each panel are tested by panel VECM and causality test for the short-run and the long-run, respectively. The results show that there are bidirectional causalities between electricity consumption and growth for each panel in the short-run. Over the long term, there are bidirectional causality between electricity consumption and economic growth for the whole and west China. For coastal provinces, the direction is running from economic growth to electricity consumption, while in the northeast and central provinces the opposite is true. The final section of this chapter gives some policy suggestions.

Chapter 6 summarizes the conclusions of this thesis and discusses possible future works.

1.8 Publications

Based on the results of the research work reported in this thesis, the following papers have been published:

- X. Ma, **Li, R** and K.L. Lo, *Power industry investment, electricity production and economic growth in China: Relationship and forecast*, in *Universities Power Engineering Conference (UPEC), 2010 45th International* 2010: Cardiff.

- **Li, R**., X. Ma and K.L. Lo, *Electricity consumption-economic growth nexus in China: Evidence from provincial panel data*, in *IEEE power & energy society general meeting*. 2011: Detroit Michigan, USA.

- **Li, R**., X. Ma and K.L. Lo, "*Electricity consumption and economic growth in*

China: Based on the provincial panel data analysis," (Under review)

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Chapter 2: Investment Theories and Project Analysis Methods

2.1 Introduction

Investment in power systems traditionally follows an integrated development programme prepared by a planning agency, usually located in the power utilities (mostly in the state bureau of power industry). This programme identifies the capacity increments to be added over the planning horizon that will meet the demand for power at minimum cost, together with the optimal utilization of existing facilities. However, electric power industries around the world are undergoing restructuring. Many countries have enacted restructuring legislation aimed at transforming the electricity supply industry away from the traditional regulated structure toward a more competition-based marketplace. The first step of this restructuring is to introduce competition into generation supply part of power system. Some plan also call for distribution to be opened to competition. Transmission, a natural monopoly, usually remains regulated. It is generally believed that opening the power industry to competition will benefit consumers with lower prices and better service.

Each year, many new investments in different types of power plant are proposed by generators all over the world. However, investment in generation projects involves large amounts of capital and long payback periods have been thought of as long term, comparable with the lifetime of the plant. Therefore, how to make the decision is really problem for investors. In this chapter, some classic and practical investment theories and project analysis tools are introduced to help investors to make best decision.

This chapter presents some useful investment concepts and project analysis approaches. Section 2.2 talks about basic investment theory – the time value of money, which include future and present value of money, perpetuity, annuity and inflation. Then, in order to value a project, company, or asset by using the concepts of the time value of money, section 2.3 introduces discounted cash flow (DCF) approach. Finally, some project analysis methods are discussed in section 2.4, such as tornado diagram, break-even analysis and levelised cost of electricity generation.

2.2 The time value of money

The time value of money is the value of money figuring in a given amount of interest earned over a given amount of time. Some standard calculations based on the time value of money, like future value, present value, present value of perpetuity and annuity.

2.2.1 Future Values and Compound Interest

"Time is money", its significance is not from its national origin in investment analysis, but from the fact that a pound received tomorrow is not equivalent to a pound in hand today. A typical capital investment decision always includes the comparison of present and future benefits.[1] Assume that a person invests £100 in a bank account today at 5 percent interest, and receive £105 in one year. That £105 is the future value of £100 investment invested at 5 percent for one year.

The future value of an investment can be calculated over a specified period of time by applying either simple interest or compound interest. Simple interest is interest paid only on the initial principal of an investment. Principal refers to the amount of money on which the interest is paid. Compound interest is interest earned on both the principle amount and the interest earned in previous periods.[2]

Financial analysts always use compound interest. Following equation gives the general algebraic formula for calculating the future value, at the end of n years, of a lump sum invested today at an interest rate of r% per period:

$$FV = PV \times (1+r)^n \tag{2.1}$$

Where

FV = future value of an investment,

PV = present value of an investment (the lump sum),

r = interest rate per period (typically 1 year),

n = number of period.

Compound growth means that value increases each period by the factor the factor (1+growth rate). The value after t periods will equal the initial value times (1+growth rate)^t. When money is invested at compound interest, the growth rate is the interest rate.[3]

Figure 2.1 shows the relationship between interest rates, the number of periods interest is earned, and the future value of £100. The figure shows that: (1) the higher the interest rate, the higher the future value; (2) the longer the period of time, the higher the future value. Note that for an interest rate of 0 percent, the future value always equals the present value, but for any interest rate greater than zero, the future value is greater than the present value.[3]

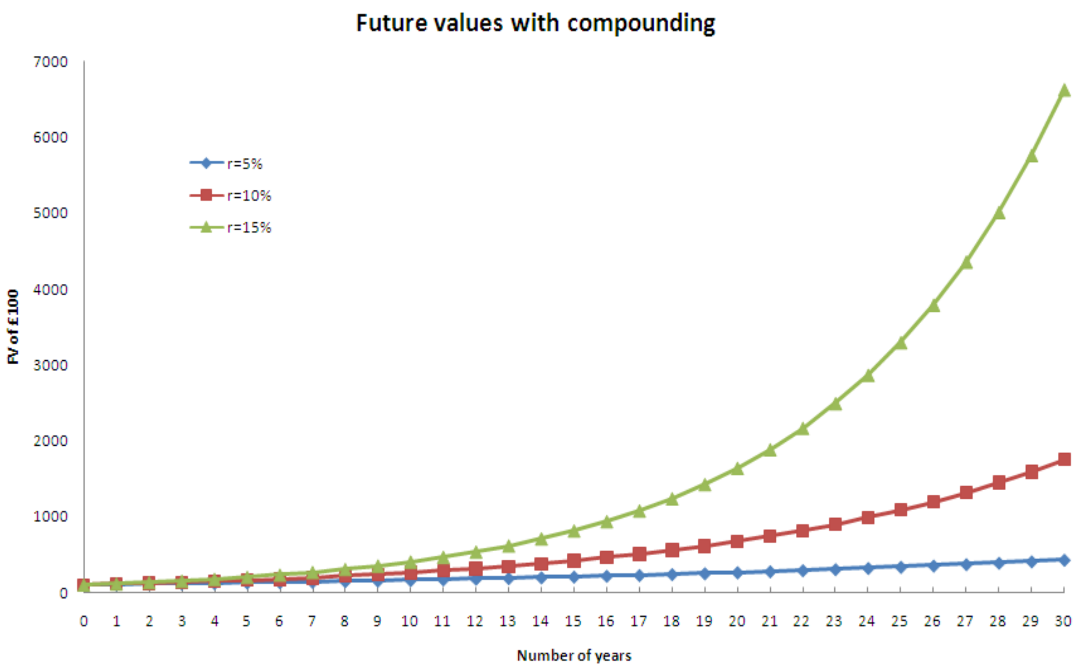

Figure 2.1: Future values with compounding

2.2.2 Present Values

Financial managers like to quote a most basic financial principle: A pound today is worth more than a pound tomorrow. In finance, the term discounting is common to see. It is used to describe the process of calculating present values. This process is actually the inverse of compounding interest. In compounding, we find the future value of present pounds invested at a given rate; in discounting, we find the present value of a future amount, assuming an opportunity to earn a given return r, on the money.[2]

In general, for a future value or payment t periods away, present value is:

Present value = future value after t periods / $(1+r)^t$ = FV/ $(1+r)^t$

To calculate present value, the future value at the interest rate r is discounted. The calculation is therefore termed a discounted cash flow (DCF) calculation, and the interest rate r is the discount rate.[3]

The present value formula is often written in another way. Instead of dividing the future payment by $(1+r)^t$, $1/(1+r)^t$ can be multiplied equally:

$$PV = \frac{FV}{(1+r)^t} = FV \times \frac{1}{(1+r)^t} \tag{2.2}$$

The expression $\frac{1}{(1+r)^t}$ is called the *discount factor* or *present worth factor*. It measures the present value of £1 received in year t.

Figure 2.2 contains two important messages for investors who expect to receive cash in the future: (1) the faster present value of a future cash payment declines the longer investors must wait to receive it; (2) the present value declines as the discount rate rises. For any discount rate great than zero, the present value falls below the future value.

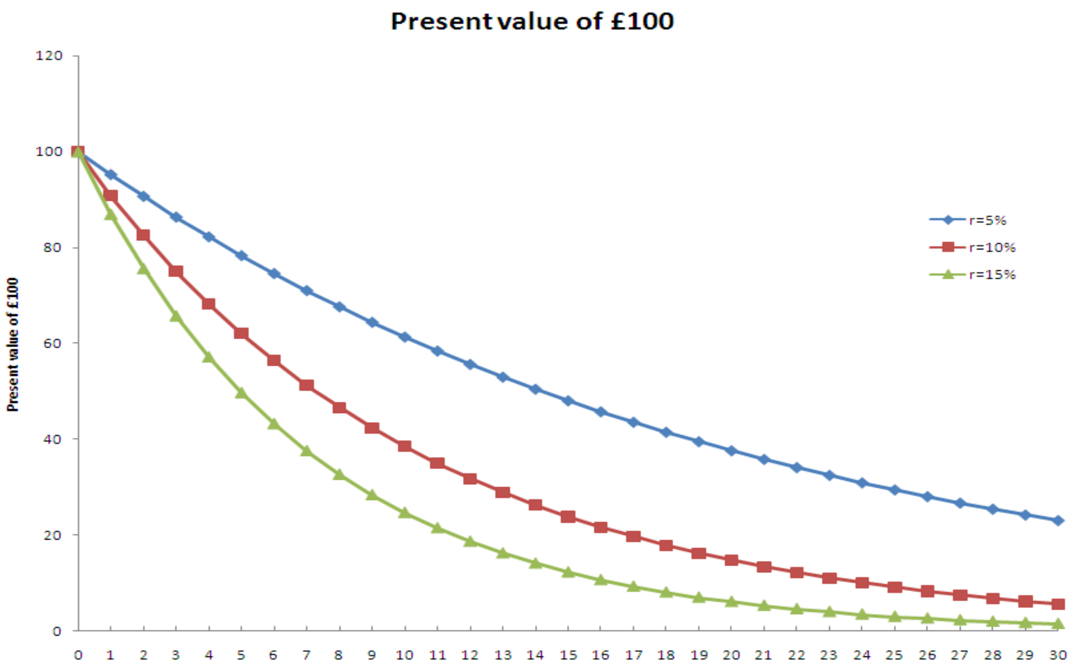

Figure 2.2: Present value of £100

2.2.3 Perpetuities and Annuities

The term annuity is used in finance theory to refer to any terminating stream of fixed payments over a specified period of time. This usage is most commonly seen in discussions of finance, usually in connection with the valuation of the stream of payments, taking into account time value of money concepts such as interest rate and future value.[4] An example of terminating stream is decommissioning of the nuclear power station. If the payment stream lasts forever, it is called perpetuity. There are few actual perpetuity in existence. UK government has issued them in the past, these are known and still trade as consol (bond).

In general, cash payment from perpetuity equate to interest rate times present value: C = r × PV. Rearrange this relationship:

$$\text{PV of perpetuity} = \frac{C}{r} = \text{cash flow (payment) / interest rate} \qquad (2.3)$$

By definition, perpetuities pay you a constant periodic value forever. However, most of cash flows have a trend to grow over time, like wages, salaries and dividend payment from corporations. Because of this trend for cash flow to grow over time, the present value of a perpetuity formula must be adjusted to calculate future cash flow. If the growth rate of wages is g, the equation of present value is:

$$PV = \frac{C_1}{1+r} + \frac{C_2}{(1+r)^2} + \frac{C_3}{(1+r)^3} + \dots$$
$$= \frac{C_1}{1+r} + \frac{C_1(1+g)}{(1+r)^2} + \frac{C_1(1+g)^2}{(1+r)^3} + \dots$$
$$= \frac{C_1}{r-g}$$

Therefore, if our benefactor wants to provide perpetually an annual sum that keeps pace with the growth rate in salaries, the amount that must be set aside today is:

$$PV = \frac{C_1}{r-g} \qquad (2.4)$$

There are two ways to value an annuity. The slow way is to value each cash flow on by one and add up the present value. The quick way is to take advantage of the following simplification, which shows in Figure 2.3:

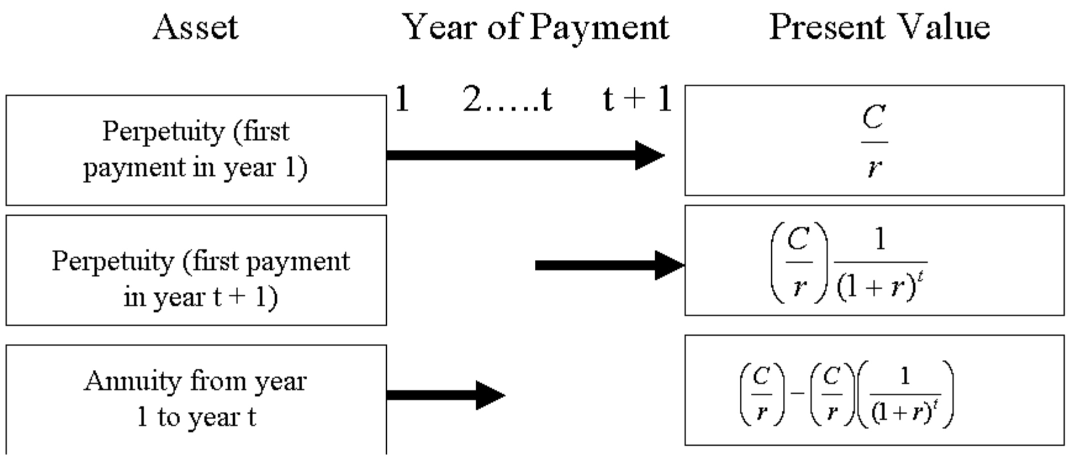

Figure 2.3: The value of an annuity is equal to the difference between the values of two perpetuities

The first row represents perpetuity that produces a cash flow of C in each year beginning in year 1, as following:

$$PV = \frac{C}{r} \tag{2.5}$$

The second row represents a second perpetuity that produces a cash flow of C in each year beginning in year t+1. It will have a present value of C/r in year t and it therefore has a present value today of:

$$PV = \frac{C}{r(1+r)^t} \tag{2.6}$$

Both perpetuities provide a cash flow from year t+1 onward. The only difference between the two perpetuities is that the first one also provides a cash flow in each of the years 1 through t. In other, the difference between the two perpetuities is an annuity of C for t years. The present value of this annuity the difference between the values of the two perpetuities:

$$\text{Present value of annuity} = C\left[\frac{1}{r} - \frac{1}{r(1+r)^t}\right] \tag{2.7}$$

The expression in square brackets shows the present value of a t-year annuity of £1 a year. It is generally known as the t-year annuity factor. Therefore, another way to write the value of an annuity is

$$\text{Present value of t-year annuity} = \text{payment} \times \text{annuity factor} \tag{2.8}$$

In power plant investment, the annuity is used to calculate the money to be repaid per year to lenders (bank).

2.2.4 Inflation

In the analysis, the prices are always assumed stable. There is an assumption that there are no general price movements within the economy, either upwards or downwards. Indeed it was made clear when dealing with the concept of the time value of money that the concept has nothing to do with inflation, and so inflation was assumed not to exist. Actually, prices of goods and services continually change. Water may become more expensive while electricity may become cheaper. An overall general rise in prices is known as inflation. Inflation can be simply defined as a situation where prices in an economy are, in general, rising over time.[5] Economists track the general level of prices using several different price indexes. The most famous one of these is *consumer price index*, or *CPI*. This measures the number of pounds that it takes to buy a specified basket of goods and services that is supposed to represent the typical family's purchases.[3] Figure 2.4 shows the CPI in China and UK from 1980 to 2012, data from World Bank, World Development indicators 2011:

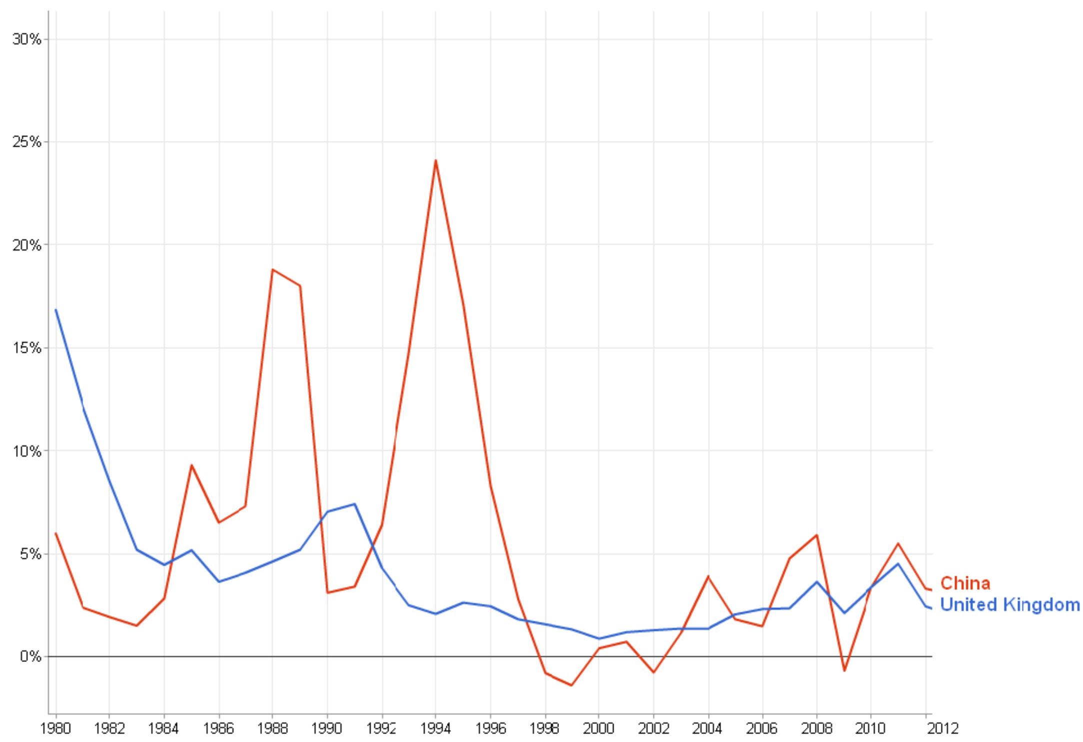

Figure 2.4: CPI in China and UK from 1980 to 2012

The existence of inflation may cause two main problems for the appraisal of investment opportunities. The first problem is that it will make the appraisal of a project's profit more difficult. With inflation, the price of cost and other variables are likely to change. Managers must estimate these changes. In other words, managers will have to estimate the future rates of inflation. The second problem is an extension of the first one. The interest rates, which can be viewed as representing the price of money, will be expected to rise when inflation exist. Thus managers have to estimate the effects of inflation on project discount rate.[5]

Economists sometimes talk about nominal pounds versus real pounds. Nominal pounds refer to the actual number of pounds of the day; real pounds refer to the amount of purchasing power. Therefore, nominal interest rate is the rate at which money invested grows and real interest rate is the rate at which the purchasing power of an investment increases.

The real rate of interest is calculated by

$$1 + \text{real interest rate} = (1 + \text{nominal interest rate}) / (1 + \text{inflation rate}) \qquad (2.9)$$

Here is a useful approximation:

$$\text{Real interest rate} \approx \text{nominal interest rate} - \text{inflation rate} \qquad (2.10)$$

The general formula for converting nominal cash flows at a future period t to real cash flows is:

$$\text{Real cash flow} = \text{nominal cash flow} / (1+\text{inflation rate})^t \qquad (2.11)$$

2.3 The Discounted Cash Flow Approach

In finance, discounted cash flow (DCF) analysis is a method of valuing a project, company, or asset using the concepts of the time value of money. All future cash flows are estimated and discounted to give their present values — the sum of all future cash flows, both incoming and outgoing, is the net present value (NPV), which is taken as the value or price of the cash flows in question.

2.3.1 Net Present Value

2.3.1.1 Finding a project's NPV

The NPV investment appraisal method works on the simple, but important, principle that an investment is worthwhile undertaking if the money got out of the investment is at least equal to – if not greater than – the money put in.[5] A project's net present value (NPV) equals the sum of its cash inflows and outflows, discounted at a rate consistent with the project's risk. Calculating an investment's NPV is straightforward. First, write down the net cash flows that the investment will generate over its life. Second, discount these cash flows at an interest rate that reflects the risk inherent in the project. Third, add up the discounted cash flows to obtain the NPV, and invest in the project only when its NPV exceeds zero.[2]

$$NPV = C_0 + \frac{C_1}{(1+r)^1} + \frac{C_2}{(1+r)^2} + ... + \frac{C_t}{(1+r)^t} \quad (2.12)$$

In this expression, C_t represents net cash flow in year t, r is the discount rate, and t represents the life period of the project. The cash flows in each year may be positive or negative. For instance, assume that the initial cash flow, C_0, is a negative number representing the initial investment to get the project started, and suppose that all subsequent cash flows are positive. In this case, the NPV can be defined as the present value of future cash inflows subtracts the initial investment:

$$\text{NPV} = \text{PV} - \text{initial investment} \quad (2.13)$$

2.3.1.2 The NPV rule

Because the objective of investment is to earn money in the future, the NPV for a project should exceed zero. The net present value rule states that managers increase shareholders' wealth by accepting all projects that are worth more than they cost. Therefore, they should accept all projects with a positive net present value. Simple stated, the NPV decision rules are:

NPV > 0 ⇒ invest

NPV < 0 ⇒ do not invest

When NPV > 0, the NPV formula can be represented as following:

$$-C_0 < \frac{C_1}{(1+r)^1} + \frac{C_2}{(1+r)^2} + \frac{C_3}{(1+r)^3} + ... + \frac{C_t}{(1+r)^t} \qquad (2.14)$$

In order to make the logic of the NPV decision rule becoming even more obvious, these tree interpretations are given:

a) A negative NPV project is unacceptable because it indicates that the project makes a loss relative to a capital market investment (i.e. an opportunity loss).
b) A negative NPV project is unacceptable because it is producing a return less than that available for a similar level of risk on the capital market.
c) A negative NPV project is unacceptable, as it would not generate sufficient cash flow to reply the financial cost of undertaking it.[5]

There are three key features of the net present value rule. First, the NPV rule recognizes that a pound today is worth more than a pound tomorrow, because the pound today can be invested to start earning interest immediately. Any investment rule which does not recognize the time value of money cannot be sensible. Second, net present value depends only on the forecasted cash flows from the project and the opportunity cost of capital. Any investment rule that is affected by the manager's taste, the company's choice of accounting method, the profitability of the company's existing business, or the profitability of other independent projects will lead to inferior decisions. Third, because present values are all measured in today's pounds, they can be added up. Thus, if there are two projects A and B, the net present value of the combined investment is:

$$\text{NPV (A+B)} = \text{NPV (A)} + \text{NPV (B)} \qquad (2.15)$$

When two projects are mutually exclusive, the decision rule is simple: calculate the NPV of each alternative, and choose the highest positive-NPV project.

2.3.2 Payback

The payback method is the simplest of all capital budgeting decision-making tools. The project payback period is the amount of time it takes for a given project's cumulative net cash inflows to recoup the initial investment.[2] The payback rule states that a project should be accepted if its payback period is less than a specified cutoff period.[3]

As a rough rule of thumb the payback rule may be adequate, but it is easy to see that it can lead to nonsensical decisions. It is can be seen in the Table 2-1.

Project	Cash Flows, Pounds				Payback Period, years	NPV at 10%
	C0	C1	C2	C3		
A	-2000	1000	1000	10000	2	7249
B	-2000	1000	1000	0	2	-264
C	-2000	0	2000	0	2	-237

Table 2-1: Payback for three projects

Project A, B and C are all have a 2 years payback period, but there NPV are different. Compare project A and B. Project A has a large positive NPV while B has a negative NPV. This is because the payback rule ignores all cash flows after the cutoff date. If the cutoff date is 2 years, the payback rule rejects project A regardless of the size of the cash inflow in year 3. Compare project B and C, they both has 2-year payback period, but C has an even lower NPV than project B. The problem with payback is that it gives equal weight to all cash flows arriving before the cutoff period, despite the fact that the more distant flows are less valuable. The payback rule says that project B and C are equally attractive, but because C's cash inflows occur earlier, C has the higher net present value at any discount rate.

Because of the above problems, some company use discounted payback rule. The discounted payback rule is essentially the same as the payback rule except that in calculating the payback, managers discount cash flows first.[2] In other words, the discounted payback method calculates how long it takes for a project's discounted cash flows to recover the initial outlay. This represents a minor improvement over the simple payback method in that it does a better job of accounting for the time value of cash flows that occur within the payback cutoff period. As with the ordinary payback rule, discounted payback totally ignores cash flows that occur beyond the cutoff point.

2.3.3 Internal rate of return

2.3.3.1 Finding a project's IRR

As methods used for evaluating investment projects, accounting rate of return, payback, and discounted payback suffer from common problems – the complete or partial failure to make adjustments for the time value of money and for risk. Alternative methods like NPV correct these shortcomings. Perhaps the most popular and most intuitive of these alternatives is known as the *internal rate of return*. The *internal rate of return (IRR)* can be defined as the rate of discount which, when applied to the project's cash flows, produces a zero NPV.[5]

There is no ambiguity in defining the true rate of return of an investment that generates a single payoff after one period:

$$\text{Rate of return } = \frac{profit}{investment} = \frac{C_1 - investment}{investment} \tag{2.16}$$

NPV of investment can be write down and find that discount rate which makes NPV= 0 (initial cash flow C_0 is negative):

$$NPV = C_0 + \frac{C_1}{1 + discount \text{ rate}} = 0 \tag{2.17}$$

Implies

$$Discount \text{ rate} = \frac{C_1}{-C_0} - 1 \tag{2.18}$$

The internal rate of return is defined as the rate of discount which makes NPV=0. It means that to find the IRR for an investment project lasting T years, the IRR must be solved in the following expression:

$$NPV = C_0 + \frac{C_1}{(1+IRR)^1} + \frac{C_2}{(1+IRR)^2} + ... + \frac{C_t}{(1+IRR)^t} = 0 \quad (2.19)$$

2.3.3.2 The IRR decision rule

The IRR decision rule is to accept an investment project if the opportunity cost (discount rate) of capital is less than the internal rate of return; otherwise reject the project.[6] The reason of this rule can be seen in Figure 2.5. If the discount rate is less than the 28%, the project has a positive NPV. If it is equal to the 28% IRR, the project has a zero NPV. And if it is greater than the IRR, the project has a negative NPV. The IRR rule will give the same answer as the NPV rule as long as the NPV of a project declines smoothly as the discount rate increases.[3]

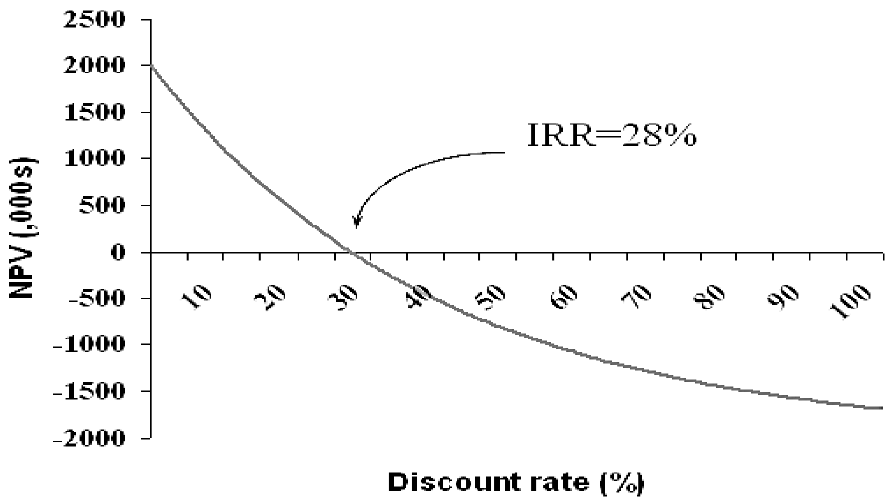

Figure 2.5: The internal rate of return is the discount rate for which NPV equals zero

2.3.3.3 Some disadvantages of IRR

Many companies use the internal rate of return rule instead of net present value. However, IRR method has some problems. When used properly, the two rules lead to the same decision, but the rate of return rule has several pitfalls that can trap the unwary. Here are two examples.

1) Lending versus Borrowing

A company established a hurdle rate of 20 percent for new investments.

Project	C_0	C_1	*IRR*	*NPV*(20%)
A	−100	+150	+50%	+25
B	+100	−150	+50%	−25

The first project displays the familiar pattern of an initial cash outflow followed by a cash inflow. Most investment projects probably fit this profile. But the second project begins with a cash inflow followed by a cash outflow. Both projects have a 50% IRR, but they are not equally. Obviously, project A is superior because it generates net cash inflow over time, while project B generates net cash outflow. And when discount rate is 20%, project A generates a positive NPV, whereas project B yield a negative NPV.

The problem here is known as the lending versus borrowing problem. Project A is analogous to lending money. Cash flows out today in exchange for a larger amount of cash in one year. When lending money, a higher interest rate, or a higher internal rate of return, is preferable. Project B is analogous to borrowing money. When borrowing money, a lower interest rate, or a lower IRR is preferred. Therefore, the IRR decision rule can be modified as follows:

a) When NPV is lower as the discount rate increases, a project is acceptable only if its opportunity cost of capital is less than its internal rate of return.
b) When NPV is higher as the discount rate increases, a project is acceptable only if its internal rate of return is less than the opportunity cost of capital.

2) Mutually exclusive projects

Companies often have to choose from among several alternative ways of doing the same job or using the same facility. In other words, they are mutually exclusive project. The IRR rule may be misleading here.

Here are two mutually exclusive projects and their cash flow, IRRs and NPVs:

Project	C_0	C_1	C_2	C_3	IRR	NPV(7%)
Initial Proposal	-350	400			14.29%	24000
Revised Proposal	-350	16	16	466	12.96%	59000

Both projects offer a positive NPV. But the revised proposal has the higher net present value and therefore is the better choice. However, the internal rate of return cannot show up that. The IRR decision rule seems to say the initial proposal should be accepted because it has the higher IRR. The Figure 2.6 shows why IRR rule gives the wrong signal. The figure plots two project's NPV as a function of the discount rate. These two NPV profiles cross at an interest rate of 12.26%. If the discount rate is higher than 12.26%, the initial proposal, with its rapid cash inflow, is the superior investment. If the discount rate is lower than 12.26%, then the revised proposal dominates.

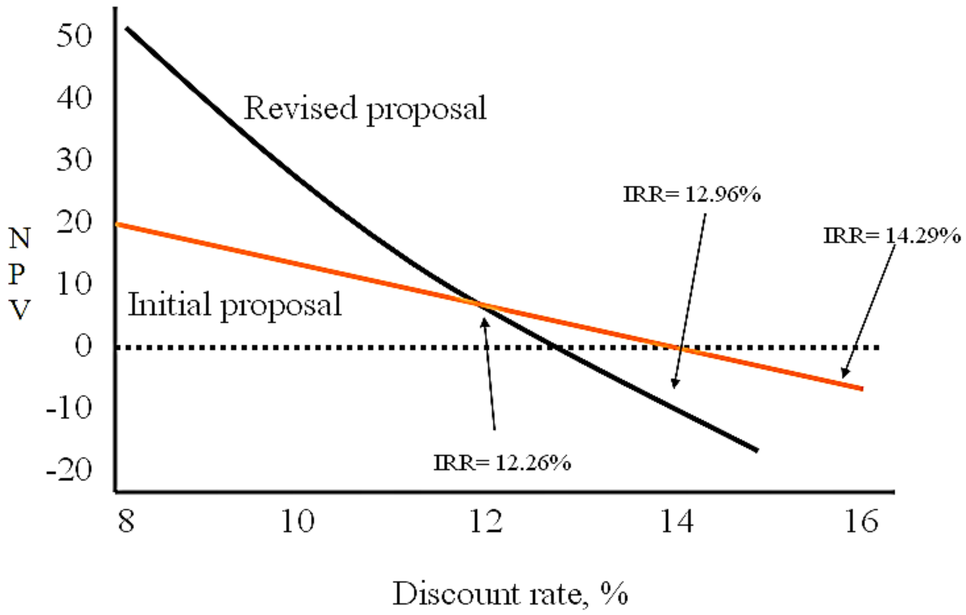

Figure 2.6: Mutually exclusive projects

In this example, the revised proposal had the longer life. Projects that earn a good rate of return for a long time often have higher NPV than those that offer high percentage rates of return but die young.

2.3.4 Weighted average cost of capital

The weighted average cost of capital (WACC) is the rate that a company is expected to pay on average to all its security holders to finance its assets. Broadly speaking, a company's assets are financed by either debt or equity. WACC is the average of the costs of these sources of financing, each of which is weighted by its respective use in the given situation. By taking a weighted average, we can see how much interest the company has to pay for every dollar it finances.

A firm's WACC is the overall required return on the firm as a whole and, as such, it is often used internally by company directors to determine the economic feasibility of expansionary opportunities and mergers. It is the appropriate discount rate to use for cash flows with risk that is similar to that of the overall firm.

2.3.5 The comments of DCF method

DCF based approaches assume implicitly that a project will be undertaken now and operated on continuously at a set time scale, until the end of its expected useful life, even though the future is uncertain. Therefore the DCF ignores the upside potential of added value that could be brought to the project through the flexibility and innovation of management to alter the course of investment. Such managerial interventions or operating decisions during the life of the project according to changes in market conditions over time provide companies with a better chance to obtain higher returns or minimize loss in a volatile marketplace.

2.4 Project Analysis methods

2.4.1 Sensitivity and Scenario Analysis

2.4.1.1 Sensitivity analysis

The appraisal of almost any investment project in real world will require analysts to make a great number of estimates before arriving at a final NPV. For example, to appraise project cash flows must require assumptions about the selling price, costs of materials, market share, and so on. All of these factors are uncertainty. Uncertainty means that more things can happen than will happen. Therefore, managers try to determine what else might happen and the effect of those possible events. This is called sensitivity analysis.

Sensitivity analysis is used to determine how "sensitive" a model is to change in the value the parameters of the model and to changes in the structure of the model.[7] In sensitivity analysis, the managers always change each factor one by one, and hold all other assumptions fixed. The project will then be appraised by calculating net present value. The preceding part of this thesis said if the NPV is positive then the appraisal is acceptance. However, in terms of risk management, the manager is also interested in how sensitive the model is. In other words, he is interested in the margin of error.

To conduct a sensitivity analysis, the manager assumes a base-case for all factors and calculates the based NPV on these assumptions. Then, the manager change one variable while holding all others fixed, recalculate the NPV based on that change. By repeating this process for all the uncertain variables in an NPV calculation, managers can see how sensitive the NPV is to changes in baseline assumptions.

Sensitivity analysis expresses cash flows in terms of assumption variables and then calculates consequent NPV. One limit of this method is it gives ambiguous results. Another problem is the underlying variables may be interrelated. Still, it does give a set of which variables should be most closely concerned.

2.4.1.2 Tornado diagram

The Tornado diagram is a useful graphical tool which used to illustrate the relative sensitivity and influence of the project's NPV to its variables. By changing only one variable at a time and calculate the resulting NPV with every change, the diagram can be produced. It can graphically express the relation between the changes of variables and the distribution of the outcomes. In brief, it highlights the great contributor to the project. The tornado diagram has a central vertical axis. The lengths of bars show the influence and sensitivity of the variables. Figure 2.7 is a tornado diagram which used to analysis the sensitivity of six variables in a coal-fired power plant project.

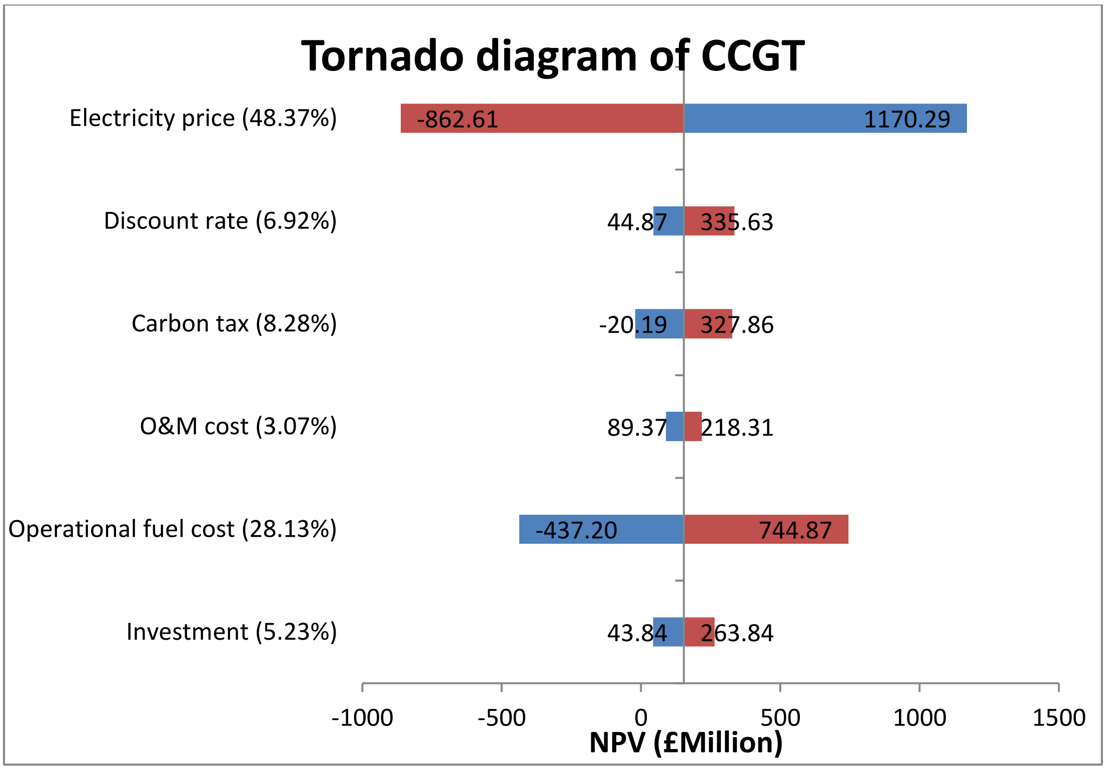

Figure 2.7: An example of tornado diagram

The percentage number is the variance contribution. The variance contribution is calculated for each variable by finding the percentage of the NPV range of change (the bar length) for that variable with respect to the total change of the NPV represented by the sum of all bar lengths. The advantage of calculating the variance contribution of each variable is to highlight the influence of each factor.

The shortcoming of tornado diagram is this method can only change one factor at a time, and cannot take into account the coupling between two factors. Sometimes, the price of natural gas and coal-based electricity may show some correction because they are both part of the energy sector. There are times when their prices will show divergence instead of correlation because the prices of coal and natural gas can be affected by different environmental factors.

Supply and demand are what drive prices, so any overall increase in demand for energy will cause both gas and coal to go up in price. Conversely, any overall increase in energy supply will drive gas and coal prices down. In that sense the prices of the two energy sources are correlated. During the winter months in temperate regions, people tend to need more heat from natural gas and stay indoors using electricity more. The two prices will be correlated because of an increase in demand for both. Divergence in the two prices can occur if there is a shortage in one and no increase in demand for the other. In the mid-2000s, there was a natural gas shortage in the world that caused the price to spike, but coal remained stable so there was no correlation.

2.4.1.3 Scenario Analysis

When the underlying variables are interrelated, managers often find a way to look at the performance of their project — put them under different scenarios. Scenario analysis allows them to look at different but consistent combinations of variables. It is just a more complex version of sensitivity analysis. Forecasters conduct scenario analysis by calculating the project NPV when a set of assumptions changes in a particular way rather than adjust one variable larger or smaller. For instance, managers always give an estimate of revenues or costs under a particular scenario rather than to give some absolute pessimistic or optimistic value.

Developing real world scenarios requires a great lot of thinking about how an NPV model's assumptions are related to each other. Managers must ask questions such as, if the market doesn't grow as fast as we expect, which other of our assumption will also probably be wrong? An extension of scenario analysis is called simulation analysis. According to probability distributions specified by the analyst, a computer generates several hundred or thousand possible combinations of variables instead of specifying a relatively small number of scenarios. Each combination of variables corresponds to one scenario. Project net present value can be calculated for each combination of variables, and the entire probability distribution of outcomes can be constructed from the simulation results.

The limit of scenario analysis is that outcome only comes from assumed factors without accurate measurement. Especially in some complex cases, assumed factors cannot correlate.

2.4.2 Levelised cost of generation

Levelised cost is the "ratio of total lifetime expenses versus total expected outputs, expressed in terms of the present value equivalent".[8] Levelised cost of generation is "the discounted lifetime cost of ownership using a generation asset converted into an equivalent unit cost of generation in £/MWh or p/kWh."[9]

There are three main components of levelised costs:

1. The investment (capital) costs of bringing the asset to a project, which include:
   - The main plant and equipment package, which called engineering, procurement and construction (EPC) price;
   - Infrastructure and connection costs including power, fuel and cooling system;
   - Development costs including permitting, advisory services and land options;

- ➢ Interest and funding cost during construction.

2. Fixed cost of keeping the plant available to generate, which include:
   - ➢ Labor (staffing) costs;
   - ➢ Fixed maintenance & operation costs;
   - ➢ Taxes, insurance network use of system charges.

3. The Variable costs, which include:
   - ➢ Fuel and carbon cost;
   - ➢ Variable repair and maintenance costs;
   - ➢ Residue disposal and treatment.

Some other factors also can affect levelised costs of generation, such as life time of plant, fuel efficiency, fuel delivery cost and so on. Figure 2.8 lists the components of levelised costs and shows their relationship.

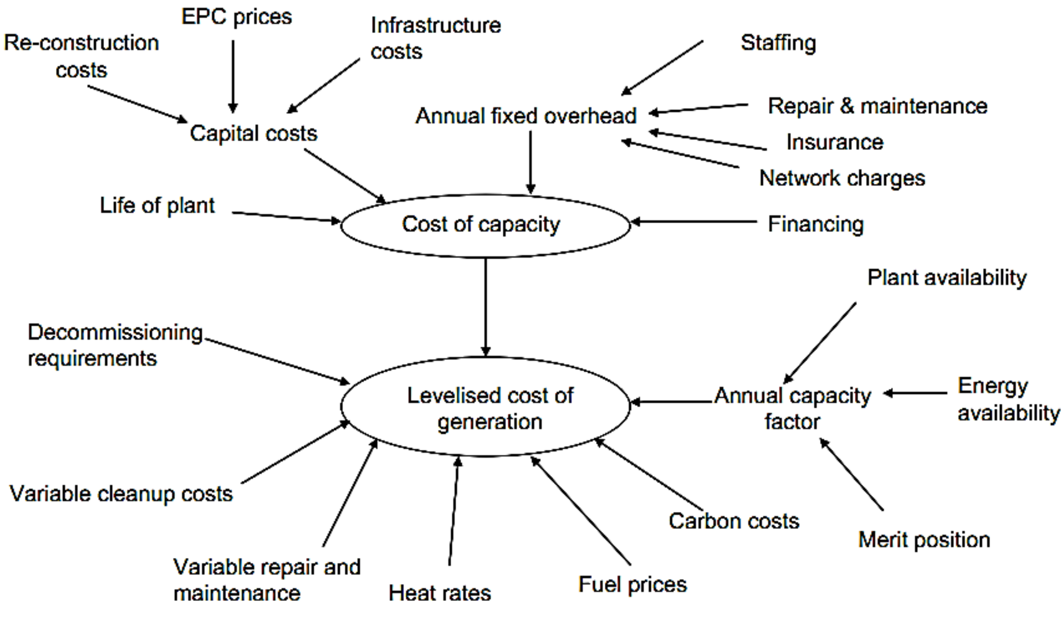

Figure 2.8: Levelised cost of generation

There are two approaches to calculate the levelised costs: the "discounting" method, and the "annuity" method.[10] Both require:

- An assessment of the costs (and the timing of those costs) that will be incurred in building and operating a plant during its lifetime, i.e. the cost stream.
- An assessment of the electrical output (and timing of that output) of the plant during its lifetime, i.e. the output stream.

The "discounting" method is shown in Eq.(2.20):

$$\mathrm{LC_D} = \frac{\mathrm{PV(Total\ Costs)}}{\mathrm{PV(Total\ Outputs)}} = \frac{\sum_{t=0}^{n} C_t/(1+r)^t}{\sum_{t=0}^{n} O_t/(1+r)^t} \tag{2.20}$$

Where C_t and O_t identify the stream of future costs and the electrical outputs in period t, and they are discounted back to the present value (PV). The levelised cost under "discounting" method LC_D is the PV of total costs divide by PV of lifetime power output. This method is used by the Nuclear Energy Agency and International Energy Agency[8] and Mott MacDonald[9].

The "annuity" method is shown in Eq.(2.21):

$$LC_A = \frac{Annual(Costs)}{Average(Output)} = \frac{(\sum_{t=0}^{n} C_t/(1+r)^t)\times(r/(1-(1+r)^{-n}))}{(\sum_{t=1}^{n} O_t)/n} \tag{2.21}$$

Where C_t and O_t identify the stream of future costs and the electrical outputs in period t. The stream of costs over the plant's lifetime is calculated and then converted to an equivalent annual cost, using *capital recovery factor* (CRF) $(r/(1-(1+r)^{-n})$. This equivalent annual cost is then divided by the average annual electrical output over the lifetime of the plant. Therefore, the Eq.(2.21) can be rewrite as:

$$LC_A = \frac{Annual(Costs)}{Average(Output)} = \frac{PV(Total\ Cost)\times CRF}{Average(Output)} \tag{2.22}$$

This method is used for construction costs in the paper of Department of Trade & Industry[11], and a working paper of UKERC (UK Energy Research Centre)[12].

Gross' report[10] states that above two approaches can lead to same results when discount rate r is same. However, in Gross's report, the annual output keeps constant over the lifetime of project. If the flow of output is not constant, the levelised costs calculated by different methods may not same.

Consider a hypothetical investment project A in Table 2-2 with the stream of costs (£) and outputs (measured in physical units). In this table, PWF (10%) means present worth factor at 10% discount rate. The blue part indicates undiscounted annual cost and annual output, while the red part shows discounted (present values) annual cost and annual output. The undiscounted annual output is constant in project A.

Year	Annual Costs	Annual Outputs	**PWF (10%)**	PV (Costs)	PV (Outputs)
0	100		**1.000**	100.000	
1	10	20	**0.909**	9.091	18.182
2	10	20	**0.826**	8.264	16.529
3	10	20	**0.751**	7.513	15.026
4	10	20	**0.683**	6.830	13.660
5	10	20	**0.621**	6.209	12.418
6	10	20	**0.564**	5.645	11.289
7	10	20	**0.513**	5.132	10.263
8	10	20	**0.467**	4.665	9.330
SUM				153.349	106.699
Levelised cost					**1.437 (£/unit)**

Table 2-2: Levelised cost calculation when annual output keeps constant

According to the "discounting" method, the levelised cost is equal to the sum of discounted annual costs divided by the sum of discounted annual outputs, so that the result is $LC_D = 153.349/106.699 = 1.437$ (£/unit). According to "annuity" approach, the CRF = $(r/(1-(1+r)^{-n}))$, therefore the levelised cost $LC_A = \frac{153.349 \times CRF}{20} = 1.437$ (£/unit). The results show that when annual output keeps constant over the lifetime of project, the levelised costs calculated by different methods are same.

Assume a project B which shows in Table 2-3. The annual output of this project is varied but the average value is 20, same as project A.

Year	Annual Costs	Annual Outputs	PWF (10%)	PV (Costs)	PV (Outputs)
0	100		**1**	100	
1	10	20	**0.909**	9.091	18.182
2	10	30	**0.826**	8.264	24.793
3	10	10	**0.751**	7.513	7.513
4	10	30	**0.683**	6.830	20.490
5	10	20	**0.621**	6.209	12.418
6	10	10	**0.564**	5.645	5.645
7	10	20	**0.513**	5.132	10.263
8	10	20	**0.467**	4.665	9.330
SUM				153.349	108.635
Levelised cost					**1.412**

Table 2-3: Levelised cost calculation when annual output is varied

The levelised cost by "discounting" method is $LC_D = 153.349/108.635 = 1.412$ (£/unit), less that project A. The result by "annuity" method is $LC_A = \frac{153.349 \times CRF}{20} = 1.437$ (£/unit), same as project A, since CRF and average output are unchanged.

Difference approaches lead to different results in project B since “annuity” method is only “appropriate where the flow of output is constant” over the lifetime of project.[13] The denominator of the formula of “annuity” method (Eq.(2.21)), $(\sum_{t=1}^{n} O_t)/n$, cannot distinguish if O_t is constant or not. If $(\sum_{t=1}^{n} O_t)/n = O_t$, t=1,2,...,n , the “annuity” method can obtain the same answer as “discounting” method; if $(\sum_{t=1}^{n} O_t)/n \neq O_t$, t=1,2,...,n , the “annuity” method may lead to inaccurate result.

In renewable energy, like wind power or tidal energy, the output would typically vary from period to period (day-to-day, month-to-month and year-to-year) due to variations in the renewable resource and outages or maintenance.[13] Hence, only “discounting” method can obtain the accurate levelised cost. In the rest chapters of this thesis, every levelised cost is calculated by “discounting” method.

2.5 Summary

This chapter introduced the main investment concepts and project analysis approaches. The first part was the time value of money, which includes some calculations such as future value, present value, perpetuity & annuity and inflation. This part discussed the value of money figuring in a given amount of interest earned over a given amount of time. The future value and present value of money indicate that a pound today is worth more than a pound tomorrow. The term annuity is used in finance theory to refer to any terminating stream of fixed payments over a specified period of time, and perpetuity means the payment stream lasts forever. Annuity calculation can be used in levelised cost calculation. The inflation item is in consideration of the price rising in project’s lifetime.

The second part was the discounted cash flow (DCF) approach. It is a method of valuing a project, company, or asset using the concepts of the time value of money. In DCF method, all future cash flows are estimated and discounted to the net present value (NPV), and find the discounted payback period and internal rate of return (IRR). The shortage of this approach is the future of project is uncertain, but DCF assume implicitly a project will be undertaken now and operated on continuously at a set time scale.

The third part was the project analysis methods, such as sensitivity analysis, scenario analysis, break-even analysis and levelised cost of generation. Sensitivity analysis is used to determine how “sensitive” a model is to change in the value the parameters of the model and to changes in the structure of the model. Scenario analysis is a process of analyzing possible future events by considering alternative possible outcomes (scenarios). Break-even analysis is based on categorizing production costs between those which are "variable" (costs that change when the production output changes) and those that are "fixed" (costs not directly related to the volume of production). Levelised cost calculation has two ways: “discounting” method and “annuity” method, and the “annuity” method is only appropriate where the generation output is constant over the lifetime of project.

All of these investment concepts and project analysis approaches will be applied in chapter 3 to analysis power plant projects in UK and China.

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Chapter 3: Project Analysis for the UK and China Power Plant

3.1 Introduction

The chapter 2 introduced some useful investment concepts and project analysis approaches. These approaches are applied in this chapter for analysis investment of eight types of electricity generation projects.

The electricity sector in UK relies mainly on fossil fuelled power with 15-20% in nuclear power. During the 1940s some 90% of the generating capacity was fired by coal, with oil providing most of the remainder. By 2004 coal use in power stations had fallen by 43.6% compared to 1980 levels, though up slightly from its lower in 1999. By 2004, total electricity production stood at 382.7 TWh, generated from the following sources:[1]

GAS	39.93%
COAL	33.08%
NUCLEAR	19.26%
RENEWABLES	3.55%
HYDROELECTRIC	1.10%
IMPORTS	1.96%
OIL	1.12%

UK Government energy policy expected that the total contribution from renewable should rise to 10% by 2010. The Scottish Executive has a target of generating 40% of Scotland's electricity from renewable by 2020.[2] At the end of 2011, there was 4,796 MW of installed renewable electricity capacity in Scotland, an increase of 9.5% (416 MW) on the end of 2010. Renewable electricity generation in 2011 was a record high at 13,750 GWh - an increase of 44.5% on 2010. Around 35% of

Scotland's electricity came from renewable in 2011, exceeding the Scottish Government's target of 31%. Scotland contributed almost 40% of the UK's renewable output in 2011.[3]

This chapter analyses the profitability and levelised cost of eight types of electricity generation projects in UK. These projects are 1) CCGT, 2) CCGT with CCS, 3) pulverised coal, 4) pulverised coal with CCS, 5) IGCC, 6) IGCC with CCS, 7) onshore wind power and 8) offshore wind power.

China is the largest consumer of coal in the world, and consumes 1.31 billion short tons of coal per year. The dominant electricity generation technology in China is coal pulverization. It is about to become the largest user of coal-derived electricity, generating 3.8975 trillion kWh per year, or 82.54% of its electricity from coal as of 2011.[4] Hydroelectric power supplied 14.03% of China's electricity need. At the end of 2011, China's installed coal-based electrical capacity was 765.6GW, or 72.5% of total electricity capacity. This chapter analyses the profitability and levelised cost of a coal-fired plant in China.

In order to investigate the performance of projects under fluctuation of costs, this chapter sets three scenarios for each project to calculate the levelised costs, which involves high scenario, base scenario and low scenario. Each scenario has a combination of different costs level. The levelised costs of three scenarios reflect the profitability and risk resistance capability of project.

The rest of this chapter is organized as the following: Section 3.2 introduces main electricity generation technologies; Section 3.3 analyses these technologies in UK by discounted cash flow and levelised cost approaches. Wind power is also mentioned in this section. A brief summary of these technologies are present at the end of this section; Section 3.4 analyses the pulverised coal-fired plant in China; The last section is the summary of this chapter.

3.2 Introduction of main electricity generation technologies

3.2.1 Combined Cycle Gas Turbine (CCGT)

3.2.1.1 Basic principle of CCGT

Combined cycle can be defined as a combination of two thermal cycles in one plant. When two cycles are combined, the efficiency that can be achieved is higher than that of one cycle alone.[5] Normally, when two cycles are combined, the cycle operating at the higher temperature level is called the topping cycle. The waste heat it produces is then used in a second process that operates at a lower temperature level, and is therefore called the bottoming cycle.

An open circuit gas turbine cycle has a compressor, a combustor and a turbine and the amount of metal that must withstand the high temperatures and pressures is small, and lower quantities of expensive materials can be used. In this type of cycle, the input temperature to the turbine (the firing temperature), is relatively high (900 to 1,400 ℃). The output temperature of the flue gas is also high (450 to 650 ℃). This is therefore high enough to provide heat for a second cycle which uses steam as the working fluid.

The combination used today for commercial power generation is that of a gas topping cycle with a water/steam bottoming cycle. Figure 3.1(this figure is from http://www.marchwoodpower.com/ccgt/) shows a simplified flow diagram for such a cycle, in which the exhaust heat of a simple cycle gas turbine is used to generate steam that will be expanded in a steam turbine.

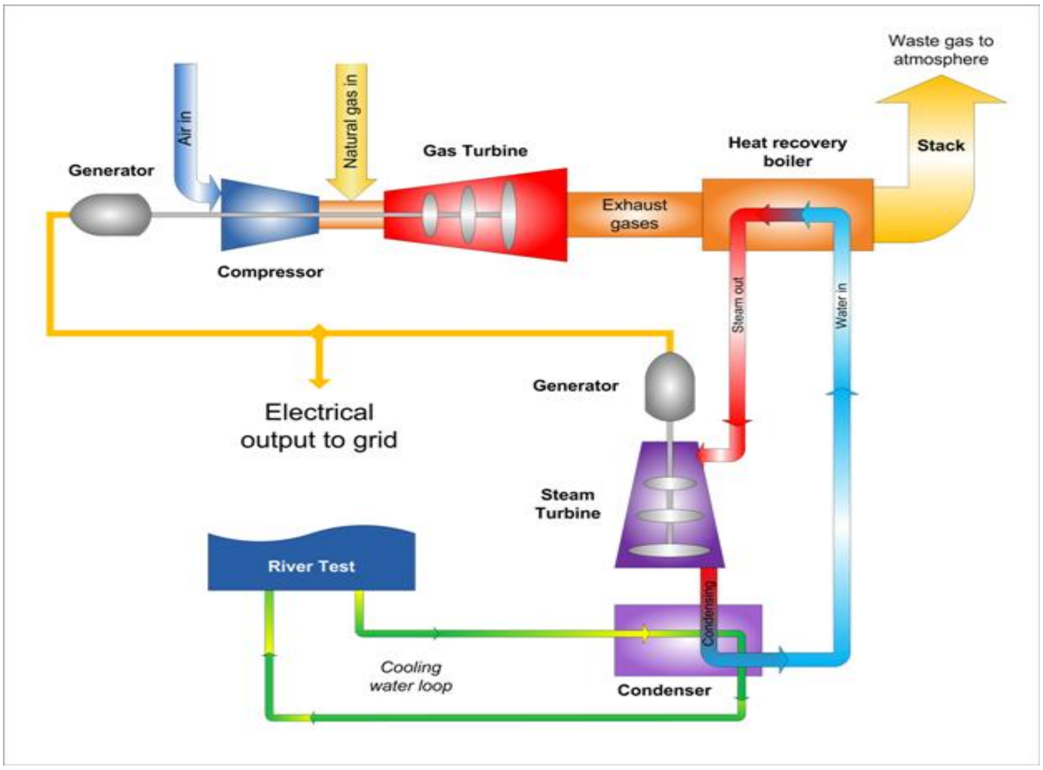

Figure 3.1: Flow diagram of a CCGT

3.2.1.2 Efficiency of CCGT plant

The Carnot efficiency is the maximum efficiency of an ideal thermal process:

$$\eta_C = \frac{T_E - T_A}{T_E} \tag{3.1}$$

where:

η_C = Carnot efficiency (%)

T_E = Temperature of the energy supplied (K)

T_A = Temperature of the environment (K)

Naturally, the efficiencies of real processes are lower because there are losses involved. The process efficiency can be improved by raising the maximum temperature in the cycle, releasing the waste heat at a lower temperature, or improving the process to minimize the internal losses.

The interest in combined cycles arises particularly from these considerations. By its nature, no single cycle can make both improvements to an equal extent. Hence, it is reasonable to combine two cycles – one with high process temperatures, and the other with a good cold end.

In a simple-cycle gas turbine, attainable process temperatures are high as energy is supplied directly to the cycle without heat exchange. The exhaust heat temperature is also quite high. In the steam cycle, the maximum process temperature is much lower than in the gas turbine process, but the exhaust heat is returned to the environment at a low temperature. The efficiency comparison of gas turbine, steam turbine and combined-cycle processes is illustrated in Table 3-1:

	GT	ST	CC
Average temperature of heat supplied (K)	1000 - 1350	640 - 700	1000 - 1350
Average temperature of exhaust heat (K)	550 - 600	300 - 350	300 - 350
Carnot efficiency (%)	44 - 55	45 - 57	65 - 78

Table 3-1: Thermodynamic comparison of gas turbine, steam turbine and combined-cycle processes

where GT = Gas Turbine, ST = Steam Turbine Power Plant and CC = Combined Cycle Power Plant. This figure can be used as an indicator of the quality of a thermal process. The values of Carnot efficiency make clear just how interesting the combined-cycle power plant is when compared to processes with only one cycle. For combined-cycle power plants actual plant efficiencies are around 75% of the Carnot efficiency.

There are also combined-cycle installations with additional firing in the heat recovery steam generator (HRSG), in which a portion of the heat is supplied directly to the steam process.

Accordingly, the general definition of the electrical efficiency of a combined-cycle plant is:

$$\eta_{CC} = \frac{P_{GT} + P_{ST}}{Q_{GT} + Q_{ST}} \tag{3.2}$$

where:

P_{GT} = Gas turbine output

P_{ST} = Steam turbine output

Q_{GT} = Gas turbine fuel consumption

Q_{SF} = Additional / Supplementary firing fuel consumption

Eq.(3.2) shows the gross efficiency of the combined cycle because no station service power consumption and electrical losses, also called auxiliary consumption (P_{Aux}), have been deducted. If station auxiliary consumption is considered, the net efficiency of the combined cycle is given by Eq.(3.3):

$$\eta_{CC,net} = \frac{P_{GT} + P_{ST} - P_{Aux}}{Q_{GT} + Q_{ST}} \tag{3.3}$$

3.2.2 Pulverised Coal Power Plant

Pulverized coal power plants first appeared in the 1920s and serve as the backbone of the power sector in the world. A pulverized coal-fired boiler is an industrial or utility boiler that generates thermal energy by burning pulverized coal (also known as powdered coal or coal dust) that is blown into the firebox. This type of boiler dominates the electric power industry, providing steam to drive large turbines. Pulverized coal provides the thermal energy which produces about 50% of the world's electric supply.

The concept of burning coal that has been pulverised into a fine powder stems from the belief that if the coal is made fine enough, it will burn almost as easily and efficiently as a gas. The feeding rate of coal according to the boiler demand and the amount of air available for drying and transporting the pulverized coal fuel is controlled by computers. Pieces of coal are crushed between balls or cylindrical rollers that move between two tracks or "races." The raw coal is then fed into the pulveriser along with air heated to about 343℃ from the boiler. As the coal gets crushed by the rolling action, the hot air dries it and blows the usable fine coal powder out to be used as fuel. The powdered coal from the pulveriser is directly blown to a burner in the boiler. The burner mixes the powdered coal in the air suspension with additional pre-heated combustion air and forces it out of a nozzle similar in action to fuel being atomized by a fuel injector in modern cars. Under operating conditions, there is enough heat in the combustion zone to ignite all the incoming fuel. Figure 3.2 (this figure is from http://www.undeerc.org/carrc/html/coalcombustion.html) shows the above processes.

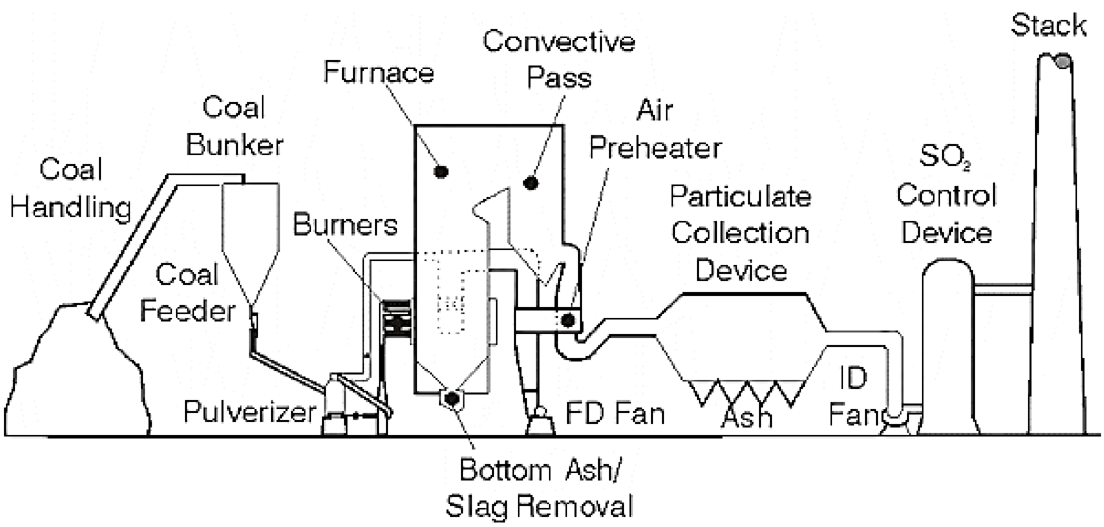

Figure 3.2: Pulverised Coal Combustion System

Pulverized coal power plants are broken down into three categories; subcritical pulverized coal (SubCPC) plants, supercritical pulverized coal (SCPC) plants, and ultra-supercritical pulverized coal (USCPC) plants. The primary difference between the three types of pulverized coal boilers are the operating temperatures and pressures. Subcritical plants operate below the critical point of water (647.096 K and 22.064 MPa). Supercritical and ultra-supercritical plants operate above the critical point. As the pressures and temperatures increase, so does the operating efficiency. Subcritical plants are at about 37%, supercritical at about 40% and ultra-supercritical in the 42-45% range.

3.2.3 Integrated Gasification Combined Cycle (IGCC)

Environmental constraints as well increasing prices of high-grade fossil fuels such as natural gas are major drivers that determine further development of fossil-fuel-fired power stations. One of the most attractive options to achieve options to achieve extremely low environmental pollution is the Integrated Gasification Combined Cycle (IGCC). The IGCC concept, shown in Figure 3.3, opens the well-proven combined-cycle concept to dirty fuels such as coal, refinery residues, biomass, and wastes by adding gasification, air separation, and gas cleaning processes to the upstream gas turbine combustor.

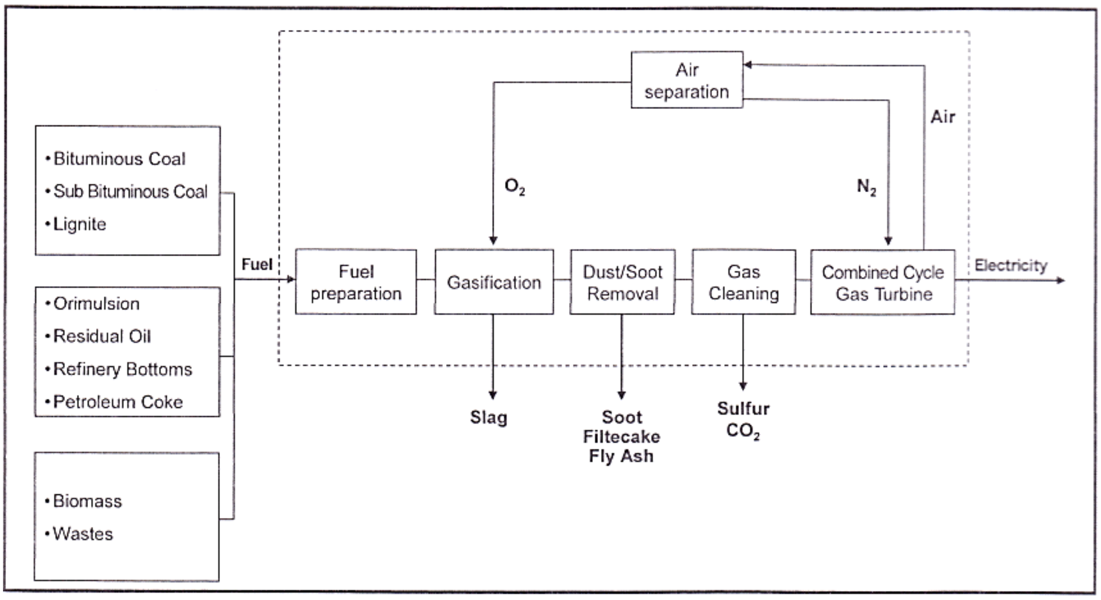

Figure 3.3: Flow diagram of IGCC [5]

Gasification is basically a partial oxidation process that converts any carbonaceous feedstock such as coal, petroleum coke, heavy oil and oil tars, biomass, and waste streams into a gaseous product called synthesis gas (syngas). Syngas mainly consists of CO and H_2 (with some CO_2, H_2O, and contaminants) with the composition depending on fuel and type of gasifier. Figure 3.4 presents the gasification reactions.

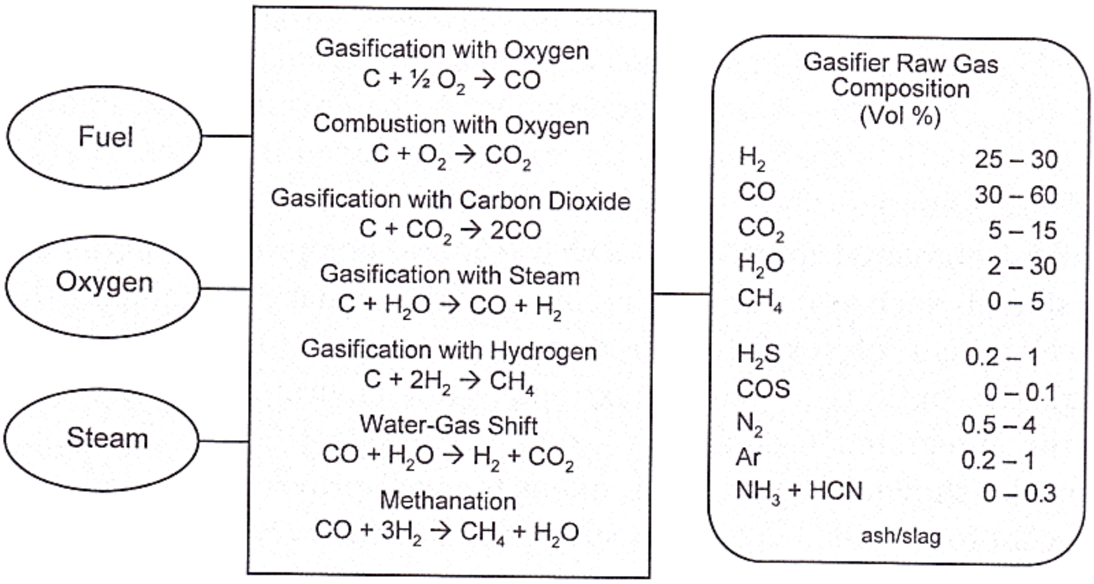

Figure 3.4: Gasification reactions [5]

After gasification, the syngas is cleaned of its contaminants such as fly ash, alkali, chlorine, and sulfur compounds. If CO_2 capture is required, additional conversion and treatment steps can be foreseen. After leaving the gas cleaning section and before feeding the gas turbine combustor, the syngas is diluted with nitrogen and water vapor to moderate combustion condition and minimize thermal NO_x formation. Finally, combustion takes place in a combined-cycle power plant with a modified gas turbine. Such a system is inherently cleaner and more efficient than conventional pulverized coal fired plants.

Due to high investment cost, IGCC technology is primarily suitable for large centralized power plants with access to low-cost feedstock such as coal and petcoke. Moreover, petcoke with its high sulfur and vanadium content is suitable only for IGCC applications. Refinery residues such as heavy oils and tars are potential sources for hydrogen production used in refinery upgrading to produce diesel and petrol. Therefore, refineries primarily focus on poly-generation concepts with hydrogen as the main product, whereas only surplus of syngas is used for electricity generation and export.

The drawback of IGCC plants, however, is that they are significantly more expensive than conventional pulverised coal power plant. Current IGCC plants in operation have suffered from relatively poor reliability and limited operational flexibility. Nevertheless, the plants built in the US and Europe have proven that IGCC is a viable power generation technology.

3.2.4 Carbon Capture and Storage (CCS)

After decades of expert and public-level discussion, the existence of global warming and its reasons are undisputed to a far extent today. Increasing ambient temperatures, more frequent heat waves, and disastrous storms and floods are indications. Among all natural or technical gases, which are assessed to be responsible for the global warming effect, CO_2 is the most important one. This result, to a lesser extent, from its physical characteristics, but more from the high amount emitted from all carbon conversion processes. The world population has grown more than four times since the beginning of the 20th century, resulting in rapidly rising energy consumption. In addition, the per-capita energy demand increased as a consequence of the growing prosperity in the industrialized countries. As most of the energy was and is based on carbon-containing fuels, the global average temperature rose by about 0.8K.

However, CO_2 can be captured and stored. Storage means the isolation of the CO_2 from the atmosphere for a long time. Carbon capture and storage (CCS) could allow the continued use of fossil fuels, also coal, whereas other CO_2- free energy sources are developed and applied. Figure 3.5 shows a conceptual plan for CCS, involving 2 of the common fossil fuels, natural gas and coal. The figure is from UK Carbon Capture and Storage Community[6].

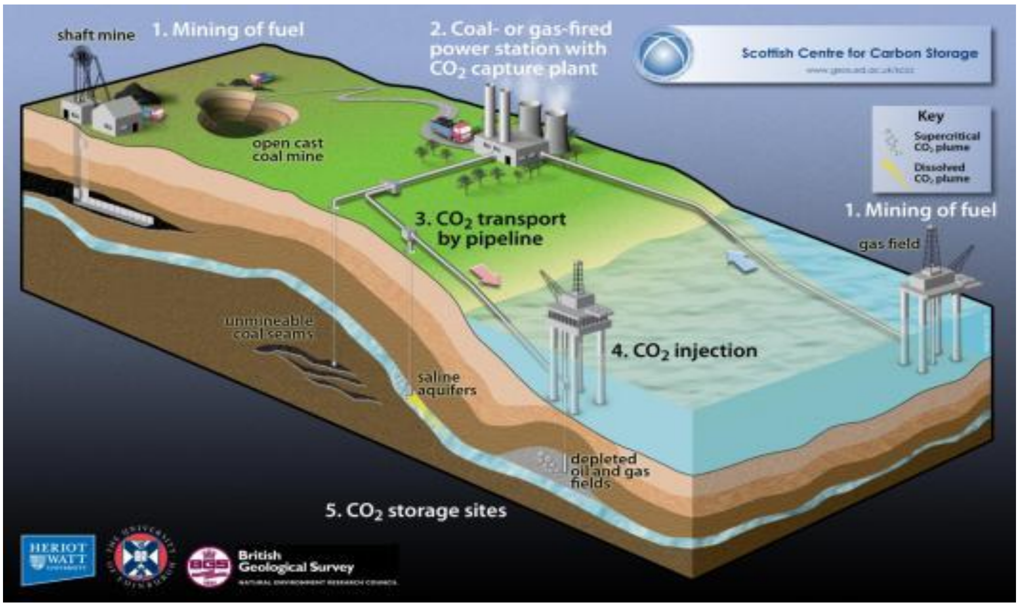

Figure 3.5: Flow diagram of Carbon Capture and Storage

Nature gas is produced from offshore gas fields, and is brought onshore by pipeline. Using existing oil-refinery technology, the gas is 'reformed' into hydrogen and CO_2. The CO_2 is then separated by a newly-designed membrane, and sent offshore, using a corrosion-resistant pipeline. The CO_2 goes to an oilfield. The CO_2 is stored in the oilfield, several km below sea level, instead of being vented into the atmosphere from the power station.

Because of the additional process units and power demand, CO_2 capture leads to reduced power generation efficiency and increased costs. The cost advantage of CCS technology is to avoid carbon tax. Carbon tax is an environmental tax levied on the carbon content of fuels.[7] It is a form of carbon pricing. Carbon is present in every hydrocarbon fuel (coal, petroleum, and natural gas) and is released as carbon dioxide (CO_2) when they are burnt. In contrast, non-combustion energy sources—wind, sunlight, hydropower, and nuclear—do not convert hydrocarbons to CO_2. CO_2 is a heat-trapping "greenhouse" gas (GHG).[8] Scientists have pointed to the potential effects on the climate system of releasing GHGs into the atmosphere (see scientific opinion on global warming). Since GHG emissions caused by the combustion of fossil fuels are closely related to the carbon content of the respective fuels, a tax on these emissions can be levied by taxing the carbon content of fossil fuels at any point in the product cycle of the fuel. Carbon taxes offer a potentially cost-effective means of reducing greenhouse gas emissions.

3.3 Electricity generation technologies analysis for UK

This section analyses 6 non-renewable generation technologies, by using the approaches in chapter 2. Onshore and Offshore wind power are also mentioned in this section for comparing with traditional fuel plants.

3.3.1 Analytical procedures of projects

Each project will be analysed by following procedures:

I. Discounted Cash Flow Approach
   a) Net present value (NPV) calculation for base scenario;
   b) Find payback period;

c) Find Internal rate of return (IRR);

d) Sensitivity analysis by Tornado diagram.

II. Levelised Cost Analysis

a) "Discounted" method for base scenario;

b) Scenario analysis for high, base and low cost scenario;

3.3.2 Key parameters assumption

Before projects analysis, the author sets the key parameters for each technology which are based on the report of Department of Trade and Industry in 2006[9]. Table 3-2 shows the key parameters for six technologies. All costs are in real price of 2006. The values in the table for each technology can be treated as a base scenario. The base electricity price is set as 40 £/MWh, and the ROC (Renewable Obligation Certificate) price is 40 £/MWh. The base discounted rate is 5%.

In scenario analysis, the assumption of gas price is based on Electricity and Gas Supply Market Report of OFGEM.[10] The assumption of coal price and carbon tax cost are based on the report of Mott MacDonald.[11] In Table 3-2,

Column 4 = Column 1 * 8760 * Column 3;

Column 8 = Column 1 * Column 7;

Column 12 = Column 4 / Column 11;

Column 14 = Column 12 / Column 13;

Column 16 = Column 14 * Column 15 * 1000;

Column 18 = Column 12 * Column 17 / 1000;

Column 20 = Column 19 * Column 12 / 1000;

Column 23 = Column 14 * Column 22 * 1000000;

Column 24 = Column 21 * Column 23 / 1000.

Mtonnes = Million tonnes

Technology	Capacity (MW)	Project Lifetime (Years)	Load Factor	Annual Production (MWh)	Construction years	Total cost of construction (k£)	Fixed O&M cost (£/kW)	Annual Fixed O&M cost (k£)
Column no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CCGT	500	35	85%	3723000	3	220000	7	3500
CCGT with CCS	500	35	85%	3723000	3	414000	12.075	6037.5
Pulverised coal	500	50	90%	3942000	4	459000	17	8500
Pulverised coal with CCS	500	50	90%	3942000	4	581000	26	13000
IGCC	500	35	90%	3942000	4	534500	19	9500
IGCC with CCS	500	35	90%	3942000	4	726000	26	13000
Onshore wind	80	20	33%	231264	2	71600	44.4	3552
Offshore wind	100	20	33%	289080	2	151300	46	4600
Technology	**Variable O&M cost (£/kW)**	**Annual Variable O&M cost (k£)**	**Net fuel efficiency**	**Fuel consumption (MWh)**	**Concersion factor (MWh per Mtonne/Mtherm fuel)**	**Fuel consumption (Mtonnes or Mtherms)**	**Cost per tonne/therm of fuel (£)**	**Annual operational fuel costs (k£)**
Column no.	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
CCGT	2	1000	52.70%	7064516.13	29370	240.54	0.36	86592.64
CCGT with CCS	1.7	850	45.45%	8191419.14	29370	278.90	0.36	100405.55
Pulverised coal	1.1	550	43.40%	9082949.31	7277778	1.25	50	62401.94
Pulverised coal with CCS	2.7	1350	34.86%	11308089.50	7277778	1.55	50	77500.00
IGCC	1.2	600	42.38%	9301557.34	7277778	1.28	50	63903.83
IGCC with CCS	2.6	1300	37.14%	10613893.38	7277778	1.46	50	72919.88
Onshore wind	0	0	0	0	0	0	0	0
Offshore wind	0	0	0	0	0	0	0	0

Technology	Fuel delivery cost (£/MWh)	Annual fuel delivery cost (k£)	Carbon tax (£/Ton CO2)	1 therm/ton of fuel products CO2 (Ton)	Annual CO2 emission (Tons)	Annual Carbon tax (k£)	Additional cost of CCS (£/MWh)
Column no.	**17**	**18**	**21**	**22**	**23**	**24**	**25**
CCGT	0.7	4945.16	20	0.0053	1274836.07	25496.72	0
CCGT with CCS	0.7	5733.99	20	0.0053	0.00	0.00	3
Pulverised coal	0.7	6358.06	20	2.3	2870489.24	57409.78	0
Pulverised coal with CCS	0.7	7915.66	20	2.3	0.00	0.00	6
IGCC	0.7	6511.09	20	2.3	2939576.05	58791.52	0
IGCC with CCS	0.7	7429.73	20	2.3	0.00	0.00	6
Onshore wind	0	0	0	0	0	0	0
Offshore wind	0	0	0	0	0	0	0

Table 3-2: Key parameters assumption for 8 technologies

3.3.3 Combined Cycle Gas Turbine (CCGT)

3.3.3.1 Discounted Cash Flow Approach

According to the parameters of CCGT, the author compiles the table of net present value (NPV), which is shown in Table 3-3. The Fixed O&M cost, Variable O&M cost and Fuel delivery cost are merged into the O&M cost in the table. The electricity price is set as 40 £/MWh, and hence the revenue is 148920 k£ (annual production *electricity price).

Year	Investment (k£)	Operational fuel costs (k£)	O&M costs (k£)	Carbon tax (k£)	Revenue (k£)	Cash flow (k£)	Present worth factor (5%)	Present value (k£)	NPV (k£)
0	220000.00	0	0	0	0	-220000.00	**1.00**	-220000.00	-220000.00
1	0	0	0	0	0	0	**0.95**	0	-220000.00
2	0	0	0	0	0	0	**0.91**	0	-220000.00
3	0	0	0	0	0	0	**0.86**	0	-220000.00
4	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.82**	22530.10	-197469.90
5	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.78**	21457.24	-176012.66
6	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.75**	20435.46	-155577.20
7	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.71**	19462.35	-136114.85
8	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.68**	18535.57	-117579.28
9	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.64**	17652.92	-99926.36
10	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.61**	16812.31	-83114.05
11	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.58**	16011.72	-67102.33
12	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.56**	15249.26	-51853.07
13	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.53**	14523.10	-37329.97
14	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.51**	13831.53	-23498.44
15	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.48**	13172.88	-10325.56
16	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.46**	12545.60	2220.04
17	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.44**	11948.19	14168.24
18	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.42**	11379.23	25547.47
19	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.40**	10837.36	36384.83
20	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.38**	10321.30	46706.13
21	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.36**	9829.81	56535.94
22	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.34**	9361.72	65897.66
23	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.33**	8915.93	74813.59

24	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.31**	8491.36	83304.94
25	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.30**	8087.01	91391.95
26	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.28**	7701.91	99093.86
27	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.27**	7335.15	106429.02
28	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.26**	6985.86	113414.88
29	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.24**	6653.20	120068.08
30	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.23**	6336.38	126404.46
31	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.22**	6034.65	132439.11
32	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.21**	5747.29	138186.40
33	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.20**	5473.60	143660.00
34	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.19**	5212.96	148872.96
35	0	86592.64	9445.16	25496.72	148920.00	27385.48	**0.18**	4964.72	**153837.68**

Table 3-3: Net present value of CCGT

In the Table 3-3, the discounted payback period is 16 years. It means this CCGT project will start to earn money from 16th year. At the end of project, the total net profit is 153837.68k £. The internal rate of return can be calculated by Eq. (2.19). The result shows that IRR of this project is 9.00%.

According to the Table 3-3, the tornado diagram can be draw by increasing or decreasing main factors of project by 50%. These main factors are electricity price, discount rate, carbon tax, O&M cost, operational fuel cost and initial investment.

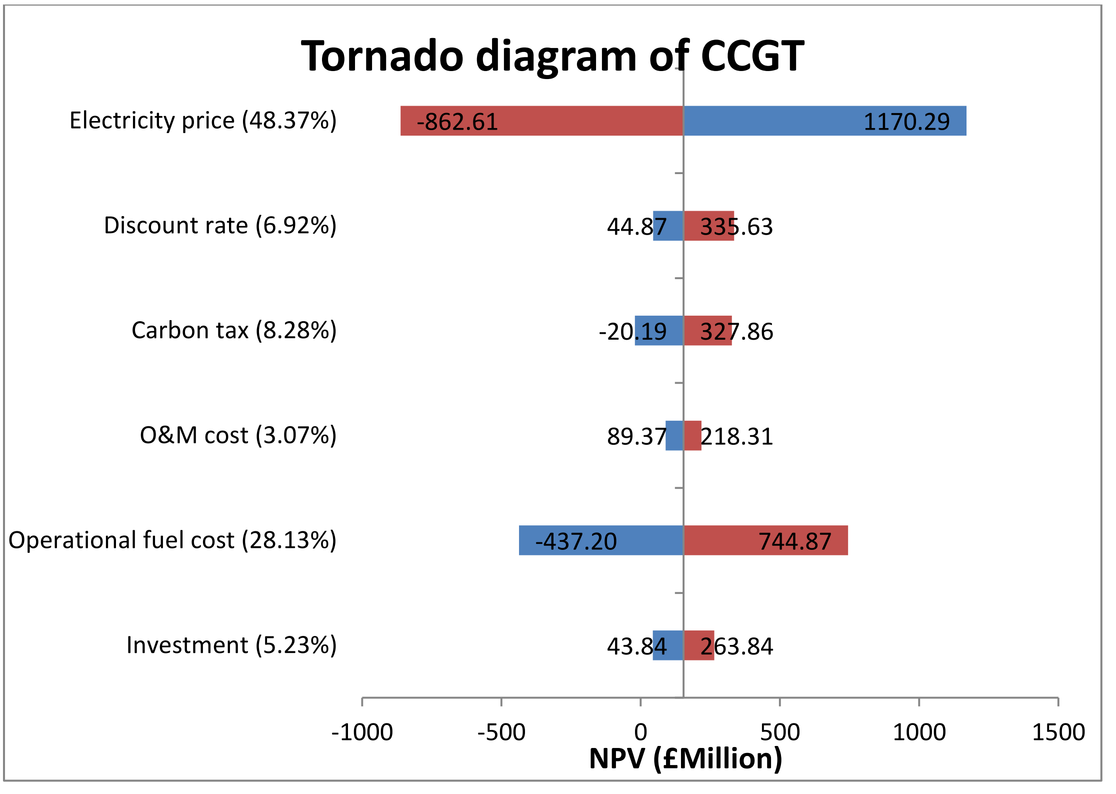

Figure 3.6: Tornado diagram of CCGT

The cross of horizontal and vertical axes is 153.84 £Million (base value), which is the NPV at the end of project lifetime in base scenario. This value is at the lower right corner of Table 3-3. This is the reference point where all the 50% perturbation would take place. As the NPV has a positive value, the project is viable in the aspect of financial return. When the NPV value becomes negative the project is not viable. High base NPV also means high risk tolerance, such as the increase of costs and the decrease of electricity price. In Figure 3.6, the lengths of bars show the influence and sensitivity of the factors. The blue bars shows the revised NPV when increasing each factor by 50%, while the red bars shows the revised NPV when decreasing each factor by 50%, with the numbers at each bar end represent the minimum and maximum NPVs for the respected change. Please note such increase or decrease is "changing only one factor at a time" (see Section 2.4.1.1), and other factors remain unchanged. The numbers at the left end of bars has negative values for the factor electricity price, carbon tax and operational fuel cost. According to the NPV rule, the negative NPV project is unacceptable (see Section 2.3.1.2).

For example, the NPV will increase from base value to 1170287.14k£ when increasing the electricity price by 50% (from 40£/MWh to 60£/MWh); and the NPV will decrease from base value to -862611.78k£ when decreasing the electricity price by 50% (from 40£/MWh to 20£/MWh). In contrast, the NPV will decrease from base value to 44871.94k£ when increasing the discount rate by 50% (from 5% to 7.5%); and the NPV will increase from base value to 335627.61k£ when decreasing the discount rate by 50% (from 5% to 2.5%).

The percentage numbers after factors are the variance contribution (see 2.4.1.1). The variance contribution is calculated for each variable by finding the percentage of the NPV range of change (the bar length) for that variable with respect to the total change of the NPV represented by the sum of all bar lengths. The advantage of calculating the variance contribution of each variable is to highlight the influence of each factor. Higher variance contribution indicates higher influence to the project NPV.

For example, in Figure 3.6, the variance contribution of electricity price is the largest, which is 48.37%. This percentage number is calculated as follow:

Variance Contribution of Electricity price

$$= \frac{\text{The NPV range of change for Electricity price}}{\text{The total NPV range of change for all factors}}$$

$$= \frac{\text{The bar length of Electricity price}}{\text{The total bar length of all factors (sum up the bar length of all factors)}}$$

$$= \frac{[1170287.14-(-862611.78)]}{[1170287.14-(-862611.78)]+(335627.61-44871.94)+[327864.87-(-20189.51)]+(218305.37-89369.98)+[744873.42-(-437198.06)]+(263837.68-43837.68)}$$

$= 48.37\%$

In contrast, in Figure 3.6, the variance contribution of O&M cost is the smallest, which is just 3.07%. This number is calculated as follow:

Variance Contribution of O&M Cost

$$= \frac{\text{The NPV range of change for O\&M Cost}}{\text{The total NPV range of change for all factors}}$$

$$= \frac{\text{The bar length of O\&M Cost}}{\text{The total bar length of all factors (sum up the bar length of all factors)}}$$

$$= \frac{(218305.37-89369.98)}{[1170287.14-(-862611.78)]+(335627.61-44871.94)+[327864.87-(-20189.51)]+(218305.37-89369.98)+[744873.42-(-437198.06)]+(263837.68-43837.68)}$$

$= 3.07\%$

Several result can be get by observing the above tornado diagram:

1) The electricity price is the most influential factor in the NPV as the NPV is ranging between -862.61£Million and 117.03£Million. It has 48.37% variance contribution over the total NPV variation. So, the electricity price can be considered as the most important factor when investment this CCGT power plant. It is also important to note that by decreasing the electricity by 50% it becomes an unviable project in the aspect of financial return.

2) The O&M cost, which merged by The Fixed O&M cost, Variable O&M cost and Fuel delivery cost, inversely, has the least influence on the NPV in this

project. The NPV changes from 863.70 £Million to 218.31 £Million. It only has 3.07% contribution.

3.3.3.2 Levelised cost analysis

Table 3-4 shows the calculation of levelised cost by discounted method for base scenario. Note the discounted rate is 5%.

	Un-discounted values						**Discounted values**				
Year	Capital cost (k £)	O&M cost (k £)	Operational gas cost (k £)	Carbon cost (k £)	Annual production (MWh)	**Present worth factor (5%)**	Capital cost (k £)	O&M costk £)	Operational gas cost (k £)	Carbon cost (k £)	Annual production (MWh)
0	220000.00	0.00	0.00	0.00	0.00	**1.00**	220000.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	**0.95**	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	**0.91**	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	**0.86**	0.00	0.00	0.00	0.00	0.00
4	0.00	9445.16	86592.64	25496.72	3723000.00	**0.82**	0.00	7770.56	71239.98	20976.22	3062921.31
5	0.00	9445.16	86592.64	25496.72	3723000.00	**0.78**	0.00	7400.53	67847.60	19977.35	2917067.92
6	0.00	9445.16	86592.64	25496.72	3723000.00	**0.75**	0.00	7048.12	64616.76	19026.05	2778159.92
7	0.00	9445.16	86592.64	25496.72	3723000.00	**0.71**	0.00	6712.50	61539.77	18120.04	2645866.59
8	0.00	9445.16	86592.64	25496.72	3723000.00	**0.68**	0.00	6392.86	58609.31	17257.18	2519872.94
9	0.00	9445.16	86592.64	25496.72	3723000.00	**0.64**	0.00	6088.44	55818.39	16435.41	2399879.00
10	0.00	9445.16	86592.64	25496.72	3723000.00	**0.61**	0.00	5798.51	53160.37	15652.78	2285599.04
11	0.00	9445.16	86592.64	25496.72	3723000.00	**0.58**	0.00	5522.39	50628.92	14907.40	2176760.99
12	0.00	9445.16	86592.64	25496.72	3723000.00	**0.56**	0.00	5259.42	48218.02	14197.53	2073105.71
13	0.00	9445.16	86592.64	25496.72	3723000.00	**0.53**	0.00	5008.97	45921.93	13521.46	1974386.39
14	0.00	9445.16	86592.64	25496.72	3723000.00	**0.51**	0.00	4770.45	43735.17	12877.58	1880367.99
15	0.00	9445.16	86592.64	25496.72	3723000.00	**0.48**	0.00	4543.28	41652.54	12264.36	1790826.66
16	0.00	9445.16	86592.64	25496.72	3723000.00	**0.46**	0.00	4326.94	39669.09	11680.34	1705549.20
17	0.00	9445.16	86592.64	25496.72	3723000.00	**0.44**	0.00	4120.89	37780.08	11124.14	1624332.57
18	0.00	9445.16	86592.64	25496.72	3723000.00	**0.42**	0.00	3924.66	35981.03	10594.41	1546983.40
19	0.00	9445.16	86592.64	25496.72	3723000.00	**0.40**	0.00	3737.77	34267.65	10089.92	1473317.52
20	0.00	9445.16	86592.64	25496.72	3723000.00	**0.38**	0.00	3559.78	32635.86	9609.45	1403159.54
21	0.00	9445.16	86592.64	25496.72	3723000.00	**0.36**	0.00	3390.27	31081.77	9151.85	1336342.42

22	0.00	9445.16	86592.64	25496.72	3723000.00	**0.34**	0.00	3228.83	29601.68	8716.05	1272707.07
23	0.00	9445.16	86592.64	25496.72	3723000.00	**0.33**	0.00	3075.07	28192.08	8301.00	1212101.97
24	0.00	9445.16	86592.64	25496.72	3723000.00	**0.31**	0.00	2928.64	26849.60	7905.72	1154382.83
25	0.00	9445.16	86592.64	25496.72	3723000.00	**0.30**	0.00	2789.18	25571.05	7529.25	1099412.22
26	0.00	9445.16	86592.64	25496.72	3723000.00	**0.28**	0.00	2656.36	24353.38	7170.72	1047059.26
27	0.00	9445.16	86592.64	25496.72	3723000.00	**0.27**	0.00	2529.87	23193.69	6829.25	997199.29
28	0.00	9445.16	86592.64	25496.72	3723000.00	**0.26**	0.00	2409.40	22089.23	6504.05	949713.61
29	0.00	9445.16	86592.64	25496.72	3723000.00	**0.24**	0.00	2294.67	21037.36	6194.33	904489.15
30	0.00	9445.16	86592.64	25496.72	3723000.00	**0.23**	0.00	2185.40	20035.58	5899.37	861418.24
31	0.00	9445.16	86592.64	25496.72	3723000.00	**0.22**	0.00	2081.33	19081.51	5618.44	820398.33
32	0.00	9445.16	86592.64	25496.72	3723000.00	**0.21**	0.00	1982.22	18172.87	5350.90	781331.74
33	0.00	9445.16	86592.64	25496.72	3723000.00	**0.20**	0.00	1887.83	17307.49	5096.09	744125.46
34	0.00	9445.16	86592.64	25496.72	3723000.00	**0.19**	0.00	1797.93	16483.32	4853.42	708690.92
35	0.00	9445.16	86592.64	25496.72	3723000.00	**0.18**	0.00	1712.32	15698.40	4622.31	674943.73
Total	220000.00	302245.16	2770964.48	815895.09	119136000.00		220000.00	128935.39	1182071.48	348054.37	50822472.94

Table 3-4: Levelised cost calculation for CCGT

From Table 3-4, the levelised cost for base scenario is

$$LC_D = \frac{PV(Total\ Costs)}{PV(Total\ Outputs)} = \frac{220000 + 128935.39 + 1182071.48 + 348054.37}{50822472.94}$$

= 0.03697 k £/MWh

= 36.97 £/MWh

The Figure 3.7 gives the cost structure for CCGT project. The data is from the discounted total values of each cost in Table 3-4. In this figure, operational gas cost accounts for the largest proportion and O&M cost accounts for the smallest proportion.

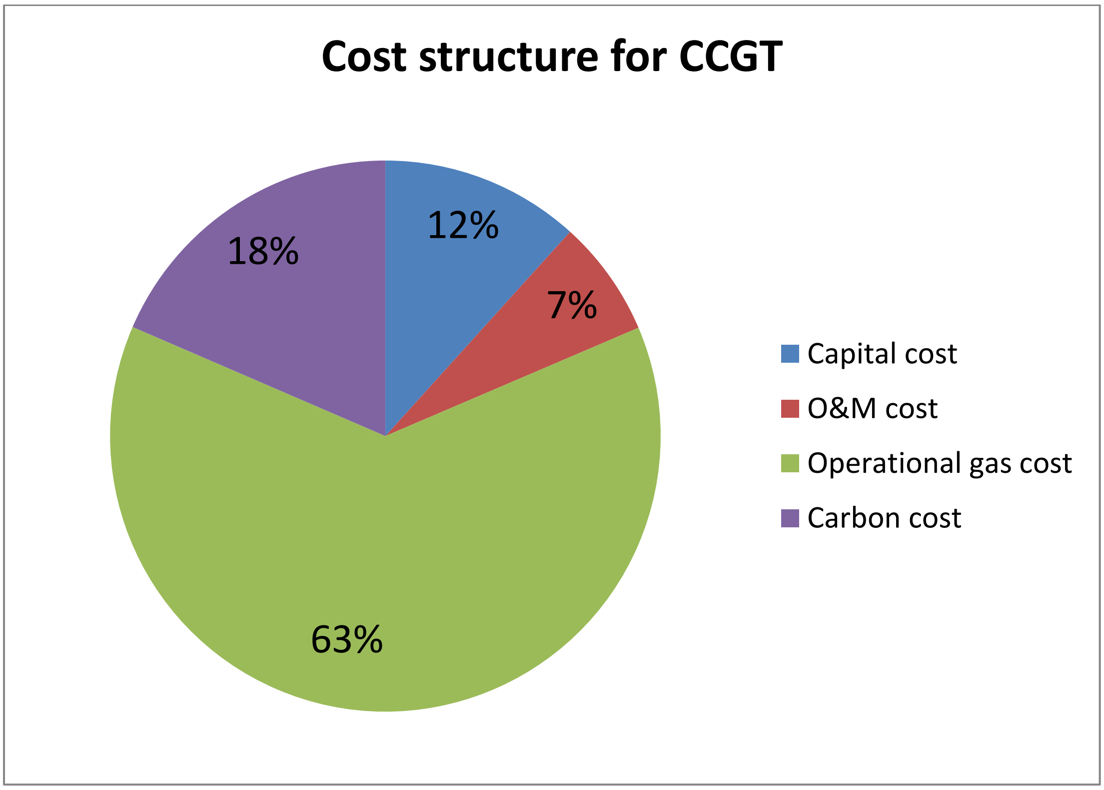

Figure 3.7: Cost structure for CCGT

In order to look at the performance of project, the author puts it under different scenarios. Relative to the base scenario, the author sets a low cost scenario and a high cost scenario. Table 3-5 gives the parameters of low and high scenario.

	Capital cost (k£)	Gas price (£/therm)	Carbon tax (£/TonCO2)	O&M Cost (k£)
LOW	150000	0.20	15	5000
BASE	220000	0.36	20	9445.16
HIGH	300000	0.60	50	15000

Table 3-5: Different scenarios of CCGT

Table 3-6 gives the results of levelised cost of different scenarios.

	Levelised cost (£/MWh)
LOW	24.41
BASE	36.97
HIGH	72.00

Table 3-6: Levelised cost of different scenarios for CCGT

3.3.4 Combined Cycle Gas Turbine (CCGT) with CCS

3.3.4.1 Discounted Cash Flow Approach

According to the parameters of CCGT with CCS, the author compiles the table of net present value (NPV), which is shown in Table 3-7. The Fixed O&M cost, Variable O&M cost and Fuel delivery cost are merged into the O&M cost in the table. The electricity price is set as 40£/MWh, and hence the revenue is 148920 k£ (annual production *electricity price).

Year	Investment (k£)	Operational fuel costs (k£)	O&M costs (k£)	Additional cost of CCS (k£)	Revenue (k£)	Cash flow (k£)	Present worth factor (5%)	Present value (k£)	NPV (k£)
0	414000	0.00	0.00	0.00		-414000.00	**1.00**	-414000.00	-414000.00
1	0.00	0.00	0.00	0.00		0.00	**0.95**	0.00	-414000.00
2	0.00	0.00	0.00	0.00		0.00	**0.91**	0.00	-414000.00
3	0.00	0.00	0.00	0.00	0.00	0.00	**0.86**	0.00	-414000.00
4	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.82**	20340.46	-393659.54
5	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.78**	19371.87	-374287.67
6	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.75**	18449.40	-355838.27
7	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.71**	17570.86	-338267.41
8	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.68**	16734.15	-321533.26
9	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.64**	15937.29	-305595.97
10	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.61**	15178.37	-290417.61
11	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.58**	14455.59	-275962.02
12	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.56**	13767.23	-262194.79
13	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.53**	13111.64	-249083.15
14	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.51**	12487.28	-236595.87
15	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.48**	11892.65	-224703.22
16	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.46**	11326.33	-213376.89
17	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.44**	10786.98	-202589.91
18	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.42**	10273.32	-192316.59
19	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.40**	9784.11	-182532.48
20	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.38**	9318.20	-173214.28
21	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.36**	8874.48	-164339.80
22	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.34**	8451.88	-155887.92
23	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.33**	8049.41	-147838.51

24	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.31**	7666.11	-140172.40
25	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.30**	7301.05	-132871.35
26	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.28**	6953.38	-125917.96
27	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.27**	6622.27	-119295.69
28	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.26**	6306.92	-112988.77
29	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.24**	6006.60	-106982.17
30	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.23**	5720.57	-101261.61
31	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.22**	5448.16	-95813.45
32	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.21**	5188.72	-90624.72
33	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.20**	4941.64	-85683.08
34	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.19**	4706.32	-80976.76
35	0.00	100405.55	12621.49	11169.00	148920.00	24723.96	**0.18**	4482.21	-76494.54

Table 3-7: Net present value of CCGT with CCS

The Table 3-7 shows that this project cannot earn money at the end of project lifetime. At the end of project, the total net profit is -76494.54 k£

According to the Table 3-7, the tornado diagram can be draw by increasing or decreasing main factors of project by 50%. These main factors are electricity price, discount rate, O&M cost, operational fuel cost and initial investment.

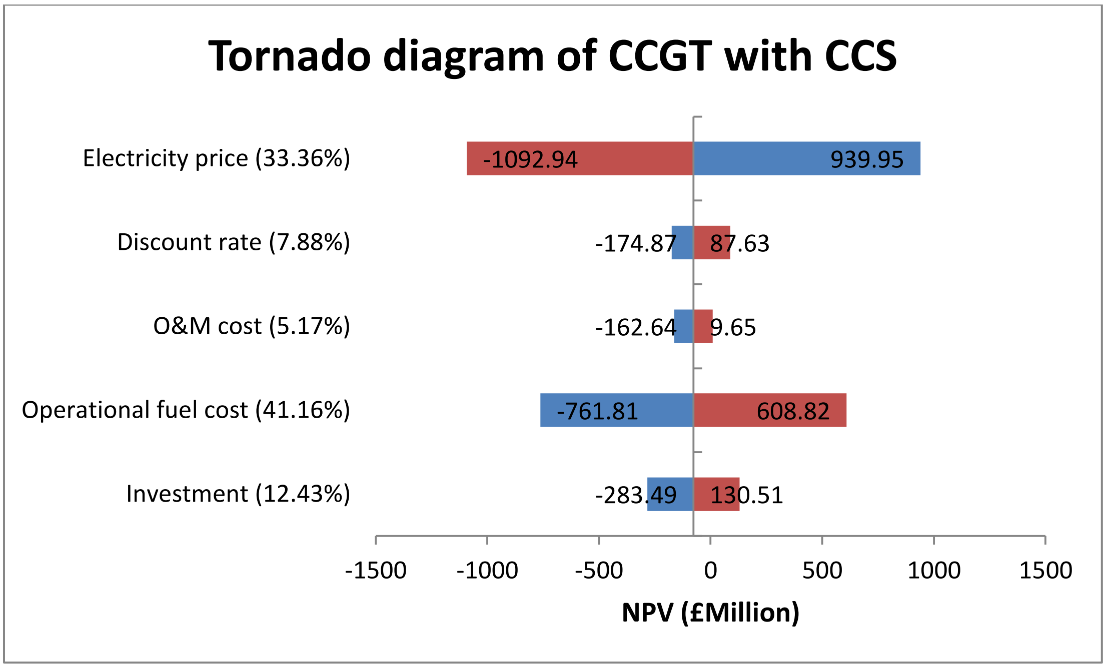

Figure 3.8: Tornado diagram of CCGT with CCS

The cross of horizontal and vertical axes is -76.49 £Million, which is the NPV at the end of project lifetime in base scenario. In Figure 3.8, the blue bars shows the revised NPV when increasing each factor by 50%, while the red bars shows the revised NPV when decreasing each factor by 50%. The numbers at each bar end represent the minimum and maximum NPVs for the respected factor.

Several result can be get by observing the above tornado diagram:

1) The electricity price is the most influential factor in the NPV as the NPV is ranging between -1092.944 £Million and 939.95 £Million. It has 33.36%

variance contribution over the total NPV variation. So, the electricity price can be considered as the most important factor when investment this CCGT with CCS power plant.

2) The O&M cost, which merged by The Fixed O&M cost, Variable O&M cost and Fuel delivery cost, inversely, has the least influence on the NPV in this project. The NPV changes from -162.64 £Million to 9.65 £Million. It only has 5.71% contribution.

3.3.4.2 Levelised cost analysis

Table 3-8 shows the calculation of levelised cost by discounted method for base scenario. Note the discounted rate is 5%.

	Un-discounted values						Discounted values				
Year	Capital cost (k £)	O&M cost (k £)	Operational fuel cost (k £)	Additional cost of CCS (k £)	Annual production (MWh)	**Present worth factor (5%)**	Capital cost (k £)	O&M cost (k £)	Operational gas cost (k £)	Additional cost of CCS (k £)	Annual production (MWh)
0	414000.00	0.00	0.00	0.00	0.00	**1.00**	414000.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	**0.95**	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	**0.91**	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	**0.86**	0.00	0.00	0.00	0.00	0.00
4	0.00	12621.49	100405.55	11169.00	3723000.00	**0.82**	0.00	10383.73	82603.89	0.00	3062921.31
5	0.00	12621.49	100405.55	11169.00	3723000.00	**0.78**	0.00	9889.27	78670.37	8751.20	2917067.92
6	0.00	12621.49	100405.55	11169.00	3723000.00	**0.75**	0.00	9418.35	74924.16	8334.48	2778159.92
7	0.00	12621.49	100405.55	11169.00	3723000.00	**0.71**	0.00	8969.86	71356.35	7937.60	2645866.59
8	0.00	12621.49	100405.55	11169.00	3723000.00	**0.68**	0.00	8542.72	67958.43	7559.62	2519872.94
9	0.00	12621.49	100405.55	11169.00	3723000.00	**0.64**	0.00	8135.93	64722.31	7199.64	2399879.00
10	0.00	12621.49	100405.55	11169.00	3723000.00	**0.61**	0.00	7748.50	61640.30	6856.80	2285599.04
11	0.00	12621.49	100405.55	11169.00	3723000.00	**0.58**	0.00	7379.53	58705.04	6530.28	2176760.99
12	0.00	12621.49	100405.55	11169.00	3723000.00	**0.56**	0.00	7028.12	55909.57	6219.32	2073105.71
13	0.00	12621.49	100405.55	11169.00	3723000.00	**0.53**	0.00	6693.45	53247.20	5923.16	1974386.39
14	0.00	12621.49	100405.55	11169.00	3723000.00	**0.51**	0.00	6374.71	50711.62	5641.10	1880367.99
15	0.00	12621.49	100405.55	11169.00	3723000.00	**0.48**	0.00	6071.15	48296.78	5372.48	1790826.66
16	0.00	12621.49	100405.55	11169.00	3723000.00	**0.46**	0.00	5782.05	45996.94	5116.65	1705549.20
17	0.00	12621.49	100405.55	11169.00	3723000.00	**0.44**	0.00	5506.72	43806.61	4873.00	1624332.57
18	0.00	12621.49	100405.55	11169.00	3723000.00	**0.42**	0.00	5244.49	41720.58	4640.95	1546983.40
19	0.00	12621.49	100405.55	11169.00	3723000.00	**0.40**	0.00	4994.75	39733.88	4419.95	1473317.52
20	0.00	12621.49	100405.55	11169.00	3723000.00	**0.38**	0.00	4756.91	37841.79	4209.48	1403159.54
21	0.00	12621.49	100405.55	11169.00	3723000.00	**0.36**	0.00	4530.39	36039.80	4009.03	1336342.42
22	0.00	12621.49	100405.55	11169.00	3723000.00	**0.34**	0.00	4314.66	34323.62	3818.12	1272707.07
23	0.00	12621.49	100405.55	11169.00	3723000.00	**0.33**	0.00	4109.20	32689.16	3636.31	1212101.97

24	0.00	12621.49	100405.55	11169.00	3723000.00	**0.31**	0.00	3913.52	31132.54	3463.15	1154382.83
25	0.00	12621.49	100405.55	11169.00	3723000.00	**0.30**	0.00	3727.16	29650.04	3298.24	1099412.22
26	0.00	12621.49	100405.55	11169.00	3723000.00	**0.28**	0.00	3549.68	28238.13	3141.18	1047059.26
27	0.00	12621.49	100405.55	11169.00	3723000.00	**0.27**	0.00	3380.65	26893.46	2991.60	997199.29
28	0.00	12621.49	100405.55	11169.00	3723000.00	**0.26**	0.00	3219.66	25612.82	2849.14	949713.61
29	0.00	12621.49	100405.55	11169.00	3723000.00	**0.24**	0.00	3066.35	24393.16	2713.47	904489.15
30	0.00	12621.49	100405.55	11169.00	3723000.00	**0.23**	0.00	2920.33	23231.58	2584.25	861418.24
31	0.00	12621.49	100405.55	11169.00	3723000.00	**0.22**	0.00	2781.27	22125.31	2461.19	820398.33
32	0.00	12621.49	100405.55	11169.00	3723000.00	**0.21**	0.00	2648.82	21071.73	2344.00	781331.74
33	0.00	12621.49	100405.55	11169.00	3723000.00	**0.20**	0.00	2522.69	20068.31	2232.38	744125.46
34	0.00	12621.49	100405.55	11169.00	3723000.00	**0.19**	0.00	2402.56	19112.68	2126.07	708690.92
35	0.00	12621.49	100405.55	11169.00	3723000.00	**0.18**	0.00	2288.15	18202.55	2024.83	674943.73
Totals	414000.00	403887.79	3212977.48	357408.00	119136000.00		414000.00	172295.33	1370630.72	143278.65	50822472.94

Table 3-8: Levelised cost calculation for CCGT with CCS

From Table 3-8, the levelised cost for base scenario is

$$LC_D = \frac{PV(Total\ Costs)}{PV(Total\ Outputs)} = 0.04132\ \text{k £/MWh} = 41.32\ \text{£/MWh}$$

The Figure 3.9 gives the cost structure for CCGT with CCS project. The data is from the discounted total values of each cost in Table 3-8. In this figure, operational gas cost accounts for the largest proportion and O&M cost accounts for the smallest proportion.

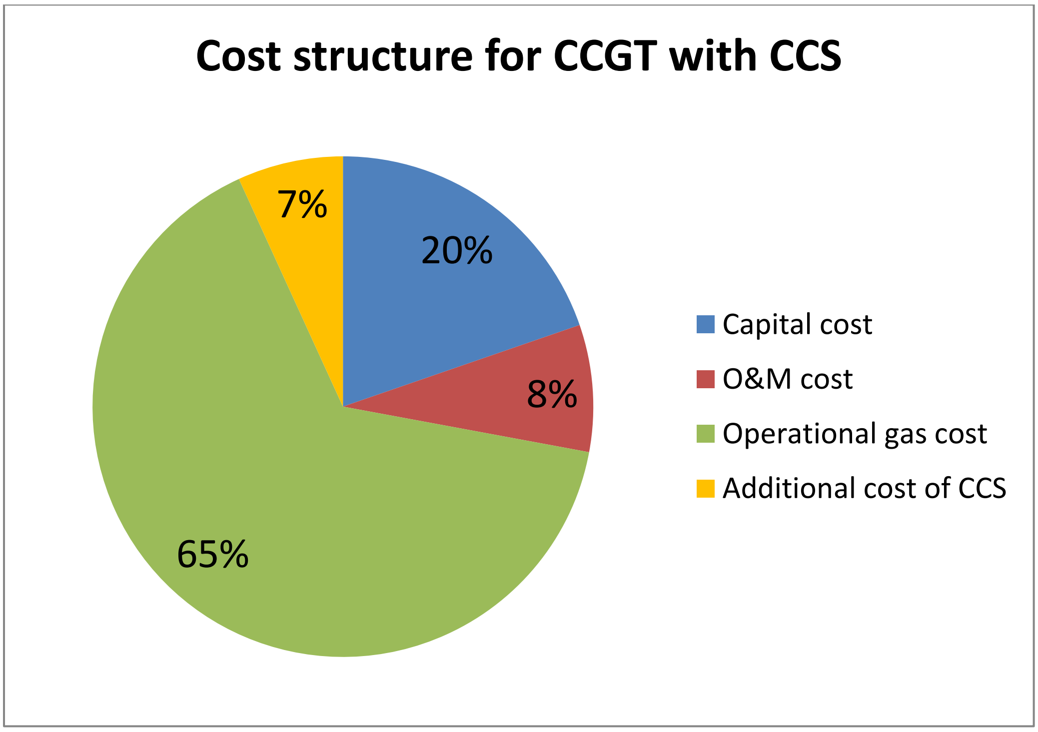

Figure 3.9: Cost structure for CCGT with CCS

For scenario analysis, the author sets a low cost scenario and a high cost scenario.

	Capital cost (k £)	**Gas price (£/therm)**	**O&M Cost (k £)**	**Additional cost of CCS (£/MWh)**
LOW	300000	0.20	8000	1.5
BASE	414000	0.36	12621.49	3

HIGH	500000	0.60	16000	4.5

Table 3-9: Different scenarios of CCGT with CCS

gives the results of levelised cost of different scenarios.

	Levelised cost (£/MWh)
LOW	24.44
BASE	41.42
HIGH	63.31

Table 3-10: Levelised cost of different scenarios for CCGT with CCS

3.3.5 Pulverised Coal Power Plant

3.3.5.1 Discounted Cash Flow Approach

According to the parameters of pulverised coal power plant, the author compiles the table of net present value (NPV), which is shown in Table 3-11. The Fixed O&M cost, Variable O&M cost and Fuel delivery cost are merged into the O&M cost in the table. The electricity price is set as 40 £/MWh, and hence the revenue is 157680 k£ (annual production *electricity price).

Year	Investment (k£)	O&M costs (k£)	Operational fuel costs (k£)	Carbon tax (k£)	Revenue (k£)	Cash flow (k£)	Present worth factor (5%)	Present value (k£)	NPV (k£)
0	459000.00	0.00	0.00	0.00	0.00	-459000.00	**1.00**	-459000.00	-459000.00
1	0.00	0.00	0.00	0.00	0.00	0.00	**0.95**	0.00	-459000.00
2	0.00	0.00	0.00	0.00	0.00	0.00	**0.91**	0.00	-459000.00
3	0.00	0.00	0.00	0.00	0.00	0.00	**0.86**	0.00	-459000.00
4	0.00	0.00	0.00	0.00	0.00	0.00	**0.82**	0.00	-459000.00
5	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.78**	42044.94	-416955.06
6	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.75**	40042.80	-376912.25
7	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.71**	38136.00	-338776.25
8	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.68**	36320.00	-302456.25
9	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.64**	34590.48	-267865.77
10	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.61**	32943.31	-234922.46
11	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.58**	31374.58	-203547.87
12	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.56**	29880.56	-173667.32
13	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.53**	28457.67	-145209.65
14	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.51**	27102.55	-118107.10
15	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.48**	25811.95	-92295.15
16	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.46**	24582.81	-67712.35
17	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.44**	23412.20	-44300.15
18	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.42**	22297.33	-22002.82
19	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.40**	21235.55	-767.26
20	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.38**	20224.34	19457.07
21	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.36**	19261.27	38718.34
22	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.34**	18344.07	57062.41
23	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.33**	17470.54	74532.96

24	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.31**	16638.61	91171.57
25	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.30**	15846.30	107017.86
26	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.28**	15091.71	122109.58
27	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.27**	14373.06	136482.63
28	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.26**	13688.63	150171.26
29	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.24**	13036.79	163208.05
30	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.23**	12415.99	175624.04
31	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.22**	11824.75	187448.79
32	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.21**	11261.67	198710.45
33	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.20**	10725.40	209435.85
34	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.19**	10214.66	219650.52
35	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.18**	9728.25	229378.77
36	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.17**	9265.00	238643.77
37	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.16**	8823.81	247467.58
38	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.16**	8403.63	255871.21
39	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.15**	8003.46	263874.67
40	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.14**	7622.34	271497.01
41	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.14**	7259.37	278756.38
42	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.13**	6913.69	285670.06
43	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.12**	6584.46	292254.53
44	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.12**	6270.92	298525.44
45	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.11**	5972.30	304497.75
46	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.11**	5687.91	310185.65
47	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.10**	5417.05	315602.71
48	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.10**	5159.10	320761.81

49	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.09**	4913.43	325675.24
50	0.00	15408.06	31200.97	57409.78	157680.00	53661.19	**0.09**	4679.46	330354.69

Table 3-11: Net present value of pulverised coal power plant

In Table 3-11, the discounted payback period is 20 years. It means this coal-fired plant will start to earn money from 20th year. At the end of project, the total net profit is 330354.69 k£ The internal rate of return can be calculated by Eq. (2.19). The result shows that IRR of this project is 8.28%.

According to the Table 3-11, the tornado diagram can be draw by increasing or decreasing main factors of project by 50%. These main factors are electricity price, discount rate, carbon tax, O&M cost, operational fuel cost and initial investment.

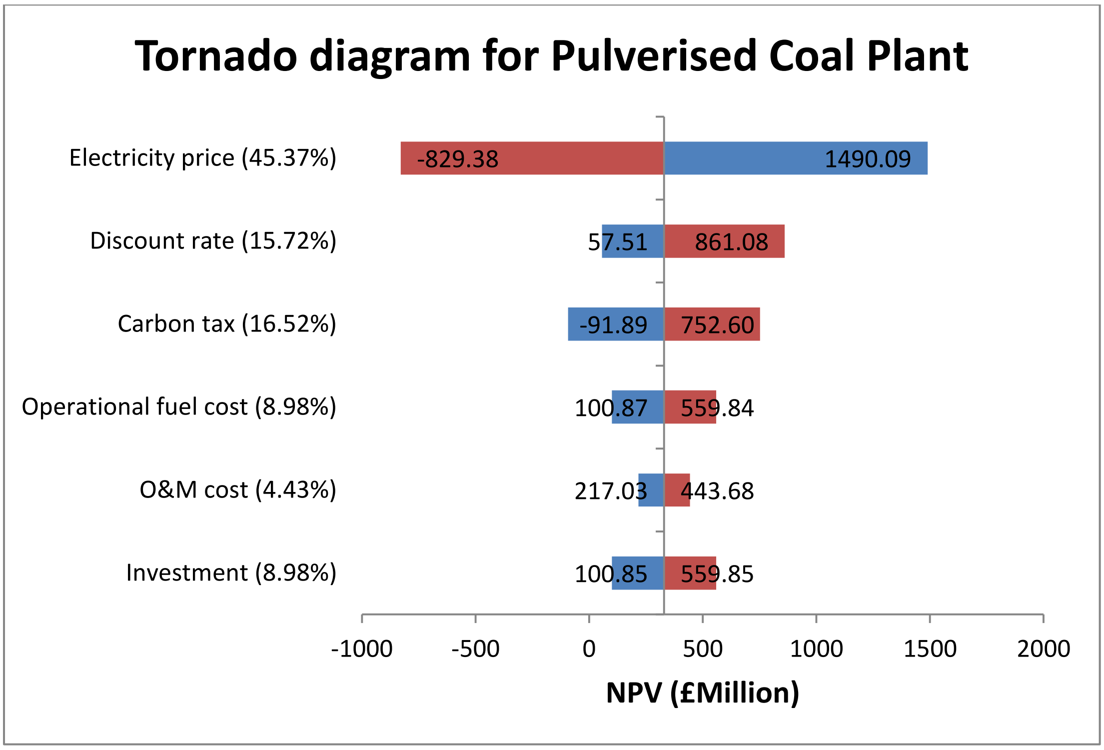

Figure 3.10: Tornado diagram of pulverised coal power plant

The cross of horizontal and vertical axes is 330.35 £Million, which is the NPV at the end of project lifetime in base scenario. In Figure 3.10, the blue bars shows the revised NPV when increasing each factor by 50%, while the red bars shows the revised NPV when decreasing each factor by 50%. The numbers at each bar end represent the minimum and maximum NPVs for the respected factor.

Several result can be get by observing the above tornado diagram:

1) The electricity price is still the most influential factor in the NPV as the NPV is ranging between -829.38 £Million and 1490.09 £Million. It has 45.37% variance contribution over the total NPV variation. So, the electricity price can be considered as the most important factor when investment this pulverised coal power plant.
2) The O&M cost, which merged by The Fixed O&M cost, Variable O&M cost and Fuel delivery cost, inversely, has the least influence on the NPV in this project. The NPV changes from 217.03 £Million to 443.68 £Million. It only has 4.43% contribution.

3.3.5.2 Levelised cost analysis

Table 3-12 shows the calculation of levelised cost by discounted method for base scenario. Note the discounted rate is 5%.

	Un-discounted values						**Un-discounted values**				
Year	Capital cost (k £)	O&M cost (k £)	Operational fuel cost (k £)	Carbon cost (k £)	Annual production (MWh)	**Present worth factor (5%)**	Capital cost (k £)	O&M cost (k £)	Operational gas cost (k £)	Carbon cost (k £)	Annual production (MWh)
0	459000.00	0.00	0.00	0.00	0.00	**1.00**	459000.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	**0.95**	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	**0.91**	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	**0.86**	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	**0.82**	0.00	0.00	0.00	0.00	0.00
5	0.00	15408.06	31200.97	57409.78	3942000	**0.78**	0.00	12072.62	24446.78	44982.07	3088660.15
6	0.00	15408.06	31200.97	57409.78	3942000	**0.75**	0.00	11497.73	23282.64	42840.07	2941581.09
7	0.00	15408.06	31200.97	57409.78	3942000	**0.71**	0.00	10950.22	22173.95	40800.06	2801505.80
8	0.00	15408.06	31200.97	57409.78	3942000	**0.68**	0.00	10428.78	21118.04	38857.20	2668100.77
9	0.00	15408.06	31200.97	57409.78	3942000	**0.64**	0.00	9932.17	20112.42	37006.86	2541048.35
10	0.00	15408.06	31200.97	57409.78	3942000	**0.61**	0.00	9459.21	19154.69	35244.63	2420046.05
11	0.00	15408.06	31200.97	57409.78	3942000	**0.58**	0.00	9008.77	18242.56	33566.31	2304805.76
12	0.00	15408.06	31200.97	57409.78	3942000	**0.56**	0.00	8579.78	17373.87	31967.92	2195053.10
13	0.00	15408.06	31200.97	57409.78	3942000	**0.53**	0.00	8171.22	16546.54	30445.63	2090526.76
14	0.00	15408.06	31200.97	57409.78	3942000	**0.51**	0.00	7782.12	15758.61	28995.84	1990977.87
15	0.00	15408.06	31200.97	57409.78	3942000	**0.48**	0.00	7411.54	15008.20	27615.09	1896169.40
16	0.00	15408.06	31200.97	57409.78	3942000	**0.46**	0.00	7058.61	14293.52	26300.08	1805875.62
17	0.00	15408.06	31200.97	57409.78	3942000	**0.44**	0.00	6722.49	13612.88	25047.70	1719881.54
18	0.00	15408.06	31200.97	57409.78	3942000	**0.42**	0.00	6402.37	12964.65	23854.95	1637982.42
19	0.00	15408.06	31200.97	57409.78	3942000	**0.40**	0.00	6097.49	12347.28	22719.00	1559983.26
20	0.00	15408.06	31200.97	57409.78	3942000	**0.38**	0.00	5807.14	11759.32	21637.14	1485698.34
21	0.00	15408.06	31200.97	57409.78	3942000	**0.36**	0.00	5530.61	11199.35	20606.80	1414950.80
22	0.00	15408.06	31200.97	57409.78	3942000	**0.34**	0.00	5267.24	10666.05	19625.53	1347572.19
23	0.00	15408.06	31200.97	57409.78	3942000	**0.33**	0.00	5016.42	10158.14	18690.98	1283402.09

24	0.00	15408.06	31200.97	57409.78	3942000	**0.31**	0.00	4777.54	9674.42	17800.93	1222287.70
25	0.00	15408.06	31200.97	57409.78	3942000	**0.30**	0.00	4550.04	9213.73	16953.27	1164083.53
26	0.00	15408.06	31200.97	57409.78	3942000	**0.28**	0.00	4333.37	8774.98	16145.97	1108650.98
27	0.00	15408.06	31200.97	57409.78	3942000	**0.27**	0.00	4127.02	8357.13	15377.11	1055858.07
28	0.00	15408.06	31200.97	57409.78	3942000	**0.26**	0.00	3930.50	7959.17	14644.87	1005579.12
29	0.00	15408.06	31200.97	57409.78	3942000	**0.24**	0.00	3743.33	7580.16	13947.50	957694.40
30	0.00	15408.06	31200.97	57409.78	3942000	**0.23**	0.00	3565.08	7219.20	13283.33	912089.90
31	0.00	15408.06	31200.97	57409.78	3942000	**0.22**	0.00	3395.31	6875.43	12650.79	868657.05
32	0.00	15408.06	31200.97	57409.78	3942000	**0.21**	0.00	3233.63	6548.03	12048.37	827292.43
33	0.00	15408.06	31200.97	57409.78	3942000	**0.20**	0.00	3079.65	6236.22	11474.64	787897.55
34	0.00	15408.06	31200.97	57409.78	3942000	**0.19**	0.00	2933.00	5939.25	10928.23	750378.62
35	0.00	15408.06	31200.97	57409.78	3942000	**0.18**	0.00	2793.33	5656.43	10407.84	714646.30
36	0.00	15408.06	31200.97	57409.78	3942000	**0.17**	0.00	2660.32	5387.08	9912.23	680615.53
37	0.00	15408.06	31200.97	57409.78	3942000	**0.16**	0.00	2533.63	5130.55	9440.21	648205.27
38	0.00	15408.06	31200.97	57409.78	3942000	**0.16**	0.00	2412.98	4886.24	8990.68	617338.35
39	0.00	15408.06	31200.97	57409.78	3942000	**0.15**	0.00	2298.08	4653.56	8562.55	587941.28
40	0.00	15408.06	31200.97	57409.78	3942000	**0.14**	0.00	2188.65	4431.96	8154.81	559944.08
41	0.00	15408.06	31200.97	57409.78	3942000	**0.14**	0.00	2084.43	4220.92	7766.49	533280.08
42	0.00	15408.06	31200.97	57409.78	3942000	**0.13**	0.00	1985.17	4019.92	7396.65	507885.79
43	0.00	15408.06	31200.97	57409.78	3942000	**0.12**	0.00	1890.64	3828.50	7044.43	483700.75
44	0.00	15408.06	31200.97	57409.78	3942000	**0.12**	0.00	1800.61	3646.19	6708.98	460667.38
45	0.00	15408.06	31200.97	57409.78	3942000	**0.11**	0.00	1714.86	3472.56	6389.51	438730.84
46	0.00	15408.06	31200.97	57409.78	3942000	**0.11**	0.00	1633.20	3307.20	6085.25	417838.89
47	0.00	15408.06	31200.97	57409.78	3942000	**0.10**	0.00	1555.43	3149.71	5795.47	397941.80
48	0.00	15408.06	31200.97	57409.78	3942000	**0.10**	0.00	1481.36	2999.73	5519.50	378992.19
49	0.00	15408.06	31200.97	57409.78	3942000	**0.09**	0.00	1410.82	2856.88	5256.66	360944.95
50	0.00	15408.06	31200.97	57409.78	3942000	**0.09**	0.00	1343.64	2720.84	5006.35	343757.09

TOTAL	459000.00	708770.76	1435244.62	2640850.10	181332000		459000.00	226652.18	458965.49	844496.50	57986721.28

Table 3-12: Levelised cost calculation for pulverised coal power plant

From Table 3-12, the levelised cost for base scenario is

$$LC_D = \frac{PV(Total\ Costs)}{PV(Total\ Outputs)} = 0.03430\ \text{k £/MWh} = 34.30\ \text{£/MWh}$$

The Figure 3.11 gives the cost structure for pulverised coal plant project. The data is from the discounted total values of each cost in Table 3-12. In this figure, carbon tax cost accounts for the largest proportion and O&M cost accounts for the smallest proportion.

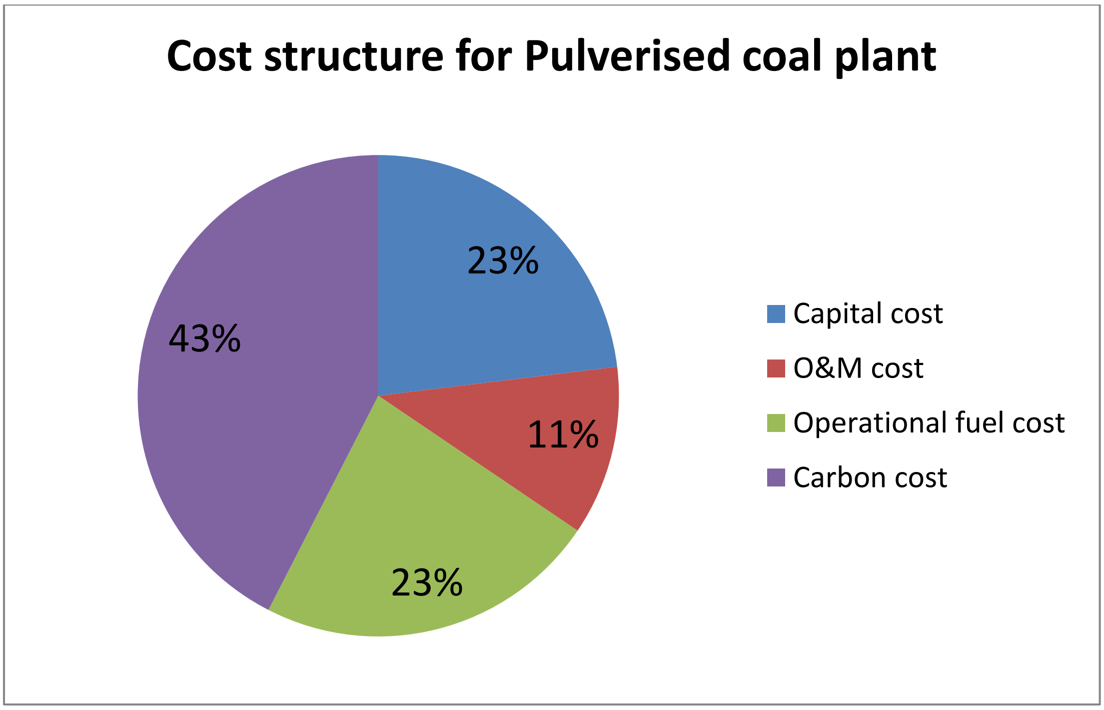

Figure 3.11: Cost structure for pulverised coal plant

For scenario analysis, the author sets a low cost scenario and a high cost scenario.

	Capital cost (k£)	O&M Cost (k£)	Coal price (£/tonne)	Carbon tax (£/ton CO2)
LOW	360000	10000	20	15
BASE	459000	15408.06	25	20
HIGH	560000	20000	50	50

Table 3-13: Different scenarios of pulverised coal power plant

Table 3-14 gives the results of levelised cost of different scenarios.

	Levelised cost (£/MWh)
LOW	26.00
BASE	34.30
HIGH	66.97

Table 3-14: levelised cost of different scenarios for pulverised coal power plant

3.3.6 Pulverised Coal with CCS Power Plant

3.3.6.1 Discounted Cash Flow Approach

According to the parameters of pulverised coal with CCS power plant, the author compiles the table of net present value (NPV), which is shown in Table 3-15. The Fixed O&M cost, Variable O&M cost and Fuel delivery cost are merged into the O&M cost in the table. The electricity price is set as 40£/MWh, and hence the revenue is 157680 k£(annual production *electricity price).

Year	Investment (k£)	O&M costs (k£)	Operational fuel costs (k£)	Additional cost of CCS (k£)	Revenue (k£)	Cash flow (k£)	Present worth factor (5%)	Present value (k£)	NPV (k£)
0	581000.00	0.00	0.00	0.00	0.00	-581000.00	**1.00**	-581000.00	-581000.00
1	0.00	0.00	0.00	0.00	0.00	0.00	**0.95**	0.00	-581000.00
2	0.00	0.00	0.00	0.00	0.00	0.00	**0.91**	0.00	-581000.00
3	0.00	0.00	0.00	0.00	0.00	0.00	**0.86**	0.00	-581000.00
4	0.00	0.00	0.00	0.00	0.00	0.00	**0.82**	0.00	-581000.00
5	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.78**	57207.08	-523792.92
6	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.75**	54482.93	-469309.99
7	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.71**	51888.51	-417421.48
8	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.68**	49417.63	-368003.86
9	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.64**	47064.41	-320939.45
10	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.61**	44823.24	-276116.21
11	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.58**	42688.80	-233427.40
12	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.56**	40656.00	-192771.40
13	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.53**	38720.00	-154051.40
14	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.51**	36876.19	-117175.21
15	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.48**	35120.18	-82055.02
16	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.46**	33447.79	-48607.23
17	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.44**	31855.04	-16752.19
18	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.42**	30338.14	13585.95
19	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.40**	28893.46	42479.41
20	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.38**	27517.58	69996.99
21	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.36**	26207.22	96204.22
22	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.34**	24959.26	121163.48

23	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.33**	23770.72	144934.20
24	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.31**	22638.78	167572.98
25	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.30**	21560.75	189133.73
26	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.28**	20534.04	209667.77
27	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.27**	19556.23	229224.01
28	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.26**	18624.98	247848.99
29	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.24**	17738.08	265587.07
30	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.23**	16893.41	282480.48
31	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.22**	16088.96	298569.44
32	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.21**	15322.82	313892.26
33	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.20**	14593.16	328485.42
34	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.19**	13898.25	342383.67
35	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.18**	13236.43	355620.10
36	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.17**	12606.12	368226.22
37	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.16**	12005.83	380232.05
38	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.16**	11434.12	391666.17
39	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.15**	10889.64	402555.82
40	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.14**	10371.09	412926.90
41	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.14**	9877.23	422804.13
42	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.13**	9406.88	432211.01
43	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.12**	8958.94	441169.95
44	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.12**	8532.32	449702.27
45	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.11**	8126.02	457828.29
46	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.11**	7739.07	465567.35
47	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.10**	7370.54	472937.89

48	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.10**	7019.56	479957.45
49	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.09**	6685.30	486642.74
50	0.00	22265.66	38750.00	23652.00	157680.00	73012.34	**0.09**	6366.95	493009.69

Table 3-15: Net present value of pulverised coal with CCS power plant

In Table 3-15, the discounted payback period is 18 years. It means this project with CCS plant will start to earn money from 18th year. At the end of project, the total net profit is 493009.69 k£. The internal rate of return can be calculated by Eq. (2.19). The result shows that IRR of this project is 8.79%.

According to the Table 3-15, the tornado diagram can be draw by increasing or decreasing main factors of project by 50%. These main factors are electricity price, discount rate, O&M cost, operational fuel cost and initial investment.

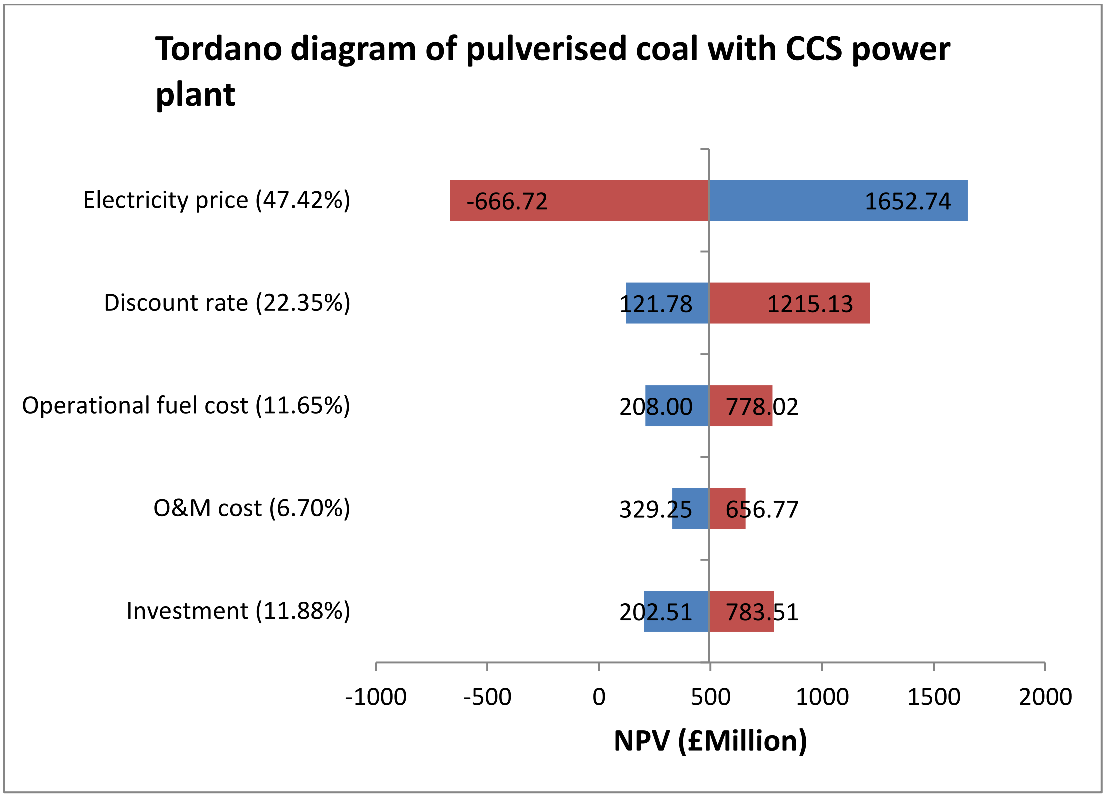

Figure 3.12: Tornado diagram of pulverised coal with CCS power plant

The cross of horizontal and vertical axes is 493.01 £Million, which is the NPV at the end of project lifetime in base scenario. In Figure 3.12, the blue bars shows the revised NPV when increasing each factor by 50%, while the red bars shows the revised NPV when decreasing each factor by 50%. The numbers at each bar end represent the minimum and maximum NPVs for the respected factor.

Several result can be get by observing the above tornado diagram:

1) The electricity price is still the most influential factor in the NPV as the NPV is ranging between -666.72£Million and 1652.74£Million. It has 47.42% variance contribution over the total NPV variation. So, the electricity price can be considered as the most important factor when investment this pulverised coal with CCS power plant.
2) The O&M cost, which merged by The Fixed O&M cost, Variable O&M cost and Fuel delivery cost, inversely, has the least influence on the NPV in this project. The NPV changes from 329.25£Million to 656.77£Million. It only has 6.70% contribution.

3.3.6.2 Levelised cost analysis

Table 3-16 shows the calculation of levelised cost by discounted method for base scenario. Note the discounted rate is 5%.

	Un-discounted Values						Discounted Values				
Year	Capital cost (k £)	O&M cost (k £)	Operational fuel cost (k £)	Additional cost of CCS (k £)	Annual production (MWh)	**Present worth factor (5%)**	Capital cost (k £)	O&M cost (k £)	Operational gas cost (k £)	Carbon cost (k £)	Annual production (MWh)
0	581000.00	0.00	0.00	0.00	0.00	**1.00**	581000.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	**0.95**	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	**0.91**	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	**0.86**	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	**0.82**	0.00	0.00	0.00	0.00	0.00
5	0.00	22265.66	38750.00	23652.00	3942000	**0.78**	0.00	17445.73	30361.64	18531.96	3088660.15
6	0.00	22265.66	38750.00	23652.00	3942000	**0.75**	0.00	16614.98	28915.85	17649.49	2941581.09
7	0.00	22265.66	38750.00	23652.00	3942000	**0.71**	0.00	15823.79	27538.90	16809.03	2801505.80
8	0.00	22265.66	38750.00	23652.00	3942000	**0.68**	0.00	15070.28	26227.53	16008.60	2668100.77
9	0.00	22265.66	38750.00	23652.00	3942000	**0.64**	0.00	14352.64	24978.60	15246.29	2541048.35
10	0.00	22265.66	38750.00	23652.00	3942000	**0.61**	0.00	13669.18	23789.14	14520.28	2420046.05
11	0.00	22265.66	38750.00	23652.00	3942000	**0.58**	0.00	13018.27	22656.32	13828.83	2304805.76
12	0.00	22265.66	38750.00	23652.00	3942000	**0.56**	0.00	12398.35	21577.45	13170.32	2195053.10
13	0.00	22265.66	38750.00	23652.00	3942000	**0.53**	0.00	11807.95	20549.95	12543.16	2090526.76
14	0.00	22265.66	38750.00	23652.00	3942000	**0.51**	0.00	11245.67	19571.38	11945.87	1990977.87
15	0.00	22265.66	38750.00	23652.00	3942000	**0.48**	0.00	10710.16	18639.41	11377.02	1896169.40
16	0.00	22265.66	38750.00	23652.00	3942000	**0.46**	0.00	10200.16	17751.82	10835.25	1805875.62
17	0.00	22265.66	38750.00	23652.00	3942000	**0.44**	0.00	9714.43	16906.50	10319.29	1719881.54
18	0.00	22265.66	38750.00	23652.00	3942000	**0.42**	0.00	9251.84	16101.43	9827.89	1637982.42
19	0.00	22265.66	38750.00	23652.00	3942000	**0.40**	0.00	8811.28	15334.69	9359.90	1559983.26
20	0.00	22265.66	38750.00	23652.00	3942000	**0.38**	0.00	8391.69	14604.47	8914.19	1485698.34
21	0.00	22265.66	38750.00	23652.00	3942000	**0.36**	0.00	7992.09	13909.02	8489.70	1414950.80

22	0.00	22265.66	38750.00	23652.00	3942000	**0.34**	0.00	7611.51	13246.68	8085.43	1347572.19
23	0.00	22265.66	38750.00	23652.00	3942000	**0.33**	0.00	7249.06	12615.89	7700.41	1283402.09
24	0.00	22265.66	38750.00	23652.00	3942000	**0.31**	0.00	6903.87	12015.13	7333.73	1222287.70
25	0.00	22265.66	38750.00	23652.00	3942000	**0.30**	0.00	6575.11	11442.98	6984.50	1164083.53
26	0.00	22265.66	38750.00	23652.00	3942000	**0.28**	0.00	6262.01	10898.08	6651.91	1108650.98
27	0.00	22265.66	38750.00	23652.00	3942000	**0.27**	0.00	5963.82	10379.12	6335.15	1055858.07
28	0.00	22265.66	38750.00	23652.00	3942000	**0.26**	0.00	5679.83	9884.88	6033.47	1005579.12
29	0.00	22265.66	38750.00	23652.00	3942000	**0.24**	0.00	5409.36	9414.17	5746.17	957694.40
30	0.00	22265.66	38750.00	23652.00	3942000	**0.23**	0.00	5151.77	8965.88	5472.54	912089.90
31	0.00	22265.66	38750.00	23652.00	3942000	**0.22**	0.00	4906.45	8538.93	5211.94	868657.05
32	0.00	22265.66	38750.00	23652.00	3942000	**0.21**	0.00	4672.81	8132.31	4963.75	827292.43
33	0.00	22265.66	38750.00	23652.00	3942000	**0.20**	0.00	4450.29	7745.06	4727.39	787897.55
34	0.00	22265.66	38750.00	23652.00	3942000	**0.19**	0.00	4238.38	7376.25	4502.27	750378.62
35	0.00	22265.66	38750.00	23652.00	3942000	**0.18**	0.00	4036.55	7025.00	4287.88	714646.30
36	0.00	22265.66	38750.00	23652.00	3942000	**0.17**	0.00	3844.33	6690.47	4083.69	680615.53
37	0.00	22265.66	38750.00	23652.00	3942000	**0.16**	0.00	3661.27	6371.88	3889.23	648205.27
38	0.00	22265.66	38750.00	23652.00	3942000	**0.16**	0.00	3486.92	6068.46	3704.03	617338.35
39	0.00	22265.66	38750.00	23652.00	3942000	**0.15**	0.00	3320.88	5779.48	3527.65	587941.28
40	0.00	22265.66	38750.00	23652.00	3942000	**0.14**	0.00	3162.74	5504.27	3359.66	559944.08
41	0.00	22265.66	38750.00	23652.00	3942000	**0.14**	0.00	3012.13	5242.16	3199.68	533280.08
42	0.00	22265.66	38750.00	23652.00	3942000	**0.13**	0.00	2868.70	4992.54	3047.31	507885.79
43	0.00	22265.66	38750.00	23652.00	3942000	**0.12**	0.00	2732.09	4754.80	2902.20	483700.75
44	0.00	22265.66	38750.00	23652.00	3942000	**0.12**	0.00	2601.99	4528.38	2764.00	460667.38
45	0.00	22265.66	38750.00	23652.00	3942000	**0.11**	0.00	2478.09	4312.74	2632.39	438730.84
46	0.00	22265.66	38750.00	23652.00	3942000	**0.11**	0.00	2360.09	4107.37	2507.03	417838.89

47	0.00	22265.66	38750.00	23652.00	3942000	**0.10**	0.00	2247.70	3911.78	2387.65	397941.80
48	0.00	22265.66	38750.00	23652.00	3942000	**0.10**	0.00	2140.67	3725.51	2273.95	378992.19
49	0.00	22265.66	38750.00	23652.00	3942000	**0.09**	0.00	2038.73	3548.10	2165.67	360944.95
50	0.00	22265.66	38750.00	23652.00	3942000	**0.09**	0.00	1941.65	3379.14	2062.54	343757.09
TOTAL	581000.00	1024220.36	1782500.00	1087992.00	1.81E+08		581000.00	327527.30	570011.53	347920.33	57986721.28

Table 3-16: Levelised calculation for pulverised coal with CCS power plant

From Table 3-16, the levelised cost for base scenario is

$$LC_D = \frac{PV(Total\ Costs)}{PV(Total\ Outputs)} = 0.03150 \text{ k£/MWh} = 31.50 \text{ £/MWh}$$

The Figure 3.13 gives the cost structure for pulverised coal plant project. The data is from the discounted total values of each cost in Table 3-16. In this figure, capital cost and operational fuel cost almost account for the same proportion and O&M cost and additional cost of CCS account for the same proportion as well.

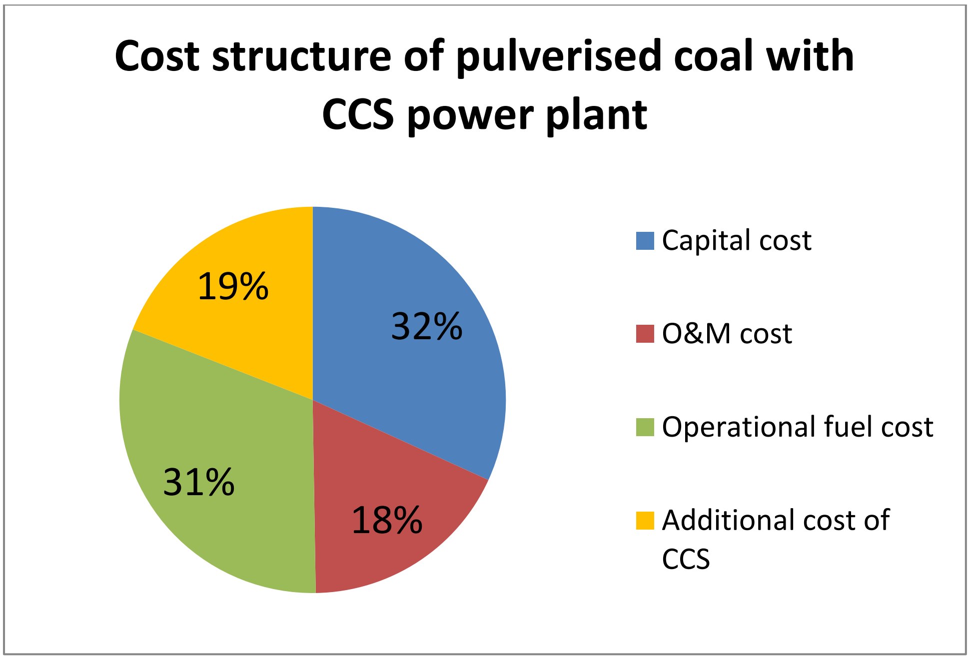

Figure 3.13: Cost structure of pulverised coal with CCS power plant

For scenario analysis, the author sets a low cost scenario and a high cost scenario.

	Capital cost (k£)	O&M Cost (k£)	Coal price (£/tonne)	Additional cost of CCS (k£)
LOW	500000	15000	20	3
BASE	581000	22265.66	25	6
HIGH	650000	30000	50	9

Table 3-17: Different scenarios of pulverised coal with CCS power plant

Table 3-18 gives the results of levelised cost of different scenarios.

	Levelised cost (£/MWh)
LOW	23.29
BASE	31.50
HIGH	47.48

Table 3-18: levelised cost of different scenarios for pulverised coal with CCS power plant

3.3.7 Integrated Gasification Combined Cycle (IGCC)

3.3.7.1 Discounted Cash Flow Approach

According to the parameters of IGCC power plant, the author compiles the table of net present value (NPV), which is shown in Table 3-19. The Fixed O&M cost, Variable O&M cost and Fuel delivery cost are merged into the O&M cost in the table. The electricity price is set as 40 £/MWh, and hence the revenue is 157680 k£ (annual production *electricity price).

Year	Investment (k£)	O&M costs (k£)	Operational fuel costs (k£)	Carbon tax (k£)	Revenue (k£)	Cash flow (k£)	Present worth factor (5%)	Present value (k£)	NPV (k£)
0	534500.00	0.00	0.00	0.00	0.00	-534500.00	**1.00**	-534500.00	-534500.00
1	0.00	0.00	0.00	0.00	0.00	0.00	**0.95**	0.00	-534500.00
2	0.00	0.00	0.00	0.00	0.00	0.00	**0.91**	0.00	-534500.00
3	0.00	0.00	0.00	0.00	0.00	0.00	**0.86**	0.00	-534500.00
4	0.00	0.00	0.00	0.00	0.00	0.00	**0.82**	0.00	-534500.00
5	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.78**	39431.33	-495068.67
6	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.75**	37553.64	-457515.03
7	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.71**	35765.38	-421749.65
8	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.68**	34062.26	-387687.39
9	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.64**	32440.25	-355247.14
10	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.61**	30895.48	-324351.66
11	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.58**	29424.26	-294927.40
12	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.56**	28023.11	-266904.29
13	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.53**	26688.67	-240215.62
14	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.51**	25417.78	-214797.83
15	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.48**	24207.41	-190590.42
16	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.46**	23054.68	-167535.74
17	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.44**	21956.84	-145578.90
18	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.42**	20911.27	-124667.63
19	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.40**	19915.50	-104752.13
20	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.38**	18967.14	-85784.98
21	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.36**	18063.95	-67721.04
22	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.34**	17203.76	-50517.28
23	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.33**	16384.53	-34132.75

24	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.31**	15604.32	-18528.44
25	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.30**	14861.25	-3667.18
26	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.28**	14153.57	10486.39
27	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.27**	13479.59	23965.98
28	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.26**	12837.71	36803.69
29	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.24**	12226.39	49030.08
30	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.23**	11644.18	60674.26
31	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.22**	11089.70	71763.96
32	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.21**	10561.61	82325.57
33	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.20**	10058.68	92384.25
34	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.19**	9579.70	101963.95
35	0.00	16611.09	31951.91	58791.52	157680.00	50325.48	**0.18**	9123.52	111087.47

Table 3-19: Net present value of IGCC

In Table 3-19, it is obviously to find that the discounted payback period is 26 years. It means this project will start to earn money from 26th year. At the end of project, the total net profit is 111087.47 k£. The internal rate of return can be calculated by Eq. (2.19). The result shows that IRR of this project is 6.26%.

According to the Table 3-19, the tornado diagram can be draw by increasing or decreasing main factors of project by 50%. These main factors are electricity price, discount rate, carbon tax, operational fuel cost, O&M cost and initial investment.

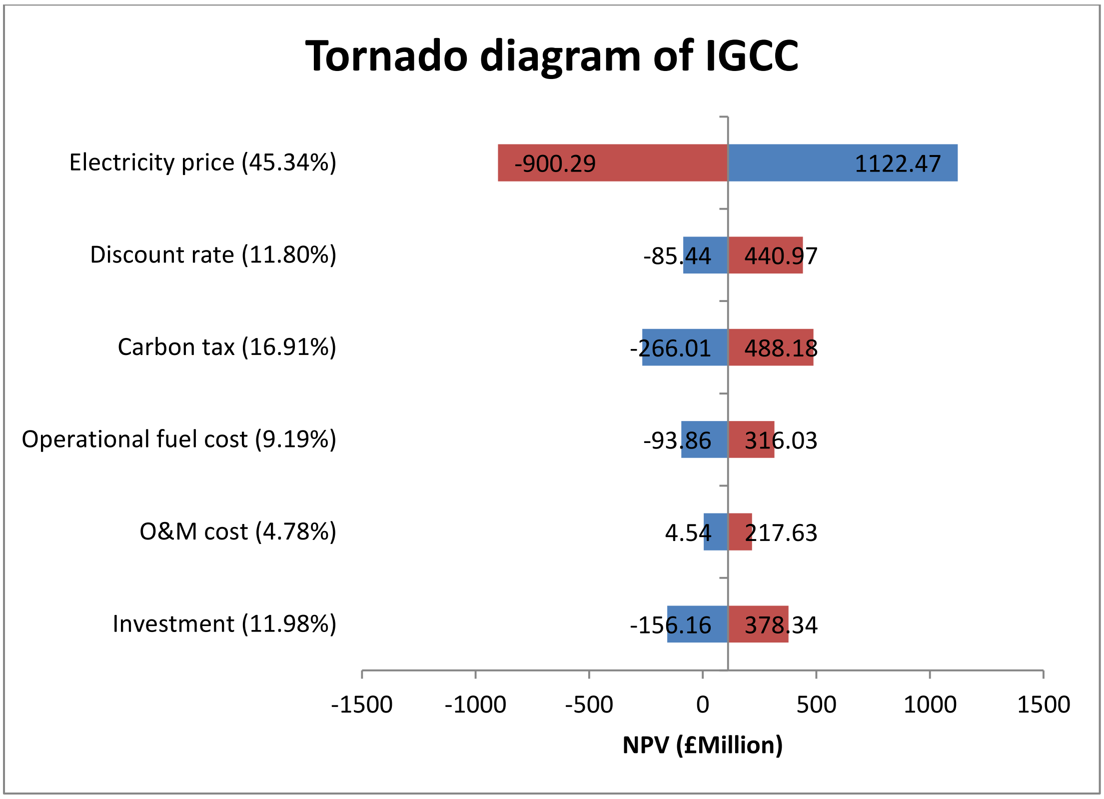

Figure 3.14: Tornado diagram of IGCC

The cross of horizontal and vertical axes is 111.09 £Million, which is the NPV at the end of project lifetime in base scenario. In Figure 3.14, the blue bars shows the revised NPV when increasing each factor by 50%, while the red bars shows the revised NPV when decreasing each factor by 50%. The numbers at each bar end represent the minimum and maximum NPVs for the respected factor.

Several result can be get by observing the above tornado diagram:

1) The electricity price is still the most influential factor in the NPV as the NPV is ranging between -900.29 £Million and 1122.47 £Million. It has 45.34% variance contribution over the total NPV variation. So, the electricity price can be considered as the most important factor when investment this IGCC plant.
2) The O&M cost, which merged by The Fixed O&M cost, Variable O&M cost and Fuel delivery cost, inversely, has the least influence on the NPV in this project. The NPV changes from 4.54 £Million to 217.63 £Million. It only has 4.78% contribution.

3.3.7.2 Levelised cost analysis

Table 3-20 shows the calculation of levelised cost by discounted method for base scenario. Note the discounted rate is 5%.

	Un-discounted values						Discounted values				
Year	Capital cost (k £)	O&M cost (k £)	Operational fuel cost (k £)	Carbon cost (k £)	Annual production (MWh)	**Present worth factor (5%)**	Capital cost (k £)	O&M cost (k £)	Operational fuel cost (k £)	Carbon cost (k £)	Annual production (MWh)
0	534500.00	0.00	0.00	0.00	0.00	**1.00**	534500.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	**0.95**	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	**0.91**	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	**0.86**	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	**0.82**	0.00	0.00	0.00	0.00	0.00
5	0.00	16611.09	31951.91	58791.52	3942000	**0.78**	0.00	13015.22	25035.16	46064.70	3088660.15
6	0.00	16611.09	31951.91	58791.52	3942000	**0.75**	0.00	12395.45	23843.01	43871.14	2941581.09
7	0.00	16611.09	31951.91	58791.52	3942000	**0.71**	0.00	11805.19	22707.63	41782.04	2801505.80
8	0.00	16611.09	31951.91	58791.52	3942000	**0.68**	0.00	11243.04	21626.31	39792.42	2668100.77
9	0.00	16611.09	31951.91	58791.52	3942000	**0.64**	0.00	10707.66	20596.49	37897.54	2541048.35
10	0.00	16611.09	31951.91	58791.52	3942000	**0.61**	0.00	10197.77	19615.70	36092.89	2420046.05
11	0.00	16611.09	31951.91	58791.52	3942000	**0.58**	0.00	9712.16	18681.62	34374.18	2304805.76
12	0.00	16611.09	31951.91	58791.52	3942000	**0.56**	0.00	9249.68	17792.02	32737.32	2195053.10
13	0.00	16611.09	31951.91	58791.52	3942000	**0.53**	0.00	8809.22	16944.78	31178.40	2090526.76
14	0.00	16611.09	31951.91	58791.52	3942000	**0.51**	0.00	8389.73	16137.89	29693.71	1990977.87
15	0.00	16611.09	31951.91	58791.52	3942000	**0.48**	0.00	7990.22	15369.42	28279.73	1896169.40
16	0.00	16611.09	31951.91	58791.52	3942000	**0.46**	0.00	7609.73	14637.54	26933.07	1805875.62
17	0.00	16611.09	31951.91	58791.52	3942000	**0.44**	0.00	7247.36	13940.51	25650.55	1719881.54
18	0.00	16611.09	31951.91	58791.52	3942000	**0.42**	0.00	6902.25	13276.68	24429.09	1637982.42
19	0.00	16611.09	31951.91	58791.52	3942000	**0.40**	0.00	6573.57	12644.46	23265.80	1559983.26
20	0.00	16611.09	31951.91	58791.52	3942000	**0.38**	0.00	6260.55	12042.34	22157.91	1485698.34
21	0.00	16611.09	31951.91	58791.52	3942000	**0.36**	0.00	5962.42	11468.90	21102.77	1414950.80

22	0.00	16611.09	31951.91	58791.52	3942000	**0.34**	0.00	5678.50	10922.76	20097.87	1347572.19
23	0.00	16611.09	31951.91	58791.52	3942000	**0.33**	0.00	5408.09	10402.63	19140.83	1283402.09
24	0.00	16611.09	31951.91	58791.52	3942000	**0.31**	0.00	5150.57	9907.26	18229.36	1222287.70
25	0.00	16611.09	31951.91	58791.52	3942000	**0.30**	0.00	4905.30	9435.49	17361.30	1164083.53
26	0.00	16611.09	31951.91	58791.52	3942000	**0.28**	0.00	4671.72	8986.18	16534.57	1108650.98
27	0.00	16611.09	31951.91	58791.52	3942000	**0.27**	0.00	4449.25	8558.27	15747.21	1055858.07
28	0.00	16611.09	31951.91	58791.52	3942000	**0.26**	0.00	4237.38	8150.73	14997.34	1005579.12
29	0.00	16611.09	31951.91	58791.52	3942000	**0.24**	0.00	4035.60	7762.60	14283.18	957694.40
30	0.00	16611.09	31951.91	58791.52	3942000	**0.23**	0.00	3843.43	7392.95	13603.03	912089.90
31	0.00	16611.09	31951.91	58791.52	3942000	**0.22**	0.00	3660.41	7040.91	12955.27	868657.05
32	0.00	16611.09	31951.91	58791.52	3942000	**0.21**	0.00	3486.11	6705.63	12338.35	827292.43
33	0.00	16611.09	31951.91	58791.52	3942000	**0.20**	0.00	3320.10	6386.31	11750.81	787897.55
34	0.00	16611.09	31951.91	58791.52	3942000	**0.19**	0.00	3162.00	6082.20	11191.25	750378.62
35	0.00	16611.09	31951.91	58791.52	3942000	**0.18**	0.00	3011.43	5792.57	10658.33	714646.30
TOTAL	534500.00	514943.79	990509.32	1822537.15	122202000		534500.00	213091.11	409886.94	754191.96	50568937.02

Table 3-20: Levelised cost calculation for IGCC

From Table 3-20, the levelised cost for base scenario is

$$LC_D = \frac{PV(Total\ Costs)}{PV(Total\ Outputs)} = 0.03780 \text{ k £/MWh} = 37.80 \text{ £/MWh}$$

The Figure 3.15 gives the cost structure for pulverised coal plant project. The data is from the discounted total values of each cost in Table 3-20. In this figure, carbon tax cost accounts for the largest proportion and O&M cost accounts for the smallest proportion.

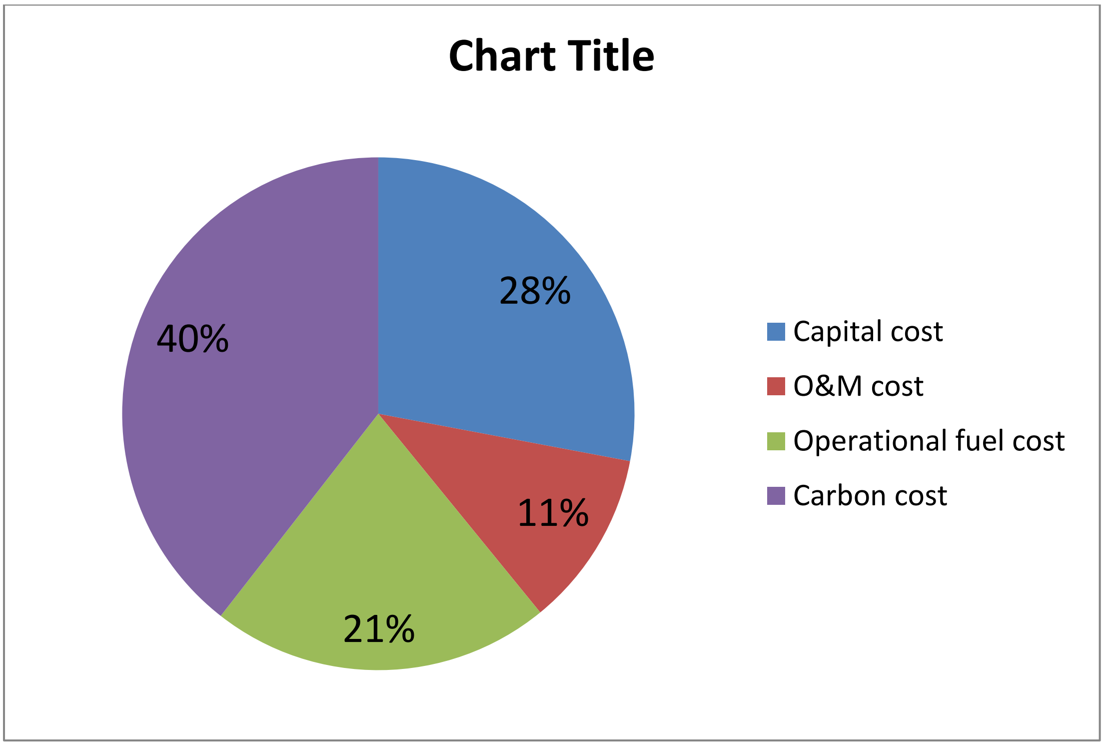

Figure 3.15: Cost structure for pulverised coal plant

For scenario analysis, the author sets a low cost scenario and a high cost scenario.

	Capital cost (k£)	O&M Cost (k£)	Coal price (£/tonne)	Carbon tax (£/ton CO2)
LOW	450000	10000	20	15
BASE	534500	16611.09	25	20
HIGH	600000	22000	50	50

Table 3-21: Different scenarios of IGCC

Table 3-22 gives the results of levelised cost of different scenarios.

	Levelised cost (£/MWh)
LOW	29.11
BASE	37.80
HIGH	70.8

Table 3-22: Levelised cost of different scenarios for IGCC

3.3.8 Integrated Gasification Combined Cycle (IGCC) with CCS

3.3.8.1 Discounted Cash Flow Approach

According to the parameters of IGCC with CCS power plant, the author compiles the table of net present value (NPV), which is shown in Table 3-23. The Fixed O&M cost, Variable O&M cost and Fuel delivery cost are merged into the O&M cost in the table. The electricity price is set as 40£/MWh, and hence the revenue is 157680 k£ (annual production *electricity price).

Year	Investment (k£)	O&M costs (k£)	Operational fuel costs (k£)	Additional cost of CCS (k£)	Revenue (k£)	Cash flow (k£)	Present worth factor (5%)	Present value (k£)	NPV (k£)
0	726000.00	0.00	0.00	0.00	0.00	-726000.00	1.00	-726000.00	-726000.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.95	0.00	-726000.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.91	0.00	-726000.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.00	-726000.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.82	0.00	-726000.00
5	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.78	59421.32	-666578.68
6	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.75	56591.73	-609986.94
7	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.71	53896.89	-556090.05
8	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.68	51330.37	-504759.68
9	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.64	48886.07	-455873.61
10	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.61	46558.16	-409315.45
11	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.58	44341.10	-364974.35
12	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.56	42229.62	-322744.73
13	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.53	40218.69	-282526.04
14	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.51	38303.51	-244222.52
15	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.48	36479.54	-207742.99
16	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.46	34742.42	-173000.57
17	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.44	33088.02	-139912.56
18	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.42	31512.40	-108400.16
19	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.40	30011.81	-78388.36
20	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.38	28582.67	-49805.68
21	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.36	27221.59	-22584.09
22	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.34	25925.33	3341.23

23	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.33	24690.79	28032.02
24	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.31	23515.03	51547.05
25	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.30	22395.27	73942.32
26	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.28	21328.83	95271.15
27	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.27	20313.17	115584.33
28	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.26	19345.88	134930.20
29	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.24	18424.64	153354.85
30	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.23	17547.28	170902.13
31	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.22	16711.70	187613.82
32	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.21	15915.90	203529.73
33	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.20	15158.00	218687.73
34	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.19	14436.19	233123.92
35	0.00	21729.73	36459.94	23652.00	157680.00	75838.34	0.18	13748.75	246872.67

Table 3-23: Net present value of IGCC with CCS

In Table 3-23, the discounted payback period is 22 years. It means this project will start to earn money from 22th year. At the end of project, the total net profit is 246872.67 k£. The internal rate of return can be calculated by Eq. (2.19). The result shows that IRR of this project is 6.99%.

According to the Table 3-23, the tornado diagram can be draw by increasing or decreasing main factors of project by 50%. These main factors are electricity price, discount rate, operational fuel cost, O&M cost and initial investment.

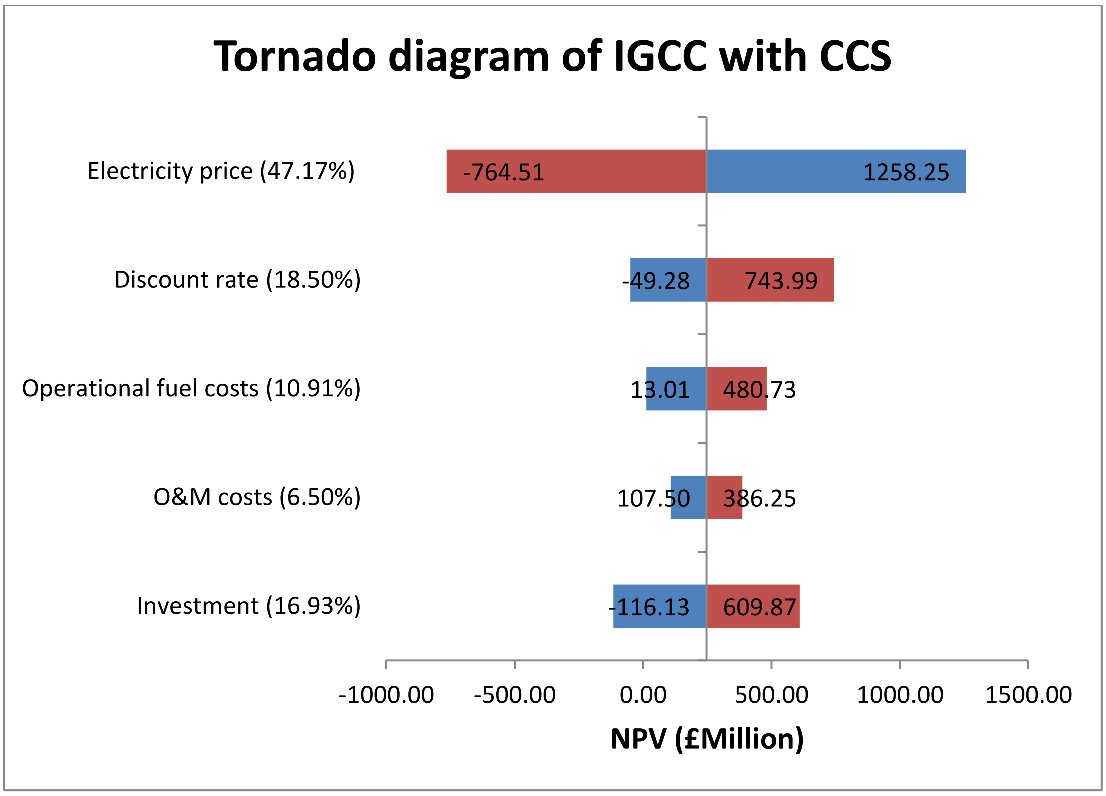

Figure 3.16: Tornado diagram of IGCC with CCS

The cross of horizontal and vertical axes is 111.09 £Million, which is the NPV at the end of project lifetime in base scenario. In Figure 3.16, the blue bars shows the revised NPV when increasing each factor by 50%, while the red bars shows the revised NPV when decreasing each factor by 50%. The numbers at each bar end represent the minimum and maximum NPVs for the respected factor.

Several result can be get by observing the above tornado diagram:

1) The electricity price is still the most influential factor in the NPV as the NPV is ranging between -764.51£Million and 1258.25£Million. It has 47.17% variance contribution over the total NPV variation. So, the electricity price can be considered as the most important factor when investment this IGCC with CCS plant.
2) The O&M cost, which merged by The Fixed O&M cost, Variable O&M cost and Fuel delivery cost, inversely, has the least influence on the NPV in this project. The NPV changes from 107.50£Million to 386.25£Million. It only has 6.50% contribution.

3.3.8.2 Levelised cost analysis

Table 3-24 shows the calculation of levelised cost by discounted method for base scenario. Note the discounted rate is 5%.

	Un-discounted values						**Discounted values**				
Year	Capital cost (k £)	O&M cost (k £)	Operational fuel cost (k £)	Additional cost of CCS (k £)	Annual production (MWh)	**Present worth factor (5%)**	Capital cost (k £)	O&M cost (k £)	Operational fuel cost (k £)	Additional cost of CCS (k £)	Annual production (MWh)
0	726000.00	0.00	0.00	0.00	0.00	**1.00**	726000.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	**0.95**	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	**0.91**	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	**0.86**	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	**0.82**	0.00	0.00	0.00	0.00	0.00
5	0.00	21729.73	36459.94	23652.00	3942000	**0.78**	0.00	17025.81	28567.32	18531.96	3088660.15
6	0.00	21729.73	36459.94	23652.00	3942000	**0.75**	0.00	16215.06	27206.97	17649.49	2941581.09
7	0.00	21729.73	36459.94	23652.00	3942000	**0.71**	0.00	15442.91	25911.40	16809.03	2801505.80
8	0.00	21729.73	36459.94	23652.00	3942000	**0.68**	0.00	14707.53	24677.52	16008.60	2668100.77
9	0.00	21729.73	36459.94	23652.00	3942000	**0.64**	0.00	14007.17	23502.40	15246.29	2541048.35
10	0.00	21729.73	36459.94	23652.00	3942000	**0.61**	0.00	13340.17	22383.24	14520.28	2420046.05
11	0.00	21729.73	36459.94	23652.00	3942000	**0.58**	0.00	12704.92	21317.37	13828.83	2304805.76
12	0.00	21729.73	36459.94	23652.00	3942000	**0.56**	0.00	12099.92	20302.26	13170.32	2195053.10
13	0.00	21729.73	36459.94	23652.00	3942000	**0.53**	0.00	11523.74	19335.48	12543.16	2090526.76
14	0.00	21729.73	36459.94	23652.00	3942000	**0.51**	0.00	10974.99	18414.75	11945.87	1990977.87
15	0.00	21729.73	36459.94	23652.00	3942000	**0.48**	0.00	10452.37	17537.85	11377.02	1896169.40
16	0.00	21729.73	36459.94	23652.00	3942000	**0.46**	0.00	9954.64	16702.72	10835.25	1805875.62
17	0.00	21729.73	36459.94	23652.00	3942000	**0.44**	0.00	9480.61	15907.35	10319.29	1719881.54
18	0.00	21729.73	36459.94	23652.00	3942000	**0.42**	0.00	9029.15	15149.86	9827.89	1637982.42
19	0.00	21729.73	36459.94	23652.00	3942000	**0.40**	0.00	8599.19	14428.44	9359.90	1559983.26
20	0.00	21729.73	36459.94	23652.00	3942000	**0.38**	0.00	8189.70	13741.37	8914.19	1485698.34
21	0.00	21729.73	36459.94	23652.00	3942000	**0.36**	0.00	7799.72	13087.02	8489.70	1414950.80

22	0.00	21729.73	36459.94	23652.00	3942000	**0.34**	0.00	7428.30	12463.83	8085.43	1347572.19
23	0.00	21729.73	36459.94	23652.00	3942000	**0.33**	0.00	7074.58	11870.31	7700.41	1283402.09
24	0.00	21729.73	36459.94	23652.00	3942000	**0.31**	0.00	6737.69	11305.06	7333.73	1222287.70
25	0.00	21729.73	36459.94	23652.00	3942000	**0.30**	0.00	6416.85	10766.72	6984.50	1164083.53
26	0.00	21729.73	36459.94	23652.00	3942000	**0.28**	0.00	6111.28	10254.02	6651.91	1108650.98
27	0.00	21729.73	36459.94	23652.00	3942000	**0.27**	0.00	5820.27	9765.73	6335.15	1055858.07
28	0.00	21729.73	36459.94	23652.00	3942000	**0.26**	0.00	5543.11	9300.70	6033.47	1005579.12
29	0.00	21729.73	36459.94	23652.00	3942000	**0.24**	0.00	5279.16	8857.81	5746.17	957694.40
30	0.00	21729.73	36459.94	23652.00	3942000	**0.23**	0.00	5027.77	8436.01	5472.54	912089.90
31	0.00	21729.73	36459.94	23652.00	3942000	**0.22**	0.00	4788.35	8034.29	5211.94	868657.05
32	0.00	21729.73	36459.94	23652.00	3942000	**0.21**	0.00	4560.33	7651.71	4963.75	827292.43
33	0.00	21729.73	36459.94	23652.00	3942000	**0.20**	0.00	4343.18	7287.34	4727.39	787897.55
34	0.00	21729.73	36459.94	23652.00	3942000	**0.19**	0.00	4136.36	6940.32	4502.27	750378.62
35	0.00	21729.73	36459.94	23652.00	3942000	**0.18**	0.00	3939.39	6609.83	4287.88	714646.30
TOTAL	726000.00	673621.49	1130258.08	733212.00	1.22E+08		726000.00	278754.21	467716.97	303413.62	50568937.02

Table 3-24: Levelised cost calculation for IGCC with CCS

According to Table 3-24, the levelised cost for base scenario is

$$LC_D = \frac{PV(Total\ Costs)}{PV(Total\ Outputs)} = 0.03512 \text{ k £/MWh} = 35.12 \text{ £/MWh}$$

The Figure 3.17 gives the cost structure for pulverised coal plant project. The data is from the discounted total values of each cost in Table 3-24. In this figure, carbon tax cost accounts for the largest proportion and O&M cost accounts for the smallest proportion.

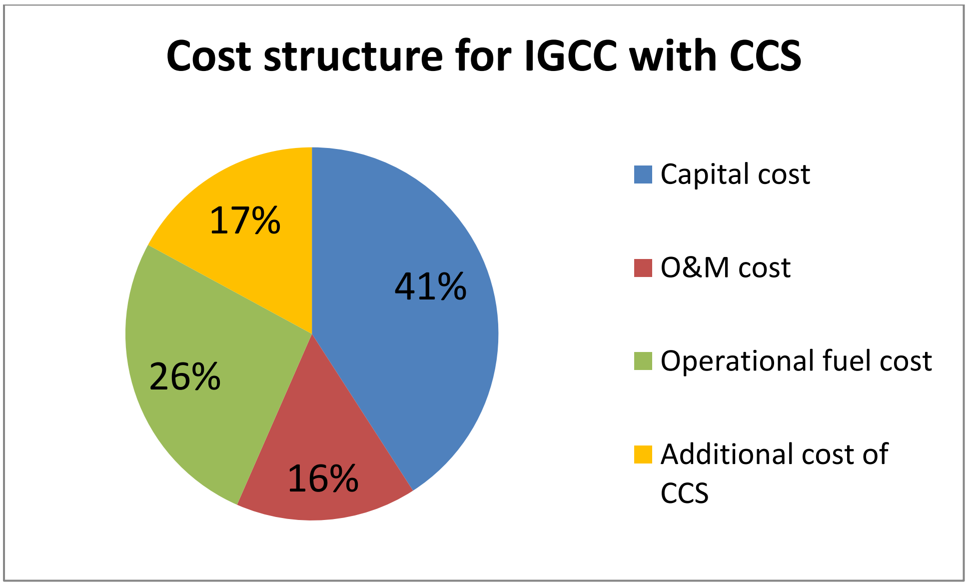

Figure 3.17: Cost structure for IGCC with CCS

For scenario analysis, the author sets a low cost scenario and a high cost scenario.

	Capital cost (k £)	O&M Cost (k £)	Coal price (£/tonne)	Additional cost of CCS (£/ton CO2)
LOW	650000	15000	20	3
BASE	726000.00	21729.73	25	6
HIGH	800000	26000	50	9

Table 3-25: Different scenarios of IGCC with CCS

Table 3-26 gives the results of levelised cost of different scenarios.

	Levelised cost (£/MWh)
LOW	27.06
BASE	35.12
HIGH	49.92

Table 3-26: Levelised cost of different scenarios for IGCC with CCS

3.3.9 Onshore wind power

3.3.9.1 Discounted Cash Flow Approach

According to the parameters of onshore wind power, the author compiles the table of net present value (NPV), which is shown in Table 3-27. The revenue is 18501.12 k£ (annual production *(electricity price + ROC)).

Year	Investment (k£)	O&M costs (k£)	Revenue (k£)	Cash flow (k£)	Present worth factor (5%)	Present value (k£)	NPV (k£)
0	71600.00	0.00	0.00	-71600.00	**1.00**	-71600.00	-71600.00
1	0.00	0.00	0.00	0.00	**0.95**	0.00	-71600.00
2	0.00	0.00	0.00	0.00	**0.91**	0.00	-71600.00
3	0.00	3552.00	18501.12	14949.12	**0.86**	12913.61	-58686.39
4	0.00	3552.00	18501.12	14949.12	**0.82**	12298.68	-46387.71
5	0.00	3552.00	18501.12	14949.12	**0.78**	11713.03	-34674.68
6	0.00	3552.00	18501.12	14949.12	**0.75**	11155.26	-23519.42
7	0.00	3552.00	18501.12	14949.12	**0.71**	10624.06	-12895.36
8	0.00	3552.00	18501.12	14949.12	**0.68**	10118.15	-2777.21
9	0.00	3552.00	18501.12	14949.12	**0.64**	9636.34	6859.13
10	0.00	3552.00	18501.12	14949.12	**0.61**	9177.46	16036.59
11	0.00	3552.00	18501.12	14949.12	**0.58**	8740.44	24777.03
12	0.00	3552.00	18501.12	14949.12	**0.56**	8324.23	33101.26
13	0.00	3552.00	18501.12	14949.12	**0.53**	7927.84	41029.10
14	0.00	3552.00	18501.12	14949.12	**0.51**	7550.32	48579.42
15	0.00	3552.00	18501.12	14949.12	**0.48**	7190.78	55770.20
16	0.00	3552.00	18501.12	14949.12	**0.46**	6848.36	62618.57
17	0.00	3552.00	18501.12	14949.12	**0.44**	6522.25	69140.82
18	0.00	3552.00	18501.12	14949.12	**0.42**	6211.67	75352.49
19	0.00	3552.00	18501.12	14949.12	**0.40**	5915.87	81268.36
20	0.00	3552.00	18501.12	14949.12	**0.38**	5634.17	86902.53

Table 3-27: Net present value of onshore wind power

In Table 3-27, the discounted payback period is 9 years. It means this project will start to earn money from 9th year. At the end of project, the total net profit is 86902.53 k£. The internal rate of return can be calculated by Eq. (2.19). The result shows that IRR of this project is 14.53%.

According to the Table 3-27, the tornado diagram can be draw by increasing or decreasing main factors of project by 50%. These main factors are electricity price, ROC price, discount rate, O&M cost and initial investment.

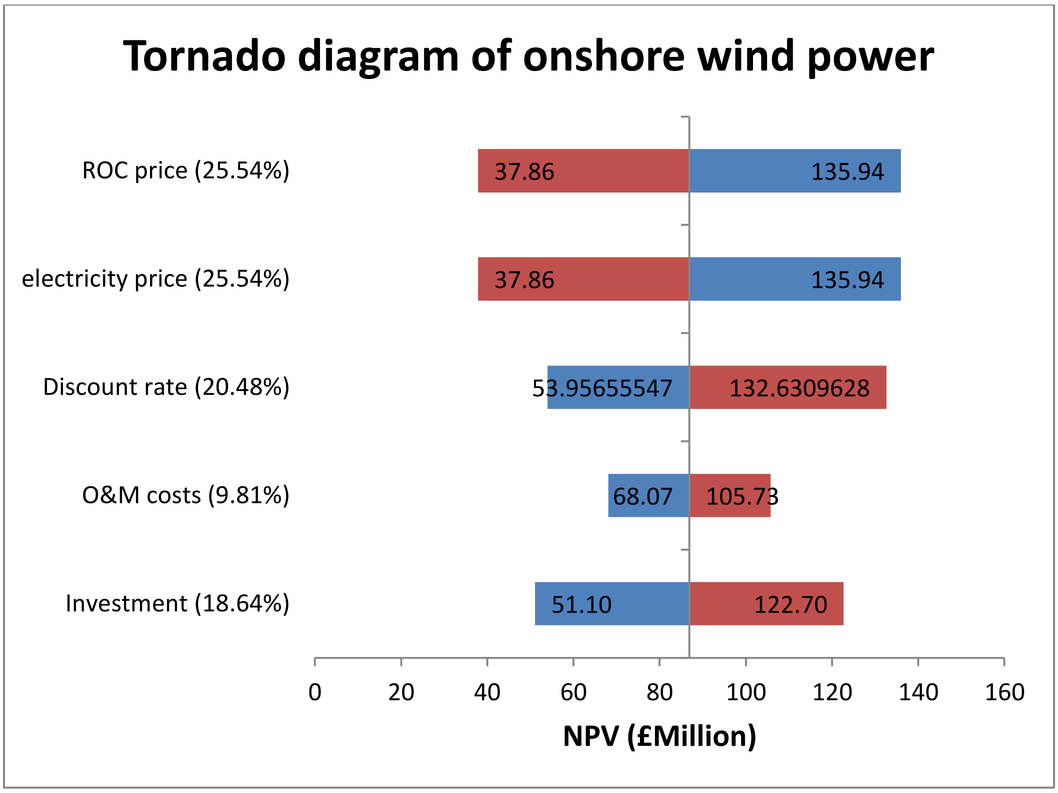

Figure 3.18: Tornado diagram of onshore wind power

The cross of horizontal and vertical axes is 86.90 £Million, which is the NPV at the end of project lifetime in base scenario. In Figure 3.18, the blue bars shows the revised NPV when increasing each factor by 50%, while the red bars shows the revised NPV when decreasing each factor by 50%. The numbers at each bar end represent the minimum and maximum NPVs for the respected factor.

Several result can be get by observing the above tornado diagram:

1) The electricity price and ROC price are the most influential factor in the NPV as the NPV is ranging between 37.86£Million and 135.94£Million. Both of them have 25.54% variance contribution over the total NPV variation. So, the electricity price and ROC price can be considered as the most important factors when investment this onshore wind power project.
2) The O&M cost has the least influence on the NPV in this project. The NPV changes from 68.07£Million to 105.73£Million. It only has 9.81% contribution.

3.3.9.2 Levelised cost analysis

Table 3-28 shows the calculation of levelised cost by discounted method for base scenario. The wind power project only has capital cost and O&M cost. Note the discounted rate is 5%.

	Un-discounted values			Present worth factor (5%)	Discounted values		
Year	Capital cost (k£)	O&M cost (k£)	Annual production (MWh)		Capital cost (k£)	O&M cost (k£)	Annual production (MWh)
0	71600.00	0.00	0.00	**1.00**	71600.00	0.00	0.00
1	0.00	0.00	0.00	**0.95**	0.00	0.00	0.00
2	0.00	0.00	0.00	**0.91**	0.00	0.00	0.00
3	0.00	3552.00	231264	**0.86**	0.00	3068.35	199774.54
4	0.00	3552.00	231264	**0.82**	0.00	2922.24	190261.47
5	0.00	3552.00	231264	**0.78**	0.00	2783.08	181201.40
6	0.00	3552.00	231264	**0.75**	0.00	2650.56	172572.76
7	0.00	3552.00	231264	**0.71**	0.00	2524.34	164355.01
8	0.00	3552.00	231264	**0.68**	0.00	2404.13	156528.58
9	0.00	3552.00	231264	**0.64**	0.00	2289.65	149074.84
10	0.00	3552.00	231264	**0.61**	0.00	2180.62	141976.03
11	0.00	3552.00	231264	**0.58**	0.00	2076.78	135215.27
12	0.00	3552.00	231264	**0.56**	0.00	1977.89	128776.45
13	0.00	3552.00	231264	**0.53**	0.00	1883.70	122644.24
14	0.00	3552.00	231264	**0.51**	0.00	1794.00	116804.04
15	0.00	3552.00	231264	**0.48**	0.00	1708.57	111241.94
16	0.00	3552.00	231264	**0.46**	0.00	1627.21	105944.70
17	0.00	3552.00	231264	**0.44**	0.00	1549.73	100899.72
18	0.00	3552.00	231264	**0.42**	0.00	1475.93	96094.97
19	0.00	3552.00	231264	**0.40**	0.00	1405.65	91519.02
20	0.00	3552.00	231264	**0.38**	0.00	1338.71	87160.97
TOTAL	71600.00	63936.00	4162752		71600.00	37661.15	2452045.92

Table 3-28: Levelised calculation for onshore wind power

According to Table 3-28, the levelised cost for base scenario is

$$LC_D = \frac{PV(Total\ Costs)}{PV(Total\ Outputs)} = 0.04456 \text{ k£/MWh} = 44.56 \text{ £/MWh}$$

The Figure 3.19 gives the cost structure for pulverised coal plant project. The data is from the discounted total values of each cost in Table 3-28.

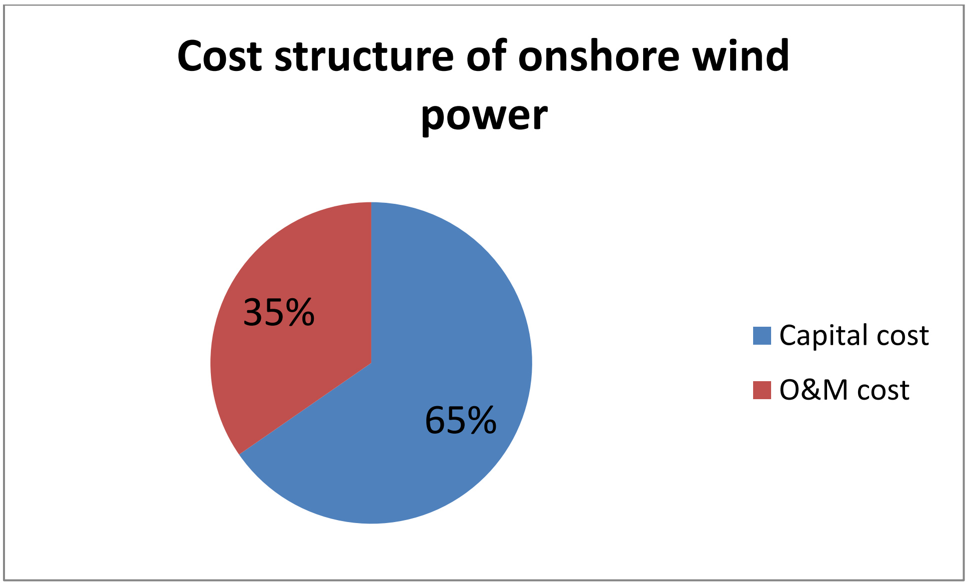

Figure 3.19: Cost structure of onshore wind power

For scenario analysis, the author sets a low cost scenario and a high cost scenario.

	Capital cost (k£)	O&M Cost (k£)
LOW	65000	3000
BASE	71600	3552
HIGH	80000	4000

Table 3-29: Different scenario of onshore wind power

Table 3-30 gives the results of levelised cost of different scenarios.

	Levelised cost (£/MWh)
LOW	39.48
BASE	44.56
HIGH	49.92

Table 3-30: Levelised cost of difference scenarios for onshore wind power

3.3.10 Offshore wind power

3.3.10.1 Discounted Cash Flow Approach

According to the parameters of offshore wind power, the author compiles the table of net present value (NPV), which is shown in Table 3-31. The revenue is 45131.71k£ (annual production *(electricity price + ROC)).

Year	Investment (k£)	O&M costs (k£)	Revenue (k£)	Cash flow (k£)	Present worth factor (5%)	Present value (k£)	NPV (k£)
0	151300.00	0.00	0.00	-151300.00	**1.00**	-151300.00	-151300.00
1	0.00	0.00	0.00	0.00	**0.95**	0.00	-151300.00
2	0.00	0.00	0.00	0.00	**0.91**	0.00	-151300.00
3	0.00	4600.00	23126.40	18526.40	**0.86**	16003.80	-135296.20
4	0.00	4600.00	23126.40	18526.40	**0.82**	15241.72	-120054.48
5	0.00	4600.00	23126.40	18526.40	**0.78**	14515.92	-105538.56
6	0.00	4600.00	23126.40	18526.40	**0.75**	13824.68	-91713.88
7	0.00	4600.00	23126.40	18526.40	**0.71**	13166.37	-78547.51
8	0.00	4600.00	23126.40	18526.40	**0.68**	12539.40	-66008.12
9	0.00	4600.00	23126.40	18526.40	**0.64**	11942.28	-54065.83
10	0.00	4600.00	23126.40	18526.40	**0.61**	11373.60	-42692.23
11	0.00	4600.00	23126.40	18526.40	**0.58**	10832.00	-31860.23
12	0.00	4600.00	23126.40	18526.40	**0.56**	10316.19	-21544.04
13	0.00	4600.00	23126.40	18526.40	**0.53**	9824.95	-11719.09
14	0.00	4600.00	23126.40	18526.40	**0.51**	9357.09	-2362.00
15	0.00	4600.00	23126.40	18526.40	**0.48**	8911.52	6549.52
16	0.00	4600.00	23126.40	18526.40	**0.46**	8487.16	15036.67
17	0.00	4600.00	23126.40	18526.40	**0.44**	8083.01	23119.68
18	0.00	4600.00	23126.40	18526.40	**0.42**	7698.10	30817.78
19	0.00	4600.00	23126.40	18526.40	**0.40**	7331.53	38149.31
20	0.00	4600.00	23126.40	18526.40	**0.38**	6982.41	45131.71

Table 3-31:Net present value for offshore wind power project

In Table 3-31, the discounted payback period is 15 years. It means this project will start to earn money from 15th year. At the end of project, the total net profit is 45131.71 k£. The internal rate of return can be calculated by Eq. (2.19). The result shows that IRR of this project is 7.82%.

According to the Table 3-31, the tornado diagram can be draw by increasing or decreasing main factors of project by 50%. These main factors are electricity price, ROC price, discount rate, O&M cost and initial investment.

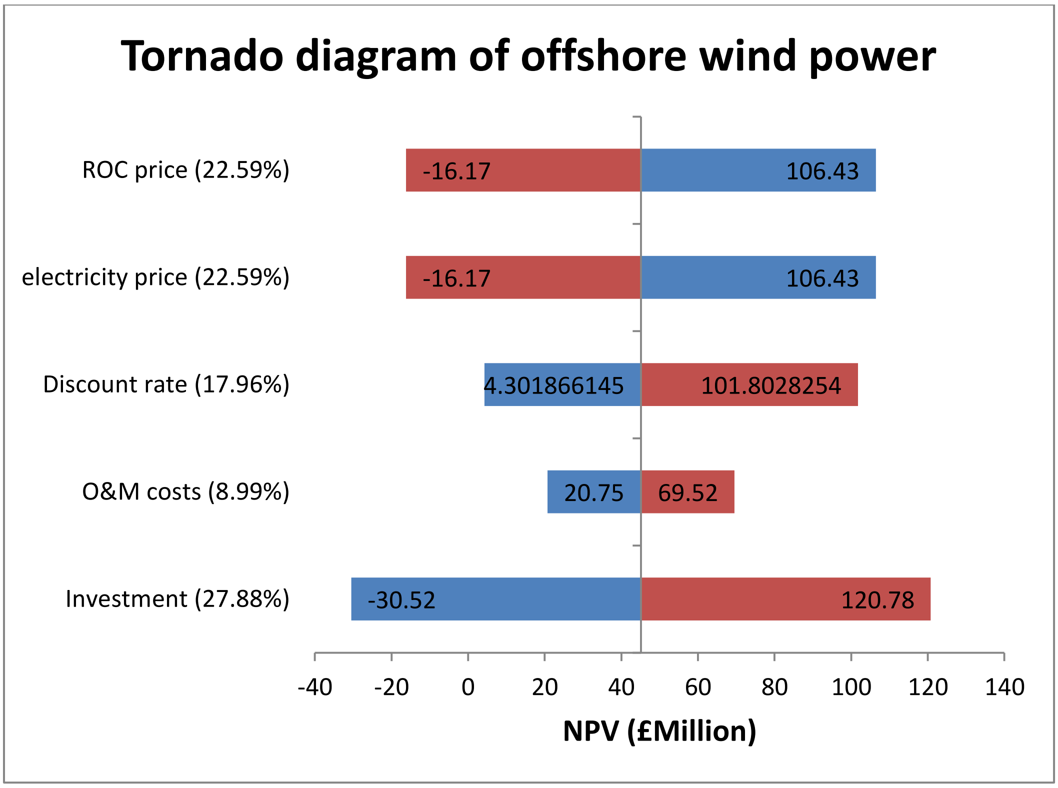

Figure 3.20: Tornado diagram of offshore wind power

The cross of horizontal and vertical axes is 45.13 £Million, which is the NPV at the end of project lifetime in base scenario. In Figure 3.20, the blue bars shows the revised NPV when increasing each factor by 50%, while the red bars shows the revised NPV when decreasing each factor by 50%. The numbers at each bar end represent the minimum and maximum NPVs for the respected factor.

Several result can be get by observing the above tornado diagram:

1) The initial investment is the most influential factor in the NPV as the NPV is ranging between -30.52£Million and 120.78£Million. Both of them have 27.88% variance contribution over the total NPV variation. So, the initial investment can be considered as the most important factors when investment this offshore wind power project.
2) The O&M cost has the least influence on the NPV in this project. The NPV changes from 20.75£Million to 69.52£Million. It only has 8.99% contribution.

3.3.10.2 Levelised cost analysis

Table 3-32 shows the calculation of levelised cost by discounted method for base scenario. The wind power project only has capital cost and O&M cost. Note the discounted rate is 5%.

	Un-discounted values			**Present worth factor (5%)**	**Discounted values**		
Year	Capital cost (k £)	O&M cost (k £)	Annual production (MWh)		Capital cost (k £)	O&M cost (k £)	Annual production (MWh)
0	151300.00	0.00	0.00	**1.00**	151300.00	0.00	0.00
1	0.00	0.00	0.00	**0.95**	0.00	0.00	0.00
2	0.00	0.00	0.00	**0.91**	0.00	0.00	0.00
3	0.00	4600.00	231264	**0.86**	0.00	3973.65	199774.54
4	0.00	4600.00	231264	**0.82**	0.00	3784.43	190261.47
5	0.00	4600.00	231264	**0.78**	0.00	3604.22	181201.40
6	0.00	4600.00	231264	**0.75**	0.00	3432.59	172572.76
7	0.00	4600.00	231264	**0.71**	0.00	3269.13	164355.01
8	0.00	4600.00	231264	**0.68**	0.00	3113.46	156528.58
9	0.00	4600.00	231264	**0.64**	0.00	2965.20	149074.84
10	0.00	4600.00	231264	**0.61**	0.00	2824.00	141976.03
11	0.00	4600.00	231264	**0.58**	0.00	2689.52	135215.27
12	0.00	4600.00	231264	**0.56**	0.00	2561.45	128776.45
13	0.00	4600.00	231264	**0.53**	0.00	2439.48	122644.24
14	0.00	4600.00	231264	**0.51**	0.00	2323.31	116804.04
15	0.00	4600.00	231264	**0.48**	0.00	2212.68	111241.94
16	0.00	4600.00	231264	**0.46**	0.00	2107.31	105944.70
17	0.00	4600.00	231264	**0.44**	0.00	2006.96	100899.72
18	0.00	4600.00	231264	**0.42**	0.00	1911.40	96094.97
19	0.00	4600.00	231264	**0.40**	0.00	1820.38	91519.02
20	0.00	4600.00	231264	**0.38**	0.00	1733.69	87160.97
TOTAL	151300.00	82800.00	4162752		151300.00	48772.88	2452045.92

Table 3-32: Levelised cost calculation for offshore wind power

According to Table 3-32, the levelised cost for base scenario is

$$LC_D = \frac{PV(Total\ Costs)}{PV(Total\ Outputs)} = 0.08159\ \text{k £/MWh} = 81.59\ \text{£/MWh}$$

The Figure 3.21 gives the cost structure for pulverised coal plant project. The data is from the discounted total values of each cost in Table 3-32.

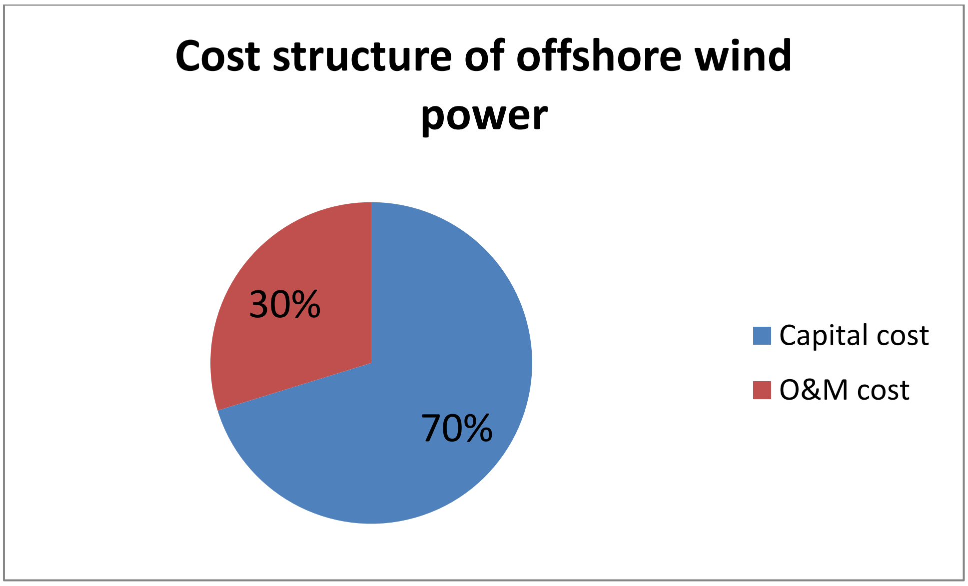

Figure 3.21: Cost structure of offshore wind power

For scenario analysis, the author sets a low cost scenario and a high cost scenario.

	Capital cost (k £)	**O&M Cost (k £)**
LOW	100000	4000
BASE	151300	4600
HIGH	200000	5000

Table 3-33: Different scenario of offshore wind power

Table 3-34 gives the results of levelised cost of different scenarios.

	Levelised cost (£/MWh)
LOW	58.08
BASE	81.59
HIGH	103.18

Table 3-34: Levelised cost of difference scenarios for offshore wind power

3.3.11 Summary of above generation technologies

According to the results of above 8 generation technologies, some conclusion can be summed up as following:

1. The net present value at the end of project lifetime shows the profitability of each project. Table 3-35 and Figure 3.22 lists the NPV at the end of project lifetime of 8 generation technologies from largest to smallest. The table demonstrate that the non-renewable technologies are always earning more money at existing technology level and investment environment, except CCGT with CCS. The CCGT with CCS project has a negative NPV since it has high capital cost and operational gas cost. The author think there are two reasons to make coal-fired plants have better performance. Firstly, the coal price assumption in this thesis is lower than the real coal price right now. The coal price in the thesis is based on the price before 2006. Secondly, the coal-fired plant's lifetime are much longer than gas-fired, but the author did not consider the decommissioning and reinvestment of plant equipment.

Technologies	NPV at the end of project lifetime (k £)
Pulverised coal with CCS	493009.69
Pulverised coal	330354.69
IGCC with CCS	246872.67
CCGT	153837.68
IGCC	111087.47
Onshore wind	86902.53
Offshore wind	45131.71
CCGT with CCS	-76494.54

Table 3-35: the NPV of 8 generation technologies in order

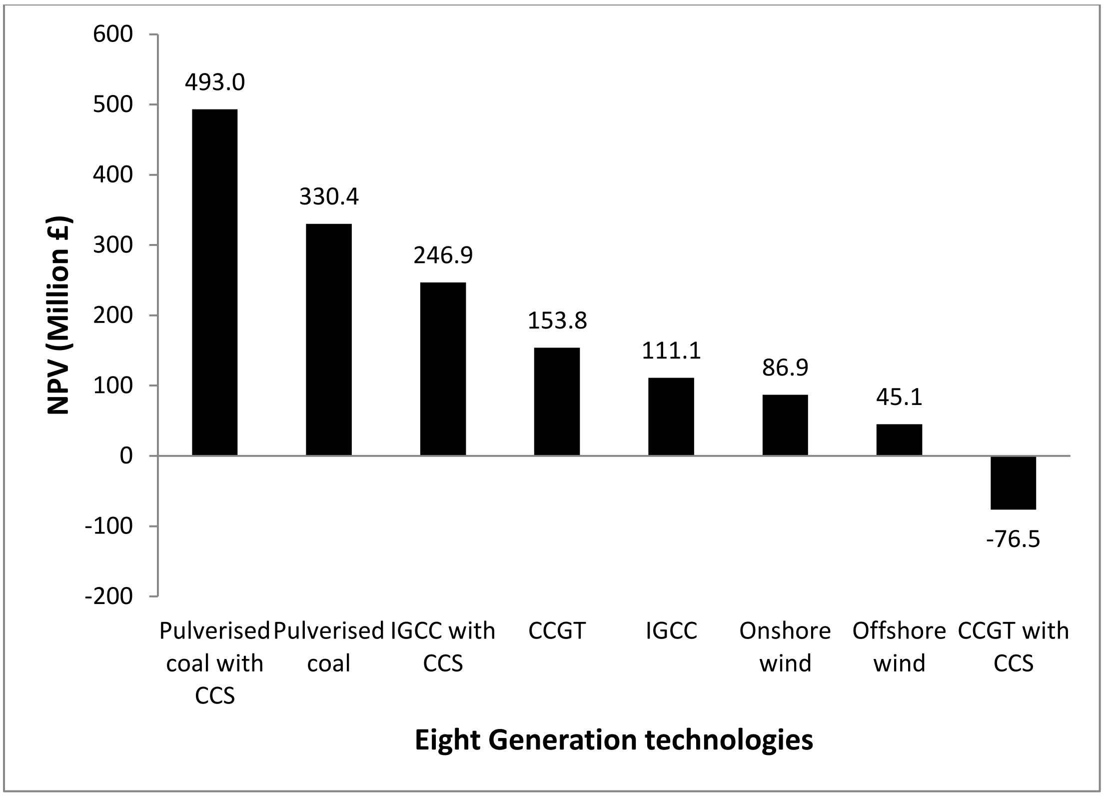

Figure 3.22: The bar chart of NPV at the end of project lifetime of 8 generation technologies

2. The tornado diagram of each project states that the electricity price (plus ROC price for wind power) is the most sensitive factor. The manager of power plant must focus on the price variation of electricity.

3. Table 3-36 gives the levelised cost of 8 generation technologies from lowest to highest. Figure 3.23 shows the levelised cost ranges for 8 electricity generation technologies under high, base and low scenarios. In Figure 3.23, the top and bottom of the vertical line for each technology represents the levelised cost of generation under the high and low cost scenario, respectively. The triangular point represents the base scenario.

In Table 3-36 and Figure 3.23, the wind power has higher levelised cost than non-renewable technologies cost, especially offshore wind power. It means the wind power project cannot get profit if there is no ROC price. The range of levelised cost of offshore wind power are much larger than onshore wind power, since the author set the larger fluctuation of capital cost of offshore wind power in scenario assumption. CCGT with CCS project has highest levelised cost in non-renewable technologies, and this is the reason of negative NPV at the end of project lifetime.

Technologies	Levelised cost of base scenario (£/MWh)
Pulverised coal with CCS	31.5
Pulverised coal	34.3
IGCC with CCS	35.12
CCGT	36.97
IGCC	37.8
CCGT with CCS	41.32
Onshore wind	44.56
Offshore wind	81.59

Table 3-36: Levelised cost of each technology in order

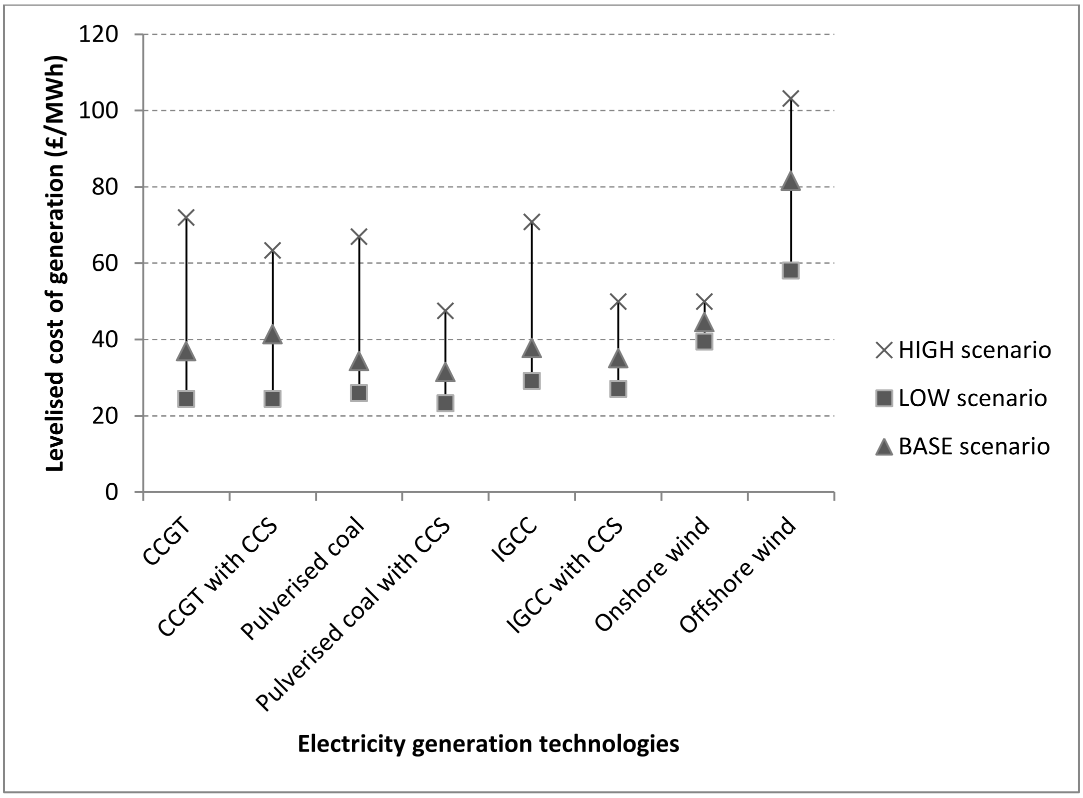

Figure 3.23: Levelised cost range for 8 generation technologies under different scenarios

4. Table 3-37 gives the proportion of each cost for 8 generation technologies. In this table, the operational fuel cost proportion of gas-fired plants are much higher than coal fired plants. It means the fluctuation of gas price has a big effect on gas-fired plant's profitability and levelised cost. The coal-fired plants emit more carbon dioxide than gas-fired plant, so the carbon tax proportion of pulverised coal plant and IGCC plant are much higher than CCGT plant, which reach to 43%. By comparison, although the capital cost proportion are higher, coal-fired plants with CCS still have advantage on profitability and levelised cost than the plants without CCS. It can be reflected in Table 3-35 and Table 3-36. With the increasing of carbon tax in UK, such advantage will be more significant in the future.

The onshore and offshore wind power only have capital cost and O&M cost. Their high capital costs lead to high levelised cost. The advantage of wind power is their levelised costs have less fluctuation than non-renewable projects. After construction, the O&M cost becomes the sole cost of wind power. The profitability is only affected by electricity and ROC price.

Technologies	Operational fuel cost proportion	Capital cost proportion	O&M cost proportion	Carbon tax proportion	Additional cost of CCS proportion
CCGT	63%	12%	7%	18%	---
CCGT with CCS	65%	20%	8%	---	7%
Pulverised coal	23%	23%	11%	43%	---
Pulverised coal with CCS	31%	32%	18%	---	19%
IGCC	23%	23%	11%	43%	---
IGCC with CCS	26%	41%	16%	---	17%
Onshore wind	---	65%	35%	---	---
Offshore wind	---	70%	30%	---	---

Table 3-37: Cost structure of 8 generation technologies

3.4 Pulverised coal power plant in China

Table 3-38 gives the parameters of pulverised coal power plant in China. The data is from a power plant in Anhui province. The base electricity price is set as 400 Yuan/MWh, which is the reality electricity price in Anhui province at 2011.

Capacity (MW)	Project Lifetime (Years)	Load Factor	Total cost of construction (kYuan)
1000	40	72.12%	4000000
Annual O&M cost (kYuan)	**Construction years**	**Annual Production (MWh)**	**Coal consumption (Mtonnes)**
279000	3	6317325	1.876
Cost per tonne(Yuan)	**Annual operational coal costs (kYuan)**		
929	1743000		

Table 3-38: Parameters of a pulverised coal plant in China

3.4.1 Discounted Cash Flow Approach

According to the parameters of IGCC power plant, the author compiles the table of net present value (NPV), which is shown in. The electricity price is set as 400 Yuan/MWh, and hence the revenue is 2526930 kYuan (annual production *electricity price).

Year	Investment (kYuan)	O&M costs (kYuan)	Operational fuel costs (kYuan)	Revenue (kYuan)	Cash flow (kYuan)	Present worth factor (5%)	Present value (kYuan)	NPV (kYuan)
0	4000000.00	0.00	0.00	0.00	-4000000.00	1.00	-4000000.00	-4000000.00
1	0.00	0.00	0.00	0.00	0.00	0.95	0.00	-4000000.00
2	0.00	0.00	0.00	0.00	0.00	0.91	0.00	-4000000.00
3	0.00	0.00	0.00	0.00	0.00	0.86	0.00	-4000000.00
4	0.00	279000.00	1743000.00	2526930.00	504930.00	0.82	415407.16	-3584592.84
5	0.00	279000.00	1743000.00	2526930.00	504930.00	0.78	395625.87	-3188966.97
6	0.00	279000.00	1743000.00	2526930.00	504930.00	0.75	376786.54	-2812180.43
7	0.00	279000.00	1743000.00	2526930.00	504930.00	0.71	358844.32	-2453336.11
8	0.00	279000.00	1743000.00	2526930.00	504930.00	0.68	341756.50	-2111579.61
9	0.00	279000.00	1743000.00	2526930.00	504930.00	0.64	325482.38	-1786097.23
10	0.00	279000.00	1743000.00	2526930.00	504930.00	0.61	309983.22	-1476114.01
11	0.00	279000.00	1743000.00	2526930.00	504930.00	0.58	295222.11	-1180891.90
12	0.00	279000.00	1743000.00	2526930.00	504930.00	0.56	281163.92	-899727.98
13	0.00	279000.00	1743000.00	2526930.00	504930.00	0.53	267775.16	-631952.82
14	0.00	279000.00	1743000.00	2526930.00	504930.00	0.51	255023.96	-376928.86
15	0.00	279000.00	1743000.00	2526930.00	504930.00	0.48	242879.96	-134048.89
16	0.00	279000.00	1743000.00	2526930.00	504930.00	0.46	231314.25	97265.36
17	0.00	279000.00	1743000.00	2526930.00	504930.00	0.44	220299.29	317564.64
18	0.00	279000.00	1743000.00	2526930.00	504930.00	0.42	209808.84	527373.49
19	0.00	279000.00	1743000.00	2526930.00	504930.00	0.40	199817.95	727191.43
20	0.00	279000.00	1743000.00	2526930.00	504930.00	0.38	190302.81	917494.24
21	0.00	279000.00	1743000.00	2526930.00	504930.00	0.36	181240.77	1098735.01
22	0.00	279000.00	1743000.00	2526930.00	504930.00	0.34	172610.26	1271345.26
23	0.00	279000.00	1743000.00	2526930.00	504930.00	0.33	164390.72	1435735.98
24	0.00	279000.00	1743000.00	2526930.00	504930.00	0.31	156562.59	1592298.57

25	0.00	279000.00	1743000.00	2526930.00	504930.00	0.30	149107.23	1741405.80
26	0.00	279000.00	1743000.00	2526930.00	504930.00	0.28	142006.88	1883412.69
27	0.00	279000.00	1743000.00	2526930.00	504930.00	0.27	135244.65	2018657.34
28	0.00	279000.00	1743000.00	2526930.00	504930.00	0.26	128804.43	2147461.77
29	0.00	279000.00	1743000.00	2526930.00	504930.00	0.24	122670.89	2270132.65
30	0.00	279000.00	1743000.00	2526930.00	504930.00	0.23	116829.42	2386962.07
31	0.00	279000.00	1743000.00	2526930.00	504930.00	0.22	111266.11	2498228.18
32	0.00	279000.00	1743000.00	2526930.00	504930.00	0.21	105967.72	2604195.90
33	0.00	279000.00	1743000.00	2526930.00	504930.00	0.20	100921.64	2705117.54
34	0.00	279000.00	1743000.00	2526930.00	504930.00	0.19	96115.85	2801233.39
35	0.00	279000.00	1743000.00	2526930.00	504930.00	0.18	91538.90	2892772.30
36	0.00	279000.00	1743000.00	2526930.00	504930.00	0.17	87179.91	2979952.21
37	0.00	279000.00	1743000.00	2526930.00	504930.00	0.16	83028.48	3062980.69
38	0.00	279000.00	1743000.00	2526930.00	504930.00	0.16	79074.75	3142055.44
39	0.00	279000.00	1743000.00	2526930.00	504930.00	0.15	75309.28	3217364.72
40	0.00	279000.00	1743000.00	2526930.00	504930.00	0.14	71723.13	3289087.85

Table 3-39: Net present value of pulverised coal power plant in China

In Table 3-39, the discounted payback period is 16 years. At the end of project, the total net profit is 3289087.85 kYuan. The internal rate of return can be calculated by Eq. (2.19). The result shows that IRR of this project is 9.31%.

According to the Table 3-39, the tornado diagram can be draw by increasing or decreasing main factors of project by 50%. These main factors are electricity price, discount rate, O&M cost, operational fuel cost and initial investment.

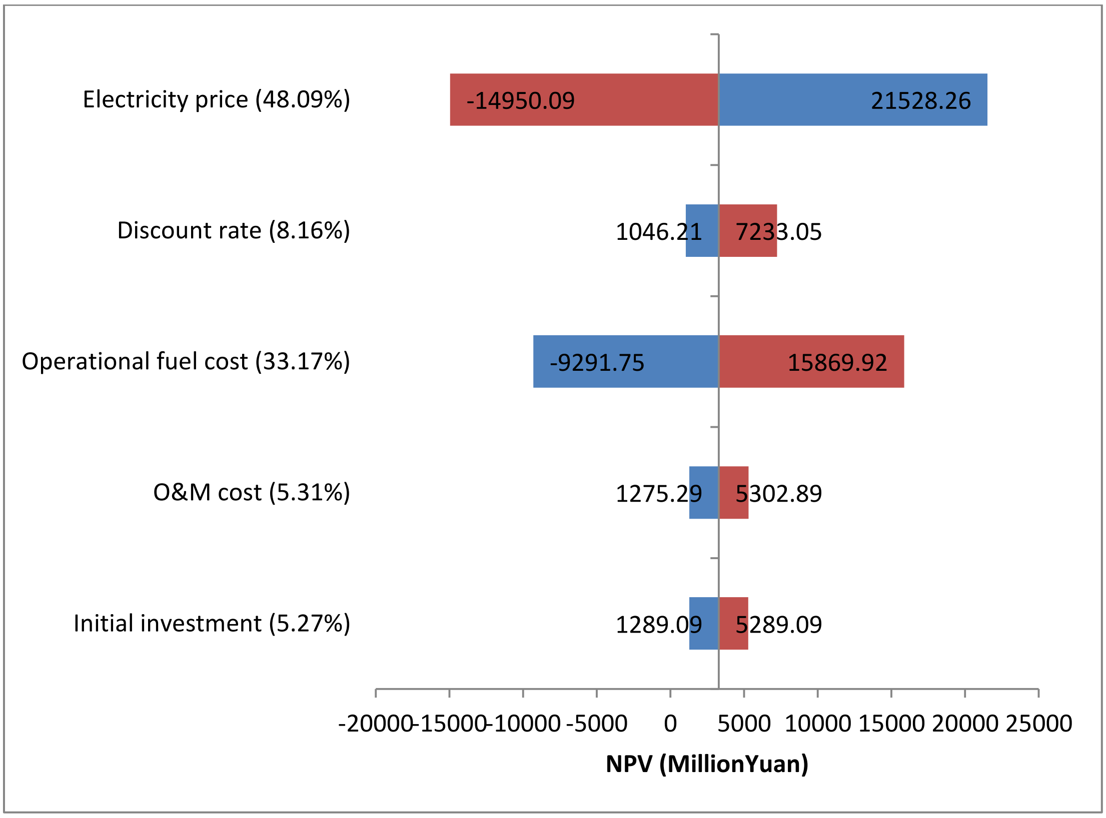

Figure 3.24: Tornado diagram of pulverised coal power plant in China

The cross of horizontal and vertical axes is 3289.09MillionYuan, which is the NPV at the end of project lifetime in base scenario. In Figure 3.24, the blue bars shows the revised NPV when increasing each factor by 50%, while the red bars shows the revised NPV when decreasing each factor by 50%. The numbers at each bar end represent the minimum and maximum NPVs for the respected factor.

Several result can be get by observing the above tornado diagram:

1) The electricity price is still the most influential factor in the NPV as the NPV is ranging between -14950.09MillionYuan and 21528.26MillionYuan. It has 48.09% variance contribution over the total NPV variation. So, the electricity price can be considered as the most important factor when investment this pulverised coal power plant.
2) The Initial investment has the least influence on the NPV in this project. It only has 5.27% contribution.
3) The operational fuel cost is also an important factor in this project. The NPV is ranging between -9291.75MillionYuan and 15869.92MillionYuan. It has 33.17% variance contribution.

3.4.2 Levelised cost analysis

Table 3-40 shows the calculation of levelised cost by discounted method for pulverised coal plant in China. Note the discounted rate is 5%.

	Un-discounted values					Discounted values			
Year	Capital cost (kYuan)	O&M cost (kYuan)	Operational fuel cost (kyuan)	Annual production (MWh)	**Present worth factor (5%)**	Capital cost (kYuan)	O&M cost (kYuan)	Operational fuel cost (kYuan)	Annual production (MWh)
0	4000000.00	0.00	0.00	0.00	**1.00**	4000000.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	**0.95**	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	**0.91**	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	**0.86**	0.00	0.00	0.00	0.00
4	0.00	279000.00	1743000.00	6317325	**0.82**	0.00	229533.99	1433970.41	5197278.91
5	0.00	279000.00	1743000.00	6317325	**0.78**	0.00	218603.80	1365686.11	4949789.44
6	0.00	279000.00	1743000.00	6317325	**0.75**	0.00	208194.10	1300653.44	4714085.18
7	0.00	279000.00	1743000.00	6317325	**0.71**	0.00	198280.09	1238717.56	4489604.93
8	0.00	279000.00	1743000.00	6317325	**0.68**	0.00	188838.18	1179731.01	4275814.22
9	0.00	279000.00	1743000.00	6317325	**0.64**	0.00	179845.89	1123553.34	4072204.02
10	0.00	279000.00	1743000.00	6317325	**0.61**	0.00	171281.80	1070050.80	3878289.54
11	0.00	279000.00	1743000.00	6317325	**0.58**	0.00	163125.52	1019096.00	3693609.09
12	0.00	279000.00	1743000.00	6317325	**0.56**	0.00	155357.64	970567.62	3517722.94
13	0.00	279000.00	1743000.00	6317325	**0.53**	0.00	147959.66	924350.11	3350212.33
14	0.00	279000.00	1743000.00	6317325	**0.51**	0.00	140913.96	880333.44	3190678.41
15	0.00	279000.00	1743000.00	6317325	**0.48**	0.00	134203.77	838412.80	3038741.34
16	0.00	279000.00	1743000.00	6317325	**0.46**	0.00	127813.11	798488.38	2894039.37
17	0.00	279000.00	1743000.00	6317325	**0.44**	0.00	121726.78	760465.13	2756227.97
18	0.00	279000.00	1743000.00	6317325	**0.42**	0.00	115930.26	724252.50	2624979.02
19	0.00	279000.00	1743000.00	6317325	**0.40**	0.00	110409.77	689764.29	2499980.02
20	0.00	279000.00	1743000.00	6317325	**0.38**	0.00	105152.17	656918.37	2380933.35
21	0.00	279000.00	1743000.00	6317325	**0.36**	0.00	100144.92	625636.54	2267555.57
22	0.00	279000.00	1743000.00	6317325	**0.34**	0.00	95376.11	595844.33	2159576.74

23	0.00	279000.00	1743000.00	6317325	**0.33**	0.00	90834.39	567470.79	2056739.75
24	0.00	279000.00	1743000.00	6317325	**0.31**	0.00	86508.95	540448.37	1958799.76
25	0.00	279000.00	1743000.00	6317325	**0.30**	0.00	82389.47	514712.73	1865523.58
26	0.00	279000.00	1743000.00	6317325	**0.28**	0.00	78466.17	490202.60	1776689.13
27	0.00	279000.00	1743000.00	6317325	**0.27**	0.00	74729.68	466859.62	1692084.88
28	0.00	279000.00	1743000.00	6317325	**0.26**	0.00	71171.12	444628.21	1611509.41
29	0.00	279000.00	1743000.00	6317325	**0.24**	0.00	67782.02	423455.44	1534770.87
30	0.00	279000.00	1743000.00	6317325	**0.23**	0.00	64554.31	403290.89	1461686.54
31	0.00	279000.00	1743000.00	6317325	**0.22**	0.00	61480.29	384086.56	1392082.42
32	0.00	279000.00	1743000.00	6317325	**0.21**	0.00	58552.66	365796.73	1325792.78
33	0.00	279000.00	1743000.00	6317325	**0.20**	0.00	55764.44	348377.84	1262659.79
34	0.00	279000.00	1743000.00	6317325	**0.19**	0.00	53108.99	331788.42	1202533.13
35	0.00	279000.00	1743000.00	6317325	**0.18**	0.00	50579.99	315988.97	1145269.65
36	0.00	279000.00	1743000.00	6317325	**0.17**	0.00	48171.42	300941.87	1090733.00
37	0.00	279000.00	1743000.00	6317325	**0.16**	0.00	45877.54	286611.31	1038793.34
38	0.00	279000.00	1743000.00	6317325	**0.16**	0.00	43692.90	272963.15	989326.99
39	0.00	279000.00	1743000.00	6317325	**0.15**	0.00	41612.28	259964.91	942216.18
40	0.00	279000.00	1743000.00	6317325	**0.14**	0.00	39630.75	247585.62	897348.74
TOTAL	4000000.00	10323000.00	64491000.00	233741025		4000000.00	4027598.89	25161666.20	91195882.34

Table 3-40: Levelised cost calculation of pulverised coal plant in China

From Table 3-40, the levelised cost for base scenario is

$$LC_D = \frac{PV(Total\ Costs)}{PV(Total\ Outputs)} = 0.36393 \text{ kYuan/MWh} = 363.93 \text{ Yuan/MWh}$$

≈ 36£/MWh

The Figure 3.25 gives the cost structure for pulverised coal plant project in China. The data is from the discounted total values of each cost in Table 3-40.

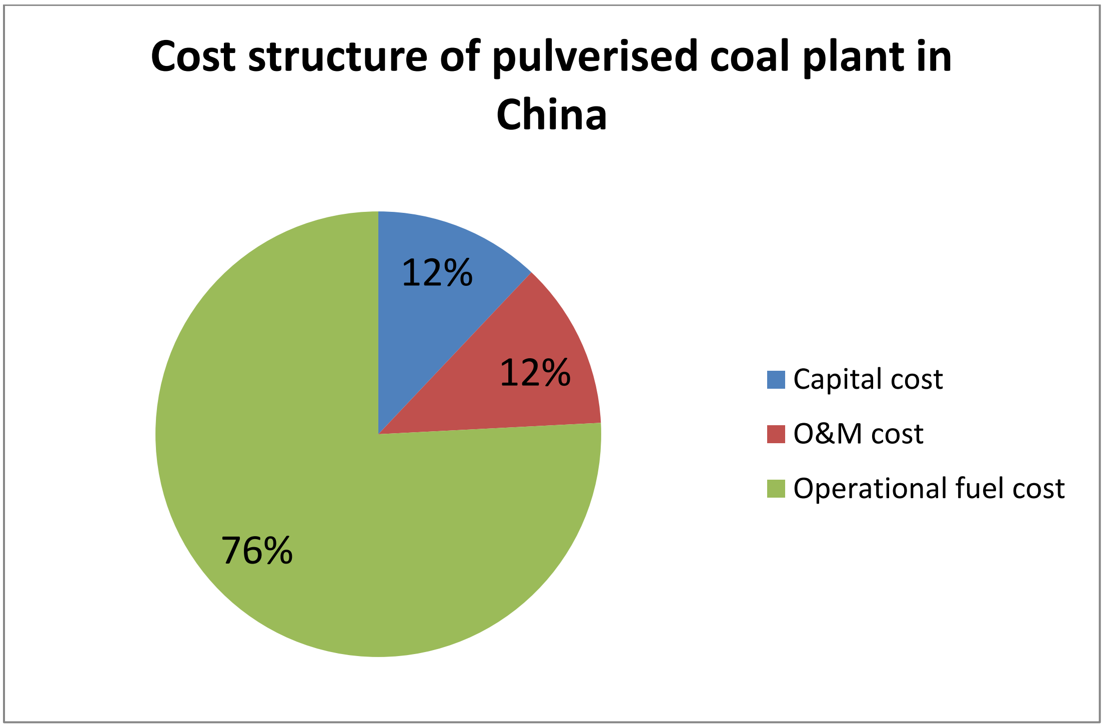

Figure 3.25: Cost structure of pulverised coal plant in China

In this figure, operational fuel cost accounts for the most of proportion. This is the main difference between pulverised coal plant in UK and China. The coal-fired plants in China do not have to take into account the carbon cost since so far these is no carbon tax. And because the electricity price is determined by government, the coal price becomes the key factor of plants' profitability.

However, recent years, coal price in China has been increasing dramatically. Many coal-fired power plants' profit space meet big reductions, some even result in loss. It leads to aggravation of the coal-fired power plant investment climate, and the investment of coal-fired power plant has been decreasing rapidly. At the end of 2011, the investment on coal-fired plant is 105.4 billion Yuan, less than half that in 2005.[12] To avoid losing on coal–fired plant, power generation companies pay their attentions on nuclear power and other renewable energy.

3.5 Summary

This chapter analysed the investment of eight types electricity generation technologies in UK and pulverised coal plant in China by the approaches introduced in chapter 2. Firstly, this chapter introduced some electricity generation technologies briefly. These technologies include combined cycle gas turbine (CCGT), pulverised coal, integrated gasification combined cycle (IGCC) and carbon capture and storage (CCS). Secondly, eight types of electricity generation technologies in UK are analysed one by one by discounted cash flow approach and levelised cost approach. Thirdly, pulverised coal project in China is also analysed by these approaches.

In the chapter, eight types of electricity generation technologies in the UK and pulverised coal plant in the China are analysed by discounted cash flow approach and levelised cost approach. The analysis results of UK's projects showed evidences for following conclusions.

Firstly, the variance contributions of tornado diagram state that the electricity price (plus ROC price for wind power) is the most influential factor for all types of UK's project. This indicates the stable electricity wholesale price is important to ensure the stable earning of a generation company. A fluctuate electricity wholesale price will have great influence on the profitability of a power plant. Therefore, getting relatively stable electricity wholesale price is crucial important to a generation project. Secondly, the coal-fired plants (pulverised coal and IGCC) with CCS have advantage on profitability and levelised cost than plants without CCS. The reason is that the carbon tax cost put great burden on coal-fired plant without CCS. The loss what the carbon tax cost brought would be larger than the initial investment on CCS equipment. By contrast, the gas-fired plants (CCGT) with CCS even has deficit at the of project lifetime. Although CCS technology can avoid carbon tax cost, the high additional investment on CCS equipment cannot be able to recoup. Thirdly, because the proportions of capital cost of coal-fired plants are higher than gas-fired plants, the fluctuation of fuel price has bigger effect on gas-fired plant's profitability and levelised cost than coal-fired plants. Fourthly, because wind power projects have huge capital cost, the non-renewable technologies are always earning more money at existing technology level and investment environment. The advantage of wind power is their levelised costs have less fluctuation than non-renewable projects. After construction, the O&M cost becomes the sole cost of wind power. The profitability is only affected by electricity and ROC price.

The research results for China's pulverised coal project show that the coal price is the key factor of coal-fired plants' profitability and levelised cost in China. It is because the electricity price is fixed and the coal price increased rapidly in recent years.

This chapter only considered the investment of power plant from microcosmic viewpoint. However, in reality, the investors also need to know the macroscopic situation of electrical industry. The macro-economy and electricity consumption of a country directly influence the future profitability and levelised cost of power plant. Therefore, chapter 4 will give the research of the relationship between electricity consumption and economic growth in UK and China.

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Chapter 4: Electricity Consumption, Economic Growth and Installed Capacity in the UK and China: Relationship and Forecast

4.1 Introduction

In the past two decades China has achieved rapid economic growth and emerged as the second largest electricity consumption country in the world, just behind the United States. By the end of 2011, the installed generation capacity in China amounted to more than 1056GW and electricity consumption is more than 4693TWH.

However, relationship between electricity supply and economic growth has never been fully studied in China. Historically there was a widespread shortage of electricity since 1960. In 1997 with the decrease of economic growth rate there emerged electricity surplus for the first time. However electricity shortage appears again emerged since 2002 and worsened in 2004. In 2004, the number of provinces with shortage in electric power amounted to 24 and the total gap is 31 GW in China.[1] Following the outbreak of global economic crisis in 2008, many factories along the coastal provinces were either faced with reduced production or in some cases economic loss or bankruptcy, demand for power has slowed. The massive investments in power plants in earlier years are beginning to come on stream and create a saturating phenomenon of generating capacity. Power industry is a typical periodic industry in China. After 30 years of rapid growth, the supply and demand of electricity in China will change from supply shortage to balance and possibly surplus. The decision making of future investment in power industry must base on scientific prediction of macroeconomic fluctuation and electricity consumption. If there is no accurate prediction, investors not only cannot obtain expected profits, but also aggravate the fluctuation of macroeconomic.

As a traditional developed country, United Kingdom is a leader in electricity industry deregulation. UK opened the electricity market by stages, from 30% in 1990 to 100% by 1998. The 1989 Electricity Act created a system of independent regulation, headed by the Director General of Electricity Supply (DGES) covering England, Scotland and Wales. The regulator's principal roles are to ensure that competition develops smoothly and effectively and where competition is inappropriate, to protect customers. In 1999, the regulatory offices for electricity and gas (OFFER and OFGAS) were merged to form the Office of Gas and Electricity Markets (OFGEM). Northern Ireland has its own regulatory body, the Office for the regulation of Electricity and Gas (OFREG). After deregulation, UK's electricity price has fallen significantly. The power supply and demand keep balance. Although scale of electricity industry in UK is far smaller than China, such scale of electricity industry can support a large economic size. Hence, the research of the relationship of UK's electricity consumption and economic growth is a valuable reference for China.

The results of causal direction can be used by government and investors. For government, different results can lead to different electricity policy, such as conservation oriented policy or encourage oriented policy. For investors, the results can give them advices on power plant investment timing, scale and location.

In this chapter, the relationship among electricity consumption, economic growth and installed capacity in UK and China are reported. The rest of this chapter is organized as following: Section 4.2 gives the recent literatures of country-specific studies on energy or electricity economy; Section 4.3 introduced main econometric analysis methodology and section 4.4 defines the variables; Section 4.5 presents the empirical results of UK and China and section 4.6 compares them and gives some policy implications.

4.2 Literature reviews

Recently, in investigating the relationship between energy or electricity consumption and economic growth, most of the published literature test for the existence and direction of causality between these two variables directly. Ozturk[2] categorized the results into four types and each type has important implications for energy policy.

Firstly, the neutrality hypothesis suggests there is no causality between energy or electricity consumption and GDP, this implies that neither conservative nor expansive policies in relation to energy or electricity consumption have any effect on economic growth. Secondly, the growth hypothesis asserts that there is the unidirectional causality running from energy or electricity consumption to economic growth. In this case, the conservation oriented energy or electricity policies which force to reduce consumption and waste may cause negative impact of economic growth. Thirdly, the conservation hypothesis postulates there is the unidirectional causality running from economic growth to energy or electricity consumption. It suggests that the conservation policy of energy or electricity consumption will have no or little effect on economic growth. Fourthly, the feedback hypothesis emphasizes there is the bidirectional causality between energy or electricity consumption and economic growth. It implies that energy or electricity consumption and economic growth are jointly determined and affected simultaneously.

For the country-specific studies on energy consumption, the initial study by Kraft and Kraft[3] found the unidirectional causality running from energy consumption to growth in USA. Oh and Lee[4] employed Granger causality test and vector error correction model (VECM) on the data for Korea during 1970-1999. The results indicated that the causality was from energy consumption to GDP. The same direction was also found in Taiwan by Lee and Chang[5]. Ang[6] found evidence of causality running from GDP to energy consumption for Malaysia in the period 1971-1999, while Erdal[7] found a bidirectional causal relationship for Turkey covering the period 1970-2005. Bowden and Payne[8] and Payne[9] both tested the USA's data during the period 1949-2006. The former's results indicated causality ran from energy consumption to growth, while the latter's results supported that no causality existed between them.

For the country-specific studies on electricity consumption-growth nexus, Yang[10] used standard Granger causality test on Taiwan's data. His results appeared to support that there was bidirectional causality between electricity consumption and growth. Narayan and Smyth[11] found a causality running from GDP to electricity consumption in Australia during 1966-1999 by employing Multivariate Granger causality test. Ho and Siu[12] supported growth hypothesis for Hong Kong during the period of 1966-2002. Hu and Lin[13] found evidence of causality from GDP to electricity consumption in Taiwan from 1982-2006. Some researchers started to focus on Africa countries. Odhiambo[14] and Akinlo[15] researched South Africa and Nigeria's situation respectively. The former found bidirectional causality in South Africa and the latter supported growth hypothesis (from electricity consumption to growth) for Nigeria.

Table 4-1 summarise the recent studies on the causal relationship between electricity consumption (EC) and economic growth (GDP) for country-specific studies. The direction of arrow indicates the direction of causality. Most of the literatures in this table have found a positive causality running from electricity consumption to economic growth.

Authors	Period	Country	Methodology	Causality relationship
Ramcharran (1990)[16]	1970-1986	Jamaica	Granger causality	ELC-->GDP
Yang (2000)[10]	1954-1997	Taiwan	Standard Granger causality test, Hsiaao's Granger	ELC<-- -->GDP
Ghosh (2002)[17]	1950-1997	India	Standard Granger causality test	GDP-->ELC
Jumbe (2004)[18]	1970-1999	Malawi	Granger causality and Error-correction model	ELC<-- -->GDP (Granger causality) GDP-->ELC (error correction test)
Morimoto and Hope (2004)[19]	1960-1998	Sri Lanka	OLS regression model, Granger causality test	Electricity supply -->GDP
Shiu and Lam (2004)[20]	1971-2000	China	Error-correction model, Cointegration	ELC-->GDP
Altinay and Karagol (2005)[21]	1950-2000	Turkey	Dolado-Lutkepohl test, Granger causality	ELC-->GDP
Yoo (2005)[22]	1970-2002	Korea	Error-correction model	ELC<-- -->GDP
Narayan and Smyth (2005)[11]	1966-1999	Australia	Multivariate Granger causality	GDP-->ELC
Yoo and Kim (2006)[23]	1971-2002	Indonesia	Engle Granger, VAR	GDP-->ELC
Zachariadis and Pashouortidou (2007)[24]	1960-2004	Cyprus	Granger causality test, Cointegration, VEC	ELC<-- -->GDP
Mozumder and Marathe (2007)[25]	1971-1999	Bangladesh	Cointegration test and vector error correction model	GDP-->ELC
Ho and Siu (2007)[12]	1966-2002	Hong Kong	Cointegration, VEC model	ELC-->GDP
Yuan et al. (2007)[26]	1978-2004	China	Cointegration test	ELC-->GDP
Narayan and Singh (2007)[27]	1971-2002	Fiji Islands	Standard Granger causality test and Cointegration test	ELC-->GDP
Halicioglu (2007)[28]	1968-2005	Turkey	Granger causality, Bounds testing	GDP-->ELC

Tang (2008)[29]	1972-2003	Malaysia	ECM based F-test, ARDL test	ELC<-- -->GDP
Hu and Lin (2008)[30]	1982-2006	Taiwan	Hansen-Seo threshold Cointegration; VEC	GDP-->ELC
Aqeel and Butt (2008)[31]	1955-1996	Pakistan	Engle Granger, VAR	ELC-->GDP
Yuan et al. (2008)[32]	1963-2005	China	Johansen Cointegration, VEC specific tests	ELC-->GDP
Odhiambo (2009a)[14]	1971-2006	Tanzania	ARDL Bounds testing approach	ELC-->GDP
Abosedra et al. (2009)[33]	1995-2005	Lebanon	Granger causality	ELC-->GDP
Ghosh (2009)[34]	1970-2006	India	ARDL bounds test, Cointegration, VEC	GDP-->electricity supply
Odhiambo (2009b)[35]	1971-2006	South Africa	Granger causality	ELC<-- -->GDP
Akinlo (2009)[36]	1980-2006	Nigeria	Johansen-Juselius, Cointegration, VEC	ELC-->GDP

Table 4-1: Summary of empirical studies on electricity consumption (EC) – economic growth (GDP) nexus for country specific studies

4.3 Methodologies

4.3.1 Time series stationarity and unit roots

4.3.1.1 Stochastic processes

A random or stochastic process is a collection of random variables ordered in time.[37] If let Y denote a random variable, and if it is continuous, it can be denoted as $Y(t)$, but if it is discrete, it is denoted as Y_t. The example of the former is the stock price or electrocardiogram, and the example of the latter is GDP or electricity consumption per year, etc. Since most economic and electrical data are collected at discrete points in time, this thesis will use the notation Y_t rather than $Y(t)$. If let Y represent GDP, for our data we have $Y_1, Y_2, ..., Y_{50}$, where the subscript 1 denotes the first observation and 50 denotes the last observation. Each of these Y 's is a random variable.

4.3.1.2 Stationary stochastic processes

A type of stochastic process that has received a great deal of attention and scrutiny by time series analysts is the so-called stationary stochastic process. Broadly speaking, a stochastic process is said to be stationary if its mean and variance are constant over time and the value of the covariance between the two time periods depends only on the distance or gap or lag between the two time periods and not the actual time at which the covariance is computed.[37] In the time series literature, such a stochastic process is known as a weakly stationary[38], or covariance stationary, or second-order stationary, or wide sense stochastic process.

There is a special type of stochastic processes, namely, a purely random, or white noise, process. A stochastic process is a white noise if it has zero mean, constant variance, and is serially uncorrelated. It is often denoted by u_t or ε_t.

4.3.1.3 Nonstationary stochastic processes

If a time series is not stationary, it is called a nonstationary time series. In other words, a nonstationary time series will have a time-varying mean or a time-varying variance or both. The classic example is the random walk model (RWM). There are two types of RWM: (1) random walk without drift (i.e. no constant or intercept term) and (2) random walk with drift (i.e. a constant term is present).

- **Random walk without drift**

Consider Eq.(4.1)

$$Y_t = Y_{t-1} + u_t \tag{4.1}$$

Where u_t is a white noise error term. Y_t here is said to be a random walk. In the random walk model, the value of Y at time t is equal to its value at time $(t-1)$ plus a random shock. Eq.(4.1) can be thought as a regression of Y at time t on its value lagged one period.

Eq.(4.1) can be written as:

$$\begin{aligned} &Y_1 = Y_0 + u_1 \\ &Y_2 = Y_1 + u_2 = Y_0 + u_1 + u_2 \\ &Y_3 = Y_2 + u_3 = Y_0 + u_1 + u_2 + u_3 \end{aligned}$$

and in general,

$$Y_t = Y_0 + \sum u_t \tag{4.2}$$

Therefore

$$E(Y_t) = E(Y_0 + \sum u_t) = Y_0 \tag{4.3}$$

and

$$\text{var}(Y_t) = t\sigma^2 \tag{4.4}$$

where σ^2 is the variance.

Eq.(4.3) and (4.4) show that the mean of Y is equal to its initial value, Y_0, but as t increases, its variance increases indefinitely, thus violating the condition of stationarity. Hence, the random walk without drift is a nonstationary stochastic process.

- **Random walk with drift**

Consider Eq.(4.5)

$$Y_t = \delta + Y_{t-1} + u_t \tag{4.5}$$

where δ is the *drift parameter*, and Eq.(4.5) is called random walk model with drift. Following the procedure discussed for random walk without drift, it can be shown that for the random walk with drift model,

$$E(Y_t) = Y_o + t \cdot \delta \tag{4.6}$$

$$\text{var}(Y_t) = t\sigma^2 \tag{4.7}$$

It can be seen that for RWM with drift the mean as well as the variance increases over time. In short, RWM, with or without drift, is a nonstationary stochastic process.

4.3.1.4 Unit root stochastic process

Rewrite the Eq.(4.1) as:

$$Y_t = \rho Y_{t-1} + u_t \qquad -1 \le \rho \le 1 \tag{4.8}$$

This model is the first-order autoregressive (AR) model. If $\rho = 1$, Eq.(4.8) becomes a RWM without drift, and it is called unit root problem. Thus the terms *nonstationarity*, *random walk*, and *unit root* can be treated as synonymous. If $|\rho| < 1$, then it can be proved that the time series Y_t is stationary. In practice, it is important to find out if a time series possesses a unit root.

4.3.1.5 Trend stationary (TS) and difference stationary (DS) stochastic processes

In the statistical analysis of time series, a stochastic process is trend stationary if any underlying trend can be removed, leaving a stationary process. If the series has a stable long-run trend and tends to revert to the trend line following a disturbance, it may be possible to smooth it by de-trending (e.g., by fitting a trend line and subtracting it out prior to fitting a model, or else by including the time index as an independent variable in a regression), perhaps in conjunction with logging or deflating. However, sometimes even de-trending is not sufficient to make the series stationary. If the mean, variance, and autocorrelations of the original series are not constant in time, even after de-trending, perhaps the statistics of the changes in the series between periods or between seasons will be constant. Such a series is said to be difference-stationary.

In general, if a nonstationary time series has to be differenced d times to make it stationary, that time series is said to be integrated of order d. A time series Y_t integrated of order d is denoted as $Y_t \sim I(d)$. If Y_t is stationary, it is denoted as $Y_t \sim I(0)$. Most economic time series are generally $I(1)$.

4.3.2 Statistical test

A statistical test provides a mechanism for making quantitative decisions about a process or processes. The intent is to determine whether there is enough evidence to "reject" a conjecture or hypothesis about the process. The conjecture is called the null hypothesis. Not rejecting may be a good result if we want to continue to act as if we "believe" the null hypothesis is true. Or it may be a disappointing result, possibly indicating we may not yet have enough data to "prove" something by rejecting the null hypothesis.

The null hypothesis is a statement about a belief. We may doubt that the null hypothesis is true, which might be why we are "testing" it. The alternative hypothesis might, in fact, be what we believe to be true. The test procedure is constructed so that the risk of rejecting the null hypothesis, when it is in fact true, is small. This risk, α, is often referred to as the *significance level* of the test. By having a test with a small value of α, we feel that we have actually "proved" something when we reject the null hypothesis. In practice, the null hypothesis is denoted by H_0, and the alternative hypothesis is denoted by H_1 or H_a.

Critical values for a test of hypothesis depend upon a test statistic, which is specific to the type of test, and the significance level, α, which defines the sensitivity of the test. A value of α= 0.05 implies that the null hypothesis is rejected 5% of the time when it is in fact true. The choice of α is somewhat arbitrary, although in practice values of 0.1, 0.05, and 0.01 (10%, 5% and 1%) are common.

Another quantitative measure for reporting the result of a test of hypothesis is the P-value. The P-value is the probability of the test statistic being at least as extreme as the one observed given that the null hypothesis is true. A small P-value is an indication that the null hypothesis is false.

The statistical test will be applied in follow sections for unit root test, cointegration test and Granger causality.

4.3.3 Unit root test

4.3.3.1 The Dickey–Fuller test

In statistics, a unit root test tests whether a time series variable is nonstationary using an autoregressive model. Eq.(4.8) indicates if $\rho = 1$, the time series is nonstationary.

Therefore, the general idea behind the unit root test is to simply regress Y_t on its lagged value Y_{t-1} and find out if the estimated ρ is statistically equal to 1.

Subtract Y_{t-1} from both sides of Eq.(4.8) to obtain:

$$Y_t - Y_{t-1} = \rho Y_{t-1} - Y_{t-1} + u_t = (\rho - 1)Y_{t-1} + u_t \tag{4.9}$$

which can be alternatively written as:

$$\Delta Y_t = \delta Y_{t-1} + u_t \tag{4.10}$$

where $\delta = (\rho - 1)$ and Δ is the first-difference operator.

In practice, the unit root test always tests the null hypothesis that $\delta = 0$.

$$H_0 : \delta = 0$$
$$H_1 : \delta \neq 0$$

If $\delta = 0$, then $\rho = 1$, that means the time series is nonstationary. If δ is negative, Y_t is stationary. Dickey and Fuller have shown that under the null hypothesis that $\delta = 0$, the estimated t value of the coefficient of Y_{t-1} in Eq.(4.10) follows the τ statistic[39]. They have computed the critical values of the τ statistic on the basis of Monte Carlo simulations.

To allow for the various possibilities, the Dickey-Fuller test is estimated in three different forms:

Y_t is a random walk:

$$\Delta Y_t = \delta Y_{t-1} + u_t \tag{4.11}$$

Y_t is a random walk with drift:

$$\Delta Y_t = \beta_1 + \delta Y_{t-1} + u_t \tag{4.12}$$

Y_t is a random walk with drift around a stochastic trend :

$$\Delta Y_t = \beta_1 + \beta_2 t + \delta Y_{t-1} + u_t \tag{4.13}$$

In each case, the null hypothesis is that $\delta = 0$, and the alternative hypothesis is that δ is negative. If the null hypothesis is rejected, it means that Y_t is a stationary time series with zero mean in the case of Eq.(4.11), and that Y_t is stationary with a nonzero mean ($= \beta_1 / (1-\rho)$) in the case of Eq.(4.12), and that Y_t is stationary around a deterministic trend in case Eq.(4.13).

4.3.3.2 The Augmented Dickey-Fuller (ADF) test and the Phillips-Perron (PP) test

The augmented Dickey-Fuller test is an augmented version of the Dickey–Fuller test for a larger and more complicated set of time series models. This test is conducted by "augmenting" the preceding three equations by adding the lagged values of the dependent variable ΔY_t. The ADF test here consists of estimating the following regression:

$$\Delta Y_t = \beta_1 + \beta_2 t + \delta Y_{t-1} + \sum_{i=1}^{m} \alpha_i \Delta Y_{t-i} + u_t \tag{4.14}$$

where $\Delta Y_{t-1} = (Y_{t-1} - Y_{t-2})$, $\Delta Y_{t-2} = (Y_{t-2} - Y_{t-3})$, etc. The number of lagged difference terms to include is often determined empirically, the idea being to include enough terms so that the error term in Eq.(4.14) is serially uncorrelated. ADF test still test null hypothesis $\delta = 0$ and follows the same asymptotic distribution as DF statistic.

An important assumption of the DF test is that the error terms u_t are independently and identically distributed. The ADF test adjusts the DF test to take care of possible serial correlation in the error terms by adding the lagged difference terms of the regressand. Phillips and Perron use nonparametric statistical methods to take care of the serial correlation in the error terms without adding lagged difference terms.[40]

The test is robust with respect to unspecified autocorrelation and heteroscedasticity in the disturbance process of the test equation.

4.3.4 Vector autoregression (VAR) and Impulse response

4.3.4.1 Vector autoregression model (VAR)

The vector autoregression (VAR) model is one of the most successful and easy to use models for processing multiple time series. It is the extension of the univariate autoregressive moving average model to dynamic multivariate time series, and is used to capture the interdependencies between multiple time series. VAR models in economics were made popular by Christopher Sims.[41]

All the variables in VAR are treated symmetrically. A VAR model describes the dynamic evolution of a number of variables from their common history. When considering, say, two variables, Y_t and X_t, the VAR consists of two equations. A first order VAR would be given by

$$Y_t = \delta_1 + \theta_{11} Y_{t\text{-}1} + \theta_{12} X_{t\text{-}1} + \varepsilon_{1t} \tag{4.15}$$

$$X_t = \delta_2 + \theta_{21} Y_{t\text{-}1} + \theta_{22} X_{t\text{-}1} + \varepsilon_{2t} \tag{4.16}$$

where ε_{1t} and ε_{2t} are two white noise processes (independent of the history of Y and X) that may be correlated. If, for instance, $\theta_{12} \neq 0$ it means that the history of X can help explaining and forecasting Y. The above system can be written as

$$\begin{pmatrix} Y_t \\ X_t \end{pmatrix} = \begin{pmatrix} \delta_1 \\ \delta_2 \end{pmatrix} + \begin{pmatrix} \theta_{11} & \theta_{12} \\ \theta_{21} & \theta_{22} \end{pmatrix} \begin{pmatrix} Y_{t-1} \\ X_{t-1} \end{pmatrix} + \begin{pmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \end{pmatrix} \tag{4.17}$$

or, with appropriate definitions, as

$$\vec{Y}_t = \delta + \Theta_1 \vec{Y}_{t-1} + \vec{\varepsilon}_t \tag{4.18}$$

where $\vec{Y_t} = (Y_t, X_t)'$ and $\vec{\varepsilon_t} = (\varepsilon_{1t}, \varepsilon_{2t})'$. This extends the first order autoregressive model to the multiple-dimensional case. Generally, VAR(p) model for a k-dimensional vector $\vec{Y_t}$ is given by

$$\vec{Y_t} = \delta + \Theta_1 \vec{Y_{t-1}} + \ldots + \Theta_p \vec{Y_{t-p}} + \vec{\varepsilon_t} \tag{4.19}$$

where each Θ_j is k*k matrix and $\vec{\varepsilon_t}$ is a k-dimensional vector of white noise terms with covariance matrix $\sum$.

The advantage of VAR model is that a more accurate forecast is possible, because the information set is extended to also include the history of the other variable. From a different perspective, Sims has advocated the use of VAR models instead of structural simultaneous equations models. According to Sims, if there is true simultaneity among a set of variables, they should all be treated on an equal position; there should not be any a priori distinction between endogenous and exogenous variables[41]. It is the spirit of Sims's VAR model.

4.3.4.2 Impulse response

Impulse response analysis is used widely in the econometrics to uncover the dynamic relationship among several variables within vector autoregressive (VAR) model and VEC mode. Impulse responses measure the time profile of the effect of a shock, or impulse, on the future values of a variable. By imposing specific restrictions on the parameters of the VAR model the shocks can be attributed an economic meaning.

The premise of impulse response is that the model should be stable. The reason is only stable system can obtain convergent results. Divergent results always have no economic meaning. This chapter checks models stability before impulse response by software. If all the roots of characteristic polynomial are smaller than 1, the models is stable. In other words, a stable model's roots of characteristic polynomial are all in the unit circle.

4.3.5 Spurious regression and Cointegration tests

4.3.5.1 Spurious regression

The assumption that the Y_t and X_t are stationary is crucial for the properties of standard estimation and testing procedures.[42] To see why stationary time series are so important, consider the following two random walk models:

$$Y_t = Y_{t-1} + \varepsilon_{1t} \tag{4.20}$$

$$X_t = X_{t-1} + \varepsilon_{2t} \tag{4.21}$$

where ε_{1t} and ε_{2t} are mutually independent. There is nothing in this data generating mechanism that leads to a relationship between Y_t and X_t. Suppose we regress Y_t and X_t:

$$Y_t = \beta_1 + \beta_2 X_t + \varepsilon_t \tag{4.22}$$

The results from this regression are likely to be characterized by a fairly high R^2 statistic (coefficient of determination, it provides a measure of how well future outcomes are likely to be predicted by the model), highly autocorrelated residuals and a significant value for β_2. From these results, it may be concluded that there is a significant statistical relationship between Y and X, whereas a priori there should be none. This phenomenon is the well-known problem of **spurious regressions**.[43] Two independent nonstationary series here are spuriously related due to the fact that they are both trended.

4.3.5.2 Cointegration tests

Consider two $I(1)$ series in Eq.(4.22), Y_t and X_t, and suppose that a linear relationship exists between them. This is reflected in the proposition that there exists some value β_2 such that $Y_t - \beta_1 - \beta_2 X_t$ is $I(0)$, although Y_t and X_t are both $I(1)$. In such case it is said that Y_t and X_t are cointegrated, and that they share a common trend. Economically speaking, two variables will be cointegrated if they have a long-term, or equilibrium, relationship between them. In the language of cointegration theory, a regression such as Eq.(4.22) is known as a cointegrating regression and the slope parameter β_2 is the cointegrating parameter. Note that the precondition of cointegration of two or more variables is that they have same order of integration.

An important ingredient in the analysis of cointegrated system is tests for cointegration. A commonly used and easy way is Engle-Granger (EG) test.[44] Firstly, in the case of Y_t and X_t in Eq.(4.22), applying unit root test to check that Y_t and X_t are both $I(1)$. Then we need to regress Y_t on X_t and consider $\varepsilon_t = Y_t - \beta_1 - \beta_2 X_t$. If Y_t and X_t are cointegrated, $\varepsilon_t = Y_t - \beta_1 - \beta_2 X_t$ is $I(0)$. So, the final step is to apply unit root test on ε_t. The null and alternative hypotheses are:

H_0: ε_t has a unit root or Y_t and X_t are not cointegrated

H_1: ε_t is stationary or Y_t and X_t are cointegrated

The additional problem is ε_t here is not observed, so that in practice we use estimated residual ε_t instead.

Another popular cointegration test is Johansen test,[45] which is used by many types of software. Johansen test does not need all the series to be in the same order of integration, so that it is more convenient than other tests like Engle-Granger test. Johansen's methodology takes its starting point in the vector autoregression (VAR) of order p given by

$$y_t = \mu + A_1 y_{t-1} + ... + A_p y_{t-p} + \varepsilon_t \tag{4.23}$$

where y_t is an n*1 vector of variables that are integrated of order one, and ε_t is an n*1 vector of innovations. This VAR can be re-written as

$$\Delta y_t = \mu + \Pi y_{t-1} + \sum_{i=1}^{p-1} \Gamma_i \Delta y_{t-i} + \varepsilon_t \tag{4.24}$$

If the coefficient matrix Π has reduced rank r<n, then there exist n*r matrices α and β each with rank r such that $\Pi = \alpha\beta^{'}$ and $\beta^{'} y_t$ is stationary. r is the number of cointegrating relationships, the elements of α are known as the adjustment parameters in the vector error correction model and each column of β is a cointegrating vector. It can be shown that for a given r, the maximum likelihood estimator of β defines the combination of y_{t-1} that yields the r that gives the largest canonical correlations of Δy_t with y_{t-1} after correcting for lagged differences and deterministic variables when present.

Johansen proposes two different likelihood ratio tests of the significance of these canonical correlations and thereby the reduced rank of the Π matrix: the trace test and maximum eigenvalue test.

4.3.6 Error correction model (ECM)

Above section shows that there is a long-run, or equilibrium, relationship between Y_t and X_t. Of course, there may be disequilibrium in short run because error term may not be zero. Therefore, the error term ε_t in Eq.(4.22) can be treated as the “equilibrium error”, and this error term can be used to tie the short-run behavior of Y_t to its long-run value.

$$Y_t = \beta_1 + \beta_2 X_t + \varepsilon_t \tag{4.22}$$

$$\varepsilon_t = Y_t - \beta_1 - \beta_2 X_t \tag{4.25}$$

The error correction model (ECM) first used by Sargan[46] and later popularized by Engle and Granger[44] corrects for disequilibrium. Engle and Granger states that if two variables Y_t and X_t are cointegrated, then the short-run dynamics can be described by the ECM. It is named Granger representation theorem.

Consider the following ECM equation:

$$\Delta Y_t = \alpha_0 + \alpha_1 \Delta X_t + \lambda \varepsilon_{t-1} + e_t \tag{4.26}$$

where Δ denotes the first difference operator, λ is expected to be negative, e_t is a random error term, and $\varepsilon_{t-1} = Y_{t-1} - \beta_1 - \beta_2 X_{t-1}$, that is, the one period lagged value of the error from the cointegrating regression Eq.(4.22). ECM Eq.(4.26)states that ΔY_t depends on ΔX_t and also on the equilibrium error term ε_{t-1}. If the ε_{t-1} is nonzero, then the model is out of equilibrium. Suppose ΔX_t is zero and ε_{t-1} is positive. This means Y_{t-1} is too high to be in equilibrium, that is, Y_{t-1} is above its equilibrium value of $\beta_1 + \beta_2 \Delta X_{t-1}$. Since λ is negative, the term $\lambda \varepsilon_{t-1}$ is negative. Therefore, ΔY_t will be negative to restore the equilibrium. That is, if Y_t is above its equilibrium value, it will start falling in the next period to correct the equilibrium error, hence the name ECM. By the same token, if ε_{t-1} is negative, $\lambda \varepsilon_{t-1}$ will be positive, which will cause ΔY_t to be positive, leading Y_t to rise in period t. Intuitively, if Y_t and X_t are cointegrated, the error term ε_t is stationary, then this implies that there must be some force always pulling the ε_t back towards zero and preventing them increasing or decreasing without limit. λ here is a short-run adjustment parameter, which decides how quickly the equilibrium is restored.

Engle and Granger suggest a way to estimate ECM when Y_t and X_t are cointegrated.[44] They suggest that estimation should take place in two stages. In the first stage the long-run parameters are estimated. This is achieved simply by estimating the cointegrating regression. Assuming cointegration, in the second stage of the Engle-Granger procedure the residuals from the cointegrating regression, the ε_t, are used as estimates of the disequilibrium errors. Hence, the ECM is estimated in following form:

$$\Delta Y_t = lagged(\Delta Y_t, \Delta X_t) - \lambda \varepsilon_{t-1} + e_t \tag{4.27}$$

The second stage of the procedure therefore consists in Eq.(4.27), with the appropriate lags on the differenced variables being determined by experimentation. It is at this stage that estimates of λ and other short-run parameters are obtained.

A vector error correction model (VECM) adds error correction features to a multi-factor model such as a vector autoregression model. A Vector Error Correction Model can lead to a better understanding of the nature of any nonstationarity among the different component series and can also improve longer term forecasting over an unconstrained model.

4.3.7 Akaike information criterion (AIC) & Bayesian information criterion (BIC)

The lag length of VAR and ECM are determined by Akaike information criterion (AIC). The Akaike information criterion is a measure of the relative goodness of fit of a statistical model. It was developed by Hirotsugu Akaike in 1974.[47] It is grounded in the concept of information entropy, in effect offering a relative measure of the information lost when a given model is used to describe reality. It can be said to describe the tradeoff between bias and variance in model construction, or loosely speaking between accuracy and complexity of the model.

In the general case, the AIC is $AIC = 2k - 2\ln(L)$, where k is the number of parameters in the statistical model, and L is the maximized value of the likelihood function for the estimated model. According to Akaike's theory, the most accurate model has the smallest AIC.

Another common used information criterion is Bayesian information criterion (BIC). Like the AIC, the preferred model is the one with the minimum BIC value.

4.3.8 Granger causality test

Causality in econometrics is a somewhat different concept to that in everyday philosophical use. It refers more to the ability to predict. Econometricians refer to Granger causality[48], which is defined as: X is said to be a Granger cause of Y if present Y can be predicted with greater accuracy by using past values of X rather than not using such past values, all other information being identical.

4.3.8.1 Granger causality test base on VAR

Granger devised test for causality by VAR model in 1969[48]. Consider following equations:

$$Y_t = \alpha_0 + \sum_{i=1}^{k} \alpha_i Y_{t-i} + \sum_{i=1}^{k} \beta_i X_{t-i} + u_t \tag{4.28}$$

$$X_t = \gamma_0 + \sum_{i=1}^{k} \gamma_i X_{t-i} + \sum_{i=1}^{k} \delta_i Y_{t-i} + \varepsilon_t \tag{4.29}$$

In Eq.(4.28), if $H_0 : \beta_i = 0\ (i = 1, 2, ..., k)$ is accepted, X term will not appear in Eq.(4.28), so that X_t fails to cause Y_t. It is called X_t *does not cause* Y_t. Similarly, if $H_0 : \delta_i = 0\ (i = 1, 2, ..., k)$ is accepted in Eq.(4.29), then Y_t *does not cause* X_t.

The results between Y_t and X_t may have four cases:

1. *Unidirectional causality from* Y_t *to* X_t is indicated if $\beta_i = 0$ is accepted and $\delta_i = 0$ is rejected statistically.
2. *Unidirectional causality from* X_t *to* Y_t is indicated if $\beta_i = 0$ is rejected and $\delta_i = 0$ is accepted statistically.
3. *Feedback, or bilateral causality*, exists when $\beta_i = 0$ and $\delta_i = 0$ are all rejected statistically.
4. Finally, *independence, or no causality*, is suggested when $\beta_i = 0$ and $\delta_i = 0$ are all accepted statistically.

The most important thing is the Y_t and X_t must be stationary. If not, taking the first difference. Otherwise, non-stationary variables may obtain spurious regression and causality.

4.3.8.2 Granger causality test base on VECM

The ECM opens up an additional causality channel which is overlooked by standard Granger testing procedures (which showed in 4.3.6.1). The VECM approach allows us to distinguish between “short-run” and “long-run” Granger causality. If Y_t and X_t are cointegrated, the VECM (Vector error correction model) should be estimated rather than a VAR as in a standard Granger causality test[49]. In the short-run, deviations from this long-run equilibrium will feed back on the changes in the dependent variable in order to force the movement towards the long-run equilibrium. If the dependent variable (ΔY_t and ΔX_t) is driven directly by this long-run equilibrium error, then it is responding to this feedback. If not, it is responding only to short-run shocks to the stochastic environment.[50] Hendry and Juselius[51] emphasize the importance of correct specification.

Suppose we regress Y_t and X_t as Eq.(4.21):

$$Y_t = \beta_1 + \beta_2 X_t + \varepsilon_t \tag{4.22}$$

Then create VECM by the Granger Representation Theorem:

$$\Delta Y_t = \theta_1 + \lambda_1 ECT_{t-1} + \sum_{i=1}^{m} \alpha_i \Delta Y_{t-i} + \sum_{i=1}^{m} \beta_i \Delta X_{t-i} + u_{1t} \tag{4.30}$$

$$\Delta X_t = \theta_2 + \lambda_2 ECT_{t-1} + \sum_{i=1}^{m} \gamma_i \Delta Y_{t-i} + \sum_{i=1}^{m} \delta_i \Delta X_{t-i} + u_{2t} \tag{4.31}$$

where error correction term $ECT_{t-1} = \varepsilon_{t-1} = Y_{t-1} - \beta_1 - \beta_2 X_{t-1}$, λ_1 and λ_2 are adjustment parameters, u_{1t} and u_{2t} are random error terms.

Sources of causation can be identified by testing for significance of the coefficients on the dependent variables in Eq.(4.30) and (4.31). It is called short-run causality since it tests the relationship between ΔY_t and ΔX_t. The testing procedures are similar with Granger causality test by VAR. If $H_0: \beta_i = 0$ for all i is accepted, ΔX_{t-i} *does not cause* ΔY; and if $H_0: \gamma_i = 0$ for all i is accepted, ΔY_{t-i} *does not cause* ΔX. Masih and Masih[50] and Asafu-Adjaye[52] interpreted the weak Granger causality as short-run causality in the sense that the dependent variable responds only to short-term shocks to the stochastic environment.

Another possible source of causation is the error correction term ECT_{t-1} in Eq.(4.30) and (4.31) since there are past term in it. It is called long-run causality. For long-run causality, if, $\lambda_1 = 0$ or $\lambda_2 = 0$, then the change in Y_t or X_t does not respond to a deviation from the long-run equilibrium in the previous period. If $\lambda_1 = 0$, X_t does not cause Y_t in long-run; and if $\lambda_2 = 0$, Y_t does not cause X_t in long-run.

Some literatures checke whether the above two sources of causation are jointly significant. This can be done, for example, by testing the joint hypotheses $H_0: \lambda_1 = 0$ and $\beta_i = 0$ for all i in Eq.(4.30) or $H_o: \lambda_2 = 0$ and $\gamma_i = 0$ for all i in Eq.(4.31). This is referred to as a **strong** Granger causality test. The joint test indicates which variable bear the burden of short run adjustment to re-establish long-run equilibrium, following a shock to the system.[52]

4.3.8.3 F test in causality tests

The above causality test can be tested by using F test. Consider two models, 1 and 2, where model 1 is 'nested' within model 2. Model 1 is the restricted model, and model 2 is the unrestricted model. That is, model 1 has p_1 parameters, and model 2 has p_2 parameters, where $p_2 > p_1$, and for any choice of parameters in model 1, the same regression curve can be achieved by some choice of the parameters of model 2. The model with more parameters will always be able to fit the data at least as well as the model with fewer parameters. Thus typically model 2 will give a better (i.e. lower error) fit to the data than model 1. But one often wants to determine whether model 2 gives a *significantly better* fit to the data. One approach to this problem is to use F test.

If there are *n* data points to estimate parameters of both models from, then one can calculate the *F* statistic (coefficient of determination), given by[53]

$$F = \frac{\left(\frac{RSS_1 - RSS_2}{p_2 - p_1}\right)}{\left(\frac{RSS_2}{n - p_2}\right)} \tag{4.32}$$

where RSS is the residual sum of squares of model. The null hypothesis and alternative hypothesis are:

H_0 : **model 2 does not provide a significantly better fit than model 1**

H_1 : **model 2 provide a significantly better fit than model 1**

We want to test Granger causality base on VAR, for example, in Eq.(4.28). If $\beta_i = 0$ for all i, X_t does not cause Y_t. Testing $\beta_i = 0$ can be seen as comparing following two models, and determining which one is better.

Model 1: $$Y_t = \alpha_0 + \sum_{i=1}^{k} \alpha_i Y_{t-i} + e_t \tag{4.33}$$

Model 2: $$Y_t = \alpha_0 + \sum_{i=1}^{k} \alpha_i Y_{t-i} + \sum_{i=1}^{k} \beta_i X_{t-i} + u_t \tag{4.28}$$

Model 1 is the restricted model here, and model 2 is the unrestricted one. The restriction here is $\beta_i = 0$. The number of parameters in model 1 is $p_1 = k + 1$ (α_1 to α_k plus α_0), and in model is $p_2 = 2k + 1$ (α_1 to α_k, plus β_1 to β_k, plus α_0). RSS_1 and RSS_2 can be obtained by software. Therefore, the F statistic is:

$$F = \frac{\left(\frac{RSS_1 - RSS_2}{p_2 - p_1}\right)}{\left(\frac{RSS_2}{n - p_2}\right)} = \frac{\left(\frac{RSS_1 - RSS_2}{k}\right)}{\left(\frac{RSS_2}{n - 2k - 1}\right)} \tag{4.34}$$

The procedures of testing Granger causality base on VECM are similar as base on VAR. For short-run causality in Eq.(4.30), we test $H_0 : \beta_i = 0$. It can be treated as comparing model 3 and 4 as follow:

Model 3: $$\Delta Y_t = \theta_1 + \lambda_1 ECT_{t-1} + \sum_{i=1}^{m} \alpha_i \Delta Y_{t-i} + u_{1t} \tag{4.35}$$

Model 4: $$\Delta Y_t = \theta_1 + \lambda_1 ECT_{t-1} + \sum_{i=1}^{m} \alpha_i \Delta Y_{t-i} + \sum_{i=1}^{m} \beta_i \Delta X_{t-i} + u_{1t} \tag{4.30}$$

Model 3 is the restricted model here, and model 4 is the unrestricted one. The restriction here is $\beta_i = 0$. The number of parameters $p_3 = m + 2$ (α_1 to α_m plus θ_1 plus λ_1), $p_4 = 2m + 2$. Hence, the F statistic is:

$$F = \frac{\left(\frac{RSS_1 - RSS_2}{p_2 - p_1}\right)}{\left(\frac{RSS_2}{n - p_2}\right)} = \frac{\left(\frac{RSS_1 - RSS_2}{m}\right)}{\left(\frac{RSS_2}{n - 2m - 2}\right)} \tag{4.36}$$

For long-run causality in Eq.(4.30), comparing model 5 and 6, the restriction is $\lambda_1 = 0$:

Model 5: $$\Delta Y_t = \theta_1 + \sum_{i=1}^{m} \alpha_i \Delta Y_{t-i} + \sum_{i=1}^{m} \beta_i \Delta X_{t-i} + u_{1t} \tag{4.36}$$

Model 6: $$\Delta Y_t = \theta_1 + \lambda_1 ECT_{t-1} + \sum_{i=1}^{m} \alpha_i \Delta Y_{t-i} + \sum_{i=1}^{m} \beta_i \Delta X_{t-i} + u_{1t} \tag{4.30}$$

where the null hypothesis here is $H_0 : \lambda_1 = 0$, the number of parameters $p_5 = 2m + 1$ and $p_6 = 2m + 2$. The F statistic is:

$$F = \frac{\left(\frac{RSS_1 - RSS_2}{p_2 - p_1}\right)}{\left(\frac{RSS_2}{n - p_2}\right)} = \frac{\left(\frac{RSS_1 - RSS_2}{1}\right)}{\left(\frac{RSS_2}{n - 2m - 2}\right)} \qquad (4.37)$$

For the joint causality, for example, in Eq.(4.30), the null hypothesis is $H_0 : \lambda_1 = 0$ and $\beta_i = 0$. Therefore, the restricted model and unrestricted model are shown below:

Model 7: $$\Delta Y_t = \theta_1 + \sum_{i=1}^{m} \alpha_i \Delta Y_{t-i} + u_{1t} \qquad (4.38)$$

Model 8: $$\Delta Y_t = \theta_1 + \lambda_1 ECT_{t-1} + \sum_{i=1}^{m} \alpha_i \Delta Y_{t-i} + \sum_{i=1}^{m} \beta_i \Delta X_{t-i} + u_{1t} \qquad (4.30)$$

The number of parameters $p_7 = m + 1$ and $p_8 = 2m + 2$. The F statistic is:

$$F = \frac{\left(\frac{RSS_1 - RSS_2}{p_2 - p_1}\right)}{\left(\frac{RSS_2}{n - p_2}\right)} = \frac{\left(\frac{RSS_1 - RSS_2}{m + 1}\right)}{\left(\frac{RSS_2}{n - 2m - 2}\right)} \qquad (4.39)$$

F will have an F distribution, with $(p_2 - p_1, n - p_2)$ degrees of freedom. The null hypothesis is rejected if the F calculated from the data is greater than the critical value of the F distribution for some desired false-rejection probability (e.g. 0.1 or 0.05). In other word, the null hypothesis is rejected if P-value less than desired false-rejection probability (P-value < 0.1 or 0.05).

4.4 Data source and definition of variables

The basic macroeconomic and electrical time series of UK and CHINA are shown in following line graphs:

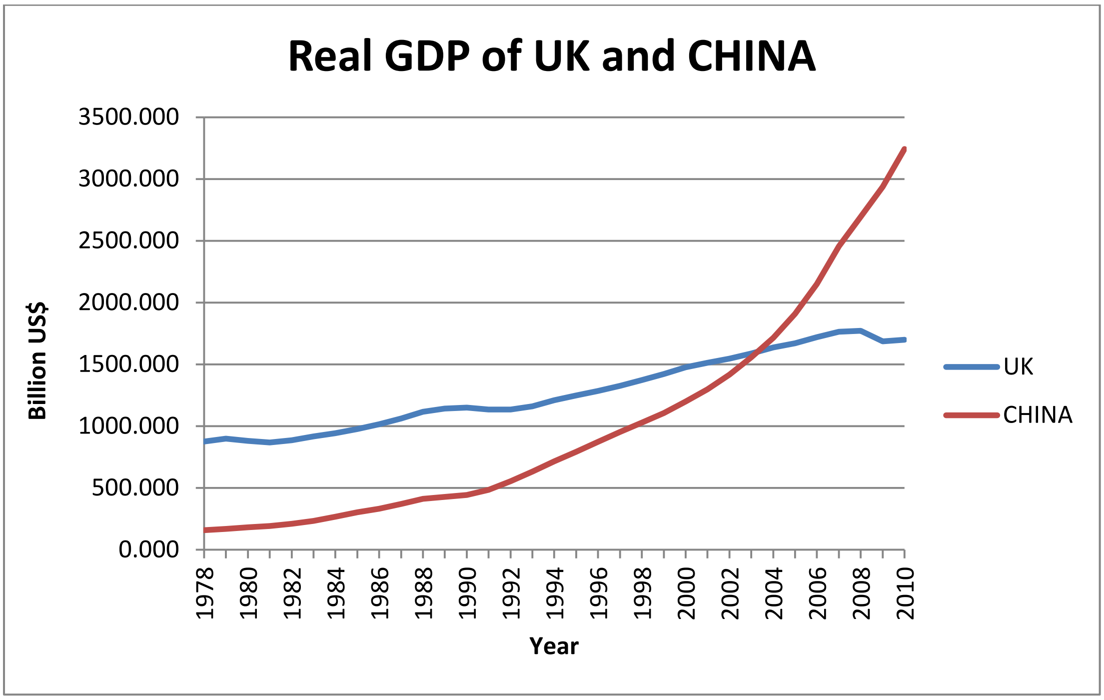

Figure 4.1: Real GDP of UK and CHINA

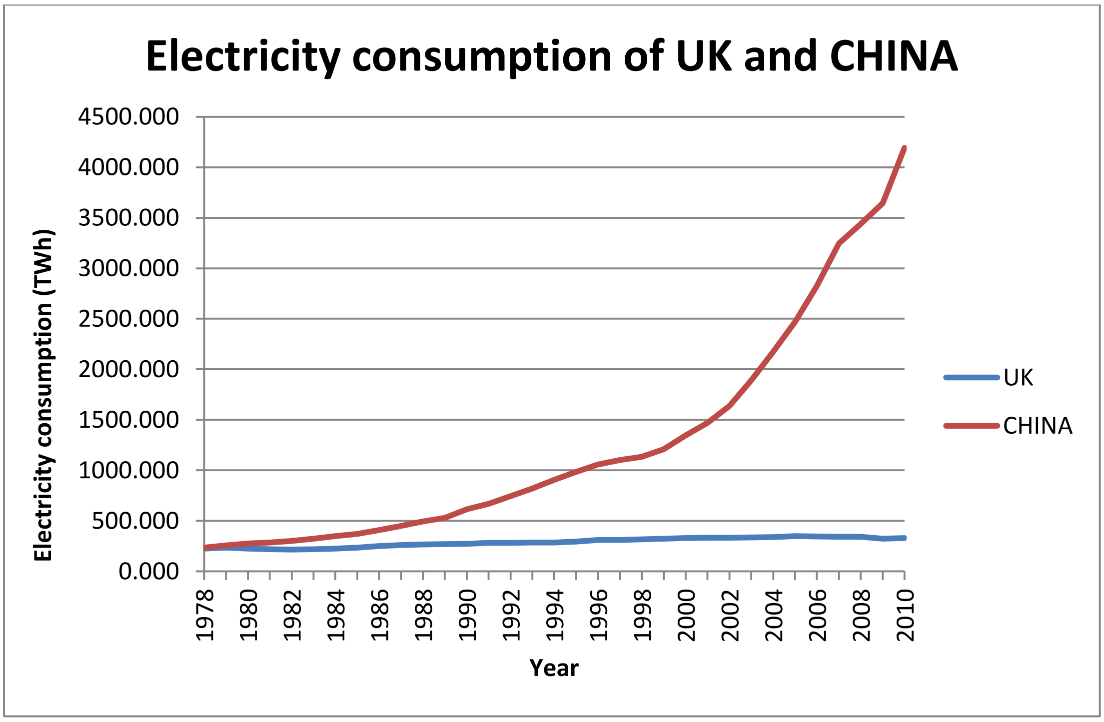

Figure 4.2: Electricity consumption of UK and CHINA

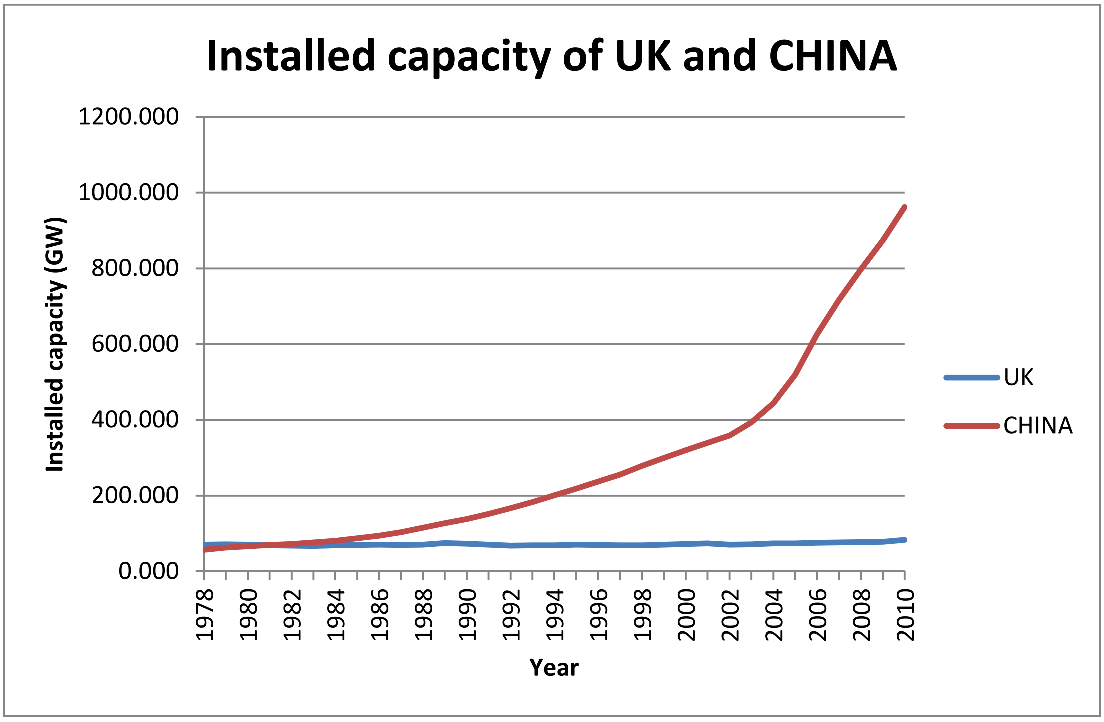

Figure 4.3: Installed capacity of UK and CHINA

GDP in UK and CHINA both are real GDP and the base year is 2000. The data source is the World Development Indicators of World Bank.[38] Electricity consumption and installed capacity in UK are from the publication of Department of Energy & Climate Change.[54] Electricity consumption and installed capacity in China are collected from China Statistical Yearbooks and China Energy Statistical Yearbooks. Note the installed capacity here is the total capacity of electricity generation. The value of cannot reflect the changes in the makeup of installed capacity.

All variables used in this chapter are employed in their natural logarithms form to reduce heteroscedasticity. In most cases, natural logarithms form has no impact on the relationship between variables. Table 4-2 lists the details of these variables.

Abbreviation	Annotation	Units	Periods
UKLnGDP	Logarithmic GDP in UK	Billion $	1978-2010

UKLnEC	Logarithmic Electricity Consumption in UK	TWh	
UKLnIC	Logarithmic Installed Capacity in UK	GW	
CNLnGDP	Logarithmic GDP in CHINA	Billion $	
CNLnEC	Logarithmic Electricity Consumption in CHINA	TWh	
CNLnIC	Logarithmic Installed Capacity in CHINA	GW	

Table 4-2: Variables used in Chapter 4

4.5 Empirical results for UK

This chapter use econometrics software Eviews 7.0 to obtain following results. Eviews (Econometric Views) is a statistical package for Windows, used mainly for time-series oriented econometric analysis. Eviews can be used for general statistical analysis and econometric analyses, such as cross-section and panel data analysis and time series estimation and forecasting. The current version of EViews is 7.2, released in Nov 2011.

4.5.1 Unit root test results for UK

This chapter use Augmented Dickey-Fuller (ADF) and Phillips–Perron **(**PP) test to test the unit roots. Table 4-3 gives the results of unit root test with and without time trend term for UKLnGDP, UKLnEC and UKLnIC.

		UKLnGDP		**UKLnEC**		**UKLnIC**	
		without trend	with trend	without trend	with trend	without trend	with trend
ADF	Level	0.8369	0.0152**	0.6517	1.0000	0.9989	0.9453
	1st Diff	0.0047***	0.0284**	0.0024***	0.0131**	0.0054***	0.0102**
PP	Level	0.8427	0.6660	0.6721	0.9380	0.9980	0.9883
	1st Diff	0.0454**	0.1863	0.0017***	0.0095***	0.0068***	0.0007***

Table 4-3: Unit root test results for UK data

The numbers in the table are the P-value (probability) of t test. Where ***, ** and * indicates statistical significance at the 1%, 5% and 10% level, respectively. It can be inferred from the Table 4-3 that the unit root hypotheses cannot be rejected when the variables are taken in levels. However, when first differences are used, the null hypotheses of non-stationary are rejected at the 1% or 5% level of significance. In other words, the P-value are larger than 0.1 when the variables are taken in levels, and less than 0.01 or 0.05 when first differences are used. Therefore, UKLnGDP, UKLnEC and UKLnIC are all $I(1)$ process.

4.5.2 Cointegration test results for UK

4.5.2.1 Engle-Granger (EG) test

This section use traditional Engle-Granger test to test the unit root of residual series of cointegration regression. Firstly, the author regress UKLnGDP and UKLnEC, like Eq.(4.22)

$$UKLnGDP = \beta_1 + \beta_2 UKLnEC + u_{1t} \tag{4.40}$$

The second step is to test unit root of u_{1t} by ADF and PP test. The result of cointegration regression is:

$$UKLnGDP = -0.956 + 1.429 UKLnEC + u_{1t} \tag{4.41}$$

and the P-values of unit root test on residual series are:

	ADF test	PP test
u_{1t}	0.8400	0.8006

The result indicates that the residual series of cointegration regression is nonstationary. It means there is no long term relationship or common trend between UKLnGDP and UKLnEC. They are not cointegrated.

Repeat above two procedures on UKLnGDP and UKLnIC, the cointegration regression is:

$$UKLnGDP = -7.307 + 3.382UKLnIC + u_{2t} \quad (4.42)$$

and the P-values of unit root test on residual u_{2t} are:

	ADF test	PP test
u_{2t}	0.4946	0.4642

The result indicates that the residual series u_{2t} is nonstationary. Hence, there is no cointegration relationship between UKLnGDP and UKLnIC.

For UKLnEC and UKLnIC, the cointegration regression is:

$$UKLnEC = -2.406 + 1.888UKLnIC + u_{3t} \quad (4.43)$$

and the P-values of unit root test on residual u_{3t} are:

	ADF test	PP test
u_{3t}	0.5496	0.5850

The result indicates that the residual series u_{3t} has unit root. Therefore, there is no cointegration relationship between UKLnEC and UKLnIC.

Overall, there is no cointegration relationship among UKLnGDP, UKLnEC and UKLnIC. Hence, these 3 variables cannot build vector error correction model.

4.5.2.2 Johansen test

Table 4-4and Table 4-5 gives the results of unrestricted cointegration rank test (Trace and Maximum eigenvalue).

Hypothesized No. of cointegration equations	Eigenvalue	Trace Statistic	Critical Value (5%)	P-values
None	0.482	33.147	42.915	0.329
At most 1	0.251	12.780	25.872	0.755
At most 2	0.116	3.806	12.518	0.770

Table 4-4: Unrestricted cointegration rank test (Trace) for UK

Hypothesized No. of cointegration equations	Eigenvalue	Max- eigen Statistic	Critical Value (5%)	P-values
None	0.482	20.368	25.823	0.223
At most 1	0.251	8.974	19.387	0.727
At most 2	0.116	3.806	12.518	0.770

Table 4-5: Unrestricted cointegration rank test (Maximum eigenvalue) for UK

These results indicate that there is no cointegration relationship among UKLnGDP, UKLnEC and UKLnIC, since the results cannot reject the null hypothesis of no cointegration equations at 5% level (P-value > 0.05). This conclusion is same as the results of Engle-Granger test.

4.5.3 VAR model and causality test

Because there is no cointegration relationship among UKLnGDP, UKLnEC and UKLnIC, VECM cannot be created. Therefore, these three series only can build VAR model and find short-run causality. According to AIC and BIC values, the lag length here of VAR model is one. The VAR model will be created as follow form.

$$UKLnGDP_t = \delta_1 + \theta_{11}UKLnGDP_{t-1} + \theta_{12}UKLnEC_{t-1} + \theta_{13}UKLnIC_{t-1} + \varepsilon_{1t} \tag{4.44}$$

$$UKLnEC_t = \delta_2 + \theta_{21}UKLnGDP_{t-1} + \theta_{22}UKLnEC_{t-1} + \theta_{23}UKLnIC_{t-1} + \varepsilon_{2t} \tag{4.45}$$

$$UKLnIC_t = \delta_3 + \theta_{31}UKLnGDP_{t-1} + \theta_{32}UKLnEC_{t-1} + \theta_{33}UKLnIC_{t-1} + \varepsilon_{3t} \tag{4.46}$$

The parameters can be calculated by using regression in Eviews 7.0:

$$\begin{bmatrix} \delta_1 & \theta_{11} & \theta_{12} & \theta_{13} \\ \delta_2 & \theta_{21} & \theta_{22} & \theta_{23} \\ \delta_3 & \theta_{31} & \theta_{32} & \theta_{33} \end{bmatrix} = \begin{bmatrix} 1.912 & 1.090 & -0.068 & -0.504 \\ 1.432 & 0.092 & 0.880 & -0.328 \\ 1.451 & 0.326 & -0.377 & 0.617 \end{bmatrix}$$

Hence:

$$UKLnGDP_t = 1.912 + 1.090 UKLnGDP_{t-1} - 0.068 UKLnEC_{t-1} - 0.504 UKLnIC_{t-1} \tag{4.47}$$

$$UKLnEC_t = 1.432 + 0.092 UKLnGDP_{t-1} + 0.880 UKLnEC_{t-1} - 0.328 UKLnIC_{t-1} \tag{4.48}$$

$$UKLnIC_t = 1.451 + 0.326 UKLnGDP_{t-1} - 0.377 UKLnEC_{t-1} + 0.617 UKLnIC_{t-1} \tag{4.49}$$

Because UKLnGDP, UKLnEC and UKLnIC are not stationary, they cannot be applied Granger causality test. However, since these variables are all $I(1)$ process, the first difference can be taken and create VAR model by differenced values to find short-run causality. The economic meaning of differenced value can be regarded as the increase rate of UKLnGDP, UKLnEC and UKLnIC.

The VAR model of ΔUKLnGDP, ΔUKLnEC and ΔUKLnIC is created as following:

$$\Delta UKLnGDP_t = \alpha_1 + \beta_{11} \Delta UKLnGDP_{t-1} + \beta_{12} \Delta UKLnEC_{t-1} + \beta_{13} \Delta UKLnIC_{t-1} + e_{1t} \tag{4.50}$$

$$\Delta UKLnEC_t = \alpha_2 + \beta_{21} \Delta UKLnGDP_{t-1} + \beta_{22} \Delta UKLnEC_{t-1} + \beta_{23} \Delta UKLnIC_{t-1} + e_{2t} \tag{4.51}$$

$$\Delta UKLnIC_t = \alpha_3 + \beta_{31} \Delta UKLnGDP_{t-1} + \beta_{32} \Delta UKLnEC_{t-1} + \beta_{33} \Delta UKLnIC_{t-1} + e_{3t}$$

(4.52)

The parameters can be calculated by software:

$$\begin{bmatrix} \alpha_1 & \beta_{11} & \beta_{12} & \beta_{13} \\ \alpha_2 & \beta_{21} & \beta_{22} & \beta_{23} \\ \alpha_3 & \beta_{31} & \beta_{32} & \beta_{33} \end{bmatrix} = \begin{bmatrix} 0.009 & 0.618 & -0.062 & -0.157 \\ 0.002 & 0.395 & 0.052 & -0.038 \\ 0.001 & 0.434 & -0.472 & 0.143 \end{bmatrix}$$

Hence:

$$\Delta UKLnGDP_t = 0.009 + 0.618\Delta UKLnGDP_{t-1} - 0.062\Delta UKLnEC_{t-1} - 0.157\Delta UKLnIC_{t-1} \quad (4.53)$$

$$\Delta UKLnEC_t = 0.002 + 0.395\Delta UKLnGDP_{t-1} + 0.052\Delta UKLnEC_{t-1} - 0.038\Delta UKLnIC_{t-1} \quad (4.54)$$

$$\Delta UKLnIC_t = 0.001 + 0.434\Delta UKLnGDP_{t-1} - 0.472\Delta UKLnEC_{t-1} + 0.143\Delta UKLnIC_{t-1} \quad (4.55)$$

To test the relationship between ΔUKLnGDP and ΔUKLnEC, the null hypothesis is $H_0 : \beta_{12} = 0 \text{ or } \beta_{21} = 0$; To test the relationship between ΔUKLnGDP and ΔUKLnIC, the null hypothesis is $H_0 : \beta_{13} = 0 \text{ or } \beta_{31} = 0$; To test the relationship between ΔUKLnEC and ΔUKLnIC, the null hypothesis is $H_0 : \beta_{23} = 0 \text{ or } \beta_{32} = 0$.

For instance, for $H_0 : \beta_{12} = 0$, p_1 =3, $p_2 = 4$,n=32. $RSS_1 = 0.010059$ and $RSS_2 = 0.010017$. According to Eq.(4.32), the F statistic can be calculated as following:

$$F=\frac{\left(\frac{RSS_1-RSS_2}{p_2-p_1}\right)}{\left(\frac{RSS_2}{n-p_2}\right)}=\frac{\left(\frac{0.010059-0.010017}{4-3}\right)}{\left(\frac{0.010017}{32-4}\right)}=0.1174 \qquad (4.56)$$

The critical value of F statistic for the 5% level of significance is 4.1960 (larger than 0.1174), with the degree of freedom (1, 28). P-value here is 0.7344, larger than 5%. The results accept the null hypothesis $H_0:\beta_{12}=0$. It means the term $\Delta UKLnEC_{t-1}$ can be removed from Eq.(4.50). In other words, ΔUKLnEC does not cause ΔUKLnGDP.

The results are summarised in Table 4-6 which gives the residual sum of squares (RSS) o f each case.

	Dependent variables		
	ΔUKLnGDP	**ΔUKLnEC**	**ΔUKLnIC**
RSS_2	0.010017	0.016669	0.016409
RSS_1	$\beta_{12}=0$ 0.010059	$\beta_{21}=0$ 0.017728	$\beta_{31}=0$ 0.017693
	$\beta_{13}=0$ 0.010353	$\beta_{23}=0$ 0.016689	$\beta_{32}=0$ 0.018850

Table 4-6: Residual sum of squares of each case in UK

Base on Eq.(4.32) and Table 4-6, the F statistic and P-value of each case can be calculated and the author sum up them in Table 4-7.

Dependent Variables		
ΔUKLnGDP	**ΔUKLnEC**	**ΔUKLnIC**
$\beta_{12} = 0$	$\beta_{21} = 0$	$\beta_{31} = 0$
0.1174 (0.7344)	1.7789 (0.1930)	2.1910 (0.1500)
$\beta_{13} = 0$	$\beta_{23} = 0$	$\beta_{32} = 0$
0.9392 (0.3408)	0.0336 (0.8559)	4.1653 (0.0508)

Table 4-7: Short-run causality test results in UK

Table denotes F-statistic values, and P-values are in parentheses. In the table, each case accepts the null hypothesis at 5% level since the P-values are all larger than 0.05. Therefore, ΔUKLnEC and ΔUKLnIC past terms are not necessary in Eq.(4.50), ΔUKLnGDP and ΔUKLnIC past terms are not necessary in Eq.(4.51), and ΔUKLnGDP and ΔUKLnEC past terms are not necessary in Eq.(4.52). In other words, there is no short-run causality among ΔUKLnGDP, ΔUKLnEC and ΔUKLnIC. Because these three variables don't have short-run and long-run (no cointegration) relationship, the author think the forecast and impulse response of VAR model is not necessary. The forecast and impulse response results will not have any economic meaning.

4.6 Empirical results for CHINA

4.6.1 Unit root test results for CHINA

Table 4-8 gives the results of unit root test with and without time trend term for CNLnGDP, CNLnEC and CNLnIC.

		CNLnGDP		CNLnEC		CNLnIC	
		without trend	with trend	without trend	with trend	without trend	with trend
ADF	Level	0.9894	0.0076***	0.9992	0.3081	0.9963	0.7054
	1st Diff	0.0022***	0.0133**	0.0310**	0.0360**	0.0892*	0.4608
PP	Level	0.9859	0.3001	0.9996	0.8049	0.9999	0.9070
	1st Diff	0.0993*	0.3412	0.0332**	0.0346**	0.2919	0.2817

Table 4-8: Unit root test results for CHINA

The numbers in the table are the P-value (probability) of t test. Where ***, ** and * indicates statistical significance at the 1%, 5% and 10% level, respectively. It is easy to know that CNLnGDP and CNLnEC both are $I(1)$ processes since the 1st differences of them reject the null hypothesis of unit root at the 1%, 5% and 10% level. For the 1st difference of CNLnIC, only ADF test without trend reject the null hypothesis of unit root at the 10% level. Combining this result and the figure of ΔCNLnIC Figure 4.4 (as usual, Δ is 1st difference operator), the author does not treat CNLnIC as a $I(1)$ process. The intrinsic reason of this result is because China suffered serious investment on power plant after 2004. Further tests show that CNLnIC is a $I(2)$ process.

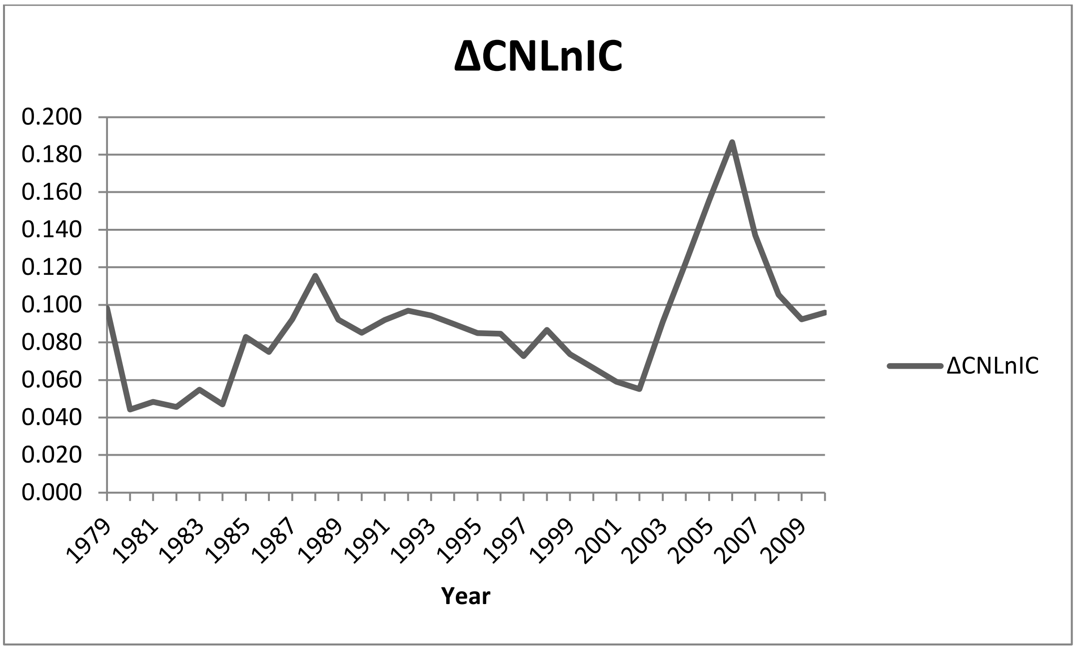

Figure 4.4: The 1st difference of CNLnIC

4.6.2 Cointegration test results for CNLnGDP and CNLnEC

4.6.2.1 Engle-Granger test

Because the precondition of cointegration of two or more variables is that they have same order of integration, CNLnGDP and CNLnEC may cointegrated. According to Engle-Granger test, the author regresses CNLnGDP on CNLnEC and tests the unit root of residual. By using software Eviews 7.0, the regressive equation is:

$$CNLnGDP = -0.618 + 1.055CNLnEC + e_t \qquad (4.57)$$

The ADF test result of e_t is 0.0461 (P-value), it's significant at 5% level. It means e_t is stationary at 5% level. Therefore, CNLnGDP and CNLnEC have a common trend, they are cointegrated.

4.6.2.2 Johansen test

Table 4-9 and Table 4-10 give the results of unrestricted cointegration rank test (Trace and Maximum eigenvalue).

Hypothesized No. of cointegration equations	Eigenvalue	Trace Statistic	Critical Value (5%)	P-values
None	0.4928	29.0467	25.8721	0.0194**
At most 1	0.2513	8.6819	12.5180	0.2009

Table 4-9: Unrestricted cointegration rank test (Trace) for CHINA

Hypothesized No. of cointegration equations	Eigenvalue	Max- eigen Statistic	Critical Value (5%)	P-values
None	0.4928	20.3648	19.3870	0.0360**
At most 1	0.2513	8.6819	12.5180	0.2009

Table 4-10: Unrestricted cointegration rank test (Maximum eigenvalue) for CHINA

Where ** indicates statistical significance at the 5% level. These results indicate that there is one cointegration relationship between CNLnGDP and CNLnEC, since the results reject the null hypothesis of no cointegration equations at 5% level (P-value < 0.05) and accept the null hypothesis of at most 1 cointegration. This conclusion is same as the results of Engle-Granger test.

4.6.3 VECM and causality test

According to Granger representation theorem, the relationship between CNLnGDP and CNLnEC can be expressed as error correction model. Hence, the author builds the vector error correction model which base on Eq.(4.27). The lag length is 3, according to minimum AIC.

$$\begin{aligned}\Delta CNLnGDP_t &= lagged(\Delta CNLnGDP_t, \Delta CNLnEC_t) - \lambda_1 ECT_{t-1} + e_{1t} \\ &= \delta_1 + (\alpha_1 \Delta CNLnGDP_{t-1} + \alpha_2 \Delta CNLnGDP_{t-2} + \alpha_3 \Delta CNLnGDP_{t-3}) \\ &\quad + (\beta_1 \Delta CNLnEC_{t-1} + \beta_2 \Delta CNLnEC_{t-2} + \beta_3 \Delta CNLnEC_{t-3}) \\ &\quad - \lambda_1 (CNLnGDP_{t-1} - \phi_2 CNLnEC_{t-1} - \phi_1) + e_{1t} \\ &= 0.079 + (0.631\Delta CNLnGDP_{t-1} - 0.301\Delta CNLnGDP_{t-2} \\ &\quad + 0.055\Delta CNLnGDP_{t-3}) \\ &\quad + (0.034\Delta CNLnEC_{t-1} - 0.024\Delta CNLnEC_{t-2} - 0.216\Delta CNLnEC_{t-3}) \\ &\quad - 0.186(CNLnGDP_{t-1} - 1.049 CNLnEC_{t-1} + 0.567)\end{aligned} \tag{4.58}$$

$$\begin{aligned}\Delta CNLnEC_t &= lagged(\Delta CNLnGDP_t, \Delta CNLnEC_t) - \lambda_2 ECT_{t-1} + e_{2t} \\ &= \delta_2 + (\theta_1 \Delta CNLnGDP_{t-1} + \theta_2 \Delta CNLnGDP_{t-2} + \theta_3 \Delta CNLnGDP_{t-3}) \\ &\quad + (\eta_1 \Delta CNLnEC_{t-1} + \eta_2 \Delta CNLnEC_{t-2} + \eta_3 \Delta CNLnEC_{t-3}) \\ &\quad - \lambda_2 (CNLnGDP_{t-1} - \phi_2 CNLnEC_{t-1} - \phi_1) + e_{2t} \\ &= 0.076 + (-0.388\Delta CNLnGDP_{t-1} + 0.067\Delta CNLnGDP_{t-2} \\ &\quad - 0.269\Delta CNLnGDP_{t-3}) \\ &\quad + (0.420\Delta CNLnEC_{t-1} + 0.083\Delta CNLnEC_{t-2} + 0.311\Delta CNLnEC_{t-3}) \\ &\quad + 0.123(CNLnGDP_{t-1} - 1.049 CNLnEC_{t-1} + 0.567)\end{aligned} \tag{4.59}$$

In Eq.(4.58), $(\alpha_1 \Delta CNLnGDP_{t-1} + \alpha_2 \Delta CNLnGDP_{t-2} + \alpha_3 \Delta CNLnGDP_{t-3})$ is the $lagged(\Delta CNLnGDP_t)$, $(\beta_1 \Delta CNLnEC_{t-1} + \beta_2 \Delta CNLnEC_{t-2} + \beta_3 \Delta CNLnEC_{t-3})$ is the $lagged(\Delta CNLnEC_t)$, and $\lambda_1 (CNLnGDP_{t-1} - \phi_2 CNLnEC_{t-1} - \phi_1)$ is the $\lambda_1 ECT_{t-1}$.

In Eq.(4.59), $(\theta_1 \Delta CNLnGDP_{t-1} + \theta_2 \Delta CNLnGDP_{t-2} + \theta_3 \Delta CNLnGDP_{t-3})$ is the $lagged(\Delta CNLnGDP)$, $(\eta_1 \Delta CNLnEC_{t-1} + \eta_2 \Delta CNLnEC_{t-2} + \eta_3 \Delta CNLnEC_{t-3})$ is the $lagged(\Delta CNLnEC_t)$, and $\lambda_2 (CNLnGDP_{t-1} - \phi_2 CNLnEC_{t-1} - \phi_1)$ is the $\lambda_2 ECT_{t-1}$.

Firstly, the author tests the short-run causality by testing $H_0 : \beta_1 = \beta_2 = \beta_3 = 0$, or $H_0 : \theta_1 = \theta_2 = \theta_3 = 0$, in other words, tests if $lagged(\Delta CNLnEC_t) = 0$ or $lagged(\Delta CNLnGDP) = 0$. If $lagged(\Delta CNLnEC_t) = 0$, it indicates CNLNEC does not cause CNLNGDP in short run; and if $lagged(\Delta CNLnGDP)=0$, it means CNLNGDP does not cause CNLNEC in short run. (See section 4.3.8.2)

Then, it is followed by testing the long-run causality by testing $H_0:\lambda_1=0$, or $H_0:\lambda_2=0$, in other words, tests if $\lambda_1 ECT_{t\text{-}1}=0$ or $\lambda_2 ECT_{t\text{-}1}=0$. If $\lambda_1 ECT_{t\text{-}1}=0$, it means there is no long-run causality from CNLNEC to CNLNGDP; and if $\lambda_2 ECT_{t\text{-}1}=0$, there is no long-run causality from CNLNGDP to CNLNEC. (See section 4.3.8.2)

Finally, the tests on joint hypotheses is done by testing $H_0:\beta_1=\beta_2=\beta_3=\lambda_1=0$, or $H_0:\theta_1=\theta_2=\theta_3=\lambda_2=0$. If $\beta_1=\beta_2=\beta_3=\lambda_1=0$, this means there is no causality from CNLNEC to CNLNGDP in both short-run and long-run; and if $\theta_1=\theta_2=\theta_3=\lambda_2=0$, it means there is no causality from CNLNGDP to CNLNEC in both short-run and long-run. (See section 4.3.8.2)

The results are summarised in Table 4-11, which gives the residual sum of squares (RSS) of each case.

	Dependent variables	
	ΔCNLnGDP	**ΔCNLnEC**
RSS_2	0.006575	0.021169
RSS_1	$H_0:\beta_1=\beta_2=\beta_3=0$ 0.0072890	$H_0:\theta_1=\theta_2=\theta_3=0$ 0.023836
	$H_0:\lambda_1=0$ .009492	$H_0:\lambda_2=0$ 0.022455
	$H_0:\beta_1=\beta_2=\beta_3=\lambda_1=0$ 0.009686	$H_0:\theta_1=\theta_2=\theta_3=\lambda_2=0$ 0.024946

Table 4-11: The residual sum of squares of each case in CHINA

Base on Eq.(4.32) and Table 4-11, the F statistic and P-value of each case can be calculated and the author summarised them together in Table 4-12.

Dependent variables	
ΔCNLnGDP	**ΔCNLnEC**
$H_0:\beta_1=\beta_2=\beta_3=0$	$H_0:\theta_1=\theta_2=\theta_3=0$
0.9049 (0.4527)	1.0499 (0.3879)
$H_0:\lambda_1=0$	$H_0:\lambda_2=0$
11.0913*** (0.0027)	1.5187 (0.2293)
$H_0:\beta_1=\beta_2=\beta_3=\lambda_1=0$	$H_0:\theta_1=\theta_2=\theta_3=\lambda_2=0$
2.9572** (0.0395)	1.1151 (0.3716)

Table 4-12: Causality test in CHINA

The table denotes F-statistic values, and P-values are in parentheses. Where *** and ** indicates statistical significance at the 1% and 5% level, respectively. Firstly, for the short-run causality, the coefficients on lagged ΔCNLnEC terms in the ΔCNLnGDP equation and lagged ΔCNLnGDP terms in the ΔCNLnEC equation are both found to be not significant. It means $H_0:\beta_1=\beta_2=\beta_3=0$ and $H_0:\theta_1=\theta_2=\theta_3=0$ are both accepted in Eq.(4.58) and (4.59). In other words, CNLNEC does not cause CNLNGDP in short run and CNLNGDP does not cause CNLNEC in short run. This result concludes that there is no short-run causality between these two variables.

Secondly, the coefficient on ECT in the ΔCNLnGDP equation (Eq.(4.58)) is significant at 1% level but not vice versa. It means $H_0:\lambda_1=0$ is rejected but

$H_0 : \lambda_2 = 0$ is accepted. This result indicates the causality in long-run is running from electricity consumption to economic growth in China.

Thirdly, in the joint causality test, $H_0 : \beta_1 = \beta_2 = \beta_3 = \lambda_1 = 0$ is rejected at 5% level but $H_0 : \theta_1 = \theta_2 = \theta_3 = \lambda_2 = 0$ is accepted. It shows the joint causality test result finds the same direction as long-run causality, which is, the causality is running from electricity consumption to economic growth in China.

To sum up, the short-run causality test supports neutrality hypothesis, while the long-run and joint test suggest growth hypothesis. The neutrality hypothesis suggests there is no causality between electricity consumption and GDP, and the growth hypothesis asserts that there is the unidirectional causality running from electricity consumption to economic growth. (See section 4.2)

4.6.4 Forecasts base on VECM

Because Eq.(4.58) and (4.59) contain historical information of CNLnGDP and CNLnEC, they can be used to forecast future values. Figure 4.5 and Figure 4.6 give the forecast results of GDP and electricity consumption. In the figures the graphs to the right of vertical line are forecast from 2011 to 2015. The graphs show that the GDP and electricity consumption in China are expected to continue to maintain sustained growth in the next 5 years.

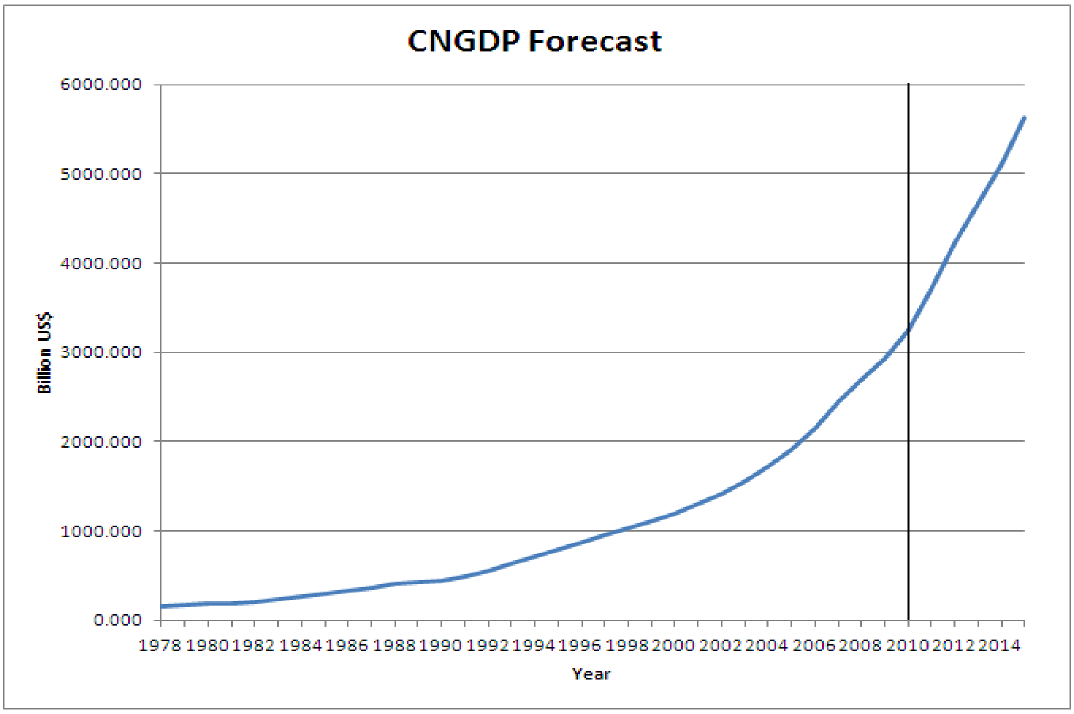

Figure 4.5: Forecast result of GDP in CHINA

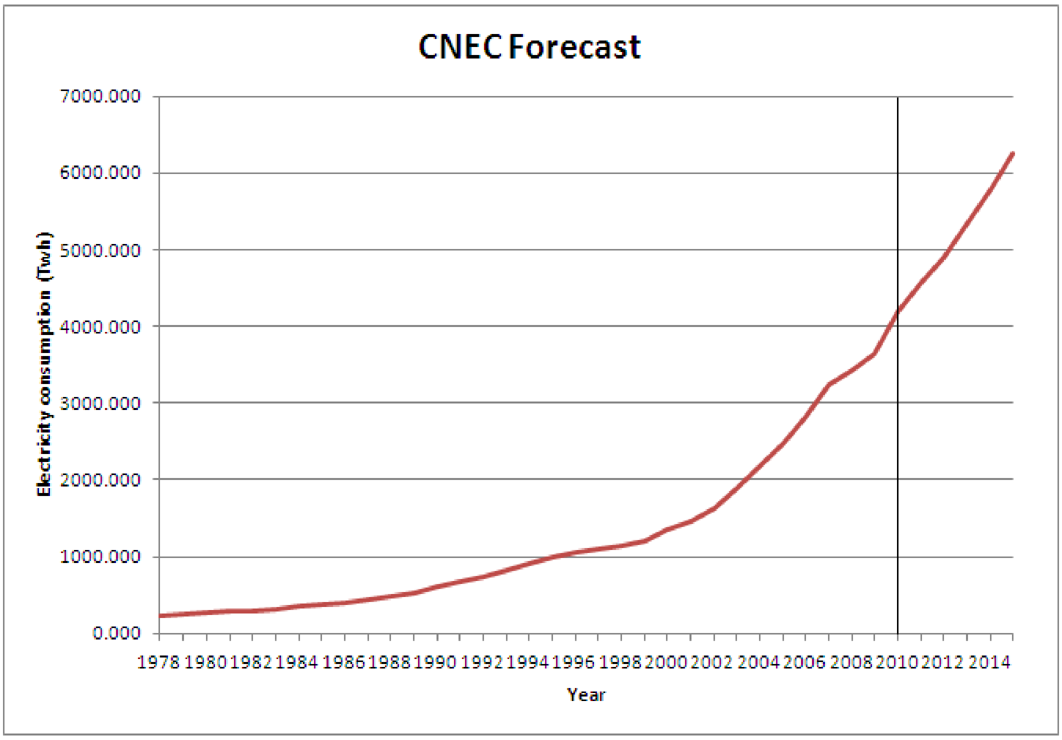

Figure 4.6: Forecast result of electricity consumption in CHINA

4.6.5 VAR and impulse response

The author tries to build a stationary VAR model and applies impulse response to find the some relationship among CNLnGDP, CNLnEC and CNLnIC. The VAR model is created by ΔCNLnGDP, ΔCNLnEC and ΔCNLnIC. The economic meaning of differenced value can be regarded as the increase rate of CNLnGDP, CNLnEC and CNLnIC.

The VAR model is shown in Eq.(4.60) to (4.62):

$$\Delta CNLnGDP_t = 0.511\Delta CNLnGDP_{t-1} + 0.178\Delta CNLnEC_{t-1} - 0.092\Delta CNLnIC_{t-1} + 0.039 \tag{4.60}$$

$$\Delta CNLnEC_t = -0.263\Delta CNLnGDP_{t-1} + 0.360\Delta CNLnEC_{t-1} + 0.259\Delta CNLnIC_{t-1} + 0.060 \tag{4.61}$$

$$\Delta CNLnIC_t = 0.086\Delta CNLnGDP_{t-1} + 0.267\Delta CNLnEC_{t-1} + 0.588\Delta CNLnIC_{t-1} + 0.004 \tag{4.62}$$

By using Eviews 7.0, all the roots of characteristic polynomial are given in Table 4-13. These prove that above VAR model is stable since the roots of characteristic polynomial are all less than one. (See section 4.3.4.2) Therefore, the impulse response method can be applied on this VAR model.

Root	**Modulus**
0.756834	0.756834
0.351044 - 0.163760i	0.387362
0.351044 + 0.163760i	0.387362

Table 4-13: Root of characteristic polynomial

The impulse response results are given in Figure 4.7 to Figure 4.9. Where D stands for Δ, like D(CNLNGDP) means $\Delta CNLnGDP_t$. The unit of horizontal axis is YEAR, and vertical axis shows the unit change by the impulse.

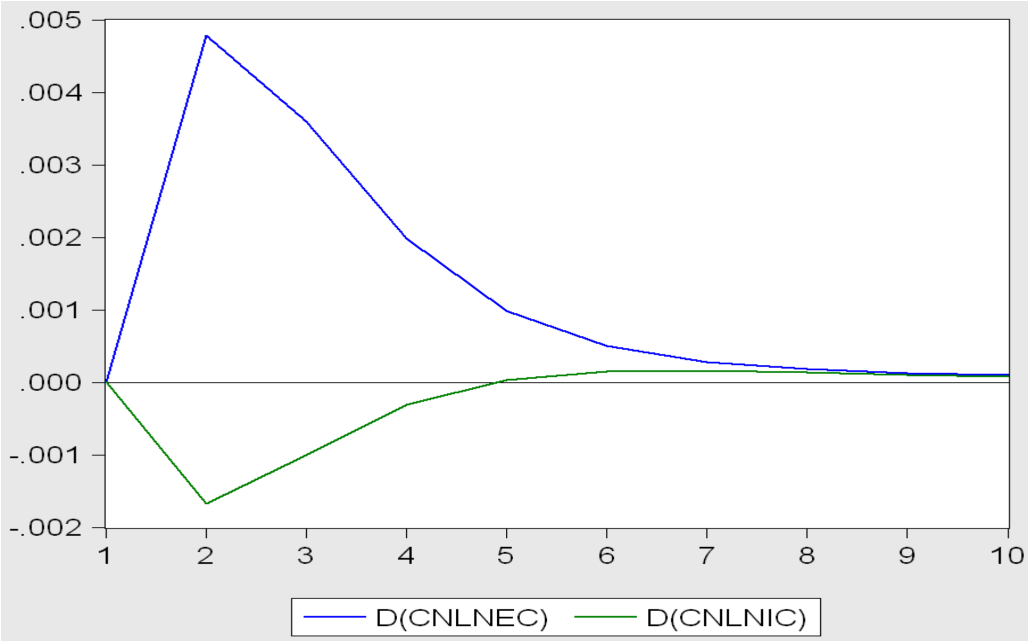

Figure 4.7: Response of ΔCNLnGDP to ΔCNLnEC and ΔCNLnIC

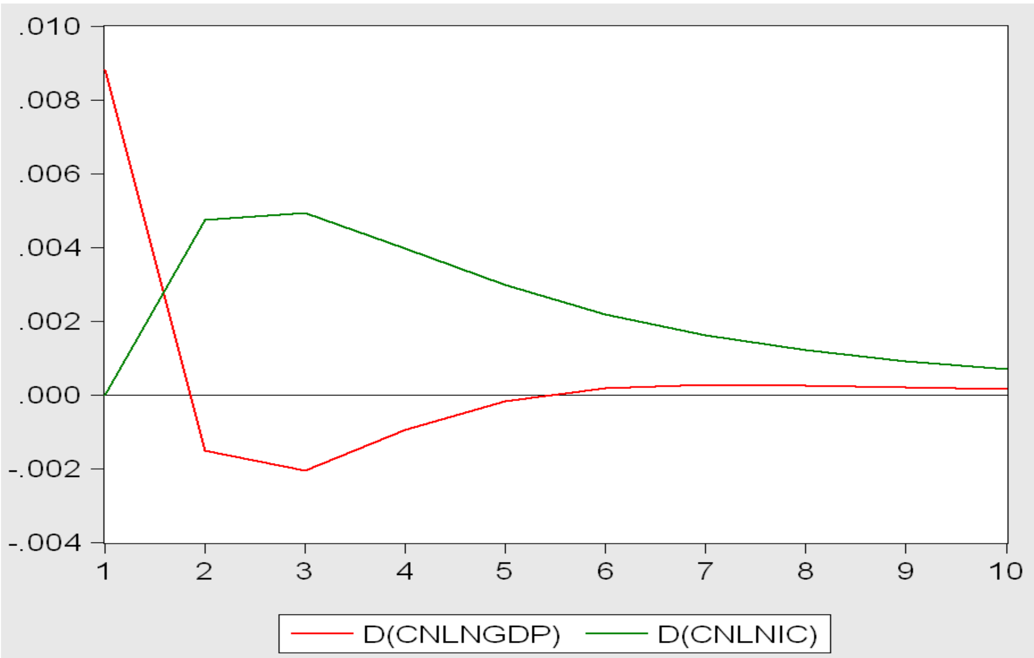

Figure 4.8: Response of ΔCNLnEC to ΔCNLnGDP and ΔCNLnIC

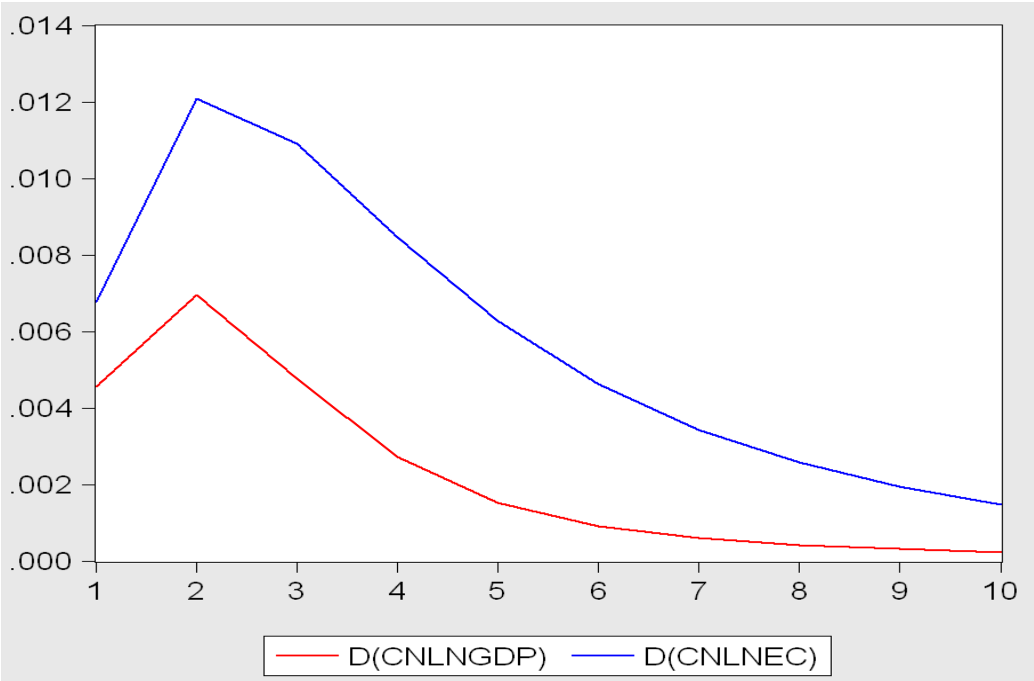

Figure 4.9: Response of ΔCNLnIC to ΔCNLnGDP and ΔCNLnEC

From Figure 4.7, we can see that an impulse of ΔCNLnEC can lead to a positive response of ΔCNLnGDP for about 7 years, but an impulse of ΔCNLnIC will cause a negative response of ΔCNLnGDP for 4 years. The Figure 4.8 shows that a sudden adjustment of ΔCNLnGDP will cause a negative response of ΔCNLnEC, but such adjustment of ΔCNLnIC can lead to positive response of ΔCNLnEC for almost a decade. The Figure 4.9 indicates an improvement of both ΔCNLnGDP and ΔCNLnEC will lead to huge positive response of ΔCNLnIC.

The above results show that an increase of electricity consumption can improve development of economy for many years but not vice versa. It reflects that the long-run causality is running from electricity consumption to economic growth. Impulse response results also point out the uncoordinated period of economic growth and installed capacity since the power generation capacity construction did not match the economic period. Some years the power generation capacity is in surplus, and some years is shortage. Figure 4.7 shows that investors in China usually respond slowly to the change of macro-economy. Moreover, installed capacity over investment can be found in Figure 4.9. The increase of GDP and electricity consumption may lead to a huge passion of investment for many years.

4.7 Comparison and analysis

From the above results, we can see that the economic growth and power industry in UK and China are significantly different. Figure 4.1 Figure 4.2 and Figure 4.3 give the direct impression of GDP, electricity consumption and economic growth in these two countries. The real GDP in UK was larger than China before 2004, but China has higher increase rate. At the end of 2010, the size of economy of China is almost twice as UK. However, the scales of electricity consumption and generation capacity in China are more than ten times as UK. This means the electricity consumption efficiency in UK is much better than China. The reason can be explained. As a developed country, UK has top-notch scientific and technical personnel, advanced energy saving technology and equipment, which can greatly reduce electricity usage. More importantly is, in UK, high electricity consumption industries have been moved to a country with low-cost manpower, such as China. The mainland of Britain remains low electricity consumption, light pollution and high technology industrial country, such as pharmacy, finance, information technology and bioengineering. These facts also can explain the causality test results in UK. Because high electricity consumption industries are not the major part of the annual output, the electricity consumption cannot have effect on economic growth and vice versa. The author thinks that neither strict nor expansive policies in relation to electricity consumption have any effect on economic growth. The installed capacity in UK is the total capacity, which cannot reflect the changes in the makeup of installed capacity. In fact, although the total value of capacity in UK remains the same level in past decade, the traditional power plants are shutting down and renewable energy are starting to generate electricity gradually.

China is the world largest developing country. Although China has made great progress in economy, their technology and science level in some area still lag behind the UK. Independent innovation in China remains a great distance behind that of the developed countries. Electricity consumption per capita is an indicator which can reflect the distance between UK and China. The electricity consumption per capita in UK is 6062 kWh, while this indicator is only 2455 kWh in China. It means the modernization in China still stay at a low level. The causality test result show that the direction of causality is running from electricity consumption to economic growth. This result reflects that the mode of economic growth in China is based on high electricity consumption. The impulse response results also find the uncoordinated period of economic growth and installed capacity in China.

Therefore, one suggestion is the Chinese government need to consolidate the heavy industry to eliminate smaller producers that create the most pollution and cost the most on energy and electricity. But the strict conservation policy must be implemented with caution since such policy may harm the economic development. The government also should balance the supply and demand of electricity industry. After the recent economic crisis, the fluctuation of macroeconomic may cause the fluctuation of electricity demand. The use of policy instrument is needed for coordination between power industry and macro-economy. For investors, scientific prediction of macroeconomic fluctuation and electricity consumption is necessary to avoid over investment and peak construction.

4.8 Summary

This chapter studied the relationship among electricity consumption, economic growth and installed capacity in UK and China respectively. The literature reviews summarized this kind of study. The recent studies categorized the relationship between electricity consumption and economy into four types: neutrality hypothesis, growth hypothesis, conservation hypothesis and feedback hypothesis. This part also listed the recent papers of country-specific studies on energy or electricity economics.

This chapter also introduced the econometric analysis methods. Firstly, the definitions of stationary and nonstationary stochastic processes were presented. Secondly, two types of unit root test were mentioned to test the stationarity of time series. Thirdly, vector autoregression model and impulse response approach could be applied on several variables to forecast future values and find the response of an innovation. Fourthly, cointegration relationship and its test methods were introduced. If two or more variables are cointegrated, (vector) error correction model may be created. Finally, the test method of causality direction is expounded, which is based on VAR model and VECM. The F test was used on causality test for model comparison.

All of the above approaches were applied on UK and China's data respectively. The unit root test results of UK showed that the logarithmic form of real GDP, electricity consumption and installed capacity in UK are all 1^{st} order process. The cointegration tests showed that there is no cointegration relationship among real GDP, electricity consumption and installed capacity in UK. After creating a VAR model, the causality test did not find any causality among these three variables. Therefore, the forecast and impulse response results will not have any economic meaning.

The unit root test results of China stated that logarithmic form of real GDP and electricity consumption are I(1) process, and the log installed capacity is I(2) process. Then, a cointegration relationship had found between real GDP and electricity consumption. Hence, these two variables built a VECM and tested short-run, long-run and joint causality. The test results indicated that there is no causality between these two variable in short-run but has unidirectional causality running from electricity consumption to economic growth in the long-run and also in the joint test. After causality test, the forecast based on VECM gave the predicted value of electricity consumption and real GDP from 2011 to 2015. Finally, a stationary VAR model was created by logarithmic real GDP, electricity consumption and installed capacity of China, and the impulse response results proved and perfectly explained the causality test results.

An explanation and comparison of UK and China's empirical results were given, followed by some policy implications.

Moreover, because the regional development in China is not balanced, the causality between electricity consumption and economic growth may be different in different regions. This topic will be discussed in chapter 5.

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Chapter 5: Electricity Consumption and Economic Growth in China: Based on the Provincial Panel Data Analysis

5.1 Introduction

The study of relationship between energy or electricity consumption and economic growth has been undertaken for a broad range of countries since the initial one performed by Kraft and Kraft[1] on the U.S. economy. This is because the direction of causality has significant policy implications, especially for developing countries.

In the past two decades, since the introduction of reform and an open-door policy, China has achieved rapid economic growth and has become the second largest electricity consumption country in the world, just following the United States. Historically, the electric power industry was designated as a driving force of China economic growth. In line with the rapid expansion of the Chinese economy after the late 1970's, there has been a steady increase in installed generation capacity and electricity consumption. By the end of 2009, the installed generation capacity in China amounted to more than 870GW and electricity consumption is more than 3600TWH. The electricity consumption is not only the foundation of industry, but it is also an important criterion for measuring economic growth. The coordination of electricity consumption and economy is crucial to sustain economic growth and, therefore, research on the relationship and causality between electricity consumption and economic growth has a positive significance on policy making and power industry investments. Because of the size of the country and the differences of economic growth and industrial development in different areas of China, the different situations of electricity consumption-growth nexuses are worthy of consideration, a different relationship may give a different policy guidance.

The aim of this chapter is an attempt to investigate the relationship and causality between electricity consumption and economic growth in China by panel-based methods. The remainder of the chapter is organized as follows: section 2 gives a review of past literatures; section 3 describes the data and section 4 discusses the methodology of the study; section 5 shows the empirical results and analysis; and the last section is discussion and conclusion.

5.2 What is panel data?

In econometrics, panel data is data observed over two dimensions (typically, time and cross-sections). A panel data set is termed "multidimensional" when the phenomenon is observed over three or more dimensions. Because panel data have both cross-sectional and time series dimensions, the application of regression models to fit econometric models are more complex than those for simple cross-sectional data sets.

There are several reasons for the increasing interest in panel data sets. An important one is that their use may offer a solution to the problem of bias caused by unobserved heterogeneity, a common problem in the fitting of models with cross-sectional data sets. A second reason is that it may be possible to exploit panel data sets to reveal dynamics that are difficult to detect with cross-sectional data. A third attraction of panel data sets is that they often have very large number of observations.

5.3 Literature reviews

5.3.1 The studies on energy consumption – economic growth nexus by panel-based method

For the multi-country studies on energy consumption, panel-based methods were began to be used by Lee[2]. He applied panel-based vector error correction model on 18 developing countries during 1975-2001 period and found unidirectional causality of these countries running from energy consumption to GDP. Apergis and Payne[3] thought 6 Central America countries had unidirectional causality running from energy consumption to growth by using panel causality test. Then, Apergis and

Payne[4] used the same approaches and steps on 11 Commonwealth of Independent States. They found bidirectional causality existing in the long-run and unidirectional causality running from energy consumption to growth in the short-run.

5.3.2 The studies on electricity consumption – economic growth nexus by panel-based method

Because the types of energy use are various and complex, some researchers found electricity consumption data have better correlation with economic growth. For the multi-country studies on electricity consumption-growth nexus, Yoo[5] used Granger causality test and Hsiao’s version of Granger causality method on 4 South East Asia countries during the period 1971-2002. He found two of them have causality from GDP to electricity consumption and two others have bidirectional causality. Ciarreta and Zarraga[6] chose 12 European countries and used panel-based methods for the periods of 1970-2004. The results showed that there was a significant long-run causality from electricity consumption to GDP and no short-run causality between them. Narayan and Smyth[7] employed panel methods on 6 Middle Eastern countries and they found bidirectional causality existed between electricity consumption and growth.

5.3.3 The studies on energy or electricity consumption – economic growth nexus in China

In the past decades, several researchers switched their attention to China. Shiu and Lam[8] analyzed the electricity data during 1971-2000. They asserted that there was a unidirectional causality running from electricity consumption to economic growth in China. Yuan, et al.[9] got the same result by using the data for the 1963-2005 period. Zhang and Cheng[10] did not support the above opinion, they suggested conversation hypothesis of energy consumption-growth nexus by using energy consumption data for 1960-2007. A major common weakness of these three papers is that the authors did not consider the differences of economic growth and environment in different regions of China. Moreover, the sample size and time period of aggregate data of China is too small and too old to ensure accurate results.

Some researchers were aware of such weakness, so they tried to sub-divide China into two or three parts and applied panel methods to embody the differences. Li, et al.[11] classified 30 China provinces into two parts. Their results showed that there was a positive long-run cointegrated relationship between real GDP per capita and energy consumption variables. A number of researchers employ conventional classification. They divided China into three parts: east, central and west parts, to investigate the relationship between energy consumption and economic growth, like Wu, et al.[12]. The authors of this chapter think these classifications are not proper. With such a vast country, China faces complicated conditions and imbalanced development among different regions. It is because the author believes that using geographical classification on its own cannot reflect the true reality of the relationship between electricity consumption and economic growth in China. Unlike these published articles, this chapter researches electricity consumption – economic growth nexus in China and classifies China’s provinces into four parts: Northeast, Coastal, Central and West. The classification is based on GDP per head, industry production per head and industrial structure. Comprehensively considering the location of each province, the under-developed ones will be grouped into the west panel, since most of them are located in the west region of China. Similarly, the better-developed provinces and the less-developed ones will be named coastal panel and central panel respectively. In this chapter, the three northeast provinces are treated as a separate group because this area has always been seen as the original base of China’s industry, especially heavy industry. Their demand of electricity is huge and it plays an important role in economic development in the northeast region.

Two reasons make the authors select electricity consumption data rather than energy consumption data. Firstly, the energy data is hard to collect because there are several types of energy consumption, like oil, coal, gas and so on. The statistical results of these types of energy need to be converted to one common measuring unit, thus the accuracy of data becomes uncertain. Secondly, the availability of different types of energy is not uniformly distributed throughout the country because energy consumption structures of different regions can differ greatly, and as such the collected energy data cannot properly reflect their impact on economic growth.

To the best of the authors' knowledge, there is yet no published article to discuss and analyze the relationship between electricity consumption and economic growth in China by using classification and panel approach. This chapter attempts to bridge this gap.

5.4 Definition of variables and classification of provincial data

This chapter uses logarithmic electricity consumption ($\ln EC_{it}$) and logarithmic real GDP ($\ln GDP_{it}$, based on 1978's price) to stand for electricity consumption and economic growth of each province respectively for the period 1985-2009. The subscript i represents different provinces. All variables are employed in their natural logarithms form to reduce heteroscedasticity. The unit is $\times 10^8 kW$ for electricity consumption and $\times 10^8$ RMB for real GDP. The data used in this chapter come from 28 provinces excluding *CHONGQIN*, *HAINAN* and *TIBET*, since the data of these 3 provinces over the period of interest are incomplete.

In order to reflect the difference in economic growth and electricity industry development in each province, 28 provinces are classified into four panels which are: 3 North-eastern provinces (*Liaoning, Jilin and Heilongjiang*); 7 better-developed provinces (*Shanghai, Beijing, Tianjin, Zhejiang, Jiangsu, Guangdong and Shandong*); 9 less-developed provinces (*Fujian, Hebei, Hubei, Shaanxi, Shanxi, Sichuan, Henan, Hunan and Jiangxi*); and 9 under-developed provinces (*Neimenggu, Xinjiang, Qinghai, Ningxia, Anhui, Guangxi, Yunnan, Gansu and Guizhou*).

The real GDP are deflated to the nominal GDP by using GDP deflators, the base year is 1978. The nominal GDP data and GDP deflators are all from China Statistical [13] from 1985 to 2009, the filename of the data is Regional GDP and Deflator. The electricity consumption data of each province during 1999-2009 are also published in the China Statistical Yearbooks[13], the filename of the data is Regional Electricity consumption per Year. Similar data during the period 1985-1998 are extracted one by one from Provincial Statistical Yearbooks of each province respectively. These Provincial Statistical Yearbooks are available for downloading from China Statistical Yearbooks Database[14]. The number of samples of real GDP and electricity consumption is respectively each 700. This equivalent to the product of 28 (provinces) times 25 (number of years).

5.5 Methodology

To investigate the relationship between LnEC and LnGDP by panel models, panel unit root test, panel cointegration test and panel causality analysis are employed. Firstly, in order to avoid spurious correction between LnEC and LnGDP, panel unit root test is used to identify the order of each panel. Secondly, this chapter tests the cointegration between these two variables in each panel by employing the heterogeneous panel cointegration test developed by Pedroni[15]. The panel cointegration test indicates whether a long-run, equilibrium, combination exists between electricity consumption and GDP in each panel. Then, the chapter applies the panel vector error correction model to investigate the direction of the causal relation between the variables after establishing the cointegration relationship. Finally, to estimate panel long-run elasticity, the chapter applies the fully modified and dynamic OLS techniques.

5.5.1 Panel unit root tests

Because only non-stationary series may have cointegration relationship, it is essential to verify that whether the variables have unit root. Common unit root tests for individual time series are deemed to have lower power. As panel data have large number of data points, recent research suggests that panel-based unit root tests have higher power than individual series unit root tests.

Many researches on panel unit root test have been published in recent years including Levin, et al.[16] *(LLC)*, Breitung[17], Im, et al.[18] *(IPS)*, Hadri[19], *Fisher-ADF (augmented Dickey–Fuller) and Fisher-PP (Phillips-Perron)* (Maddala and Wu[20] and Choi[21].

Assume that panel data { y_{i0} ,…, y_{iT} } are generated for each i by first-order autoregressive process:

$$y_{it} = (1-\alpha_i)\mu_i + \alpha_i y_{i,t-1} + \varepsilon_{it} \tag{5.1}$$

where $i = 1,2,...,N$. μ_i is the deterministic component and the errors ε_{it} are identically, independently distributed across i and t with $E(\varepsilon_{it}) = 0$, $E({\varepsilon_{it}}^2) = \sigma^2 < \infty$ and $E({\varepsilon_{it}}^4) < \infty$. This process can be written as Dickey-Fuller (DF) regression:

$$\Delta y_{it} = -\phi_i \mu_i + \phi_i y_{i,t-1} + \varepsilon_{it} \tag{5.2}$$

where $\Delta y_{it} = y_{it} - y_{i,t-1}$, $\phi_i = \alpha_i - 1$. Let $y_{it} = y_{it} - \mu_i$, Eq.(5.1) can be rewritten as:

$$y_{it} = \alpha_i y_{i,t-1} + \varepsilon_{it} \tag{5.3}$$

and the corresponding DF regression is given by:

$$\Delta y_{it} = \phi_i y_{i,t-1} + \varepsilon_{it} \tag{5.4}$$

The null hypothesis of unit root for each individual (province) is:

$$H_0 : \phi_1 = ... = \phi_N = 0 .$$

This means that all the time series of each individual are independent random walks. Consider two alternatives:

$$H_{1a} : \phi_1 = ... = \phi_N = \phi \text{ and } \phi<0$$
$$H_{2a} : \phi_1 < 0,...,\phi_{N_0} < 0,\ N_0 \le N$$

Under H_{1a} it is assumed that the autoregressive parameter is uniform for all cross-section units. This is called the homogeneous alternative. Levin, et al.[16] use this kind of alternative. It assumes that there is a common unit root process so that ϕ_1 is identical across all cross-sections. H_{2a} allows for individual unit root processes so that ϕ_i may vary across cross-sections. This is referred to as the heterogeneous alternatives, which is used in Im, et al.[18]. IPS tests unit root for each cross-section unit and defines their t-bar statistic as the average of individual ADF statistics, t_{iT} , for the null as:

$$\bar{t} = \frac{1}{N}\sum_{i=1}^{N} t_{iT} \tag{5.5}$$

Maddala and Wu[20] and Choi[21] proposed a very simple test that combines the P-values from individual unit root test. There exist many possible combinations and the one by Fisher turns out to be a better choice and is called Fisher-type test. Choi considers the model:

$$y_{it} = d_{it} + x_{it} \tag{5.6}$$

with $i = 1, 2, ..., N,\ t = 1, 2, ...T$, and

$$d_{it} = \alpha_{i0} + \alpha_{i1} t + ... + \alpha_{im_t} t^{m_i},\ x_{it} = \rho_i x_{i,t-1} + u_{it} \tag{5.7}$$

where u_{it} is stationary, d_{it} is a non-stochastic process and x_{it} is a stochastic process. Each time series y_{it} can have different sample size and different specification of non-stochastic and stochastic component depending on i . It means it does not require a balanced panel as in the *IPS* test. Let p_i be the p-value of a unit root test for cross-section i , the null hypothesis is: $H_0 : \rho_i = 1$ for all i , which implies that all the individuals are unit root non-stationary. The alternative hypothesis may be:

$H_{1a} : |\rho_i| < 1$ for at least one i for finite N

$H_{1b} : |\rho_i| < 1$ for some i's for infinite N

The Fisher-type test is: $P = -2\sum_{i=1}^{N} \ln p_i$ which combines the p-value from unit root test for each individual (province) to test for panel unit root. P is distributed as $\chi^2(2N)$ as $T_i \to \infty$ for all N.

In this chapter, LLC, IPS, and Fisher-type tests are used to test unit roots of LnEC and LnGDP in each panel.

5.5.2 Panel cointegration test

Cointegration analysis introduced the idea that even if the underlying time series are non-stationary, linear combinations of these series might be stationary. The traditional cointegration test methods (e.g., residual-based method) are only suitable for individual time series. For the 28 provinces, heterogeneity may arise because of the differences in economic growth conditions in each province. To ensure wide applicability of any panel cointegration test, it is important to allow for as much heterogeneity as possible among the individual members of the panel. Pedroni[15, 22] developed a methodology to test for panel data cointegration which can be considered as an extension of the traditional Engle and Granger[23] residual-based method. This chapter applies Pedroni's method to test cointegration relationship in heterogeneous panel data and considers the following cointegrating regression:

$$\ln GDP_{it} = \alpha_i + \delta_i t + \beta_i \ln EC_{it} + e_{it} \tag{5.8}$$

where α_i is the province-specific intercept and $\delta_i t$ is a deterministic time trend specific to an individual province in the panel. The slope coefficient β_i is also permitted to be different for different provinces, so that in general the cointegrating vectors may be heterogeneous across members of the panel.

Pedroni derives the asymptotic distributions and explores the small sample performances of seven different statistics, four of which are based on polling along the within-dimension (called 'panel' hereafter), while the other three are based on pooling along the between-dimension (called ‘group’ hereafter). The formers are based on estimators that effectively pool the autoregressive coefficients across different members for the unit root tests on the estimated residuals, while the latters are based on estimators that simply average the individually estimated coefficients for each i. The panel statistics are (a) panel v (variance)-statistic, (b) panel rho (ρ)-statistic, (c) panel PP-statistic and (d) panel ADF-statistic. The group statistics are (e) Group rho-statistic, (f) Group PP-statistic and (g) Group ADF-statistic. The details of these statistics are listed in the **Appendix.**

To test for the null of no cointegration, the following unit root test is conducted on the residuals as follows:

$$e_{it} = \gamma_i e_{i,t-1} + \mu_{it} \tag{5.9}$$

where e_{it} is the estimated residual and γ_i is the estimated autoregressive coefficient of the residuals in the i th unit. The panel statistics and group statistics depend on the null hypothesis of no cointegration, $H_0 : \gamma_i = 1 \text{ for all } i$, against the alternative hypothesis $H_1 : \gamma_i = \gamma < 1$ and $H_1 : \gamma_i < 1 \text{ for all } i$, respectively. Thus, the group statistics allow one to model an additional source of potential heterogeneity across individual members of panel.

5.5.3 Panel FMOLS and DOLS estimates

Once the cointegration relationship has been found, the next step is to estimate cointegration vector β_i, which is the coefficient of $\ln EC_{it}$ in Eq. (5.8).This coefficient can be thought of as the long-run elasticity of electricity consumption to real GDP, or electricity elasticity. It is determined by using FMOLS and DOLS techniques. These techniques can correct the standard OLS for bias induced by endogeneity and serial correction of the regressor. Single equation Fully Modified Ordinary Least Squares (FMOLS) is presented by Phillips and Hansen[24]. They propose an estimator that employs a semi-parametric correction to eliminate the problems caused by the long run correlation between the cointegrating equation and stochastic regressor innovations. The resulting FMOLS estimator is asymptotically unbiased and has fully efficient mixture normal asymptotic, allowing for standard Wald tests using asymptotic Chi-square statistical inference. Dynamic Ordinary Least Squares (DOLS) is a simple approach to constructing an asymptotically efficient estimator that eliminates the feedback in the cointegrating system, this is advocated by Saikkonen[25] and Stock and Watson[26].

Pedroni[27] proposed more powerful tests, when compared with single equation methods, that investigate directly the condition on the cointegrating vector that holds strong relation. This chapter applies group-mean panel FMOLS and DOLS, which pooled the data along the between-dimension but Pedroni[28] shows that they appeared to suffer from much lower small-sample size distortion than from the within-dimension estimators.

Consider the FMOLS regression:

$$\ln GDP_{it} = \alpha_i + \beta_i \ln EC_{it} + \mu_{it} \tag{5.10}$$

where i=1,2,…,N, t=1,2,…,T. $LnGDP_{it}$ and $LnEC_{it}$ are cointegrated with slope β_i, which may or may not be homogeneous across i. μ_{it} is a stationary error term. Test statistics constructed from the between-dimension estimators are designed to test the null hypothesis $H_o : \beta_i = 1$ against the alternative hypothesis $H_A : \beta_i \neq 1$ for all i. Let $\xi_{it} = (\hat{\mu}_{it}, \Delta \ln EC_{it})'$ be a stationary vector consisting of the estimated residuals from the cointegrating regression and the differences in electricity consumption, and let $\Omega_i \equiv \lim_{T\to\infty} E[T^{-1}(\sum_{t=1}^{T}\xi_{it})(\sum_{t=1}^{T}\xi_{it}')]$ be the long-run covariance for this vector process which can be decomposed into $\Omega_i = \Omega_i^0 + \Gamma_i + \Gamma_i^{'}$, where Ω_i^0 is contemporaneous and Γ_i is a weighted sum of autocovariances. The expression for the between-dimension, group-mean panel FMOLS estimator is given as

$$\hat{\beta}^{*}_{GFM} = N^{-1}\sum_{i=1}^{N}\left[\sum_{t=1}^{T}(\ln EC_{it} - \overline{\ln EC}_{it})^2\right]^{-1} \times \left[\sum_{t=1}^{T}(\ln EC_{it} - \overline{\ln EC}_{it})\ln GDP_{it}^{*} - T\hat{\gamma}_i\right],$$

where

$\ln GDP_{it}^{*} = (\ln GDP_{it} - \overline{\ln GDP_{it}}) - \frac{\hat{\Omega}_{21i}}{\hat{\Omega}_{22i}} \Delta \ln EC_{it}$ and

$\hat{\gamma}_i \equiv \hat{\Gamma}_{21i} + \hat{\Omega}_{21i}^{0} - \frac{\hat{\Omega}_{21i}}{\hat{\Omega}_{22i}} (\hat{\Gamma}_{22i} + \hat{\Omega}_{22i}^{0})$. The between-dimension estimator can be constructed simply as $\hat{\beta}_{GFM}^{*} = N^{-1}\sum_{i=1}^{N} \hat{\beta}_{FM,i}^{*}$, where $\hat{\beta}_{FM,i}^{*}$ is the conventional FMOLS estimator, applied to the i th member of the panel. The associated t-statistic is calculated as $t_{\hat{\beta}_{GFM}^{*}} = N^{-0.5}\sum_{i=1}^{N} t_{\hat{\beta}_{FM,i}^{*}}$.

The DOLS regression augments the cointegrating regression with lead and lag differences of the regressor to control endogenous feedback effects.

$$\ln GDP_{it} = \alpha_i + \beta_i \ln EC_{it} + \sum_{k=-K_i}^{K_i} \gamma_{ik} \Delta p_{it-k} + \mu_{it}^{*} \tag{5.11}$$

From this regression, [27] constructs the group-mean panel DOLS estimator as $\hat{\beta}_{GD}^{*} = N^{-1}\sum_{i=1}^{N} (\sum_{t=1}^{T} z_{it} z_{it}^{'})^{-1} (\sum_{t=1}^{T} z_{it} \ln GDP_{it})$, where z_{it} is the $2(K+1)\times 1$ vector regressor, $z_{it} = (\ln EC_{it} - \overline{\ln EC}_{it}, \Delta \ln EC_{it-K}, ..., \Delta \ln EC_{it+K})$ and $\ln GDP_{it} = \ln GDP_{it} - \overline{\ln GDP}_{it}$. Again, the between-dimension estimator can be constructed simply as $\hat{\beta}_{GD}^{*} = N^{-1}\sum_{i=1}^{N} \hat{\beta}_{D,i}^{*}$ and t-statistic is calculated as $t_{\hat{\beta}_{GD}^{*}} = N^{-0.5}\sum_{i=1}^{N} t_{\hat{\beta}_{D,i}^{*}}$, where $\hat{\beta}_{D,i}^{*}$ is the conventional DOLS estimator, applied to the i th member of the panel.

5.5.4 Panel causality analysis

Panel cointegration test shows whether there is a long-run relationship between electricity consumption and real GDP, but it doesn't indicate the direction of causality in the long-run and the short-run. The vector error correction model (VECM) opens up an additional causality channel which is overlooked by standard Granger testing procedures. The VECM approach allows us to distinguish between "short-run" and "long-run" Granger causality. Once the variables are co-integrated, according to the Granger representation theorem, Granger and Weiss[29], co-integrated variables can be represented in the form of a dynamic error correction model. This chapter uses the two-step procedure to estimate the panel-based vector error correction model. The first step is to estimate the co-integrating relationship between LnEC and LnGDP for each province. The equation is the same as Eq. (5.10). Note that Eq. (5.10) allows the slope of the co-integrating relationship β_i to vary across provinces.

The second step is to construct the disequilibrium term ECT (error correction term) by using the estimated co-integrating relationship,

$$ECT_{it} = \hat{\mu}_{it} = \ln GDP_{it} - \hat{\alpha}_i - \hat{\beta}_i \ln EC_{it} \tag{5.12}$$

and is added into the following dynamic error correction model. Thus:

$$\Delta \ln GDP_{i,t} = \theta_{1,j} + \lambda_{1,i} ECT_{i,t-1} + \sum_K \theta_{11i,k} \Delta \ln GDP_{i,t-k} + \sum_K \theta_{12i,k} \Delta \ln EC_{i,t-k} + u_{1i,t} \tag{5.13}$$

$$\Delta \ln EC_{i,t} = \theta_{2,j} + \lambda_{2,i} ECT_{i,t-1} + \sum_K \theta_{21i,k} \Delta \ln GDP_{i,t-k} + \sum_K \theta_{22i,k} \Delta \ln EC_{i,t-k} + u_{2i,t} \tag{5.14}$$

where the term Δ denotes first difference. The vector error correction model is a dynamical system with the characteristic that the deviation of current state from its long-run relationship will be fed into its short-run dynamics, and the error correction term ECT represents how far these two variables are from the equilibrium relationship. The coefficient of ECTs, λ, is called adjustment coefficient, which decides how quickly the equilibrium is restored. The Granger representation theorem implies that at least one of the adjustment coefficients must be non-zero if there is a long-run relationship between the variables.

In order to find the direction of causality, the chapter uses panel-based Granger causality test. Granger[30] indicates that a variable X causes effects on another variable Y if the current value of Y can better be predicted by using past values of X than by not doing so. So, the sources of causation can be identified by testing the significance of the coefficients of the dependent variables in Eq. (5.13) and Eq. (5.14). This chapter tests the null hypothesis of $H_0:\theta_{12i,k}=0$ or $H_0:\theta_{21i,k}=0$ for all i and k. If $\theta_{12i,k}=0$, the $\Delta\ln EC$ term will not appear in Eq. (5.13), the change of LnEC does not cause the change of LnGDP; and if $\theta_{21i,k}=0$, the $\Delta\ln GDP$ term does not cause $\Delta\ln EC$. This is called 'short-run' causality, or weak Granger causality. The short-run effect can be considered transitory.

Another possible source of causation is the error correction terms in Eq. (5.13) and (5.14) since there are past (t-1) terms in ECTs. It is called 'long-run' causality. For long-run causality, the chapter tests $H_0:\lambda_{1,i}=0$ or $H_0:\lambda_{2,i}=0$ for all i. If $\lambda_{1,i}=0$, it means that the change in LnGDP does not respond to deviation from long-run equilibrium in the precious period, and vice versa for $\lambda_{2,i}=0$.

The chapter uses standard *F*-test (same as chapter 4, see 4.3.7.3) to test the null hypothesis because all the variables are entered into the model in stationary form. For instance, for short-run causality, $H_0:\theta_{12i,k}=0$, $p_1=i\times k+i+1$, $p_2=2\times i\times k+i+1$, the F statistic is:

$$F = \frac{\left(\frac{RSS_1 - RSS_2}{p_2 - p_1}\right)}{\left(\frac{RSS_2}{n - p_2}\right)} = \frac{\left(\frac{RSS_1 - RSS_2}{i \times k}\right)}{\left(\frac{RSS_2}{n - (2 \times i \times k + i + 1)}\right)} \tag{5.15}$$

And for long-run causality, $H_0 : \lambda_{1,i} = 0$, $p_1 = 2 \times i \times k + 1$, $p_2 = 2 \times i \times k + 2$, the F statistic is:

$$F = \frac{\left(\frac{RSS_1 - RSS_2}{p_2 - p_1}\right)}{\left(\frac{RSS_2}{n - p_2}\right)} = \frac{\left(\frac{RSS_1 - RSS_2}{1}\right)}{\left(\frac{RSS_2}{n - (2 \times i \times k + i + 1)}\right)} \tag{5.16}$$

Similar to the chapter 4, F statistic will have an F distribution, with $(p_2 - p_1, n - p_2)$ degrees of freedom. The null hypothesis is rejected if the F calculated from the data is greater than the critical value of the F distribution for some desired false-rejection probability (e.g. 0.1 or 0.05).

5.6 Empirical results and analysis

This chapter use econometrics software Eviews 7.0 to obtain following results.

5.6.1 Panel unit root test results

Table 5-1 gives the results of panel unit root tests with and without time trend term for LnGDP and LnEC for the whole of China, northeast, coastal, central and west areas of China, respectively.

	Without trend		With trend		Without trend		With trend	
	LnGDP	LnEC	LnGDP	LnEC	D(LnGDP)	D(LnEC)	D(LnGDP)	D(LnEC)
The whole china								
LLC	10.155	2.573	0.96	-0.314	-6.597***	-14.045***	-9.411***	-11.406***
IPS	17.794	9.932	1.692	-0.809	-6.712***	-14.146	-9.282***	-11.193***
Fisher-ADF	4.526	5.397	71.266*	58.446	149.531***	290.605***	183.341***	220.083***
Fisher-PP	1.217	5.491	19.307	32.074	146.812***	327.394***	126.089***	302.945***
Northeast provinces								
LLC	7.823	-0.213	2.909	0.391	-2.007**	-7.974***	-7.224***	-6.995***
IPS	8.442	1.934	3.575	0.156	-1.493*	-7.329***	-5.926***	-6.487***
Fisher-ADF	0.009	1.59	0.281	4.716	12.540*	49.780***	37.606***	39.891***
Fisher-PP	0.001	1.808	0.165	5.145	16.149**	48.974***	12.167*	39.024***
Coastal provinces								
LLC	0.597	0.58	-1.974**	-0.452	-3.610***	-5.012***	-3.063***	-3.559***
IPS	4.649	4.703	-2.622***	-0.129	-4.629***	-5.960***	-3.951***	-4.376***
Fisher-ADF	3.983	1.639	28.146**	11.735	48.252***	61.677***	39.231***	45.301***
Fisher-PP	0.742	1.422	10.464	5.832	33.432***	61.171***	20.662	45.320***
Central provinces								
LLC	5.692	1.985	0.705	-0.13	-3.088***	-7.884***	-4.044***	-6.507***
IPS	10.136	5.886	0.19	-0.333	-3.241***	-8.140***	-4.538***	-6.543***
Fisher-ADF	0.22	1.145	26.835	19.782	40.756***	94.627***	52.591***	73.089***
Fisher-PP	0.188	1.133	5	12.713	47.106***	133.384***	41.481***	153.681***
West provinces								
LLC	7.547	2.045	0.979	-0.072	-4.499***	-7.723***	-5.543***	-6.270***
IPS	12.545	6.373	3.187	-1.058	-3.611***	-7.342***	-4.946***	-5.628***
Fisher-ADF	0.314	1.024	16.004	22.214	47.984***	84.522***	53.912***	61.803***
Fisher-PP	0.286	1.127	3.678	8.383	50.126***	83.865***	51.780***	64.919***
Note: ***, ** and * indicates statistical significance at the 1%, 5% and 10% level, respectively.								

Table 5-1: Panel unit root test results

It can be inferred from the Table 5-1 that the unit root hypothesis cannot be rejected when the variables are taken in levels. However, when first differences are used, the hypothesis of unit-root non-stationary is rejected at the 1%, 5% or 10% level of significance, indicating LnGDP and LnEC are I(1) process in each panel.

5.6.2 Panel cointegration test results

Because LnGDP and LnEC of each panel are non-stationary and have the same order, they may have long-run stationary linear combinations (cointegration). Table 5-2 shows the Pedroni's panel cointegration test results for each panel.

Within demension	**Whole China**	**Northeast**	**Coastal**	**Central**	**West**
Panel v-Statistic	2.944***	0.813	0.648	2.201**	1.798**
Panel rho-Statistic	-1.987**	-1.134	0.038	-1.438	-1.364*
Panel PP-Statistic	-2.650**	-1.896**	-0.059	-1.678**	-1.799**
Panel ADF-Statistic	-3.533***	-1.849**	-1.269	-3.075***	-2.451***
Between demension					
Group rho-Statistic	0.03	-0.208	0.293	0.044	-0.129
Group PP-Statistic	-1.590**	-1.492*	-0.175	-0.841	-0.948
Group ADF-Statistic	-3.102***	-1.478*	-2.085**	-3.536***	-2.453***
Note: ***, ** and * indicates statistical significance at the 1%, 5% and 10% level, respectively.					

Table 5-2: Panel cointegration test results

Pedroni[22] re-investigated the small sample size properties for the seven statistics via Monte Carlo simulations. In terms of empirical power of test, for small sample (in this chapter, T=25, N=28, 9, 7 or 3), the Group-ADF statistics is the most powerful, followed by Panel-ADF statistics. So, we can only focus on these two statistics. In Table 5-2, both the Group-ADF statistic and Panel-ADF statistic reject the null hypothesis of no cointegration at 1%, 5% or 10% level for each panel. According to these results, we can accept that there are long-run equilibrium (cointegration) relationship between electricity consumption and economic growth in the whole, northeast, coastal, central and west areas of China.

5.6.3 Panel FMOLS and DOLS results

Table 5-3 reports the results of individual and panel FMOLS and DOLS for each province and panel.

	FMOLS	t-stat	DOLS	t-stat
Northeast				
liaoning	1.61***	28.54***	1.64***	24.32***
jilin	1.98***	21.44***	1.99***	18.40***
heilongjiang	1.88***	14.50***	1.96***	14.69***
Group-mean results	**1.83*** **	**37.23*** **	**1.86*** **	**33.15*** **
Coastal				
shanghai	1.38***	58.40***	1.39***	47.06***
beijing	1.35***	59.42***	1.34***	52.73***
tianjin	1.47***	37.47***	1.50***	28.05***
zhejiang	0.99***	24.63***	1.01***	17.61***
jiangsu	1.15***	17.08***	1.23***	15.41***
guangdong	1.00***	47.95***	0.98***	41.77***
shandong	1.23***	20.89***	1.28***	22.23***
Group-mean results	**1.22*** **	**100.47*** **	**1.25*** **	**84.99*** **
Central				
fujian	1.09***	31.13***	1.10***	28.62***
hebei	1.20***	21.14***	1.26***	19.60***
hubei	1.43***	24.46***	1.49***	27.64***
shanxi2	1.32***	34.25***	1.34***	32.80***
shanxi	1.10***	32.74***	1.12***	32.57***
sichuan	1.50***	12.47***	1.55***	14.58***
henan	1.16***	30.48***	1.20***	29.31***
hunan	1.26***	24.47***	1.30***	27.02***
jiangxi	1.27***	15.73***	1.35***	17.73***
Group-mean results	**1.26*** **	**75.62*** **	**1.30*** **	**76.63*** **
West				
neimenggu	0.92***	27.51***	0.95***	24.04***
xinjiang	0.88***	56.12***	0.89***	104.04***
qinghai	0.76***	14.82***	0.81***	27.47***
ningxia	0.78***	26.46***	0.79***	25.42***
anhui	1.25***	15.64***	1.31***	14.71***
guangxi	1.08***	78.56***	1.09***	63.77***
yunnan	0.92***	29.59***	0.94***	35.19***
gansu	1.30***	24.51***	1.33***	25.59***
guizhou	0.85***	32.43***	0.84***	29.30***
Group-mean results	**0.97*** **	**101.88*** **	**0.99*** **	**116.51*** **
Whole China				
Group-mean results	**1.22*** **	**163.05*** **	**1.25*** **	**162.84*** **
Note: *** indicates statistical significance at the 1% level.				

Table 5-3: Panel FMOLS and DOLS results

According to FMOLS results, the panel long-run elasticity of log electricity consumption with respect to log real GDP is 1.22 at 1% significant level for the Whole China panel. It means a 1% increase in log electricity consumption leads to 1.22% increase in log GDP in the whole of China. For the different regions, a 1% increase in log electricity consumption leads to 1.83%, 1.22%, 1.26% and 0.97% increase in log GDP in the northeast, coastal, central and west regions, respectively. The DOLS results indicate that a 1% increase in log electricity consumption leads to 1.25% increase in log GDP in the whole of China. A 1% increase in log electricity consumption leads to 1.86%, 1.25%, 1.30% and 0.99% increase in log GDP in the northeast, coastal, central and west regions, respectively. The significant high FMOLS and DOLS values of northeast provinces indicate the need for separating this region, the results support of our original proposal to treat the northeast provinces as a separate region.

5.6.4 Panel causality analysis results

After establishing cointegration relationship, panel vector error correction model can be estimated to perform panel-based Granger-causality tests. Table 5-4 reports the results of long-run and short-run Granger causality tests. The optimum lag length is chosen at K=3 by Akaike information criterion (AIC).

Dependent variable		Sources of causation (independent variable)		
		Short-run		Long-run
		ΔLnGDP	ΔLnEC	ECT
ΔLnGDP	***Whole China***	----	7.5689***	6.7578***
			(0.0000)	(0.0000)
	Northeast		1.8378*	29.9286***
			(-0.0828)	(0.0000)
	Coastal		5.0141***	1.6361
			(0.0000)	(0.1312)
	Central		8.1618***	11.5879***
			(0.0000)	(0.0000)
	West		11.3120***	5.9165***
			(0.0000)	(0.0000)
ΔLnEC	***Whole China***	8.1897***	----	2.7863***
		(0.0000)		(0.0000)
	Northeast	2.0054*		1.7425
		(-0.0568)		(0.1695)
	Coastal	11.4753***		2.3495**
		(0.0000)		(0.0274)
	Central	6.3547***		1.4844
		(0.0000)		(0.1577)
	West	8.3151***		3.6036***
		(0.0000)		(0.0000)
Note: ***, ** and * indicates statistical significance at the 1%, 5% and 10% level, respectively.				
Figures denote F-statistic values and p-vaules are in parentheses.				

Table 5-4: Panel causality analysis results

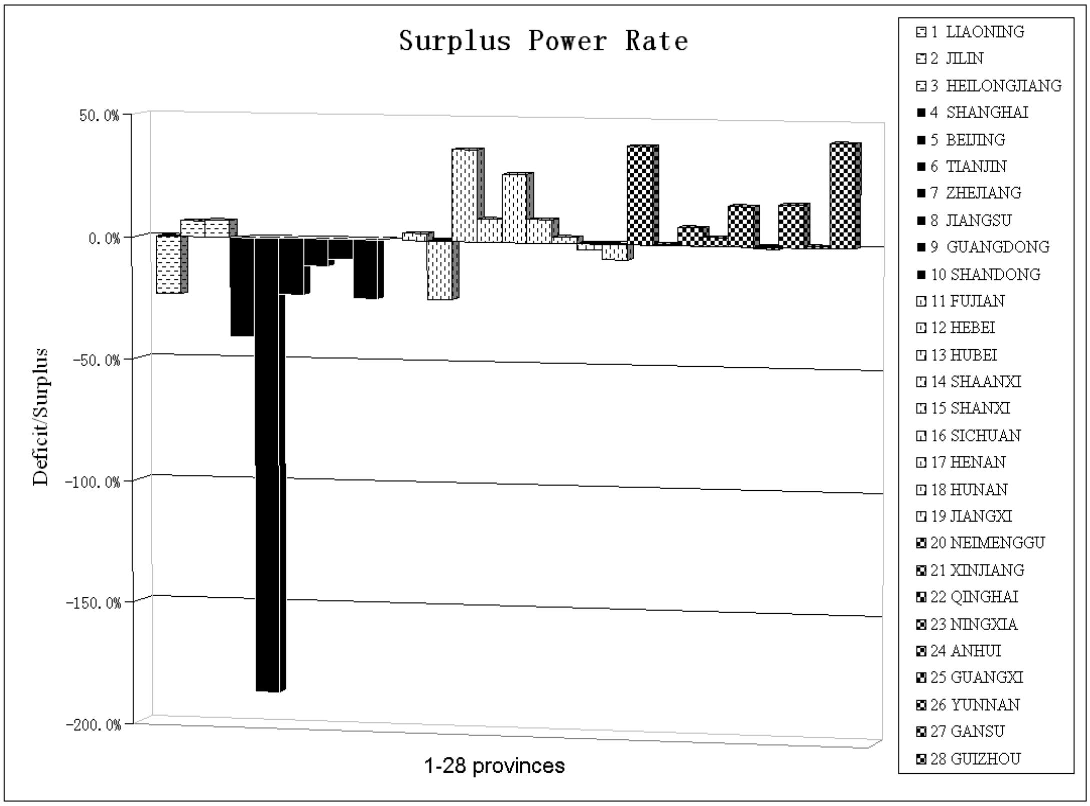
For short-run causality, whatever the dependent variable is, the coefficients of error correction terms in each panel are significant at 1% or 10% level. It means that there are bidirectional causality between electricity consumption and growth for the whole, northeast, coastal, central and west areas of China. The results support feedback hypothesis in short-run, the electricity consumption and economic growth are jointly determined and affected at the same time.

For long-run causality, the F-statistics reject the $H_0 : \lambda_{1,i} = 0$ and $H_0 : \lambda_{2,i} = 0$ for the whole China and west provinces, it means there are bidirectional causality between electricity consumption and economic growth for whole China and west area of China. For the Northeast and Central areas, the direction of causality is running from electricity consumption to economic growth since the statistics only reject $H_0 : \lambda_{1,i} = 0$ and accept $H_0 : \lambda_{2,i} = 0$. In contrast, the direction of causality is running from economic growth to electricity consumption for coastal provinces since the statistics only reject $H_0 : \lambda_{2,i} = 0$ and accepts $H_0 : \lambda_{1,i} = 0$. These results show that, over the long term, conservative electricity policy has little to no effect on economic growth for the coastal area of China, while such policy may cause serious economic recession in the northeast and central provinces.

The results of panel FMOLS and DOLS from high to low are: northeast panel, central panel, coastal panel, west panel. Such a sequence explains appearance of the long-run causality direction in each panel. Northeast and central provinces have higher long-run elasticity of electricity consumption to GDP than other provinces, and it also means their electricity utilization efficiency is higher than other provinces. The reason behind such a phenomenon is that many cities in these two regions are industry base of China, especially in the northeast.

Northeast has always been a traditional base for heavy industry in China and direct correlation between electricity consumption and GDP is expected. Heavy foreign investments such as car industry and chemical engineering industry are replacing old and inefficient ones in this region. These investments bring in more modern and energy efficient manufacturing equipment. This is reflected in the higher long-run elasticity of electricity consumption to GDP than other provinces. A similar phenomenon also exists in the ‘central’ where these provinces are mostly traditional farming areas. In China the energy consumption of farming communities are normally low and less efficient. The attraction of investments in heavy industry resulted in a number of high electricity and energy consumption enterprises. These enterprises consume huge quantity of electricity and promote economic development. Therefore, the long-run elasticity of electricity consumption to GDP in the northeast and central regions also remains at a high level.

The area covered by the ‘west’ is enormous. Provinces such as Xinjiang, Qinghai and Gansu are amongst the largest ones in term of geographical area and are also, relatively in comparison with others, less densely populated. Traditionally it is an area of lower economic wealth and hence the west region has the lowest elasticity, indicating low electricity utilization efficiency. This may be because the industrial level and the technological level still need modernisation. However several provinces in the west such as Qinghai, Guizhou, Yunnan and Guangxi contain large reserve of hydro power for electricity generation. Some of these sites have been developed and many more are at the planning and developing stages. The majority of electricity generated from these sites are not consumed locally but are transmitted using long distance transmission lines to the coastal cities. A 3D bar chart illustrating the surplus and deficit of electricity generation in each province is given in Figure 5.1. The chart indicates the percentage of surplus and deficit of electricity consumption and is defined as (production - consumption)/production from 2005 to 2009. In the chart, it is obvious that some provinces are seriously short of electricity supply and have to import electricity from power surplus provinces. The coastal provinces are all electricity hungry provinces while the west provinces are the ones with big surpluses. Hence it makes economic sense to transmit electricity generated in the reserve rich west to the power country coastal cities. In the west, the power generation industry also makes available cheaper electricity locally and this contributes to higher electricity consumption and stimulates GDP growth, albeit at a much lower level when compared to the other panels. This is borne out in the results obtained.



Note: Calculate methods: Surplus power rate= (Electricity production - Electricity consumption)/Electricity production*100%
The data in the chart are the average value from 2005 to 2009.
1-3 are northeast provinces; 4-10 are coastal provinces; 11-19 are central provinces; 20-28 are west provinces.

Figure 5.1: Surplus power rate of each province

The interpretation of the situation in coastal provinces is more complex and less straightforward. The result of FMOLS and DOLS estimates proves the causality test result in the coastal region indicating that the increase in electricity consumption cannot lead to the remarkable increase in GDP, and that the direction of causality is not running from electricity consumption to growth. From the enormous large amount of investments, mostly foreign ones, the region possesses advanced industrial and modern manufacturing technological equipment and should indicate good elasticity of electricity consumption to GDP and yet the results indicate low elasticity. One possible explanation is the low electricity utilization efficiency of supporting and tertiary industry. All large manufacturing industry need continuous supply of components and most of them are manufactured locally, but with some of the key ones still imported. The investments tend to concentrate in the core part of the industry and do not yet spread out to supporting industry. This could explain the results in the coastal region. The results in the coastal region also give a warning that to improve elasticity modernisation of supporting and tertiary industry is essential.

5.7 Policy implications

From the analysis of results, three policy suggestions could be concluded. Firstly, because regional differences in the relationship between electricity consumption and economic growth are significant, the ultimate decision on the power generation investment strategy of a region should take account of the electricity elasticity and causality direction of that region. The northeast area is the traditional heavy industrial base of China. The direction of causality is from electricity consumption to economic growth, and the electricity elasticity of this region reaches 1.86, which indicates the high sensitivity of economic growth to electricity consumption. In order to realize a sustainable development for northeast provinces, the government should encourage investment in power industry as a priority. Thus, the constraint of electricity supply as a "bottleneck" on economic development may be relieved in this region. The electricity elasticity of the coastal region is 1.22 and causality is running from GDP to electricity consumption. Nevertheless, causality test result should not be interpreted that the region has no need of power generation investment. The total amount of electricity consumption in the coastal region is huge and the demand increases yearly. There is also a lack of energy resources in this region but being a technological advanced area, key generation investment is likely to be wind power, nuclear power and solar energy. The central and west regions of China have the advantage of good energy and natural resource, especially coal. In these regions the construction of traditional power plants, especially the use of clean coal-fired technology, is a suitable investment. Similar to the situation in the northeast region, central provinces also need to relieve the phenomenon of "bottleneck" of electricity supply. The west region has bidirectional causality between electricity consumption and economic growth. Following the implementation of the Central State Government's Great Western Development Strategy, a number of sizeable industrial projects are already being planned or are under construction. The rapid rise of electricity demand is totally predictable. It is now even more important that an overall strategy in simultaneous economy and power generation investment should be properly coordinated.

Secondly, policy makers should take note of the results of electricity elasticity and causality direction in the different regions when they formulate development policies. Take for example in the northeast region, besides encouraging power generation investment, this region also needs to gradually reduce its big increase on electricity consumption so as to avoid the occurrence of periodic power supply shortage. Frequent power supply interruption may cause unwarranted economic fluctuation, and even local recession. Encouragement should be given to electricity utilization efficiency, electricity conservation and improvement to manufacturing techniques with respect to reduce electricity demand. A more balanced policy to simultaneously encourage the development of heavy and light power demand industry is desirable. The electricity elasticity of the coastal and central regions is between 1.2-1.3. The range generally reflects the state of economic growth and electricity consumption in most part of China. With the rapid development of the economy the problem of power supply shortage in these regions would become more evident. To reduce the impact of power shortage these regions should quicken industrial restructuring, update and replacement of old equipment whilst at the same time encourages the development of service industry. The per unit cost of labour is rising rapidly in the coastal provinces, partly due to inflation and partly due to the rising value of the RMB. On the contrary the per unit labour cost is still low in the west provinces and the central provinces when compared with the coastal ones. To maintain a sustainable development in term of cost and electricity demand the labour intensive and power consumption intensive industry should be encouraged to re-locate from the coastal to the west and central provinces. The central provinces have years of industrial base and should have no difficulty in accommodating the re-location. The west provinces have an electricity elasticity of less than unity and this indicates that there is a need for industrialisation. This can result in a more balanced long term economic development since the west provinces possess good reserve of energy and natural resources, and at the same time it would reduce the reliance of the coastal provinces for electricity transmitted from the west provinces. To ensure the successful implementation of such a policy of simultaneous modernisation and re-location of certain industry the Central State Government needs to set up a strategy to improve the public road and railway transport system. A good and reliable public transport system is a vital lifeline to a flourishing industry.

Thirdly, ultra-high-voltage (UHV) electric transmission lines can be treated as a reliable scheme to transmit surplus electricity in one region to another one where there is a deficit. Coal and hydropower resources are mainly deposited on the west and central provinces. However, such resources are a scarcity in the coastal provinces where there is a relatively higher level of industrialization and high demand for electric power. During the summer months the demand for electricity is particularly acute when air conditioning load is at its highest and the high environmental air temperature also meant that electric transmission networks cannot work at their maximum capacity. This means power stoppage is a frequent occurrence in the coastal provinces. Therefore, the construction of cross-regional ultra-high-voltage electric transmission networks to transmit electricity to meet demand imbalance among different regions is strongly encouraged.

5.8 Summary

The objective of this study is to examine the relationship and direction of causality between electricity consumption and economic growth in China. The chapter applies the panel data for log electricity consumption and log GDP for 28 provinces from 1985 to 2009 and classifies them into four groups: northeast, coastal, central and west groups. Therefore, panel-based methods are employed on for the following: whole China panel, northeast provinces panel, coastal provinces panel, central provinces panel and west provinces panel. The results of panel unit root tests and panel cointegration tests show that electricity consumption and economic growth are I(1) process and co-integrated in each panel. The directions of causality of each panel are tested by panel VECM and causality test for the short-run and the long-run, respectively. The results show that there are bidirectional causalities between electricity consumption and growth for each panel in the short-run. Over the long term, there are bidirectional causality between electricity consumption and economic growth for the whole and west China. For coastal provinces, the direction is running from economic growth to electricity consumption, while in the northeast and central provinces the opposite is true. At the end of this chapter, some policy implications were given based on the above results.

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Chapter 6: Conclusions and Future work

6.1 Conclusion

This thesis investigates the investment appraisal in electricity generation investment, and gives the nexus of electric industry and economic growth in the UK and China respectively. The former considers power plant investment from microscopic viewpoint, while the latter is from macroscopic viewpoint. Microscopic viewpoint is from the point of operation and profit return angle. It focuses on project net present value, payback period, internal rate of return, sensitivity of main factors (tornado diagram), and levelised cost of generation. The macroscopic viewpoint of power plant investment focus on investment environment in a country, such as the relationship among electricity consumption, installed capacity and economic growth, long-run and short-run causality direction between electricity consumption and GDP, and the electricity elasticity on GDP.

In the thesis, eight types of electricity generation technologies in UK but pulverised coal plant only in the China are analysed by discounted cash flow and levelised cost approach. The analysis results of UK's projects showed evidences for following conclusions. Firstly, the variance contributions of tornado diagram state that the electricity price (plus ROC price for wind power) is the most influential factor for all types of UK's project. This indicates the stable electricity wholesale price is important to ensure the stable earning of a generation company. A fluctuate electricity wholesale price will have great influence on the profitability of a power plant. Therefore, getting relatively stable electricity wholesale price is crucially important to a generation project. Secondly, the coal-fired plants (pulverised coal and IGCC) with CCS have advantage on profitability and levelised cost than plants without CCS. The reason is that the carbon tax cost puts great burden on coal-fired plant without CCS. The loss because of the carbon tax cost would be larger than the initial investment on CCS equipment. By contrast, the gas-fired plants (CCGT) with CCS even has deficit at the of project lifetime. Although CCS technology can avoid carbon tax cost, the high additional investment on CCS equipment cannot be able to recoup at the end of project lifetime. Thirdly, because the proportions of capital cost of coal-fired plants are higher than gas-fired plants, the fluctuation of fuel price has a bigger effect on gas-fired plant's profitability and levelised cost than coal-fired plants. Fourthly, because wind power projects have huge capital cost, the non-renewable technologies are always earning more money at existing technology level and investment environment. The advantage of wind power is their levelised costs have less fluctuation than non-renewable projects. After construction, the O&M cost becomes the sole cost of wind power. The profitability is only affected by electricity and ROC price.

The research results for China's pulverised coal project show that the coal price is the key factor of coal-fired plants' profitability and levelised cost in China. It is because the electricity price is fixed and the coal price has increased rapidly in recent years. Many coal-fired power plants' profit margin meet big reductions, some even result in loss. It leads to aggravation of the coal-fired power plant investment climate, and the investment of coal-fired power plant has been decreasing rapidly. At the end of 2011, the investment on coal-fired plant is 105.4 billion Yuan, less than half that in 2005. To avoid losing on coal–fired plant, power generation companies pay their attentions on nuclear power and other renewable energy.

The relationship among electricity consumption, economic growth and installed capacity in the UK and China are studied respectively in this thesis. For the UK, the cointegration tests showed that there is no cointegration relationship among real GDP, electricity consumption and installed capacity in the UK. After creating a VAR model, the causality test did not find any causality among these three variables. Therefore, the forecast and impulse response results will not have any economic meaning. As a developed country, UK has top-notch scientific and technical personnel, advanced energy saving technology and equipment, which can greatly reduce electricity usage. More importantly is, in the UK, high electricity consumption industries have moved to a country with low-cost manpower, such as

China. The mainland of Britain remains a low electricity consumption, light pollution and high technology industrial country, such as pharmacy, finance, information technology and bioengineering. Because high electricity consumption industries are not the major part of the annual output, the electricity consumption cannot have affect on economic growth and vice versa.

For China, the causality test results indicated that there is no causality between these two variable in short-run but has unidirectional causality running from electricity consumption to economic growth in the long-run and that is also true in the joint test. The forecast results of GDP and electricity consumption indicate that the GDP and electricity consumption in China are expected to continue to maintain a sustained growth in the next 5 years. The impulse response results show that the uncoordination of electricity consumption, installed capacity and economic growth exists in China. Although China has made great progress in economy, their technology and science level in some area still lag behind those in the UK. Independent innovation in China remains a great distance behind that of the developed countries. The electricity consumption per capita in the UK is 6062 kWh, while this indicator is only 2455 kWh in China. It means the modernization in China is still at a low level. The causality test result reflects that the mode of economic growth in China is based on high electricity consumption. Therefore, one suggestion is the Chinese government need to consolidate the heavy industry to eliminate smaller producers that create the most pollution and cost the most on energy and electricity. But the strict conservation policy must be implemented with caution since such policy may harm the economic development. The government should balance the supply and demand of electricity industry. After the recent economic crisis, the fluctuation of macroeconomic may cause the fluctuation of electricity demand. The use of policy instrument is needed for coordination between power industry and macro-economy. For investors, scientific prediction of macroeconomic fluctuation and electricity consumption is necessary to avoid over investment and peak construction.

In order to better understand the power plant investment environment in China, the relationship and direction of causality between electricity consumption and economic growth in China are studied by panel-based approaches and provincial data in this thesis. The results show that there are bidirectional causalities between electricity consumption and growth for each panel in the short-run. Over the long term, there are bidirectional causality between electricity consumption and economic growth for the whole and west China. For coastal provinces, the direction is running from economic growth to electricity consumption, while in the northeast and central provinces the opposite is true.

From the analysis of results, three policy suggestions could be concluded. Firstly, because regional differences in the relationship between electricity consumption and economic growth are significant, the ultimate decision on the power generation investment strategy of a region should take account of the electricity elasticity and causality direction of that region. The northeast area is the traditional heavy industrial base of China. The direction of causality is from electricity consumption to economic growth, and the electricity elasticity of this region reaches 1.86, which indicates the high sensitivity of economic growth to electricity consumption. In order to realize a sustainable development for northeast provinces, the government should encourage investment in power industry as a priority. Thus, the constraint of electricity supply as a “bottleneck” on economic development may be relieved in this region. The electricity elasticity of the coastal region is 1.22 and causality is running from GDP to electricity consumption. Nevertheless, causality test result should not be interpreted that the region has no need of power generation investment. The total amount of electricity consumption in the coastal region is huge and the demand increases yearly. There is also a lack of energy resources in this region but being a technological advanced area, key generation investment is likely to be wind power, nuclear power and solar energy. The central and west regions of China have the advantage of good energy and natural resource, especially coal. In these regions the construction of traditional power plants, especially the use of clean coal-fired technology, is a suitable investment. Similar to the situation in the northeast region, central provinces also need to relieve the phenomenon of “bottleneck” of electricity supply. The west region has bidirectional causality between electricity consumption and economic growth. Following the implementation of the Central State Government's Great Western Development Strategy, a number of sizeable industrial projects are already being planned or are under construction. The rapid rise of electricity demand is totally predictable. It is now even more important that an overall strategy in simultaneous economy and power generation investment should be properly coordinated. Secondly, policy makers should take note of the results of electricity elasticity and causality direction in the different regions when they formulate development policies. Take for example in the northeast region, besides encouraging power generation investment, this region also needs to gradually reduce its big increase on electricity consumption so as to avoid the occurrence of periodic power supply shortage. Frequent power supply interruption may cause unwarranted economic fluctuation, and even local recession. Encouragement should be given to electricity utilization efficiency, electricity conservation and improvement to manufacturing techniques with respect to reduce electricity demand. A more balanced policy to simultaneously encourage the development of heavy and light power demand industry is desirable. The electricity elasticity of the coastal and central regions is between 1.2-1.3. The range generally reflects the state of economic growth and electricity consumption in most part of China. With the rapid development of the economy the problem of power supply shortage in these regions would become more evident. To reduce the impact of power shortage these regions should quicken industrial restructuring, update and replacement of old equipment whilst at the same time encourages the development of service industry. The per unit cost of labour is rising rapidly in the coastal provinces, partly due to inflation and partly due to the rising value of the RMB. On the contrary the per unit labour cost is still low in the west provinces and the central provinces when compared with the coastal ones. To maintain a sustainable development in term of cost and electricity demand the labour intensive and power consumption intensive industry should be encouraged to re-locate from the coastal to the west and central provinces. The central provinces have years of industrial base and should have no difficulty in accommodating the re-location. The west provinces have an electricity elasticity of less than unity and this indicates that there is a need for industrialisation. This can result in a more balanced long term economic development since the west provinces possess good reserve of energy and natural resources, and at the same time it would reduce the reliance of the coastal provinces for electricity transmitted from the west provinces. To ensure the successful implementation of such a policy of simultaneous modernisation and re-location of certain industry the Central State Government needs to set up a strategy to improve the public road and railway transport system. A good and reliable public transport system is a vital lifeline to a flourishing industry. Thirdly, ultra-high-voltage (UHV) electric transmission lines can be treated as a reliable scheme to transmit surplus electricity in one region to another one where there is a deficit. Coal and hydropower resources are mainly deposited on the west and central provinces. However, such resources are a scarcity in the coastal provinces where there is a relatively higher level of industrialization and high demand for electric power. During the summer months the demand for electricity is particularly acute when air conditioning load is at its highest and the high environmental air temperature also meant that electric transmission networks cannot work at their maximum capacity. This means power stoppage is a frequent occurrence in the coastal provinces. Therefore, the construction of cross-regional ultra-high-voltage electric transmission networks to transmit electricity to meet demand imbalance among different regions is strongly encouraged.

6.2 Future Work

Due to the time constraint, some issues were not addressed in this research. There are several possible improvements that can be suggested for the methods and concepts proposed in this thesis. These include:

- The parameter assumption of generation technologies in Chapter 3 can be in more detail, like the reinvestment in some part of plant in some years after operation.

- The nuclear power and hydroelectric can be taken into account in Chapter 3, and then the comparison between renewable energy and traditional energy can be done.

- The profitability of power plant in UK can take into account the fluctuation of day-ahead wholesale electricity price.

- Modeling the electricity market and the relationship between fuel costs and electricity prices should be investigated in the future.

- In chapter 5, labor and capital can be put in the model as well. So that the model can better reflect the situation of electric industry and economy.

- The sample size of China's data in Chapter 5 can be larger if possible.

Appendix

The panel statistics are

Panel v (variance)-statistic

$$T^2N^{3/2}Z_{v_{N,T}} \equiv T^2N^{3/2}\left(\sum_{i=1}^{N}\sum_{t=1}^{T}\hat{L}_{11i}^{-2}\hat{e}_{i,t-1}^{2}\right)^{-1}$$

Panel rho (ρ)-statistic

$$T\sqrt{N}Z_{\rho_{N,T}-1} \equiv T\sqrt{N}\left(\sum_{i=1}^{N}\sum_{t=1}^{T}\hat{L}_{11i}^{-2}\hat{e}_{i,t-1}^{2}\right)^{-1}\sum_{i=1}^{N}\sum_{t=1}^{T}\hat{L}_{11i}^{-2}(\hat{e}_{i,t-1}\Delta\hat{e}_{i,t}-\hat{\lambda}_i)$$

Panel PP-statistic

$$Z_{t_{N,T}} \equiv \left(\tilde{\sigma}_{N,T}^{2}\sum_{i=1}^{N}\sum_{t=1}^{T}\hat{L}_{11i}^{-2}\hat{e}_{i,t-1}^{2}\right)^{-1/2}\sum_{i=1}^{N}\sum_{t=1}^{T}\hat{L}_{11i}^{-2}(\hat{e}_{i,t-1}\Delta\hat{e}_{i,t}-\hat{\lambda}_i)$$

Panel ADF-statistic

$$Z_{t_{N,T}}^{*} \equiv \left(\tilde{s}_{N,T}^{*2}\sum_{i=1}^{N}\sum_{t=1}^{T}\hat{L}_{11i}^{-2}\hat{e}_{i,t-1}^{2}\right)^{-1/2}\sum_{i=1}^{N}\sum_{t=1}^{T}\hat{L}_{11i}^{-2}\hat{e}_{i,t-1}^{*}\Delta\hat{e}_{i,t}^{*}$$

The group statistics are

Group rho-statistic

$$TN^{-1/2}Z_{\rho_{N,T}-1} \equiv TN^{-1/2}\sum_{i=1}^{N}\left(\sum_{t=1}^{T}\hat{e}_{i,t-1}^{2}\right)^{-1}\sum_{t=1}^{T}(\hat{e}_{i,t-1}\Delta\hat{e}_{i,t}-\hat{\lambda}_i)$$

Group PP-statistic

$$N^{-1/2}Z_{t_{N,T}} \equiv N^{-1/2}\sum_{i=1}^{N}\left(\hat{\sigma}_{i}^{2}\sum_{t=1}^{T}\hat{e}_{i,t-1}^{2}\right)^{-1/2}\sum_{t=1}^{T}(\hat{e}_{i,t-1}\Delta\hat{e}_{i,t}-\hat{\lambda}_i)$$

Group ADF-statistic

$$N^{-1/2}Z_{t_{N,T}}^{*} \equiv N^{-1/2}\sum_{i=1}^{N}\left(\sum_{t=1}^{T}\hat{s}_{i}^{*2}\hat{e}_{i,t-1}^{*2}\right)^{-1/2}\sum_{t=1}^{T}(\hat{e}_{i,t-1}^{*}\Delta\hat{e}_{i,t}^{*})$$

where

$$\lambda_i = \frac{1}{T}\sum_{s=1}^{k_i}\left(1-\frac{s}{k_i+1}\right)\sum_{t=s+1}^{T}\mu_{i,t}\mu_{i,t-s} \quad , \quad \hat{s}_i^2 \equiv \frac{1}{T}\sum_{t=1}^{T}\mu_{i,t}^2 \quad , \quad \sigma_i^2 = \hat{s}_i^2 + 2\lambda_i \quad ,$$

$$\sigma_{N,T}^2 \equiv \frac{1}{N}\sum_{i=1}^{N}L_{11i}^{-2}\sigma_i^2 \quad , \quad \hat{s}_i^{*2} \equiv \frac{1}{t}\sum_{t=1}^{T}\mu_{i,t}^{*2} \quad , \quad \hat{s}_{N,T}^{*2} \equiv \frac{1}{N}\sum_{i=1}^{N}\hat{s}_i^{*2} \quad ,$$

$$L_{11i}^2 = \frac{1}{T}\sum_{t=1}^{T}\eta_{i,t}^2 + \frac{2}{T}\sum_{s=1}^{k_i}\left(1-\frac{s}{k_i+1}\right)\sum_{t=s+1}^{T}\eta_{i,t}\eta_{i,t-s} \; ,$$

and where the residuals $\mu_{i,t}$, $\mu_{i,t}^*$ and $\eta_{i,t}$ are obtained from the following regressions:

$$\hat{e}_{i,t} = \gamma_i \hat{e}_{i,t-1} + \mu_{i,t} \; , \; \hat{e}_{i,t} = \gamma_i \hat{e}_{i,t-1} + \sum_{k=1}^{K_i}\gamma_{i,k}\Delta\hat{e}_{i,t-1} + u_{i,t}^* \; , \; \Delta y_{i,t} = \sum_{m=1}^{M}\hat{b}_{mi}\Delta x_{mi,t} + \eta_{i,t}$$