

**POLITECNICO DI MILANO**

Department of Energy

Master of Science in Energy Engineering



**Modelling and Simulation of  
Bilateral Electricity Market in China**

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## **Abstract**

As an on-going event, China has launched a new round of power industry reform since 2015. Competition will be introduced to the retail market and new electricity price mechanism will be adopted to promote energy conservation, enhance the development of renewables and improve the total social surplus. The policy of direct power purchase for large users (DPLU) will be further promoted. Under this policy, generation companies will sell electric power to grid enterprises at transaction price, which is decided by the negotiation between generation companies and large users. The DPLU is a typical form of bilateral electricity market. Thus, it is important to understand how such a bilateral market model will integrate in China, what impact will have on energy price and which are going to be the main actors.

This thesis presents a bilateral electricity market model for the Chinese electricity market by using the Conjectural Variation Equilibrium (CVE) model with the aim of maximizing the market participants' profits and seeking the market equilibrium point. Based on the target reform results, the structure and characteristics of Chinese bilateral electricity market is studied. Both generation and demand sides of the wholesale market are investigated. Therefore, generation companies' behaviors and strategies are studied by applying the CVE method. Generation companies with multi-generation resources are investigated to find the optimal allocation of generation capacities. Meanwhile, the retailers' behaviors are taken into consideration. The equilibrium of both quantity and price in the bilateral electricity market has been obtained through the coordinating algorithm that includes CVE model iterations of both markets. A hierarchical optimization approach, using the genetic optimization algorithm, has been adopted to find the equilibrium point of both markets and optimize the profits as well.

Transmission congestion has potential implications for the intensity of competition in generation markets. Thus, at the final stage of this research, the effect of transmission constraints on bilateral electricity market is analyzed and new market equilibrium with transmission cost is solved.

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## List of Abbreviations

AC	Alternating Current
Big Five	China Huaneng Group, China Huadian Corporation, China Guodian Corporation, China Datang Corporation, and China Power Investment Corporation.
CV	Conjectural Variation
CVE	Conjectural Variation Equilibrium
$CV_{id}$	Conjectural Variation value of the other retailers over retailer $i$
$CV_{ig}$	Conjectural Variation value of the other generation companies over generation company $i$
DC	Direct Current
Disco	Distribution Company
DPLU	Direct Power Purchase for Large Users
EHV	Extra-High Voltage
ETS	Emissions Trading Scheme
Genco	Generation Company
GA	Genetic Algorithm
IEA	International Energy Agency
IPP	Independent Power Producer
ISO	Independent System Operator
LCP	Linear Complementary Problem
NDRC	National Development and Reform Commission
PX	Power Exchange
SFE	Supply Function Equilibrium

SPC State Power Corporation  
TSO Transmission System Operator  
UHV Ultra-High Voltage

# **1. Introduction**

## **1.1 Background and Problem Statement**

As an international trend starting from 1980s, the traditional vertically integrated electricity utility systems have been experiencing several market-orientated reforms. In many countries around the world, competition has been introduced to both generation section and supply section to liberalize the electricity market, improve market efficiency and social welfare. The market-orientated reform was pioneered by Chile, and followed by UK, Norway and most of the developed countries. These new changes resulted in different schemes of market organizations, of which, centralized electricity pool market and decentralized bilateral electricity market are widely adopted.

Electricity pool market allows all the market participants to take part in the central auction and the market clearing price is calculated by the Power Exchange (PX), which guarantees the competitiveness of the market, making electricity pool market widely acceptable and successful. In bilateral electricity market, generators sell electricity through bilateral contracts with eligible customers or retailers which in turn supply end-use customers with electricity. More choices and flexibilities are provided in the bilateral electricity market.

In China, power industry reform has been carried out in 2002 under the guidance of Electricity Reform Plan (No. 5 Document) by the Central Government with the overall objective to develop the Chinese electricity market system with the goal of separating government function from business and promoting fair competition [1][2]. Thus, the State Power Corporation (SPC) was dismantled with its main generation divided into five big generation corporations (Big Five), and its transmission and distribution assets inherited by two giant transmission companies. All these achievements made the reform in 2002 a milestone in the Chinese electricity market-oriented reform. However, due to the power shortage from 2003 to 2004, the market-oriented reform has been stifled. The government focused on increasing generation capacity to satisfy the fast-growing electricity demand required by industrialization and economy boost. Since the Big Five are state-owned companies, they have financial advantages. The generation capacity of Big Five increased a

lot since 2002 and reached around 50% of the total generation capacity in 2010 (China Electricity Council). Besides, they are all multi-technology companies with different generation resources. Thus, with the huge market share, the Big Five can exercise significant market power, which will distort the market competition. Meanwhile, the two transmission companies are natural monopoly. They share the market by different regions and it is not possible to have competition between them.

For a long time, the Chinese electricity market has been featured with twisted pricing mechanism and inefficient utilization of renewable energy [3]. Therefore, on March 25th, 2015, the Chinese State Council issued a document named Relative Policies on Deepening the Reform of Power Industry (No. 9 Document), to guide a new round of power industry reform. A new pricing mechanism will be adopted by encouraging direct power purchase for large users (DPLU), which is a form of bilateral market. Generation plants will sell power to grid enterprises at transaction price, which is decided by the negotiation between generation companies and eligible users. The Chinese government has started to pilot DPLU since 2002 and has made some progress in reducing the on-grid price in the piloting provinces [3]. Besides, competition will be introduced to the retail market.

The National Development and Reform Commission (NDRC) will determine the transmission and distribution price based on the investment and operation cost of power grids. However Transmission Rights and other financial tools, which can better reveal the scarcity of transmission capacity, are not mentioned. As a matter of fact, transmission constraints can be an important source of market power in electricity market. Transmission congestion has significant influence on the competition in the generation side of bilateral electricity market. Thus, market mechanism concerning transmission constraints and transmission capacity allocation should be developed.

All these open interesting direction of research, as it is important to understand how such a bilateral market model will integrate in China, what impact will have on energy price and what strategies market participants will adopt to maximize their profit. However, there are few studies on modeling the Chinese bilateral electricity market.

## **1.2 Objective of the Study**

The main objective of this research is to model and simulate the bilateral electricity market in China.

First is the investigation on basic bilateral electricity market structure and characteristics.

Second is the study of the present situation in Chinese electricity market and specific policy issued to further reform the electricity market.

Third is to investigate the basic behaviors of generation companies and model oligopolistic electricity market.

Forth is to study the optimal strategy in generation capacity allocation for multi-technology generation companies to maximize their profit.

Fifth is to investigate the basic behaviors of retailers and model oligopsonistic electricity market.

Sixth is to study the potential transmission capacity market and the influence of transmission capacity allocation on electricity market.

Last is to find out the equilibrium point of the market, while all market participants are making profit.

## **1.3 Methodology**

The main characteristic of bilateral contract when compared with pool market is decentralized trading. The amount of electricity delivered, price and delivering period are negotiated directly between market participants before day-ahead market. The advantage in scheduling flexibility enables bilateral contract to hedge risks in market. Nevertheless, a variety of new challenges are faced by the market participants in optimizing their strategies to increase profits due to the variable bilateral contract price compared with the uniform market clearing price in pool market. This research will focus on the imperfect bilateral electricity market modeling for profit maximization on both sides of the market and seeking equilibrium point of the market.

First, a detailed review of economic models applied to the electricity industry was carried out to identify the most suitable approach for modeling Chinese electricity market. Three

categories of models are widely used to analyze electricity market: equilibrium models, optimization models and simulation models. In equilibrium and simulation models, the behavior of each participant is modeled taking into account competition among all participants while the behavior of only one firm is considered in optimization models [4]. Compared with equilibrium model, simulation model is more appropriate for medium or long-term modelling with complex characteristics. Thus in the study of bilateral market, equilibrium model is adopted.

Different equilibrium models are defined based on whether firms compete in quantity strategies or supply curve strategies. However, all the models are aiming at achieving the Nash equilibrium; the market reaches equilibrium when each firm's strategy is the best response to the strategies actually employed by its competitors. The most widely used models are based on Cournot competition, in which firms compete in quantity, and Supply Function Equilibrium (SFE), where firms compete in both quantities and prices.

In Cournot model, players compete on quantity and will choose a level of output with respect to the rival's production decisions. In the Bertrand model, firms compete on price and try to maximize profit by setting price. Cournot model can be used in bilateral electricity market due to the fact that the market participants negotiate the quantity of electricity to be delivered in the future. However due to the naive assumption that one firm's output decision will not have any effect on the decisions of its rivals, the reactions of competitors in reality are not considered in Cournot model. In SFE model the firms compete in both price and quantity. Accordingly, SFE model is appropriate for electricity pool in which each generation company submits its bid as a form of supply function and the PX calculates the market-clearing price rather than bilateral electricity market.

To improve the Cournot model and better fit it to the reality, the Conjectural Variation Equilibrium (CVE) model has been developed to add variation into Cournot model by changing the conjectures that generators may be expected to assume about their competitors' strategic decisions, in terms of the possibility of future reactions (CV) [4]. In other word, in CVE model, each generating firm conjectures how rival firms adjust their outputs in response to its output. Different values of CV indicate different market behaviors of firms. If the value



of CV is consistent with the local response of competitors, the market performance can be well simulated.

We choose CVE method to represent strategic interaction of firms in the Chinese electricity market, as this approach is a more realistic and flexible framework for modeling imperfect competition in the Chinese electricity market. Compared to other models, CVE helps all the decision makers in both sides of the bilateral electricity market to take into account the strategies of all competitors, which brings robustness into the modeling of the oligopolistic and oligopsonistic electricity markets. In addition, the transmission constraints and its effect on the electricity market can be well included in the CVE model. Since CVE equilibria can be calculated for very large transmission networks with integration of transmission constraints, the strategic interactions among firms in Chinese electricity market can be better represented by CVE approach. Furthermore, compared with SFE model, CVE method can be an appropriate approach for modeling bilateral electricity markets. Since in bilateral market, the quantity price is negotiated between generators and suppliers directly. There is no uniform market clearing price. Information about contract price and quantity is not disclosed.

To summarize, the Chinese electricity market is modeled as follows:

- Representing the strategic interaction of generation companies in oligopolistic market using CVE approach;
- Representing the strategic interaction of retailers in oligopsonistic market using CVE approach;
- Representing transmission system as a linearized “DC” system;
- The price of transmission services is based upon the uniform transmission price;
- Solving the market equilibrium with the maximization of social welfare with genetic algorithm.

## **1.4 Achievements and Contributions**

The major achievement of this research work is the development of an electricity market model for Chinese bilateral electricity market in a realistic and flexible framework for analyzing followings:

- The optimal behaviors and strategies of market participants in both sides of bilateral electricity market;
- The optimal strategy in generation capacity allocation for multi-technology companies;
- The impacts of transmission cost and transmission capacity allocation on the power section;
- The optimal market equilibrium for the design and implementation of the bilateral electricity market.

## **1.5 Outline of the Thesis**

The remaining chapters of this thesis are organized as follows:

Chapter 2 defines the basic concepts of electricity market and provides a review of electricity market development. Meanwhile, different electricity market models applied to the electricity industry are reviewed. Transmission constraints and major transmission capacity allocation schemes are analyzed briefly.

Chapter 3 introduces the development history, present situation, on-going reform and future development of the Chinese electricity industry.

Chapter 4 focuses on the modelling of bilateral electricity market. The development of an electricity market model for Chinese electricity industry is described in detail. Both oligopolistic and oligopsonistic electricity markets are investigated by using CVE model. Interactions within and between generators and suppliers are analyzed in detail. Behaviors of generation companies with capacity of different technologies are studied and optimal strategy in capacity allocation is proposed. Effects of transmission constraints and transmission capacity allocation on electricity market are analyzed. Finally market equilibrium under each situation is calculated. Genetic algorithm is used as the optimization technique.

Chapter 5 presents the case study of oligopolistic and oligopsonistic markets as well as market equilibrium by using the models developed above. A specific case of Chinese electricity market is analyzed as well.

Chapter 6 concludes the thesis by summarizing the work, drawing conclusions in terms of market design and issues that should be tackled in further work.

## 2. Electricity Market

### 2.1 Introduction

Electricity market reform is widely called electricity industry deregulation or simply called the electricity market liberalization. In the past theory of economics about deregulation and competition, the power industry has always been excluded due to the almost unidentified utility attributes, even if the so-called electricity market has been existed for over one century. The vertical integration of the power industry in the form of monopoly is widely accepted and the electricity tariff, entry and exit of electricity market are strictly controlled.

Starting from the 1980s, with the change of world political and economic situation, the market economy and globalization has become a world trend. At the same time, various cross-border trade organizations based on market economy, such as the "Tariff and Trade Association", and its successor, "World Trade Organization", have been shaped, especially through the development of various world trade agreements. Gradually the internal trade laws and rules are unified and become global uniform trading standards. This trend of globalization is based on general global market, aiming at eliminating trade barriers between countries, making domestic and foreign manufacturers enjoy fair treatment to further promote the global trade.

In 1979, the British Prime Minister Margaret Thatcher put forward the 3E (efficiency, effectiveness, economy) policy, as the promotion of public service innovation and the standards of public utilities [5]. Regardless of the initial motive of privatization policy, whether it is to reduce government expenditure or to improve the efficiency of public utilities, privatization policy became a worldwide wave.

Furthermore, with the evolution of the contemporary digital revolution, the cost of information acquisition has dropped significantly, and a variety of trading technology and real-time pricing system continues to develop. This contributes to the unbundling of electricity industry, which had to be integrated as vertical utility in the past due to technical constraints.

Driven by the above economic liberalization, privatization of public utilities and progress of digital technology, the traditional idea of regarding power industry as monopoly of public utility became weaker. Thus, the power industry restructuring, privatization, and liberalization

has become a global trend. From a global perspective, the primary target of power market reform is to establish a competitive electricity market with the following steps:

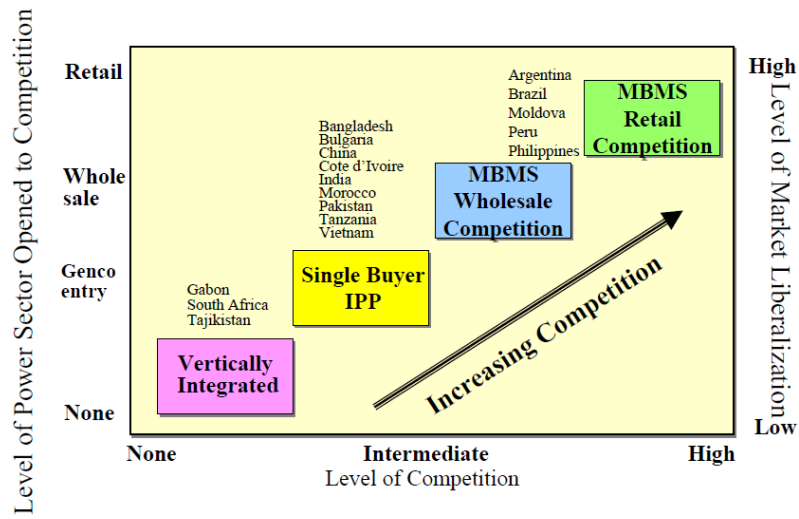
- Breaking traditional integrated organizational structure, based on the industry supply chain, to power generation, transmission, distribution and retail sections;
- Introducing competition mechanism to the generation side and retail side;
- Regulating transmission and distribution as a natural monopoly more effectively;
- Establishing market competition rules and market trading system.

In the process of market-oriented reform of electricity industry in the world, the government is often the organizer of power reform and plays a vital role in the process. This is because in many countries, the power industry was originally monopolized by the state. The power industry is the basic industries of the national economy and public utilities. Therefore, the reform of electricity market in different countries is basically led and organized by the government.

The expected result of electricity market reform is to increase the operating efficiency through the industrial segmentation and free competition. Besides, the customers can enjoy better services with reasonable price. In this new paradigm, the role of the government is the regulator and supervisor to guarantee the benefit of whole society instead of the previous role as industry owner.

## **2.2 Electricity Market Development**

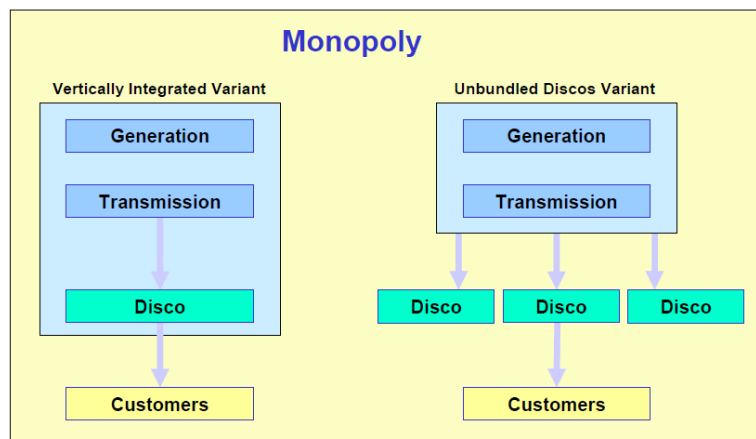
From large vertical integration to market-oriented liberalization, the restructuring of electricity market undergoes different processes and arrive at different levels of competition in different countries. The common direction is to introduce competition to the electricity market to reduce power cost, increase the quality of service and lower the price, thus benefiting the market participants and promoting economic growth. In developing countries, the reform is also important in introducing commercial principles that will attract investment and improve the reliability, quality, and coverage of service [6].



**Figure 2.1 Electricity market reform process [6]**

Figure 2.1 shows the restructuring processes of electricity market. By moving to the right, the level of completion increases. Accordingly, there are four electricity market models indicating different levels of competition. Details of these models are described as below:

**Monopoly Model:** The power section is dominated by vertically integrated utilities of the whole supply chain of the electricity section. The integration of electricity generation and high voltage transmission wires was a common feature. It is an absolute monopoly and the tariff is either self-regulated or regulated by other government institutions. During the time of Ministry of Electric Power and State Power Corporation, the Chinese electricity market is exactly a monopoly.



**Figure 2.2 Monopoly electricity market [6]**

Single Buyer Model: The utility is still vertically integrated, but there is competition in the generation side of the electricity market. However the central transmission dispatch company purchases all the wholesale power and becomes the single buyer who has strong market power in the market. From the 2002 reform to 2015, the Chinese electricity market was a single buyer market and caused several problems, which will be analyzed in detail in Chapter 3.

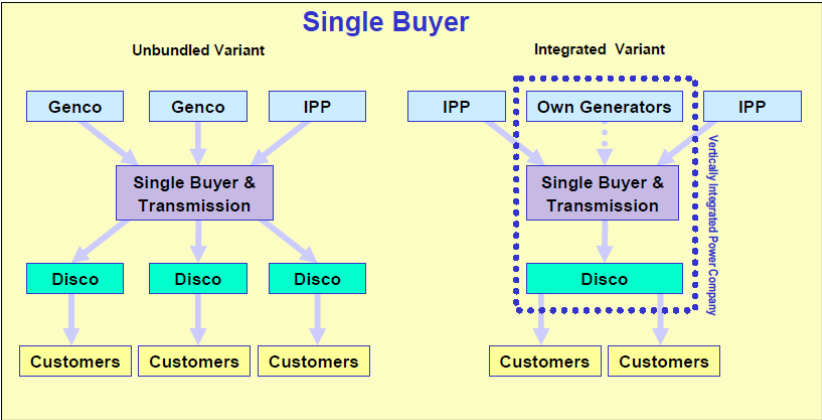


Figure 2.3 Single buyer electricity market [6]

Wholesale Competition Model: The power section is unbundled to generation, transmission, and distribution companies. A third independent regulatory authority is established to supervise the multi-buyer, multi-seller competitive power market. There is competition in the wholesale market. The largest consumers are often allowed to purchase electricity directly on the wholesale market [7].

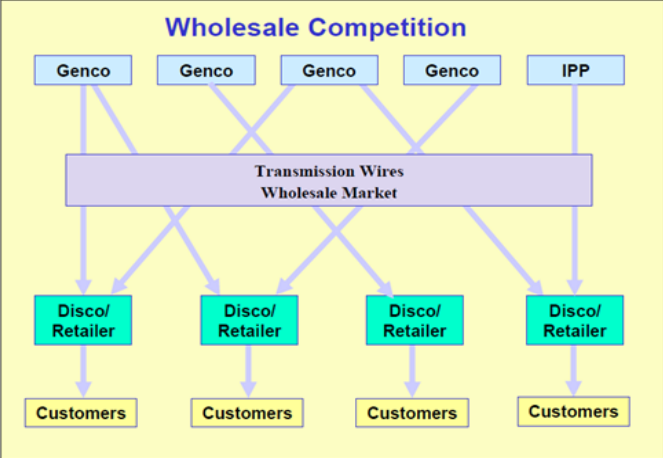


Figure 2.4 Wholesale competition electricity market [6]

Retail Competition Model: Based on the wholesale competition model, retail competition model introduces competition to the retail market. Hence, consumers can choose different retailers and large customers can purchase electricity directly from the wholesale market. This model is more efficient compared with the other three models, as the electricity tariff is set through market interactions [7].

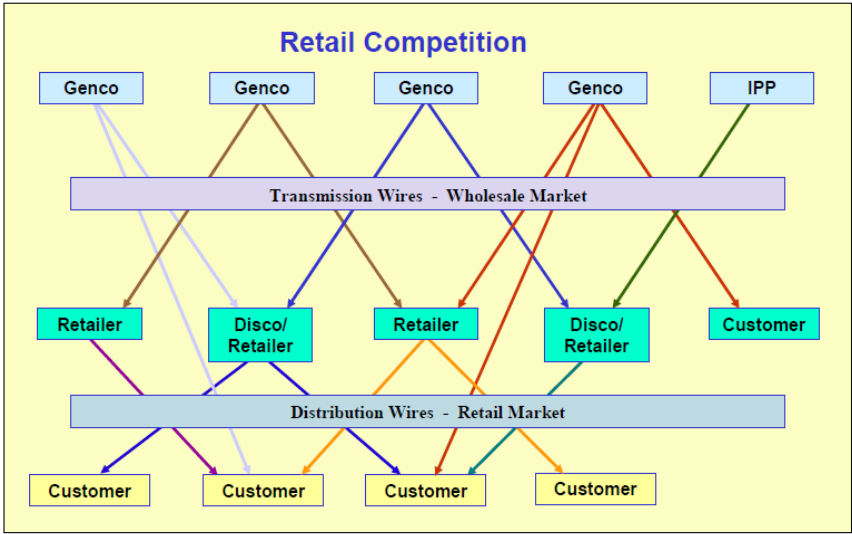


Figure 2.5 Retail competition electricity market [6]

**2.3 Electricity Trading Mechanism**

The UK electricity market reform was widely regarded as a landmark when the electricity Pool market was introduced. Electricity pool market allows all the market participants to take part in the central auction and the market clearing price is calculated by the system operator. However, since it is in the form of central auction, a lot of competitive generation companies and retailers are needed and transmission companies need to be independent. Thus, market participants do not have more choices than the pool. Besides, in pool market, competition is generally enhanced in the generation side. The participation of the demand side in price setting is limited to a few very large industrial consumers [8].

In several states of USA bilateral contracts are used. In bilateral electricity market, generators sell electricity through bilateral contracts with eligible customers or retailers which sell electricity to end-use customers. In bilateral market, the market participants are decentralized.



The change from centralized to self-dispatched market created a wide range of challenges for all market participants to optimize their strategies in order to maintain or increase their profits and decreases their exposures to the risk, because of the time duration of the price volatility in spot and balancing markets [9][10].

In a lot of countries, the hybrid electricity market is adopted, which allows the market participants to trade through central pool bidding and bilateral contracts. In this case, the generators, suppliers and users have more choices and certain flexibilities and the market fairness is enhanced.

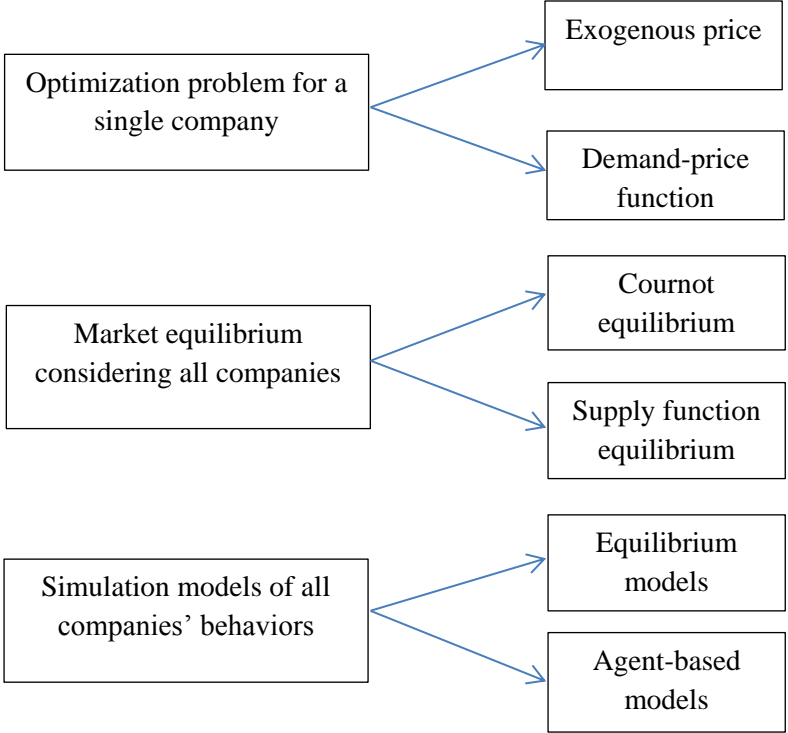
## **2.4 Electricity Market Models**

This section will introduce and classify the main economic models adopted to represent the electricity market behaviors. By comparing different models, their advantages and drawbacks will be analyzed and the reason why Conjectural Variation Equilibrium (CVE) model is chosen in our research is specified.

Due to the barriers to entry, normally high investment cost, there is limited number of companies in the electricity market. Besides, transmission constraints isolate consumers from effective reach of many generators. Furthermore, transmission losses discourage consumers from purchasing power from distant suppliers [11]. All these features differ electricity market from perfect competitive market, where the suppliers are price-takers and cannot influence the market price, thus, the social welfare is maximized. Therefore, the real electricity markets may be better regarded as oligopoly than of perfect competition. In oligopoly markets, only a few firms compete with each other, which results in high market concentration and they can exercise market power through altering prices away from competitive levels in a profitable way [12]. A part from controlling the output and price, other possible ways are exploiting transmission capacity limits and manipulating pollutant emission permits market [12][13][14][15].

Therefore, in the study of electricity market, not only the key factors such as market clearing price and quantities, but also the strategic behaviors which could affect the key factors need to be investigated. To achieve this, several models ranging from traditional Game Theory models

to complex system based models such as multi agent models have been developed. The most widely used models are illustrated in Figure 2.6.



**Figure 2.6 Electricity market modeling approaches [4]**

**2.4.1 Optimization Models**

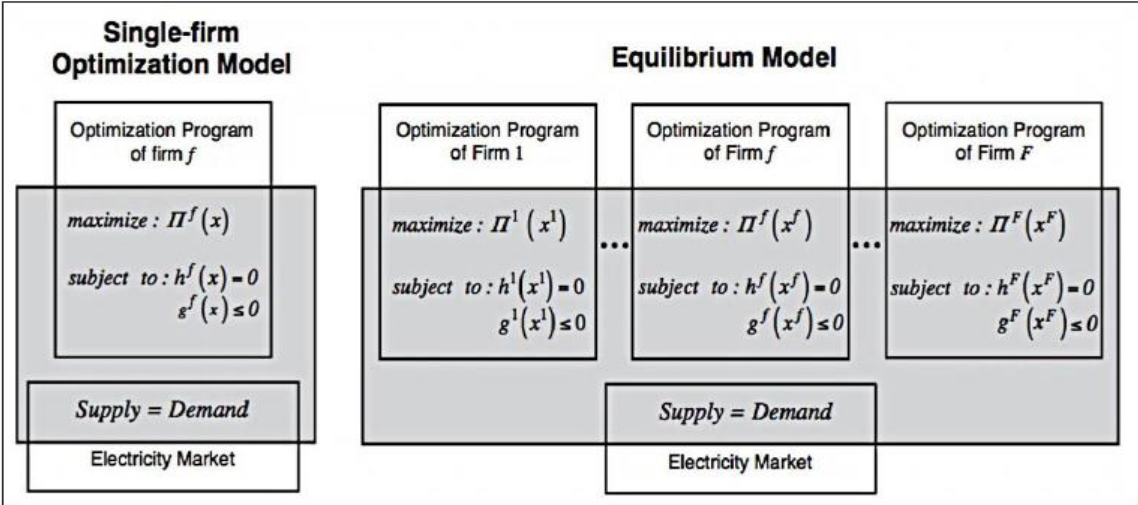
The main objective of optimization model is to solve the optimization problem for one firm competing in the electricity market while operational constraints and price clearing process are taken into consideration. Based on the fact whether price is defined as an exogenous variable or modeled as a demand function of the firm to study, the optimization models are classified in two categories [4]. In the case of exogenous price, the market price is calculated exogenously and the competitive behaviors of the market participants will not influence the price. Thus, the revenue of each firm is only a function of its output. The strategic reactions between the competitive companies are not considered.

As for the situation of demand-price function, the price is associated with the output of the firms. In the case of generation companies, through introducing the residual demand function,

the amount of electricity and the price at which the firm of interest is going to sell is decided. In order to achieve the residual demand function, the total demand function and all the other competitors' generation functions are needed. Nevertheless, in bilateral electricity market, due to the fact that all the information about bilateral contracts is not disclosed, generation functions of competitors cannot be achieved. Thus, the optimization models are not appropriate for the study of bilateral electricity market.

**2.4.2 Equilibrium Models**

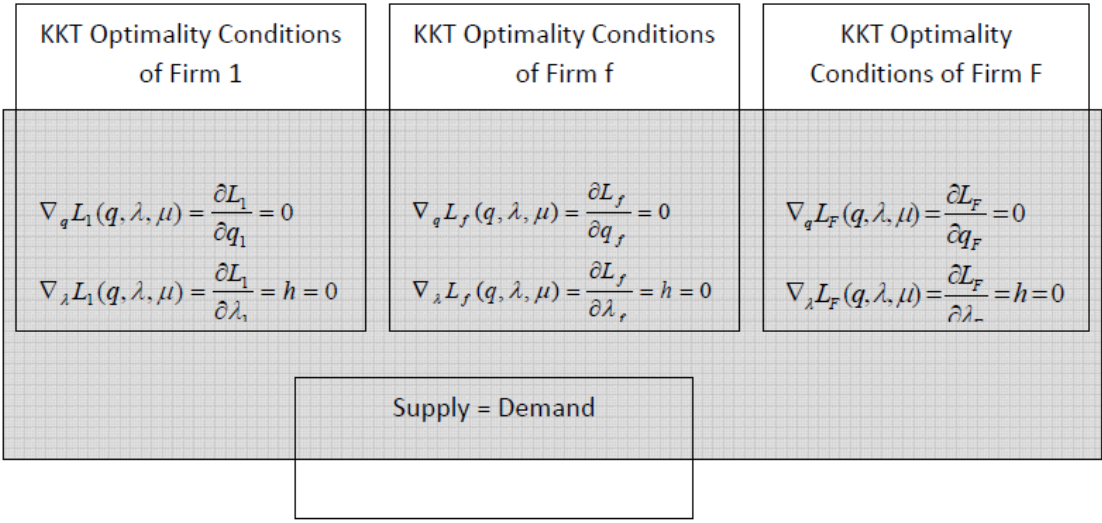
Equilibrium models have been widely used in modelling electricity market as in equilibrium models competitive behaviors among market participants are considered simultaneously which offers a more robust view of the market. Figure 2.7 shows the basic mathematical structure of both optimization and equilibrium methods.



**Figure 2.7 Mathematical structure of optimization and equilibrium model [4]**

In equilibrium models, the main objective is to solve profit maximization problems with the consideration of associated technical and economic constraints. First the market clearing condition should be satisfied, that is to say the energy demand should be satisfied by the generation. Besides, the first-order conditions, the Karush-Kuhn-Tucker (KKT) conditions, should be reached for the market participants to maximize their profits. In this case, the Nash Equilibrium will be formed and none of the market participants will have any incentive to

unilaterally change their strategies in order to make more profit, according to Game Theory specifications, since their strategies will be the best response to their rivals' strategies [16].



**Figure 2.8 Market equilibrium with KKT conditions satisfied [4]**

Equilibrium models are in conformity with the basic features of Game theory. Game theory is widely used to study the behaviors of market participants in environment with different competitiveness, which is exactly the case of electricity market. Game theory includes three decision variables: price, quantity and combination of price and quantity, which can result in different equilibrium models [9]. Based on these characteristics, several market models have been developed: Pure Competition, Collusion, Bertrand Model (Game in prices), Cournot Model (Game in quantities), Stackelberg Model, Conjectural Variation Equilibrium Model (CVE), Supply Function Equilibrium Model (SFE).

**2.4.2.1 Collusion**

The electricity market worldwide is more akin to oligopoly than perfect market competition. Collusion happens when rival companies cooperate for their mutual benefit, which often exists within the market environment of oligopoly, where the decision of a few firms to collude can significantly impact the market as a whole. Dynamic collusions among, and static market power abuse by, generation companies are two major manifestations of such market, and they could threaten the competitiveness as well as reduce the operating efficiency of the market

[17]. The collusion can be in the explicit form which can be established and maintained through negotiations, contracts and side payments. Due to the constraints of contracts, this kind of collusion is stable, and is usually forbidden by the law. Another form of collusion is implicit and is usually called tacit collusion. In this case, the collusion is formed through communication. This kind of collusion is not constrained by any contracts. Therefore, it is less stable, hard to be recognized and cannot be forbidden by law.

Through collusion, generation companies can exercise more market power and block new entries into the market. For example, generation companies with large generation capacity may have an agreements to make the electricity prices in wholesale market very high.

#### **2.4.2.2 Stackelberg Model**

In the Stackelberg model, the electricity market is dominated by a large leading generation company [18][19]. The leading firm will move first and follower firms will follow the strategy and move sequentially. The players of this game are a leader and a follower and they compete on quantity. The reactions of the competitive companies can be well predicted by the leader, while the followers are not aware of the effect of their strategies on the leader's decision. And the leader is aware of this situation.

If the firms have some advantages in moving first, they can participate in the Stackelberg competition. In the monopolistic electricity market, if the leader is the incumbent monopoly, the leader may move first, while the new entrants will act as followers. The Stackelberg competition can also happen if the leader holds excess capacity. Consequently, this approach is appropriate for monopolistic electricity market.

#### **2.4.2.3 Bertrand Model**

Bertrand model focuses on profit maximization through price setting. Instead of competing in quantity, in Bertrand model firms compete in price. The most important assumption in this model is that homogeneous products are produced and the output of one firm can satisfy the whole market demand. It takes place when one firm maximizes its market share through decreasing the price. Bertrand model is appropriate for the duopoly market. The following

equation demonstrates that the output of generation company  $i$ , is a function of its own output and other rivals' generation:

$$pq_i = p_i q_i(p_i, p_{-i}) \quad (2.1)$$

where,  $p_i$  is the decision variable of firm  $i$  and  $p_{-i}$  are the assumed prices of its rivals in response to  $p_i$ .

The model assumes that the rivals' prices stay the same in reaction to firm  $i$ 's price. Thus, firm  $i$  will supply the whole market as far as  $p_i$  remains the lowest price in the market. However, due to the increasing marginal cost and generation capacity and transmission capacity limits, firm  $i$  will not be able to satisfy the whole demand of the market [20]. Also, if different products are produced, the above result will not be obtained. Thus, some key technical and market constraints are not considered in this model. Besides, Bertrand is not able to predict the reaction of all rivals in the market. As a result, the Bertrand model is not widely used in modelling electricity market.

#### 2.4.2.4 Cournot Model

As one of the most widely used equilibrium models, Cournot model is a game of quantity instead of game in price in Bertrand model. More specifically, in Cournot model each company tries to maximize its profit while considering its output will not influence the decision of its competitors [4]. Therefore, in Cournot model, with the known inverse demand function  $p(q)$ , assuming the output of rival companies  $q_{-i}$  is fixed, the output of generation company  $i$  will be chosen. The revenue of company  $i$  will be calculated as below:

$$R_i = p(q_i, q_{-i})q_i \quad (2.2)$$

Just as stated above, the market equilibrium is reached with satisfying the KKT optimality conditions of market participants and market clearing conditions. In this case the marginal revenue will equal the marginal cost. They are described as below:

$$MR = \frac{\partial}{\partial q_i} (pq_i) = p + q_i \frac{\partial p}{\partial q_i} \quad (2.3)$$

$$MR = p + q_i \frac{\partial p}{\partial q} \frac{\partial q}{\partial q_i} \quad (2.4)$$

$$\text{and } q = q_i + q_{-i} \quad (2.5)$$

$$MR = p + q_i \frac{\partial p}{\partial q} \left( 1 + \frac{\partial q_{-i}}{\partial q_i} \right) \quad (2.6)$$

According to the assumption that the output of rivals is fixed,  $\frac{\partial q_{-i}}{\partial q_i} = 0$ :

Hence, the KKT optimality condition for firm  $i$  in Cournot model is:

$$MR = p + q_i \frac{\partial p}{\partial q} = MC \quad (2.7)$$

As it can be seen from the above equation, optimal output of each company is a function of the sum of the others' output and the calculation is simple and easy. All these make Cournot model popular in electricity market modelling ranging from market power analysis to transmission congestion. However, since the competition is only based on quantity, the result is highly sensitive to the demand elasticity. And if the assumption of the output of others is under-established, there will be an overestimation of observed market price.

To summarize, in Cournot model, the market share and demand elasticity are included. Besides, several examples of integration of transmission constraints in electricity market modeling using Cournot model can be found in [21][22]. However, due to the naïve assumption that the output of rivals is fixed, the reactions of rivals over the change in strategy has not been considered. Hence, Cournot model is not an effective method to model imperfect bilateral electricity market.

#### **2.4.2.5 Supply Function Equilibrium (SFE) Model**

The Supply Function Equilibrium (SFE) model is often adopted to model the complex real electricity market. In SFE model the firms compete in both price and quantity instead of only quantity in Cournot model or price in Bertrand Model [4][23]. Accordingly, SFE model is appropriate for electricity pool in which each generation company submits its bid as a form of supply function and market operator calculates the market clearing price. In SFE models, the decision variables for each firm are the parameters  $\varphi_i$  of its bid function  $q_i(p/\varphi_i)$ . The parameters  $\varphi_i$  describe the functional form of the bid function, such as intercept and slope of linear bid function. Thus, the revenue of firm  $i$  can be written as:

$$pq_i = p(q_i(p/\varphi_i) + \sum_{-i} q_{-i}(p/\varphi_{-i}^*))q_i(p/\varphi_i) \quad (2.8)$$

The asterisk in  $\varphi_{-i}^*$  indicates that company  $i$  treats bid function from other firms as if they are fixed. To calculate the revenue, a set of differential equation need to be solved, while in Cournot and Bertrand models, typical set of algebraic equations are dealt with. Furthermore, the SFE model results in multiple equilibria. Therefore the outcome of this model will cover a wide range of equilibria. This diversity can bring complexity to the market. Additionally, the calculation of these equilibria is difficult, especially for large system, therefore, SFE are mainly adopted for simple systems [24].

SFE models are widely used in the study of electricity markets, especially pool market, as their realistic review of the electricity market, namely demand and supply functions, though equilibria remains a problem unsettled. Improvements have been made in dealing with equilibria problem through assuming on the number of firms and the functional forms of demand, cost and supply functions [25].

#### 2.4.2.6 Conjectural Variation Equilibrium (CVE) Model

As discussed before, the reactions of rivals over the change in strategy has not been considered in Cournot model. To deal with this drawback, the CVE model was further developed through introducing some variation into Cournot-based models. Conjectures about the company's competitors' strategic decisions will be made in terms of the possibility of future reactions. The conjecture of one firm is defined as its belief or expect of how its rivals will show reaction to the change of its output [26][27]. In the CVE model, as in the case of oligopolistic electricity market, each firm rationally maximizes its profit while considering the reactions of the rivals. More specifically, in the CVE model, the firm will estimate how rival firms regulate their outputs in response to its output. Hence, the revenue of firm  $i$  can be written as:

$$pq_i = p(q_i + q_{-i}(q_i))q_i \quad (2.9)$$

Firm  $i$ 's KKT condition to maximize its profit is:

$$MR = p + q_i \frac{\partial p}{\partial q} \left(1 + \frac{\partial q_{-i}}{\partial q_i}\right) \quad (2.10)$$



$$MR = p + q_i \frac{\partial p}{\partial q} (1 + CV_i) = MC \quad (2.11)$$

where,  $CV_i$  is the constant conjecture value. As can be seen from the above equation, the CVE model attempts to understand pricing behavior by generalizing how firms react to changes in the strategic decisions of other firms. Different values of  $CV_i$  indicate different market behaviors the firm. In Cournot model, each firm assumes that its own output decision will not have an effect on the decisions of its rivals. Therefore,  $CV_i = 0$  yields the Cournot game. If the  $CV_i$  value matches the real response of rivals, then it can be called a “consistent conjectures” model. Thus, with the appropriate estimation of  $CV_i$  value of the firms, their market behavior can be well analyzed.

The CVE model can be used to model not only the generation side, but also the retailers’ behaviors while taking into account the strategies of all competitors. Compared to other models, CVE brings robustness into modeling the oligopoly electricity markets. Hence, CVE model can be an appropriate approach for modeling bilateral electricity markets. CVE model has been applied to study the electricity spot market [26][27]. In [28][29], CVE models have been adopted to investigate the generation side of electricity market. In the study of *Alikhanzadeh* (2011, 2012), CVE model is adopted to model the bilateral electricity market and, by matching the quantity and price of both sides of the bilateral electricity market, the market equilibrium is solved [9][10].

#### **2.4.2.7 Conjectured Supply Function (CSF) Model**

In the CSF model, each firm assumes how rival firms adjust their outputs in response to its price change. Thus  $q_{-i} = q_{-i}(p)$ . And the revenue of firm  $i$  is calculated as below:

$$pq_i = p(q_i + q_{-i}(p))q_i \quad (2.12)$$

A CSF is a function representing the beliefs of a firm concerning how total supply from rival firms will react to price. There are two versions of a linear CSF: one in which the slope of conjectured supply response is constant and the intercept is to be solved for, and another in which the intercept is given but the slope is to be determined [24]. As a model developed on the basis of SFE, the CSF model uses assumed parameters (intercept or slope) to represent the

response of competitors. This difference allows SFE to be formulated as mixed complementary problems that are relatively easy to solve and yield solutions whose existence and uniqueness properties can be demonstrated [30][31]. Therefore, CSF model is widely used to model the spot pool market.

### **2.4.3 Simulation Models**

Simulation models have been experiencing an increasing popularity in the modelling of electricity market especially when the considered problem is too complex to be addressed within a formal equilibrium framework and meanwhile, investment decisions, hedging strategies and learning processes can be included as endogenous variables in the simulation models [4][32].

Agent-based model is a typical simulation model and the market participants can be modeled as agents in this method. The agents interacting with each other are able to learn from repeated interactions and develop their own strategies to achieve their goals with respect to the technical and financial constraints. Apart from agents, environment and rules will be defined in the agent-based model. The environment is the place where agents situate and the trade takes place. The rules are the interactions between agents and the response of agents to environment changes. Thus, aspects like learning effects in repeated interactions, asymmetric information, imperfect competition, or strategic interaction and collusion can be included in a more realistic way in agent-based models [32][33].

In the case of bilateral electricity market, CVE model can be used as the basic research method, while agent-based model can be adopted for future study of the strategic behaviors of market participants with considering of different technical, financial and political constraints and factors.

## **2.5 Transmission Constraints and Transmission Capacity allocation**

Competing generators must rely on the transmission network to schedule and dispatch their plants to support sales of electricity in organized spot and forward markets and through bilateral contracts with end-use customers or marketing intermediaries (including distribution companies) which in turn supply end-use customers with electricity [34]. Despite the

liberalization of electricity market, transmission networks are still recognized as natural monopolies, such will be the case in China, where the transmission section will be regulated by the government, while generation, supply and retail sides will remain competitive. This is mainly because, the fixed costs for transmission are high and variable costs are comparably low in the transmission section. Electricity grids exhibit large economies of scale and must be physically interconnected for maximum trading efficiency, making the grid a natural monopoly within a defined region [35].

Due to the demand variation, contingency of equipment failures, equipment maintenance or the technical constraints, like thermal or stability limits, some lines on the network can become congested and cannot accommodate all the power flows that would occur if the transmission capacity constraints did not exist. In addition, as mentioned before, transmission constraints is one of the reasons why imperfect electricity market are formed, transmission congestion has potential implications for the intensity of competition in generation markets. Thus optimal strategies in allocating scarce transmission capacity should be developed to avoid congestion in an efficient manner. The basic rules associated with physical and economic system properties should be respected in the process of network access and transmission capacity allocation. More specifically, transmission resources have to be allocated respecting Kirchhoff's law and rules of non-discriminatory, market-based, transparent and feasible methodologies.

The efficient allocation of scarce transmission capacity is one of the main tasks of congestion management. Normally two approaches are adopted: capacity allocation and capacity alleviation methods [36]. In this research capacity allocation method will be studied. Four approaches of capacity allocation methodologies are widely used: locational marginal pricing, zonal pricing, uniform pricing and explicit auctioning.

Locational pricing maximizes social welfare taking into account transmission constraints and losses, and is performed by a centralized Independent System Operator (ISO) [37][38]. In the case of pool market, both generators and suppliers submit bids to trade energy at specific locations on the network. The market clearing price in this is location is calculated by the ISO and equals the marginal cost of providing electricity at that location. In a locational pricing

system, the congestion fee for transferring electricity between two locations is calculated as the difference in locational prices times the quantity transferred. The methodology comprehends that electricity has not only to be generated, but also has to be delivered to a particular node, taking into account transmission constraints and electrical losses.

In zonal pricing, a group of nodes is aggregated to one zone. These zones are mostly defined a priori as the concept focusses on certain flowrates, which may be subject to congestion. In a zonal pricing system, the fee is calculated as the difference between the zonal prices times the quantity transferred. The Transmission System Operator (TSO) receives a surplus during transmission congestion periods and when losses are present, because net payments from loads exceed net payments to generators.

As analyzed above, in zonal pricing where several buses are grouped into zones and the price differentials between the nodes in one zone are not distinguished. Therefore, such a zone can be regarded as a uniform price zone. The method uniform-pricing is efficient in the case of uncongested network. In the case of congestion, other financial tool like uplift payment is needed to cover the cost of congestion relief.

In explicit auction, transmission capacities are auctioned separately and before the allocation of wholesale energy. The seller (TSO) determines ex ante the available transmission capacity considering security analysis accepts bids from potential buyers and allocates the capacity to the ones that value it most [39][40][41]. The selection of the bids and the determination of the equilibrium price result from the maximization of the profits from the auction under the transmission constraints [41]. Thus, explicit auctioning is a market-based concept, which provides economic signals. Explicit auctions are particularly appropriate for the allocation of long-term capacity rights.

# 3. Electricity Market in China

## 3.1 Introduction

Starting from 1978, economic development has been the primary objective of China. To achieve this objective, energy supply has been increasing sharply to satisfy the fast growing energy demand of industrialization. And electricity is the main form of energy consumption. As it can be seen from Figure 3.1, the GDP grew from 2223.7 billion (2010 USD) in 2000 to 8230.12 billion (2010 USD) in 2014, while the electricity consumption increased from 1253.74 TWh to 5357.55 TWh [42].

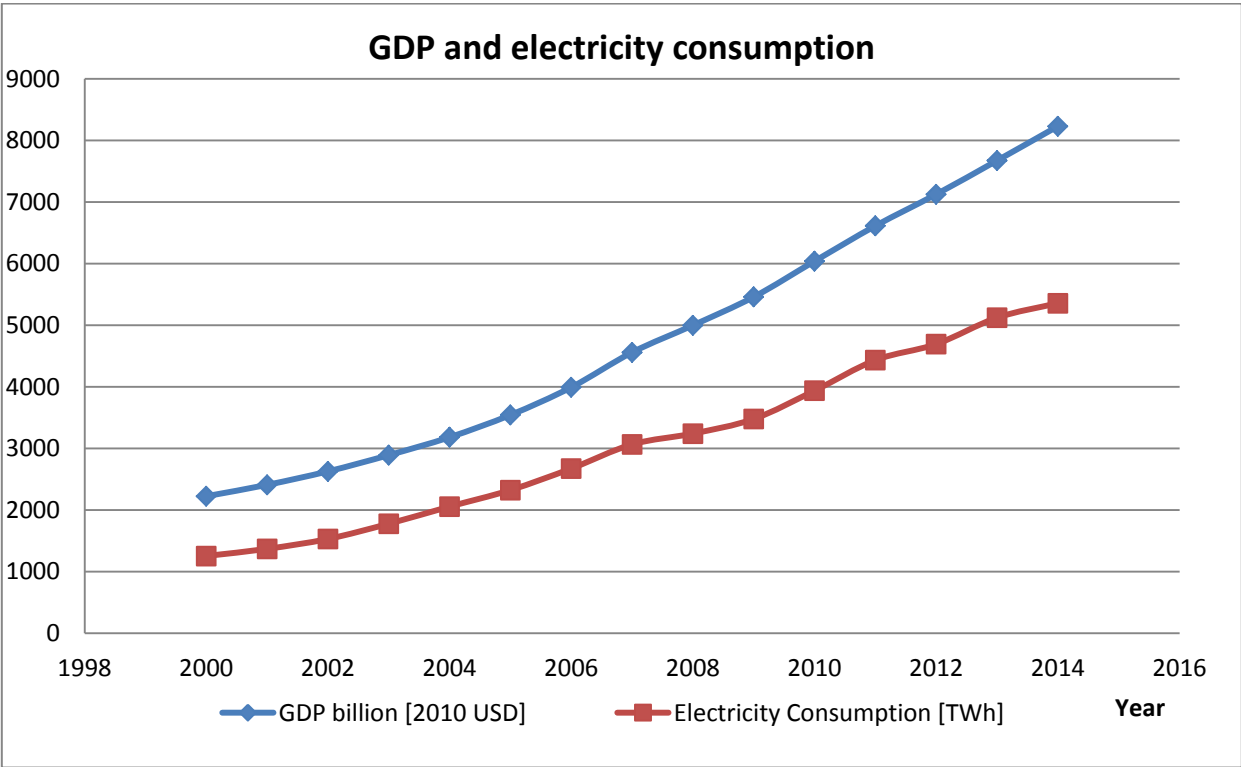
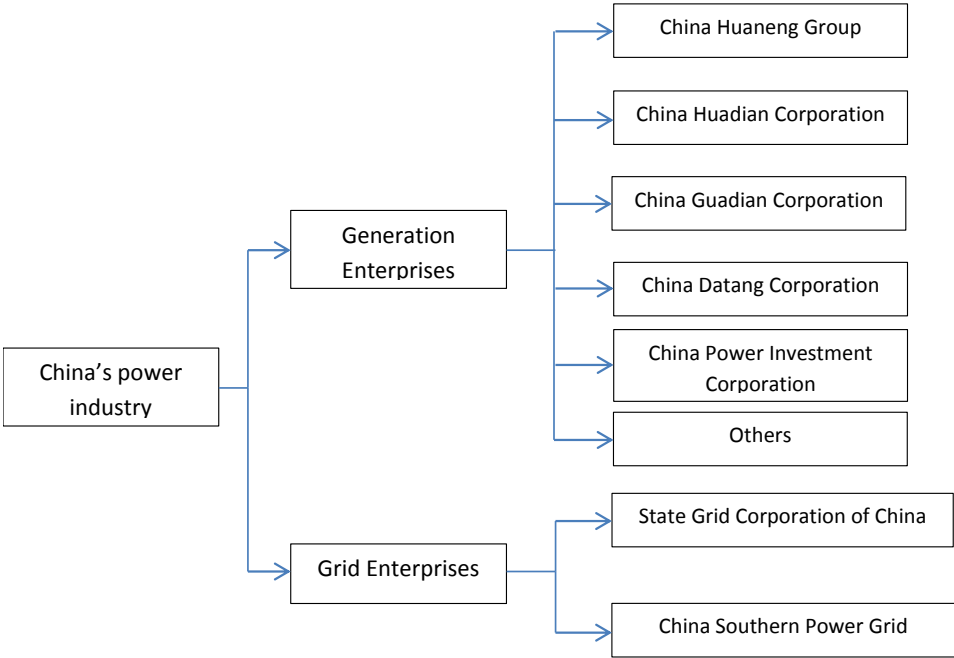


Figure 3.1 GDP and electricity consumption from 2000 to 2014 [42]

Along with the fast economy development and increase of power production, the traditional vertically integrated Chinese electricity utility systems have been experiencing several deregulations and market-orientated reforms. Competition has been introduced to both generation section and supply section to liberalize the electricity market, improve market efficiency and social welfare.

Before 1985, the Chinese electricity section has been a vertically-integrated, centrally planned, state-owned electricity monopoly. The administration, resources allocation, investment decisions, and pricing in the electricity industry have been fully controlled by the central government [1][2][3][43][44]. For a long time, to guarantee the security of important resources, private and foreign capital was not allowed to invest in the electricity industry. As a result, electricity supply is in shortage for a long time, which restricts the economy development in China. From 1978, China started the market economy and opened the market gradually. Starting from 1985, the generation side of electricity section was open to local governments, private and foreign investment, which boosted the generation capacity.

In 1997, the State Power Corporation (SPC) was established which led to the dissolution of Ministry of Electric Power. However, the newly founded SPC became a new monopolist. The SPC controlled half of the country's generation assets and almost all of the transmission and distribution assets. As a result, the SPC itself has become a key obstacle for market-oriented reform of the Chinese electricity industry [1][2][3]. The on-grid price and electricity tariff are decided by National Development and Reform Commission (NDRC). The administrative approval of generation projects and grid construction projects belong to NDRC as well.



**Figure 3.2 The structure of China's power industry after the reform of 2002**

However, in China's electric power industry, the investment for generation side and power grids was still inadequate and the gap between power supply and demand kept enlarging. In order to relieve the problems above, power industry reform has been carried out in 2002 under the guidance of Electricity Reform Plan (No. 5 Document) by the Central Government. The reform in 2002 is regarded as a milestone in the Chinese electricity market-oriented reform. The main measures were breaking the state monopoly and advancing the energy pricing mechanism. The SPC was dismantled, with its generation assets reallocated to big five state-owned generation corporations (Big Five): China Huaneng Group, China Huadian Corporation, China Guodian Corporation, China Datang Corporation, and China Power Investment Corporation. Its transmission and distribution assets were reallocated to two giant state-owned transmission companies: State Grid Corporation of China and China Southern Power Grid Company Limited. All the seven companies are big state-owned giants and in the list of Fortune Global 500.



**Figure 3.3 Regional and provincial grid control areas in China**

The power grid in China is divided into 7 regions: South China, Central China, East China, North China, North East, North West and Tibet. China Southern Power Grid Company Limited is responsible for South China. The rest is occupied by the State Grid Corporation. The structure of Chinese electricity market by geography is shown in Figure 3.3.

### 3.2 Generation Sector in China

Since 2011, China has been the world’s largest electricity producer. The power production increased a lot from 3.68 PWh in 2009 to 5.54 PWh (24% of global production) in 2014 [42], while generation capacity grew sharply from 874 GW to 1370 GW at the same time [45]. With the generation capacity over 150 GW at the end of 2014, China Huaneng Group became the biggest generation company in the world.

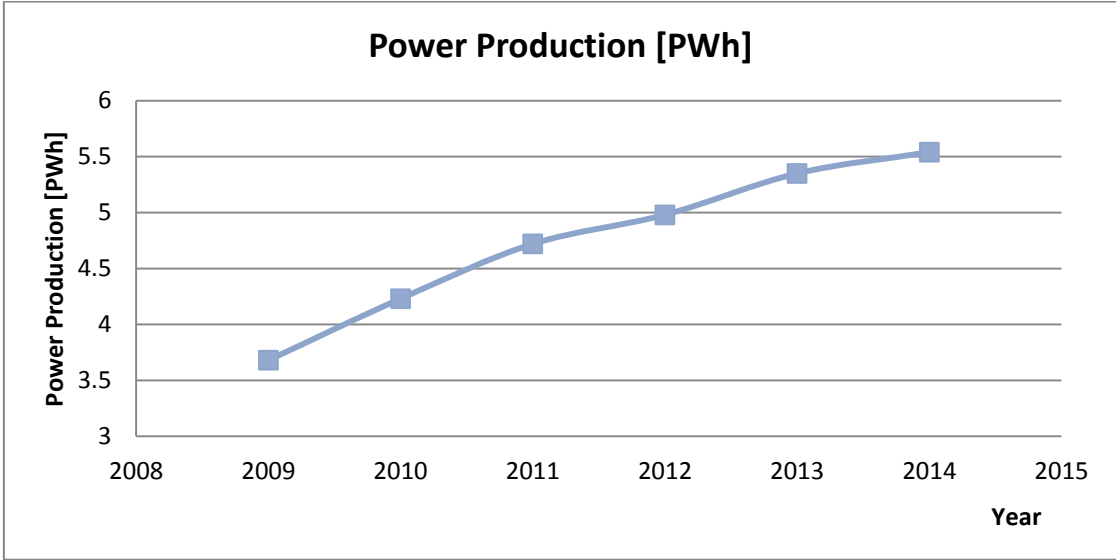


Figure 3.4 Power production from 2009 to 2014 [42]

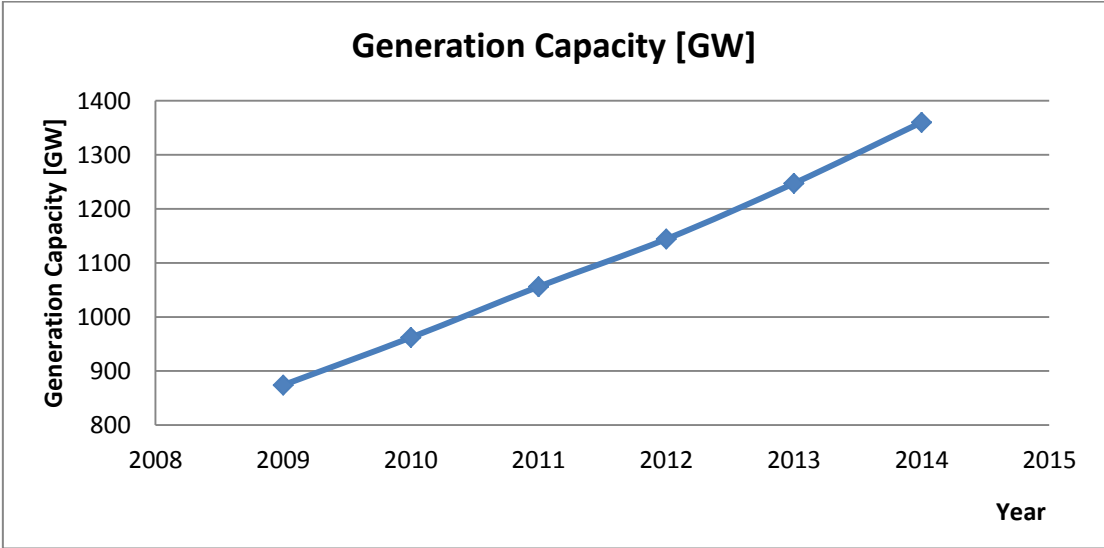


Figure 3.5 Generation capacity from 2009 to 2014 [45]



China’s power production mainly depends on coal power plants, which accounts for 72.46% in 2014. With 18.74% of market share, hydro ranks second. Wind, nuclear and gas have market shares of 2.75%, 2.33%, 2.01% respectively. Solar, biofuels, geothermal and others account for the rest 1.7%. China is the fastest growing nuclear market now, with an annual growing rate of 16.5%, China plans to increase the generation capacity of nuclear power to 58 GW by the end of 2020. This kind of fuel structure is mainly decided by the resource endowment, since China is rich in coal, poor in natural gas and oil. Too much rely on coal has caused very serious environmental problems in China. A typical example is the serous smog in north China.

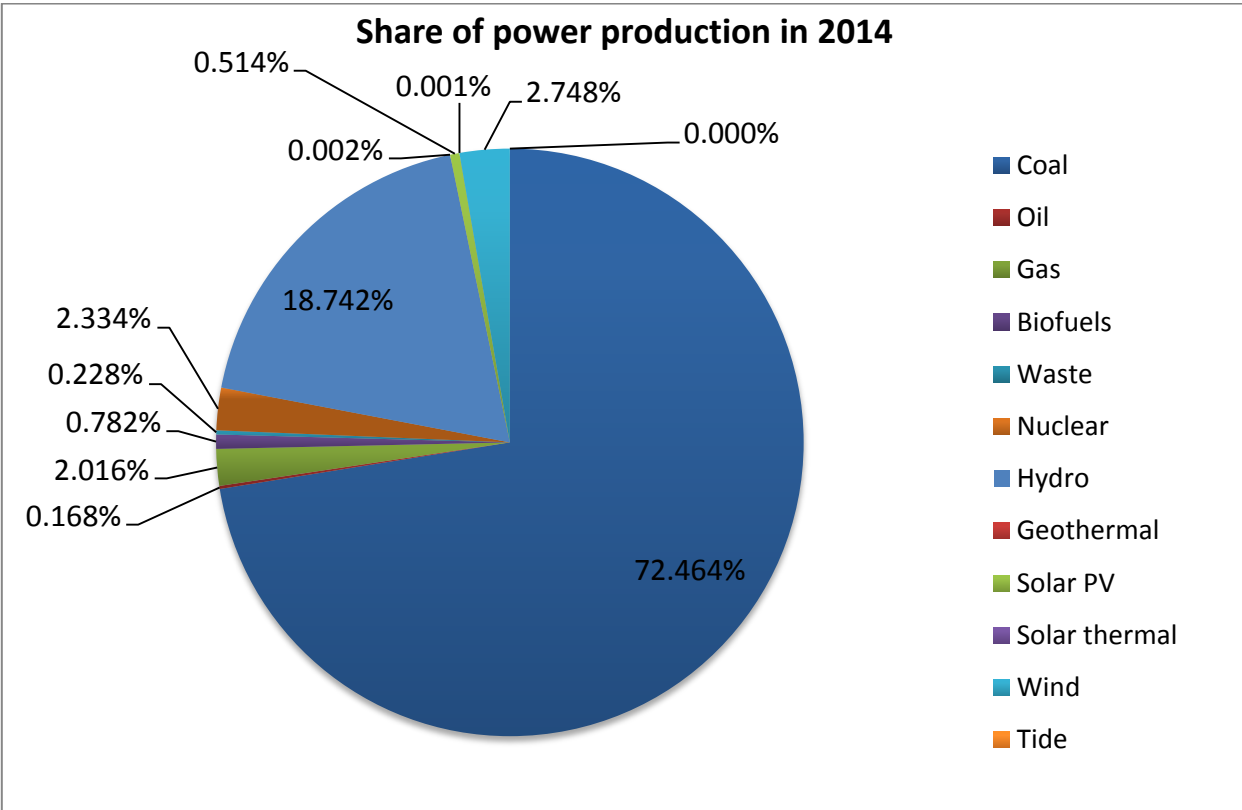
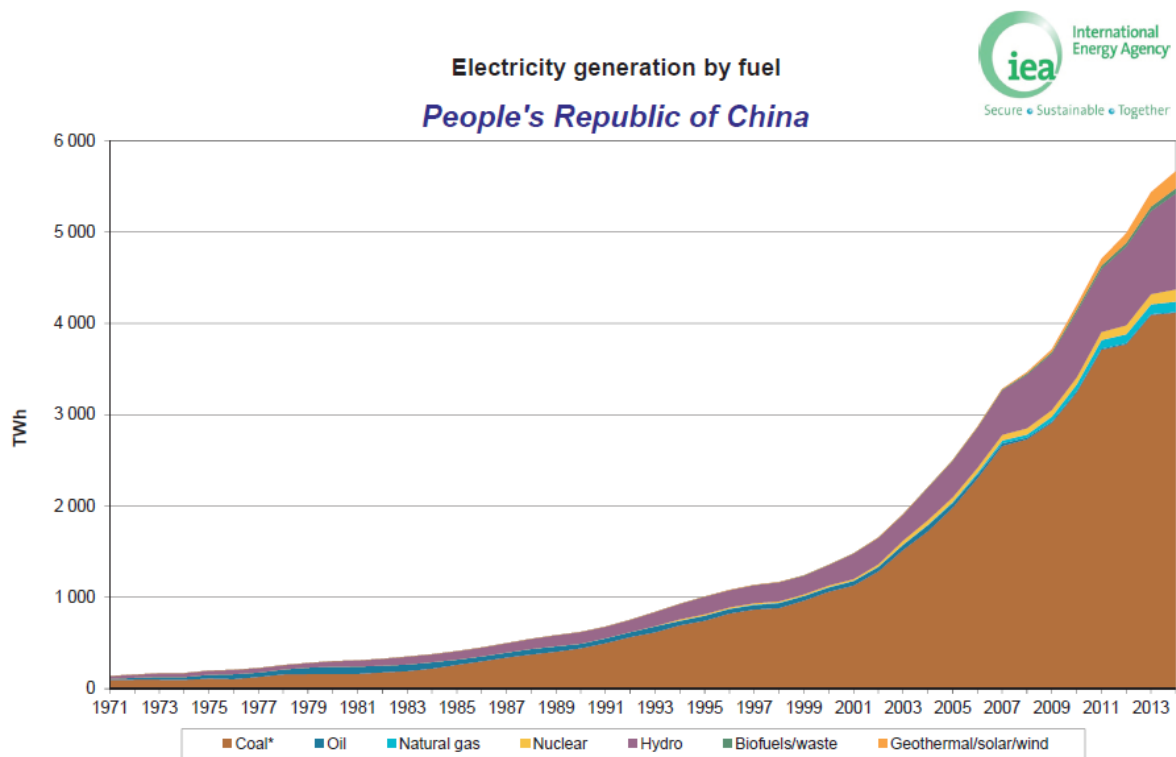


Figure 3.6 Share of power production in 2014 [46]



**Figure 3.7 Electricity generation by fuel [47]**

One of the main features of Chinese generation section is the unbalanced distribution of generation capacity in different regions. The load center is in east China (Shanghai, Jiangsu, Zhejiang) and south China (Shenzhen, Guangzhou). However, the generation resources are abundant in northwest and central China. This motivates the construction of high voltage transmission line for inter-regional power delivery. The generation capacity in each province is shown in Table 3.1.

Region	TOTAL		Hydro		Thermal		Nuclear		Wind		Solar		Other
	2014	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014
National	1370180	1257680	304860	280440	923630	870090	20080	14660	96570	76520	24860	15890	188
Beijing	10900	7920	1010	1010	9700	6760	0	0	150	150	25	0	10
Tianjin	13570	11370	10	10	13230	11120	0	0	290	230	47	16	0
Hebei	55440	52200	1820	1810	42830	41870	0	0	9630	8250	1145	251	19
Shanxi	63040	57670	2440	2430	55640	52050	0	0	4550	3160	413	35	0
Shandong	79710	77180	1078	1078	72030	70980	0	0	6220	5000	306	118	71
Liaoning	41920	39660	2930	2730	30840	30280	2000	1000	6080	5630	70	23	0
Jilin	25600	25180	3770	4450	17680	16940	0	0	4080	3770	61	10	3
Heilongjiang	24990	23930	970	970	19480	19030	0	0	4540	3920	11	11	4
Inner Mongolia	92730	84850	1770	1080	67100	63860	0	0	21000	18540	2854	1368	0
Shanghai	21840	21620	0	0	21380	21270	0	0	370	320	87	7	0
Jiangsu	86110	82410	1140	1140	77270	75550	2120	2120	3020	2560	2562	1046	0
Zhejiang	74120	64780	9950	9860	57460	49950	5490	4330	730	450	498	180	4
Anhui	43220	39330	2880	2820	39110	35970	0	0	820	490	400	50	0
Fujian	44490	42010	12880	12850	26670	26580	3270	1090	1590	1460	78	26	0
Jiangxi	20780	19990	4840	4570	15370	15030	0	0	370	300	204	85	0
Henan	61960	60520	3960	3950	57350	56280	0	0	440	270	201	20	0
Hubei	62130	58960	36270	36160	25010	22400	0	0	770	350	86	48	6
Hunan	35670	33640	15100	14010	19830	19290	0	0	699	340	49	1	0
Shanxi	28660	25900	2530	2510	24980	22730	0	0	840	590	313	63	0
Gansu	41910	34890	8140	7550	18500	16010	0	0	10080	7030	5173	4298	30
Qinghai	18290	17110	11430	11180	2420	2350	0	0	320	100	4124	3481	0
Ningxia	24240	22310	430	430	17900	17310	0	0	4180	3020	1734	1551	0
Xinjiang	54640	42530	5730	5170	37910	29390	0	0	7740	5210	3261	2771	0
Chongqing	17740	15090	6520	6420	11130	8580	0	0	100	100	0	0	0
Sichuan	78740	68620	62930	52660	15470	15820	0	0	100	100	0	0	0
Tibet	1440	1100	870	580	400	390	0	0	10	0	130	110	27
Guangdong	91630	85980	13230	13190	68630	64880	7210	6120	2040	1740	511	44	0
Guangxi	32150	31400	16260	15820	15720	15420	0	0	120	120	45	42	0
Hainan	5040	4970	830	830	3760	3750	0	0	310	300	139	89	0
Guizhou	46690	44760	19550	19080	24820	24330	0	0	2330	1350	0	0	0
Yunnan	70780	59790	53610	44090	14020	13940	0	0	2870	1650	282	110	0

**Table 3.1 Generation capacity in each province [MW] [48]**

Another typical phenomenon is the high concentration of market share in some big companies, like Big Five. The main generation companies and their capacity are specified in Table 3.2.

Company	TOTAL		Hydro		Thermal		Nuclear		Wind	
	2014	2013	2014	2013	2014	2013	2014	2013	2014	2013
Huaneng	151490	142240	20450	18350	118670	113560	0	0	11510	9730
Guodian	125180	122790	12960	12580	91770	92270	0	0	19760	17320
Huadian	122540	112760	23290	20840	89590	85630	0	0	8420	5380
Datang	120480	115350	19790	17780	90010	87670	0	0	10060	9370
China power investment	96670	89680	20710	19250	63330	62090	2240	1120	6670	4710
Shenhua	66850	65620	130	130	61220	60290	0	0	5380	5100
Three Gorge	50030	42260	46320	39490	0	0	0	0	2580	2030
Huarun	36520	30840	470	470	32340	27430	0	0	3710	2940
Guotou	32050	27210	16120	12520	15330	14090	0	0	490	500
Zhejiang	27270	24520	850	850	26410	23660	0	0	10	10
Guangdong	26950	26850	2150	2150	24520	24460	0	0	210	200
Zhongguanghe	21280	15340	1480	1470	680	680	11620	8330	6930	4330
Beijingnengyuan	17320	14700	560	500	14800	12280	0	0	1650	1650
Hegongye	9190	6520	0	0	0	0	8690	6520	500	0
Hebeijianshe	8770	8610	0	0	7350	7260	0	0	1400	1350
Jiangsuguoxin	7710	7300	100	100	7390	7040	0	0	170	120
Shenneng	6760	6710	0	0	6670	6670	0	0	90	40
Hubeinengyuan	5830	5770	3670	3650	2000	2000	0	0	160	110
Shenzhennengyuan	5830	5710	0	0	5410	5400	0	0	370	310
Anhuinengyuan	5550	5520	0	0	5550	5520	0	0	0	0
Gansudianli	4620	3970	1740	1620	1970	1640	0	0	800	600
Shanxiguoji	4030	1830	130	130	3470	1610	0	0	290	80
Guangzhoufazhan	3170	3110	0	0	3170	3110	0	0	0	0
Xinlinengyuan	2700	2700	0	0	2700	2700	0	0	0	0
Zhonglvningxia	2640	2580	0	0	1320	1320	0	0	1150	1130
Jiangxitouzi	1500	1500	100	100	1400	1400	0	0	0	0
Huanghewanjia	1500	1500	1500	1500	0	0	0	0	0	0

**Table 3.2 Generation capacity of the main companies in 2014 [MW] [48]**

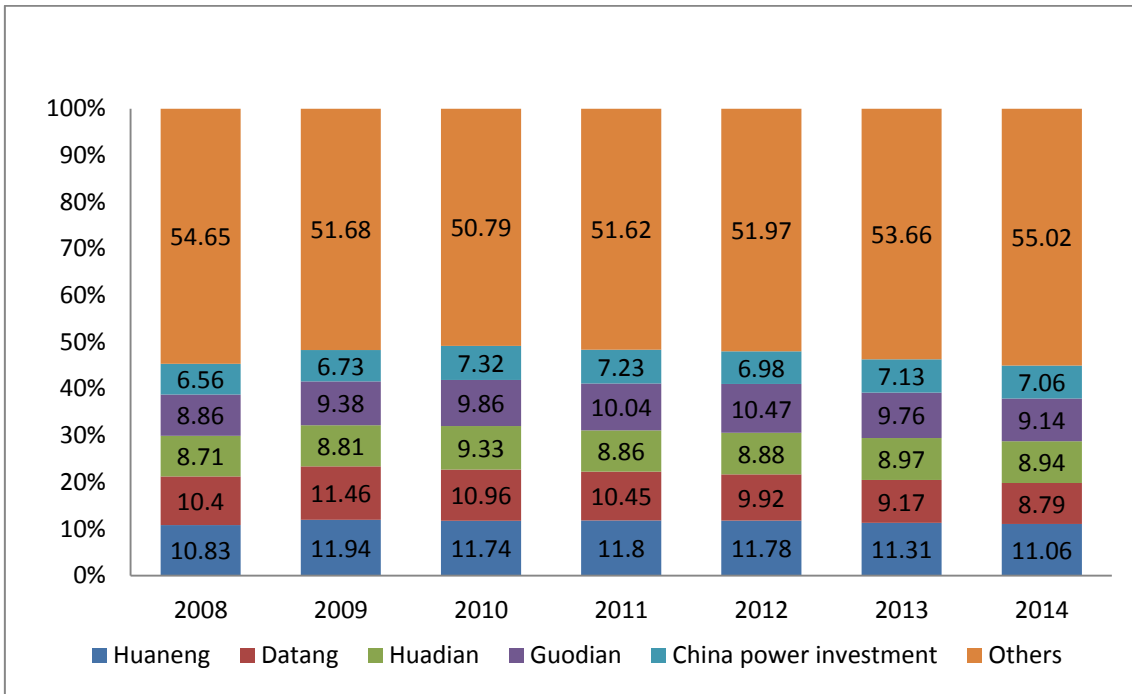


Figure 3.8 Share of Big Five in total capacity [48][49]

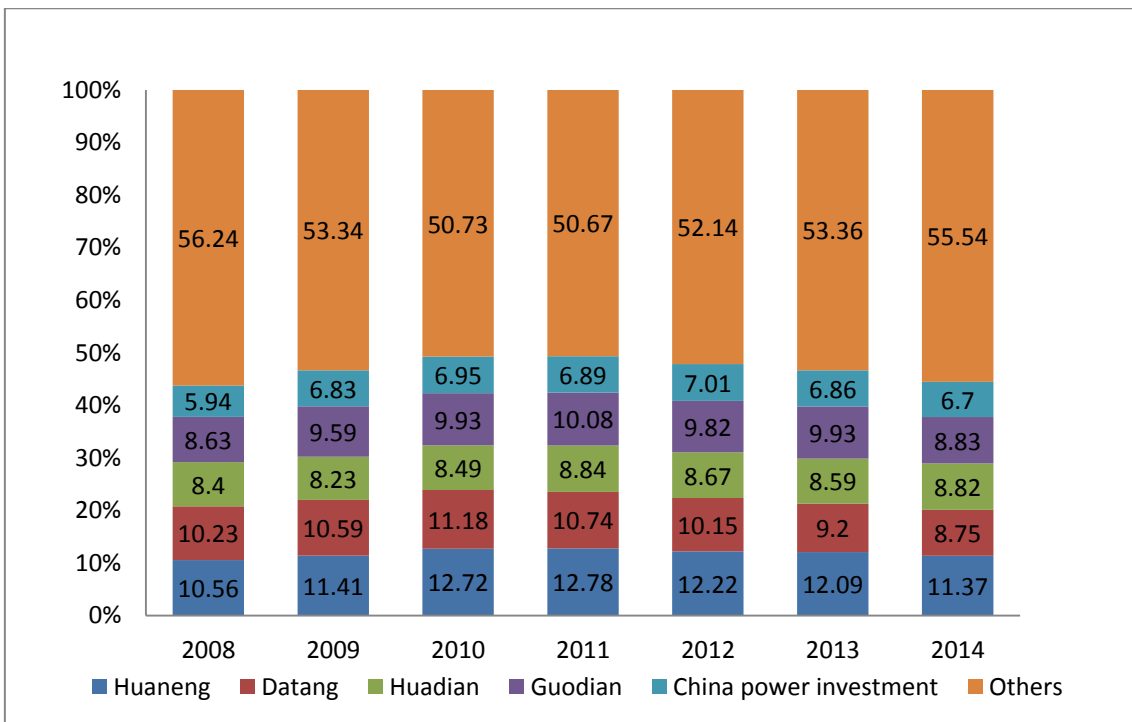


Figure 3.9 Share of Big Five in total generation [48][49]

From the above data we can see that, with very big market share, the Big Five can exercise significant market power. Besides, the Big Five are multiple companies with different generation resources, ranging from traditional coal-fired power plants to renewable energy. The Big Five shared 33.8% of the nation's generation capacity in 2002, when they were established. However, due to the serious power shortage from 2003 to 2004, increasing generation capacity and guaranteeing energy supply has been the main focus of the government. The Big Five are the leading companies in expanding generating capacity. And they controlled 49.21% of the total nation's generation capacity in 2010. Apart from Big Five and other 2 relatively large generation companies, the rest generation companies are small local companies with less market share, as shown in Table 3.2.

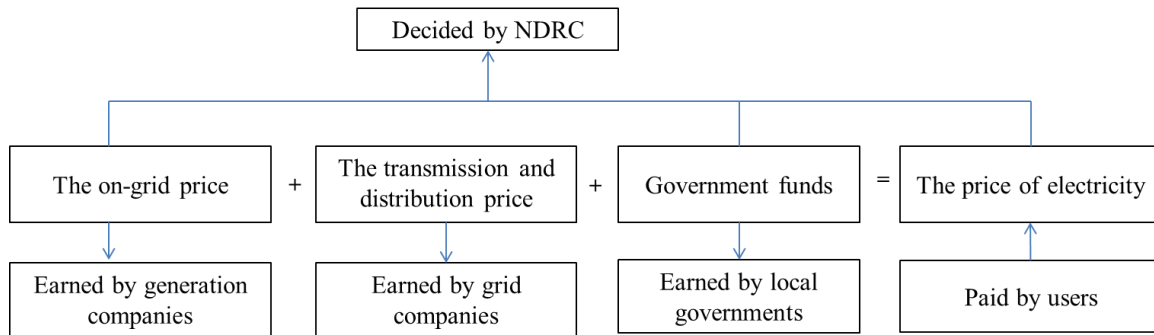
The initial division into five companies was to ensure effective competition in the generation side. However, the increasing size of these companies became a barrier to the emergence of a competitive market.

### **3.3 Transmission Sector in China**

The transmission system in China is shared by two giant transmission companies: China State Grid Corporation and China Southern Power Grid Company Limited, ranking 2 and 95 in the list of 2016 Fortune Global 500, respectively. By assets in 2014, State Grid is four times larger than China Southern Grid and three times larger than the largest generator [48]. Since these two companies share the market by regions, there is no competition between them. They continue to integrate transmission, distribution and retailing within the service fields, which is the monopoly of retailing for nearly all the customers. As a result the two companies exercise tremendous power in the supply chain and the process of electricity market reform.

After the reform in 2002, the price at which the generation companies sell to the grid company is called the on-grid price. This price is supposed to be decided by market competition. However, since the main market participants are the seven big state-owned companies, the unfair competition was very common. Gradually the on-grid price was decided by the NDRC [50]. The disparities between the electricity tariff for end-users and the on-grid price are the transmission and distribution price and government funds. The government funds are also

determined by the NDRC. The price structure of power industry after 2002 in China is shown as below:



**Figure 3.10 Price structure of electricity tariff in China [3]**

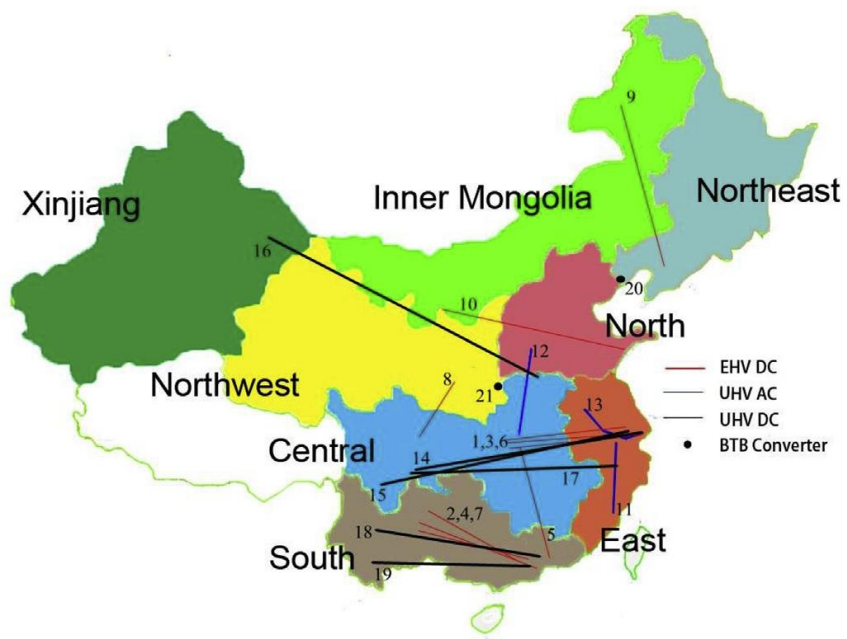
As discussed above, the generation capacities are distributed in different regions according to the resources endowment. Thus, transmission lines are needed if the cheap generation sources are far away from the load center. China has been rapidly building transmission network to meet China's regional power demand and better allocate natural resources, especially from the west to the east. Since the large hydro power (mainly in Sichuan, Hubei and Yunnan), coal reserves (mainly in Northwest China) and renewable energy (mainly in Inner Mongolia, Ningxia and Xinjiang) are in the west and the load centers are located in the east around Shanghai. Extra-High Voltage (EHV) and Ultra-High Voltage (UHV) transmission lines already completed are listed in Table 3.3, 3.6.

No.	Name (Pathway)	Operation year	Category	Voltage(kV)	Length(km)	Capacity(MW)	Linked regions
1	Gezhou Dam - Shanghai	1990	EHV DC	±500	1045	3000	Central-East
2	Tianshengqiao - Guangzhou	2001	EHV DC	±500	960	1800	South
3	Three Gorges - Changzhou	2003	EHV DC	±500	860	3000	Central-East
4	Guizhou - Guangdong	2004	EHV DC	±500	882	3000	South
5	Three Gorges - Guangdong	2004	EHV DC	±500	960	3000	Central-South
6	Three Gorges - Shanghai	2006	EHV DC	±500	1040	3000	Central-East
7	Guizhou - Shenzhen	2007.12	EHV DC	±500	1194	3000	South
8	Baoji - Deyang	2009.12	EHV DC	±500	534	3000	Northwest-Central
9	Hulunbeir - Liaoning	2010.9	EHV DC	±500	908	3000	InnerM.-Northeast
10	Ningdong - Shandong	2011.2	EHV DC	±660	1335	4000	Northwest-North
11	Zhejiang north - Fuzhou	2015.3	UHV AC	1000	596	6000	East
12	Jin southeast - Jingmen	2008.12	UHV AC	1000	654	6000	North-Central
13	Wan - Shanghai	2013.9	UHV AC	1000	656	21,000	East
14	Xiangjia Dam - Shanghai	2010.7	UHV DC	±800	1892	6400	Central-East
15	Jinping - Suzhou south	2012.12	UHV DC	±800	2100	7200	Central-East
16	Hami south - Zhengzhou	2014.1	UHV DC	±800	2192	8000	Northwest-Central
17	Xiluodu Dam to Zhejiang	2014.7	UHV DC	±800	1653	8000	Central-East
18	Yunnan to Guangdong	2009.12	UHV DC	±800	1413	5000	South
19	Nuozhadu Dam to Guangdong	2013.9	UHV DC	±800	1413	5000	South
20	Lingbao	2005	Back to Back DC Converter			1110	Northwest-Central
21	Liaoning Gaoling	2012.11	Back to Back DC Converter			3000	Northeast-North

**Table 3.3 Completed EHV and UHV transmission lines in China [51]**

Type	Voltage	2014	2013	2012
AC (km)	1000kV	3111	1936	639
	750kV	13881	12666	10088
	500kV	152107	146166	137104
	330kV	25146	24065	22701
	220kV	358377	339075	318217
	110kV	566571	545815	517983
	35kV	484296	464525	456168
	Total	1603489	1534248	1462900
DC (km)	800KV	10132	6904	5314
	660KV	1336	1400	1400
	500KV	11875	10653	9145
	400KV	1640	1031	1031
	Total	24983	19988	16890

**Table 3.4 Expansion of Chinese transmission and distribution grid [48]**



**Figure 3.11 Completed EHV and UHV transmission lines in China [51]**



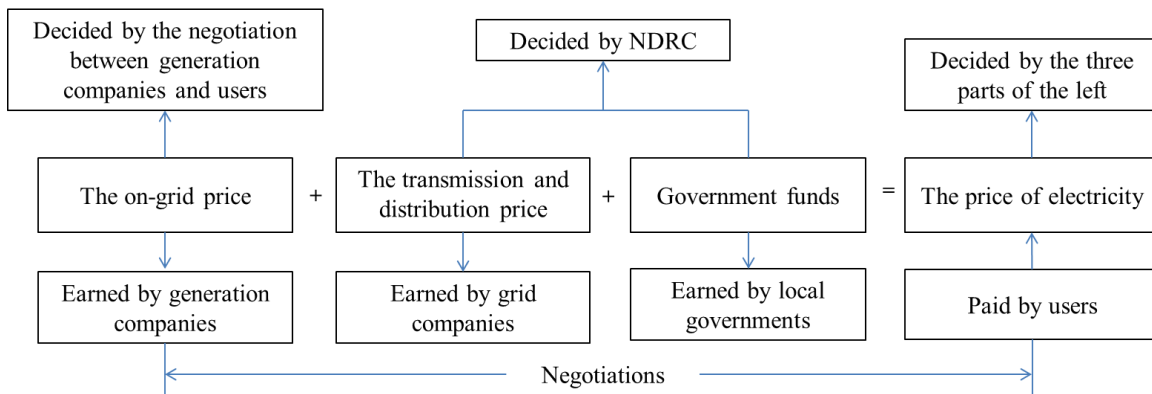
### **3.4 Electricity Market Reform in 2015 and Future Development**

The strict regulation and lack of competition in Chinese electricity section has distorted the market mechanism. Twisted pricing mechanism and inefficient utilization of renewable energy are the typical problems faced by the Chinese electricity market [3]. These problems have prevented the power industry from developing and resulted in high economic burden to end users, especially industrial users, since the electricity tariff in China is expensive for industrial users and relatively cheap for agricultural and resident users. To deal with these problems, the government started a new round of power industry reform under the guide of Relative Policies on Deepening the Reform of Power Industry (No.9 Document), which was issued on March 25th, 2015 by the State Council.

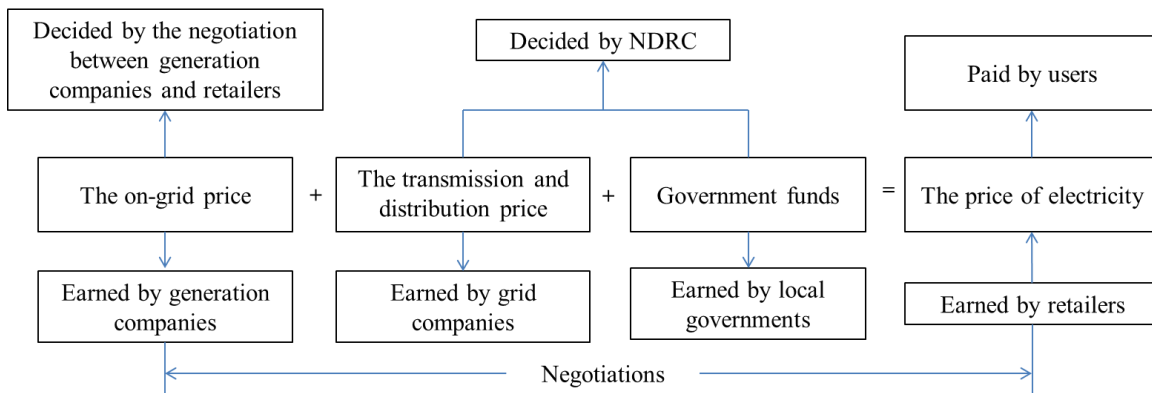
In this round of reform, the policy of direct power purchase for large users (DPLU) will be further promoted. The DPLU is a typical form of bilateral electricity market and allows direct negotiations between large users and generation plants to determine the electricity price. The Chinese government has started to pilot and carry out policies about DPLU since 2002 and has achieved some improvements in decreasing the price in some provinces [52]. Therefore, under the new policy, the on-grid price will be replaced by transaction price, which will be decided by market and negotiated between generators and eligible users, mainly industrial users and part of commercial users at present.

Besides, competition will be introduced to the retail market and power retailers are encouraged to be established. For the small users who are not eligible to take part in the DPLU, they can choose to buy electricity from the retailers or the distribution company as in the former pricing mechanism. The retailers can act as large users and negotiate directly with generators for the quantity and price through bilateral contracts.

Furthermore, the transmission and distribution section will remain regulated by the government. However, the transmission and distribution price are separated, and are decided by NDRC. The price will be evaluated according to the investment and operation cost of power grids. The government funds are also decided by NDRC in this new price mechanism.



**Figure 3.12 Price structure of DPLU [3]**



**Figure 3.13 Price structure of retail market [3]**

Apart from price mechanism, No. 9 Document has also published policies about the future development of the generation companies and power grid. Investment in renewable energy generation, flexible coal-fired power generation and flexible power grids are encouraged. Construction of smart grid should be further enhanced to promote the demand side management and improve the energy efficiency, especially with the integration of more renewable energy in the system. Besides, more EHV and UHV transmission lines will be constructed to deliver the power generated from renewable generation plants of northwest to east China. The future development plan for UHV transmission lines are listed in the two figures below.

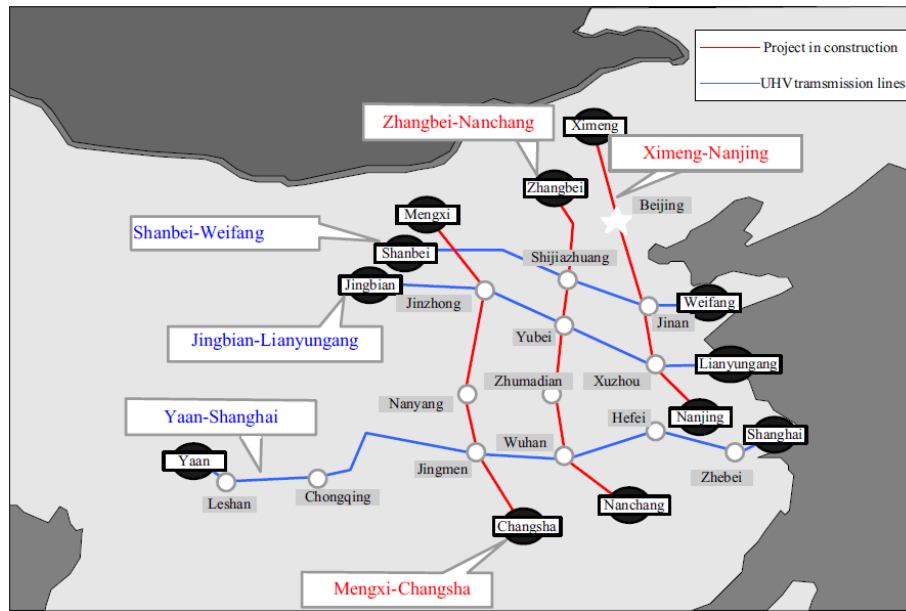


Figure 3.14 Planned and under-construction UHV lines in 2015 [3]

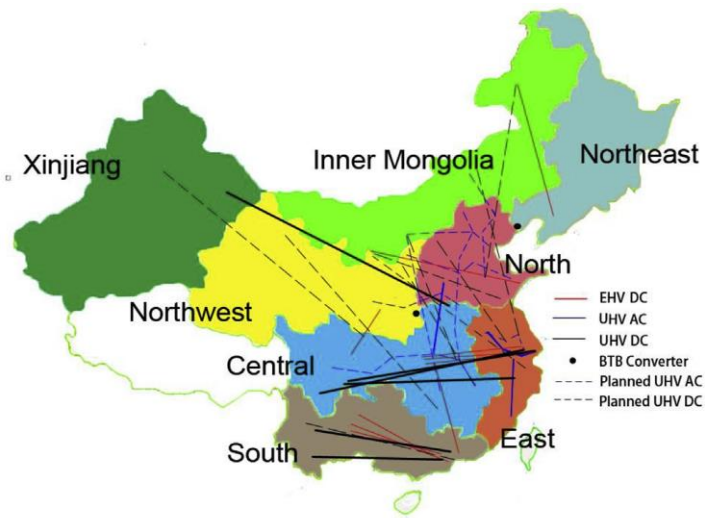


Figure 3.15 Planned and under-construction UHV lines by 2020 [51]

On November 11st, 2016, the National Energy Administration published the “13th Five-Year Plan for Electricity Development (2016-2020)”. China will start the pilot of electricity spot trading market by the end of 2018 and launch the electricity spot trading market in the whole country in 2020.

In order to fulfill its obligations under the Paris agreement with the goal of limiting the increase in global average temperature to well below 2 °C and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, China would need to cut carbon emissions by 60-65% per unit of GDP by 2030, compared with 2005 levels, and boost its use of non-fossil fuels so they account for 20% of its energy consumption, and peak its carbon emissions by 2030. In its 13th Five-Year Plan (2016-2020), China pledged to cut carbon dioxide emissions per unit of GDP by 18 percent over the next five years. China planned to build a nationwide Emissions Trading Scheme (ETS) mechanism in 2017. Obviously the ETS will have a vital effect on the electricity industry, especially in the case that the majority of China's generation capacity is coal-fired power plants. The interaction between the electricity market and emission trading market is complicated, especially when tradable permits is adopted, it may be possible for firms with relatively larger market shares to exercise market power in both electricity and permit market [12][13][14][15].

As can be seen from the above analysis, the future of the electricity market in China will be the combination of both bilateral market (mainly long term contract) and spot market with the implementation of ETS while the transmission and distribution network remains a regulated monopoly. However, the DPLU contracts are not surrounded by a thriving ecosystem of hedging instruments. Transmission Rights and other financial tools to deal with transmission constraints are not mentioned in No. 9 Document or 13th Five-Year Plan for Electricity Development. As a matter of fact, transmission constraints can be an important source of market power in electricity market. Thus, market mechanism concerning transmission constraints and transmission capacity allocation for the Chinese electricity market should be developed in the future.

## 4. Bilateral Electricity Market Modelling

### 4.1 Introduction

In the above section, electricity market development and electricity market models are analyzed in detail. Current situation of Chinese electricity market, on-going reform, future development are studied in depth. This chapter will focus on the modelling of bilateral electricity market. The development of an electricity market model for Chinese electricity industry is described in detail.

First practical behaviors and potential market power of both generation companies and retailers are analyzed briefly. Second, the mathematical models and formulas for both oligopolistic and oligopsonistic electricity markets developed by *Alikhanzadeh* (2011, 2012) by using CVE model are summarized. Interactions within and between generators and suppliers are analyzed in detail. More specifically, the Conjectural Variation (CV) is defined as the response of the rival companies to the change in strategy of target firm. The range of CV value for both generation companies and retailers are analyzed.

Since in the Chinese electricity market, the leading generation companies like Big Five are giant multi-technology companies. Thus it is important to understand the behaviors and strategies of these companies. Behaviors of generation companies with capacity of different technologies are further studied and developed in this model. Optimal strategy in capacity allocation will be drawn based on the simulation results in Chapter 5. Transmission constraints are integrated in the bilateral electricity market model to study the effects of transmission constraints and transmission capacity allocation on the market.

Finally market equilibrium under each situation is calculated. The Hierarchical Optimization Algorithm using Genetic Algorithm as the optimization technique is adopted in solving market equilibrium point. Iterations are conducted by updating the values of slope and intercept of demand and generation functions.

## **4.2 Oligopolistic Electricity Market Modeling**

This section focuses on the modelling of the generation side of bilateral electricity market. Theoretical analysis and mathematical formulations have been presented to study the market behaviors and output of generation companies in the oligopolistic market.

### **4.2.1 Generation Companies' Behaviors**

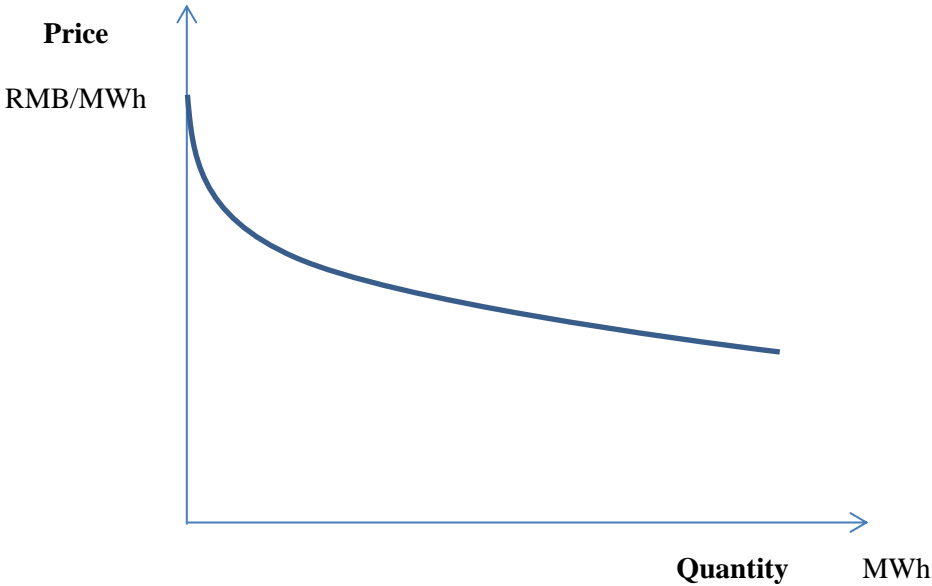
After the reform in 2002, generation companies in China are divided into grid-owned generation companies and Independent Power Producers (IPP). Due to the difference in company characteristics and the way of management, these two kinds of companies have different market behaviors.

Grid-owned generation company is the internal accounting unit of the grid company and directly accepts the grid company's administrative management, including personnel, financial, technological transformation and equipment updates. This vertical integration of the management model turns the power plant's objective to complete the grid company's generation task, especially the daily operation of the security objectives. Although the generation costs of grid-owned generation companies vary widely, the grid company's internal "cross subsidy" makes up for this difference. Obviously this will inevitably inhibit the initiative of low cost, high efficiency generation companies. However, the grid company's monopoly position enhances this inefficient, high-cost operating mechanism. Thus, the production efficiency is very low and the power plant lacks vitality. Meanwhile, the competitive IPPs cannot achieve symmetry information and equal negotiation power as grid-owned companies. All these resulted in bad survival environment of IPPs and hindered the formation of electricity market mechanism.

Independent power producers, at the beginning of construction, will negotiate with grid companies to reach an agreement on energy transaction price. With one price for one company, the price difference between different generation companies will be very large. As the unit profit of the independent power producers has been determined, for the pursuit of profit maximization, effort will be devoted to pursuing more output instead of reducing generation cost and speeding up technological innovation. Luckily only few generation companies now in

China are grid-owned. The majority of generation companies are independent power producers.

With the reform starting from 2015, in the bilateral electricity market, the behaviors and strategies of generation companies are deeply influenced by the quantity of electricity they are going to generate and the market price. Since electricity can't be stored in big quantities, the generation companies will try to satisfy the real-time energy demand in the electricity grid. That is to say the primary behaviors of generation companies are their response to the demand. Thus, the characteristics of the demand curve in the oligopolistic electricity market are very important. Normally, from the perspective of retailers, the quantity of electricity purchased by retailers normally increases with the decrease in the price and vice versa. This relationship is shown in the inverse demand curve as illustrated in Figure 4.1.



**Figure 4.1 Inverse demand curve**

As it can be seen from the demand curve, the demand of retailers decreases as the price increases, which is already discussed earlier. Besides, we can see the willingness of retailers to pay for extra amount of electricity. If the purchase amount of electricity is small, the retailers are willing to pay a high price for additional electricity. On the contrary, if the consumption of electricity is high, the marginal willingness to pay is low. This is the typical case of demand elastic. On the other hand, if the relative change in demand is smaller than the relative change

in price then the demand is inelastic to the price. Generally, the inverse demand curve in oligopolistic electricity market is inelastic. Therefore, inverse demand function plays an important role in oligopolistic electricity markets and generation companies' behaviors and strategies.

#### 4.2.2 Oligopolistic Electricity Market Modeling Using CVE Model

In the research of *Alikhanzadeh* (2011, 2012), CVE model has been developed to study the oligopolistic electricity market [9][10]. The model developed by *Alikhanzadeh* is summarized in this paragraph and will be adopted as the basic approach in modelling the behaviors of generation companies in the bilateral electricity market in this research. The main sets and parameters are listed below:

$n$ : Number of generation companies

$\pi_{ig}$ : Profit of generation company  $i$

$q_{ig}$ : Output of generation company  $i$

$q_{jg}$ : Output of generation company  $j$

$q_{ig\ min}$ : Lower limit of output of generation company  $i$

$q_{ig\ max}$ : Upper limit of output of generation company  $i$

$q_{-ig}$ : The total output of all the other generation companies except generation company  $i$

$p_d$ : Contract price of bilateral electricity market

$e_d$ : Intercept of inverse demand curve

$f_d$ : Slope of inverse demand curve

$C_{ig}(q_{ig})$ : Cost function of generation company  $i$

$a_i, b_i, c_i$ : Coefficient of cost function of generation company  $i$

$D(p)$ : Total demand function

$G_{-i}$ : Aggregation of productions of all generation companies except generation company  $i$ .



$MR_i(q_i)$ : Marginal revenue of generation company  $i$

$MC_i(q_i)$  : Marginal cost of generation company  $i$

$CV_{ijg}$ : Conjectural variation value of generation company  $i$  about the rival company  $j$ 's reaction to the change of its output

$CV_{ig}$ : Conjectural variation value of generation company  $i$  about all the rival companies' reaction to the change of its output

In oligopolistic electricity market, each generation company tries to maximize its profit as defined in the following equation:

$$\text{Max } \pi_{ig} = p_d q_{ig} - C_{ig}(q_{ig}) \quad (i = 1, \dots, n) \quad (4.1)$$

where  $p_d$  represents the price at which the generation company will sell electricity to the retailers at this price, which is given by the point at the inverse demand curve corresponding to the total sold quantity of electricity. As a matter of fact, in real bilateral electricity market, generation companies negotiate price with eligible customers directly through bilateral contracts. The price is different according to each contract and there is no uniform market clearing price. So it is not possible to obtain the inverse demand function based on historical data in the bilateral electricity market and use it for each generation company, as the price and amount of traded electricity in bilateral trading is not disclosed.

A lot of research uses residual demand function, as illustrated in Equation 4.2, to denote the demand information. However, due to the same reason of disclosure of information of bilateral contracts, it is hard to estimate the competitors' output and generation function, especially when most of the trade in bilateral electricity market is in the form of forward contracts.

The residual demand function for generation company  $i$  is:

$$RDC_i(p) = D(p) - G_{-i} \quad (i = 1, \dots, n) \quad (4.2)$$

Besides, in the case of oligopolistic electricity market, behaviors of generation companies, especially the internal reactions between generation companies, are the primary research focus. To simplify, the general demand function  $p_d$  is adopted. The interactions between generation

companies and retailers will be discussed later in this chapter. To maximize the profit, the optimal solution of Equation 4.1 for generation company  $i$  is:

$$\frac{\partial \pi_{ig}}{\partial q_{ig}} = 0 \quad (i = 1, 2, \dots, n) \quad (4.3)$$

And marginal revenue should equal to the marginal cost:

$$MR_i(q_i) = MC_i(q_i) \quad (i = 1, \dots, n) \quad (4.4)$$

And  $p_d$  is a function of  $q_{ig}$  ( $i = 1, 2, \dots, n$ ), and  $q_{jg}$  ( $i \neq j$ ) (the output of other generation companies except generation company  $i$ ) is an implicit function of  $q_{ig}$ , therefore the marginal revenue will be:

$$MR_i(q_i) = \frac{\partial(p_d q_{ig})}{\partial q_{ig}} = \left( \frac{\partial p_d}{\partial q_{ig}} + \frac{\partial p_d}{\partial q_{jg}} \frac{\partial q_{jg}}{\partial q_{ig}} \right) q_{ig} + p_d \quad (i \neq j) \quad (4.5)$$

Furthermore, the cost function of Generation companies can be defined as follow:

$$C_{ig}(q_{ig}) = a_i + b_i q_{ig} + \frac{1}{2} c_i q_{ig}^2 \quad (4.6)$$

Thus, the marginal cost will be:

$$MR_i(q_i) = \frac{\partial(p_d q_{ig})}{\partial q_{ig}} = b_i + c_i q_{ig} \quad (4.7)$$

Combine the above equations:

$$\left( \frac{\partial p_d}{\partial q_{ig}} + \frac{\partial p_d}{\partial q_{jg}} \frac{\partial q_{jg}}{\partial q_{ig}} \right) q_{ig} + p_d = b_i + c_i q_{ig} \quad (4.8)$$

Thus the Conjectural Variation (CV) for generation companies in oligopolistic electricity market can be defined as follow:

$$CV_{ijg} = \frac{\partial q_{jg}}{\partial q_{ig}} \quad (i, j = 1, 2, \dots, n) \quad (i \neq j) \quad (4.9)$$

The  $CV_{ijg}$  is the estimation of market participant about the rival companies' reactions to the changes of its output. It originates from the nature of generation companies to maximize its

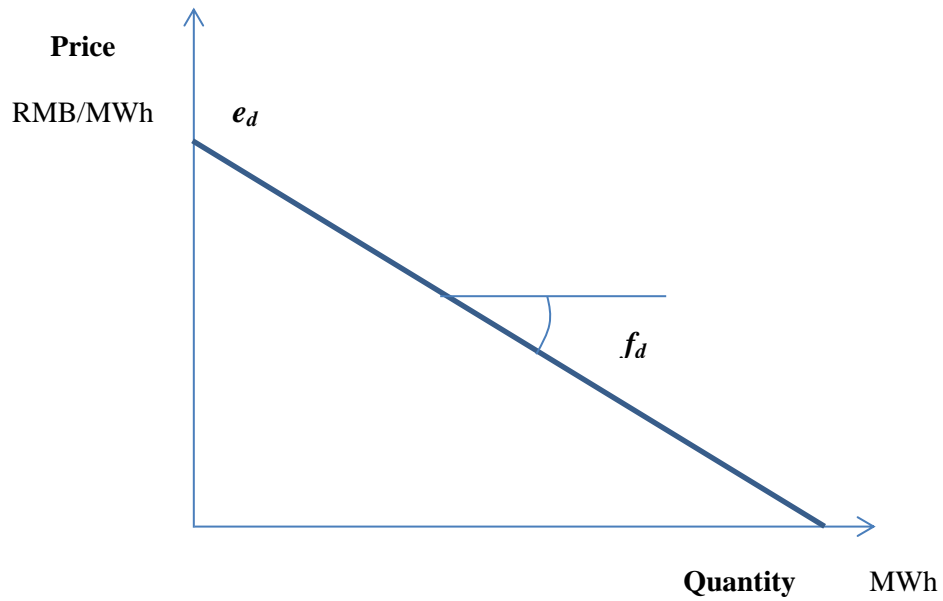
profit through strategic market behaviors. Different CV values represent different strategies of generation companies and will result in different market models.

Equation 4.8 can be transformed to:

$$\left( \frac{\partial p_d}{\partial q_{ig}} + \frac{\partial p_d}{\partial q_{jg}} CV_{ijg} \right) q_{ig} + p_d = MC_i(q_i) \quad (4.10)$$

The inverse demand function can be formulated as a linear curve to simplify the calculations:

$$p_d = e_d - f_d Q \quad (4.11)$$



**Figure 4.2 Linear demand curve**

Also, according to the market clearing conditions, the total generation  $Q$  and is equal to the total demand  $D$ .

$$Q = D = \sum_{i=1}^n q_{ig} \quad (4.12)$$

Assuming all generation companies are playing rationally in oligopolistic electricity market, Equation 4.1 will be transformed to:

$$\text{Max } \pi_{ig} = (e_d - f_d Q)q_{ig} - (a_i + b_i q_{ig} + 1/2 c_i q_{ig}^2) \quad (4.13)$$

Subject to the generation limit:  $q_{ig \min} \leq q_{ig} \leq q_{ig \max}$

In order to optimize the profit, the derivative of Equation 4.13 will be:

$$\frac{\partial \pi_{ig}}{\partial q_{ig}} = e_d - f_d \frac{\partial(Qq_{ig})}{\partial q_{ig}} - b_i - c_i q_{ig} = 0 \quad (4.14)$$

According to Equation 4.12, the above equation will be:

$$\begin{aligned} \frac{\partial \pi_{ig}}{\partial q_{ig}} &= e_d - f_d \frac{\partial q_{ig} \sum_{i=1}^n q_{ig}}{\partial q_{ig}} - b_i - c_i q_{ig} = 0 \\ &= e_d - 2f_d q_{ig} - f_d \sum_{\substack{j=1 \\ j \neq i}}^n q_{jg} - f_d q_{ig} \sum_{\substack{i=1 \\ i \neq j}}^n CV_{ijg} - b_i - c_i q_{ig} = 0 \end{aligned} \quad (4.15)$$

Thus, the output of each generation company in oligopolistic market taking into consideration other rivals' reactions can be derived as follows:

$$q_{ig} = \frac{e_d - f_d \sum_{\substack{j=1 \\ j \neq i}}^n q_{jg} - b_i}{f_d(2 + \sum_{\substack{j=i \\ j \neq i}}^n CV_{ijg}) + c_i} \quad (4.16)$$

As discussed earlier, the  $q_{jg}$  is the output of rival  $j$  in the bilateral electricity market. In order to simplify the above equation the aggregation of other competitors' output can be simplified as follow:

$$q_{-ig} = \sum_{\substack{j=1 \\ j \neq i}}^n q_{jg} = Q - q_{ig} \quad (4.17)$$

As can be seen from Equation 4.16, the sum of the production of the other generation companies and the corresponding conjecture values are needed to calculate the output of a specific company. However, as stated above, the information is hard to achieve in the bilateral electricity market. To simplify, all the rival companies are aggregated as one company. Thus, the new conjectural value can be defined as:

$$CV_{ig} = \sum_{\substack{j=1 \\ j \neq i}}^n CV_{ijg} \quad (4.18)$$

Therefore the amount of electricity produced by generation company  $i$  is:

$$q_{ig} = \frac{e_d - f_d q_{-ig} - b_i}{f_d(2 + CV_{ig}) + c_i} \quad (4.19)$$

Consequently, the output of generation company  $i$  will be a function of slope and intercept of inverse demand function, its own cost function's coefficients and its estimation about other rivals reactions in the market.

Despite the fact that the basic parameters of demand function and the strategies of rival companies are taken into consideration in the model of *Alikhanzadeh*, some other very important technical factors and constraints, such as generation capacity, generation resource and transmission capacity, are not taken into consideration. All these factors can have vital effect on the bilateral electricity market, influencing not only the contract quantity and price but also the market power in a more general way. Thus the CVE model for bilateral electricity market is further developed in this research with the inclusion of generation capacity, generation resource and transmission capacity.

### 4.2.3 Generation Companies with Capacity of Different Resources

In real electricity market, big generation companies usually produce electricity from different generation resources. This is typically the case of China, where the state owned Big Five have generation capacity of different resources, ranging from coal, hydro to renewable energy, due to their advantages in financial investment and policy priority. This gives the Big Five advantages not only in market share but also in technologies, which contributes to their strong market power in the bilateral electricity market. Therefore, it is important to understand the behaviors of multi-resource generation companies and their strategy in generation capacity allocation in the bilateral electricity market.

In this section, the CVE model of multi-resource generation companies is developed with the objective of profit maximization. The generation capacity limits of each resource are included.

The total output of company  $i$  is the sum of the output of each generation resource in this company. Therefore, in this model both equality and inequality constraints are included. To better solve this problem of profit optimization, lagrangian multipliers and KKT conditions are adopted. To simplify, the linear cost function is applied. The main sets and parameters are listed below:

$n$ : Number of generation companies

$v$ : Number of generation resources in generation company  $i$

$\pi_{ig}$ : Profit of generation company  $i$

$q_{ig}$ : Output of generation company  $i$

$q_{jg}$ : Output of generation company  $j$

$q_{igk}$ : Amount of electricity produced from resource  $k$  in generation company  $i$

$q_{igk}^{min}$ : Lower limit of generation from resource  $k$  in generation company  $i$

$q_{igk}^{max}$ : Upper limit of generation from resource  $k$  in generation company  $i$

$q_{-ig}$ : The total output of all the other generation companies except generation company  $i$

$b_{ik}$ : Cost of resource  $k$  in generation company  $i$

$\lambda_i, \underline{r}_{ik}, \overline{r}_{ik}$ : Lagrangian multipliers

$CV_{ijg}$ : Conjectural value of generation company  $i$  about the rival company  $j$ 's reaction to the change of its output

$CV_{ig}$ : Conjectural value of generation company  $i$  about all the rival companies' reaction to the change of its output

Given the relationships and variables defined above, with  $v$  generation resources in company  $i$ , its profit maximization problem is defined as follows:

$$\text{Max } \pi_{ig} = q_{ig} \cdot p_d - \sum_{k=1}^v b_{ik} q_{igk} \quad (i = 1, \dots, n, k = 1, \dots, v) \quad (4.20)$$

Subject to:

$$\text{Generation balance:} \quad q_{ig} = \sum_{k=1}^v q_{igk} \quad (k = 1, \dots, v) \quad (4.21)$$

$$\text{Generation limits:} \quad q_{igk}^{\min} \leq q_{igk} \leq q_{igk}^{\max} \quad (4.22)$$

Equivalently it is the minimum problem of the following equation:

$$\text{Min} \quad -\pi_{ig} = -q_{ig} \cdot p_d + \sum b_{ik} q_{igk} \quad (4.23)$$

The Lagrange function can be written as:

$$\begin{aligned} L( q_{ig}, q_{igk}, \lambda_i, \underline{r}_{ik}, \overline{r}_{ik} ) \\ = -q_{ig} \cdot p_d + \sum b_{ik} q_{igk} - \lambda_i \left( -q_{ig} + \sum q_{igk} \right) - \sum \underline{r}_{ik} (q_{igk} - q_{igk}^{\min}) \\ - \sum \overline{r}_{ik} (q_{igk}^{\max} - q_{igk}) \end{aligned} \quad (4.24)$$

Accordingly, the KKT optimality conditions are:

$$\frac{dL}{dq_{ig}} = \lambda_i - \frac{d(q_{ig} \cdot p_d)}{dq_{ig}} = 0 \quad (4.25)$$

$$\frac{dL}{dq_{igk}} = b_{ik} - \lambda_i - \underline{r}_{ik} + \overline{r}_{ik} = 0 \quad (4.26)$$

$$\frac{dL}{d\lambda} = q_{ig} - \sum q_{igk} = 0 \quad (4.27)$$

$$\frac{dL}{d\underline{r}_{ik}} = -q_{igk} + q_{igk}^{\min} \leq 0 \quad (4.28)$$

$$\frac{dL}{d\overline{r}_{ik}} = q_{igk} - q_{igk}^{\max} \leq 0 \quad (4.29)$$

And the complementary conditions are:

$$\underline{r}_{ik} (q_{igk} - q_{igk}^{\min}) = 0 \quad (4.30)$$

$$\overline{r}_{ik} (q_{igk}^{\max} - q_{igk}) = 0 \quad (4.31)$$

Subject to:

$$\lambda_i, \underline{r_{ik}}, \overline{r_{ik}} \geq 0 \quad (4.32)$$

Based on Equation 4.25 further derivation of the equation is expressed as below:

$$\begin{aligned} \frac{dL}{dq_{ig}} &= \lambda_i - \frac{d(q_{ig} \cdot p_d)}{dq_{ig}} = 0 \\ \lambda_i - \frac{d(q_{ig}(e_d - f_d Q))}{dq_{ig}} &= 0 \\ \lambda_i - \frac{d(q_{ig}(e_d - f_d \sum_{i=1}^n q_{ig}))}{dq_{ig}} &= 0 \\ \frac{\partial(q_{ig}(e_d - f_d q_{ig} - f_d \sum_{\substack{j=1 \\ j \neq i}}^n q_{jg}))}{\partial q_{ig}} - \lambda_i &= 0 \end{aligned} \quad (4.33)$$

$$e_d - f_d q_{ig} - f_d \sum_{\substack{j=1 \\ j \neq i}}^n q_{jg} + \left( -f_d - f_d \frac{\partial \sum_{\substack{j=1 \\ j \neq i}}^n q_{jg}}{\partial q_{ig}} \right) q_{ig} - \lambda_i = 0$$

$$e_d - 2f_d q_{ig} - f_d \sum_{\substack{j=1 \\ j \neq i}}^n q_{jg} - f_d q_{ig} \sum_{\substack{i=1 \\ i \neq j}}^n CV_{ijg} - \lambda_i = 0$$

$$e_d - f_d \sum_{\substack{j=1 \\ j \neq i}}^n q_{jg} - \lambda_i = f_d \left( 2 + \sum_{\substack{i=1 \\ i \neq j}}^n CV_{ijg} \right) q_{ig}$$

$$q_{ig} = \frac{e_d - f_d \sum_{\substack{j=1 \\ j \neq i}}^n q_{jg} - \lambda_i}{f_d \left( 2 + \sum_{\substack{i=1 \\ i \neq j}}^n CV_{ijg} \right)} \quad (4.34)$$

As in the case of generation company with single generation resource, information about the specific output and strategy of other competitors in bilateral electricity market is hard to



achieve. To simplify, both the outputs and conjecture variation values of the other companies are summed together respectively, as described in Equation 4.17, 4.18.

Thus, the output of generation company  $i$  is:

$$q_{ig} = \frac{e_d - f_d q_{-ig} - \lambda_i}{f_d(2 + CV_{ig})} \quad (4.35)$$

The output of generation company  $i$  is a function of slope and intercept of inverse demand function, its estimation about other rivals reactions in the market and multiplier  $\lambda_i$  instead of cost function's coefficients.  $\lambda_i$  is a function of cost coefficient  $b_{ik}$  and multipliers  $\underline{r_{ik}}$ ,  $\overline{r_{ik}}$ , as shown in Equation 4.26.

In the case of two generation companies:

$$q_{1g} = \frac{e_d - f_d q_{-1g} - \lambda_1}{f_d(2 + CV_{1g})}, \quad q_{2g} = \frac{e_d - f_d q_{-2g} - \lambda_2}{f_d(2 + CV_{2g})} \quad (4.36)$$

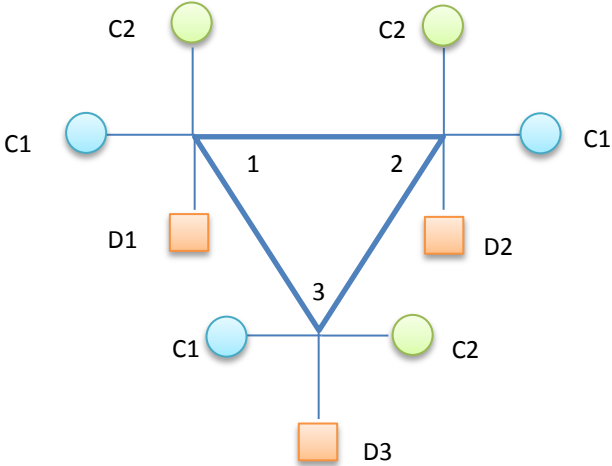
The complementary problems can be solved linearly in TOMLAB [53][54]. Besides, they can be implemented as nonlinear constraints in Genetic Algorithm (GA). In this research, both TOMLAB and GA are adopted to implement this model. Details of case study are presented in Chapter 5.

#### 4.2.4 Impact of Transmission Constraints on Generation Companies

As discussed in Chapter 2, due to the change of demand or contingency of equipment, transmission network can be congested. Besides, transmission constraints isolate consumers from effective reach of many generators. Therefore, transmission capacity is an important source of market power and the competitiveness of real electricity market can be restricted by the limits of transmission capacity. To see better the effect of transmission constraints on bilateral electricity market, the CVE model with integration of transmission constraints is developed in this section.

The primary objective of this model is still to maximize the profit of generation companies. The basic rules associated with physical and economic system properties are respected in the process of network access and transmission capacity allocation. More specifically, Kirchhoff's

law and rules of non-discriminatory, transparent and feasible methodologies are respected. Due to the fact that the present transmission capacity allocation in China is based on the uniform transmission price mechanism with the aim of investment recovery, the economic signal of scarcity of transmission capacity is not well indicated. Thus, the present policy of transmission capacity allocation is not perfectly market-based. To reveal the practical effect of the present policy, the fixed transmission price is adopted. To simplify the model, the transmission network is assumed as linearized DC system and linear cost function is adopted.



**Figure 4.3 Three nodes transmission network**

The model is developed for general case in which generation companies have branches at each node and generators at each node can sell electricity to all the nodes. A simple example is shown in Figure 4.3. There are two companies, company 1 (C1) and company 2 (C2). Each company has branches at all the three nodes and each node has demand (D1, D2 and D3). In this model both equality and inequality constraints are included. Thus, in the process of profit optimization, lagrangian multipliers and KKT conditions are adopted. Sets and parameters are listed as below:

- $n$ : Number of companies
- $m$ : Number of nodes
- $n_i$ : Number of transmission lines
- $\pi_{ig}$ : Profit of generation company  $i$

$\pi_{ci}^j$ : Profit that generation company  $i$  gains in node  $j$ .

$p_k$ : Electricity price at node  $k$

$q_{ci}^{j \rightarrow k}$ : Amount of electricity of generation company  $i$  sold to node  $k$  from node  $j$

$q_{ci}^{k \rightarrow k}$ : Amount of electricity of generation company  $i$  sold to node  $k$  from node  $k$

$q_{ci}^{j \rightarrow j}$ : Amount of electricity of generation company  $i$  sold to node  $j$  from node  $j$

$q_{ci}^j$ : Amount of electricity of generation company  $i$  produced on node  $j$

$q_{ci}^{jmin}, q_{ci}^{jmax}$ : Lower and upper generation limits of generation company  $i$  on node  $j$

$q_{cw}^{l \rightarrow k}$ : Amount of electricity of generation company  $w$  sold to node  $k$  from node  $l$

$q_{ci}^{-(j \rightarrow k)}$ : The total amount of electricity that all the other generators sold to node  $k$  except  $q_{ci}^{j \rightarrow k}$

$b_{ci}^j$ : Generation cost of generation company  $i$  at node  $j$

$t_{xy}$ : Transmission price on transmission line  $xy$

$T_{xy}$ : Power flow on transmission line  $xy$

$T_{xy}^{min}, T_{xy}^{max}$ : Lower and upper limits of transmission capacity

$PTDF_{xy}^j$ : Distribution factor of bilateral transaction on transmission line  $xy$  over injection in node  $j$

$CV_{ci}^{(l \rightarrow k) \rightarrow (j \rightarrow k)}$ : Conjectural variation value of branch  $j$  of generation company  $i$  about the reaction of any other amount of electricity sold to node  $k$  from node  $l$  over the change of the amount of electricity of generation company  $i$  sold to node  $k$  from node  $j$ .

$CV_{ci}^{j \rightarrow k}$ : Conjectural variation value of branch  $j$  of generation company  $i$  about the reaction of all the other amount of electricity sold to node  $k$  over the change of the amount of electricity of generation company  $i$  sold to node  $k$  from node  $j$ .

$\lambda_{ij}, \underline{r}_{ik}, \overline{r}_{ik}$ : Lagrangian multipliers

For company  $i$ , the profit it gains at node  $j$  is:

$$\pi_{ci}^j = \sum_{k=1}^m p_k \cdot q_{ci}^{j \rightarrow k} - \sum_{k=1}^m b_{ci}^j q_{ci}^{j \rightarrow k} - \sum_{xy=1}^{n_l} (|t_{xy} \cdot PTDF_{xy}^j| \cdot (q_{ci}^j - q_{ci}^{j \rightarrow j})) \quad (4.37)$$

where,  $q_{ci}^j - q_{ci}^{j \rightarrow j}$  is the power injection in bus  $j$  by branch  $j$  of company  $i$ .

For company  $i$ , the total profit it gains is:

$$\begin{aligned} \pi_{ci} &= \sum_{j=1}^m (\pi_{ci}^j) \\ &= \sum_{j=1}^m \sum_{k=1}^m p_k \cdot q_{ci}^{j \rightarrow k} \\ &\quad - \sum_{j=1}^m \sum_{k=1}^m b_{ci}^j q_{ci}^{j \rightarrow k} - \sum_{j=1}^m \sum_{xy=1}^{n_l} (|t_{xy} \cdot PTDF_{xy}^j| \cdot (q_{ci}^j - q_{ci}^{j \rightarrow j})) \end{aligned} \quad (4.38)$$

Subject to:

$$q_{ci}^j = \sum_{k=1}^m q_{ci}^{j \rightarrow k} \quad (4.39)$$

$$q_{ci}^{jmin} \leq q_{ci}^j \leq q_{ci}^{jmax} \quad (4.40)$$

Under market clearing conditions, total generation equals to total demand:

$$\sum_{i=1}^n q_{ci} = \sum_{j=1}^m D^j \quad (4.41)$$

And the power flow on line  $xy$  is limited by the transmission constraints:

$$T_{xy}^{min} \leq T_{xy} = \sum_{j=1}^m PTDF_{xy}^j ((\sum_{i=1}^n q_{ci}^j) - D^j) \leq T_{xy}^{max} \quad (4.42)$$

where,  $(\sum_{i=1}^n q_{ci}^j) - D^j$  is the real physical power injection in node  $j$ .

Alternatively, the maximization problem can be written as the minimization problem as below:

$$\begin{aligned}
Min - \pi_{ci} = & - \sum_{j=1}^m \sum_{k=1}^m p_k \cdot q_{ci}^{j \rightarrow k} \\
& + \sum_{j=1}^m \sum_{k=1}^m b_{ci}^j q_{ci}^{j \rightarrow k} + \sum_{j=1}^m \sum_{xy=1}^{n_l} (|t_{xy} \cdot PTDF_{xy}^j| \cdot (q_{ci}^j - q_{ci}^{j \rightarrow j}))
\end{aligned} \tag{4.43}$$

Therefore, the lagrangian function of generation company  $i$  is expressed as below:

$$\begin{aligned}
L(q_{ci}^{j \rightarrow k}, q_{ci}^{j \rightarrow j}, q_{ci}^j, \lambda_{ij}, \underline{r}_{ij}, \overline{r}_{ij}) \\
= & - \sum_{j=1}^m \sum_{k=1}^m p_k \cdot q_{ci}^{j \rightarrow k} \\
& + \sum_{j=1}^m \sum_{k=1}^m b_{ci}^j q_{ci}^{j \rightarrow k} + \sum_{j=1}^m \sum_{xy=1}^{n_l} (|t_{xy} \cdot PTDF_{xy}^j| \cdot (q_{ci}^j - q_{ci}^{j \rightarrow j})) - \sum_{j=1}^m \lambda_{ij} (q_{ci}^j \\
& - \sum_{k=1}^m q_{ci}^{j \rightarrow k}) - \sum_{j=1}^m \underline{r}_{ij} (q_{ci}^j - q_{ci}^{jmin}) - \sum_{j=1}^m \overline{r}_{ij} (q_{ci}^{jmax} - q_{ci}^j)
\end{aligned} \tag{4.44}$$

The KKT optimality conditions of generation company  $i$  are:

$$\frac{dL}{dq_{ci}^{j \rightarrow k}} = -p_k - \frac{\partial p_k}{\partial q_{ci}^{j \rightarrow k}} q_{ci}^{j \rightarrow k} + b_{ci}^j + \lambda_{ij} = 0 \quad (j \neq k, j = 1 \dots m, k = 1 \dots m) \tag{4.45}$$

$$\frac{dL}{dq_{ci}^{j \rightarrow k}} = \frac{dL}{dq_{ci}^{j \rightarrow j}} = -p_k - \frac{\partial p_k}{\partial q_{ci}^{j \rightarrow j}} q_{ci}^{j \rightarrow j} + b_{ci}^j - \sum_{xy=1}^{n_l} |t_{xy} \cdot PTDF_{xy}^j| + \lambda_{ij} = 0$$

$$(j = k, j = 1 \dots m) \tag{4.46}$$

$$\frac{dL}{dq_{ci}^j} = \sum_{xy=1}^{n_l} |t_{xy} \cdot PTDF_{xy}^j| - \lambda_{ij} - \underline{r}_{ij} + \overline{r}_{ij} = 0 \quad (j = 1 \dots m) \tag{4.47}$$

$$\frac{dL}{d\lambda_{ij}} = -q_{ci}^j + \sum_{k=1}^m q_{ci}^{j \rightarrow k} = 0 \tag{4.48}$$

$$\frac{dL}{d\underline{r}_{ij}} = -q_{ci}^j + q_{ci}^{jmin} \leq 0 \tag{4.49}$$

$$\frac{dL}{d\bar{r}_{ij}} = q_{ci}^j - q_{ci}^{jmax} \leq 0 \quad (4.50)$$

And the complementary conditions of generation company  $i$  are:

$$\underline{r}_{ij}(q_{ci}^j - q_{ci}^{jmin}) = 0 \quad (4.51)$$

$$\bar{r}_{ij}(q_{ci}^{jmax} - q_{ci}^j) = 0 \quad (4.52)$$

$$\text{Subject to: } \lambda_{ij}, \underline{r}_{ik}, \bar{r}_{ik} \geq 0 \quad (4.53)$$

The demand function is defined as below:

$$p_k = e_{dk} - f_{dk} \sum_{i=1}^n \sum_{j=1}^m q_{ci}^{j \rightarrow k} \quad (4.54)$$

Thus, Equation 4.45 can be expressed as follow:

$$\begin{aligned} \frac{dL}{dq_{ci}^{j \rightarrow k}} &= -p_k - \frac{\partial p_k}{\partial q_{ci}^{j \rightarrow k}} q_{ci}^{j \rightarrow k} + b_{ci}^j + \lambda_{ij} = 0 \quad (j \neq k, j = 1 \dots m, k = 1 \dots m) \\ &= - \left( e_{dk} - f_{dk} \sum_{i=1}^n \sum_{j=1}^m q_{ci}^{j \rightarrow k} \right) - \frac{\partial (e_{dk} - f_{dk} \sum_{i=1}^n \sum_{j=1}^m q_{ci}^{j \rightarrow k})}{\partial q_{ci}^{j \rightarrow k}} q_{ci}^{j \rightarrow k} + b_{ci}^j + \lambda_{ij} \\ &= -e_{dk} + f_{dk} \sum_{i=1}^n \sum_{j=1}^m q_{ci}^{j \rightarrow k} - \frac{\partial (e_{dk} - f_{dk} \sum_{i=1}^n \sum_{j=1}^m q_{ci}^{j \rightarrow k})}{\partial q_{ci}^{j \rightarrow k}} q_{ci}^{j \rightarrow k} + b_{ci}^j + \lambda_{ij} \end{aligned} \quad (4.55)$$

Similar to Equation 4.17, 4.18, the aggregated output and conjecture variable value of rival companies are defined as:

$$q_{ci}^{-(j \rightarrow k)} = \sum_{w=1}^n \sum_{\substack{l=1 \\ l \neq j}}^m q_{cw}^{l \rightarrow k} = Q - q_{ci}^{j \rightarrow k} \quad (4.56)$$

$$CV_{ci}^{j \rightarrow k} = \sum_{i=1}^n \sum_{\substack{l=1 \\ l \neq j}}^m CV_{ci}^{(l \rightarrow k) \rightarrow (j \rightarrow k)} \quad (4.57)$$

Hence, Equation 4.55 can be expressed as below:

$$\begin{aligned}
\frac{dL}{dq_{ci}^{j \rightarrow k}} &= -e_{dk} + f_{dk} (q_{ci}^{j \rightarrow k} + q_{ci}^{-(j \rightarrow k)}) + \frac{\partial (f_{dk} (q_{ci}^{j \rightarrow k} + q_{ci}^{-(j \rightarrow k)}))}{\partial q_{ci}^{j \rightarrow k}} q_{ci}^{j \rightarrow k} + b_{ci}^j + \lambda_{ij} \\
&= -e_{dk} + f_{dk} (q_{ci}^{j \rightarrow k} + q_{ci}^{-(j \rightarrow k)}) + f_{dk} q_{ci}^{j \rightarrow k} + \frac{f_{dk} \partial q_{ci}^{-(j \rightarrow k)}}{\partial q_{ci}^{j \rightarrow k}} q_{ci}^{j \rightarrow k} + b_{ci}^j + \lambda_{ij} \\
&= -e_{dk} + 2f_{dk} q_{ci}^{j \rightarrow k} + f_{dk} q_{ci}^{-(j \rightarrow k)} + \frac{f_{dk} \partial q_{ci}^{-(j \rightarrow k)}}{\partial q_{ci}^{j \rightarrow k}} q_{ci}^{j \rightarrow k} + b_{ci}^j + \lambda_{ij} \\
&= -e_{dk} + 2f_{dk} q_{ci}^{j \rightarrow k} + f_{dk} q_{ci}^{-(j \rightarrow k)} + f_{dk} CV_{ci}^{j \rightarrow k} q_{ci}^{j \rightarrow k} + b_{ci}^j + \lambda_{ij} = 0
\end{aligned}$$

Hence, the amount of electricity of generation company  $i$  sold to node  $k$  from node  $j$  is defined:

$$q_{ci}^{j \rightarrow k} = \frac{e_{dk} - f_{dk} q_{ci}^{-(j \rightarrow k)} - b_{ci}^j - \lambda_{ij}}{f_{dk}(2 + CV_{ci}^{j \rightarrow k})} \quad (4.58)$$

The amount of electricity of generation company  $i$  sold to node  $k$  from node  $j$  will be a function of slope and intercept of inverse demand function, cost function, its estimation about other rivals reactions in the market and lagrangian multiplier  $\lambda_{ij}$ .

Similarly according to equation 4.46:

$$\frac{dL}{dq_{ci}^{j \rightarrow k}} = \frac{dL}{dq_{ci}^{j \rightarrow j}} = \frac{dL}{dq_{ci}^{k \rightarrow k}} = -p_k - \frac{\partial p_k}{\partial q_{ci}^{k \rightarrow k}} q_{ci}^{k \rightarrow k} + b_{ci}^k - \sum_{xy=1}^{n_l} |t_{xy} \cdot PTDF_{xy}^k| + \lambda_{ik} = 0$$

( $j = k, j = 1 \dots m$ )

$$\begin{aligned}
&= - \left( e_{dk} - f_{dk} \sum_{i=1}^n \sum_{j=1}^m q_{ci}^{j \rightarrow k} \right) - \frac{\partial (e_{dk} - f_{dk} \sum_{i=1}^n \sum_{j=1}^m q_{ci}^{j \rightarrow k})}{\partial q_{ci}^{k \rightarrow k}} q_{ci}^{k \rightarrow k} + b_{ci}^k + \lambda_{ik} \\
&\quad - \sum_{xy=1}^{n_l} |t_{xy} \cdot PTDF_{xy}^k|
\end{aligned}$$

$$\begin{aligned}
\frac{dL}{dq_{ci}^{j \rightarrow k}} &= -e_{dk} + f_{dk} \sum_{i=1}^n \sum_{j=1}^m q_{ci}^{j \rightarrow k} - \frac{\partial(e_{dk} - f_{dk} \sum_{i=1}^n \sum_{j=1}^m q_{ci}^{j \rightarrow k})}{\partial q_{ci}^{k \rightarrow k}} q_{ci}^{k \rightarrow k} + b_{ci}^k + \lambda_{ik} \\
&\quad - \sum_{xy=1}^{n_l} |t_{xy} \cdot PTDF_{xy}^k| \quad (j = k, j = 1 \dots m) \\
&= -e_{dk} + f_{dk} (q_{ci}^{k \rightarrow k} + q_{ci}^{-(k \rightarrow k)}) + \frac{\partial(f_{dk} (q_{ci}^{k \rightarrow k} + q_{ci}^{-(k \rightarrow k)}))}{\partial q_{ci}^{k \rightarrow k}} q_{ci}^{k \rightarrow k} + b_{ci}^k + \lambda_{ik} \\
&\quad - \sum_{xy=1}^{n_l} |t_{xy} \cdot PTDF_{xy}^k| \\
&= -e_{dk} + f_{dk} (q_{ci}^{k \rightarrow k} + q_{ci}^{-(k \rightarrow k)}) + f_{dk} q_{ci}^{k \rightarrow k} + \frac{f_{dk} \partial q_{ci}^{-(k \rightarrow k)}}{\partial q_{ci}^{k \rightarrow k}} q_{ci}^{k \rightarrow k} + b_{ci}^k + \lambda_{ik} \\
&\quad - \sum_{xy=1}^{n_l} |t_{xy} \cdot PTDF_{xy}^k| \\
&= -e_{dk} + 2f_{dk} q_{ci}^{k \rightarrow k} + f_{dk} q_{ci}^{-(k \rightarrow k)} + \frac{f_{dk} \partial q_{ci}^{-(k \rightarrow k)}}{\partial q_{ci}^{k \rightarrow k}} q_{ci}^{k \rightarrow k} + b_{ci}^k + \lambda_{ik} - \sum_{xy=1}^{n_l} |t_{xy} \cdot PTDF_{xy}^k| \\
&= -e_{dk} + 2f_{dk} q_{ci}^{k \rightarrow k} + f_{dk} q_{ci}^{-(k \rightarrow k)} + f_{dk} CV_{ci}^{k \rightarrow k} q_{ci}^{k \rightarrow k} + b_{ci}^k + \lambda_{ik} - \sum_{xy=1}^{n_l} |t_{xy} \cdot PTDF_{xy}^k| = 0
\end{aligned}$$

Therefore, the amount of electricity of generation company  $i$  sold to node  $k$  from node  $k$  is defined:

$$q_{ci}^{k \rightarrow k} = \frac{e_{dk} - f_{dk} q_{ci}^{-(k \rightarrow k)} - b_{ci}^k - \lambda_{ik} + \sum_{xy=1}^{n_l} |t_{xy} \cdot PTDF_{xy}^k|}{f_{dk} (2 + CV_{ci}^{k \rightarrow k})} \quad (4.59)$$

The amount of electricity of generation company  $i$  sold to node  $k$  from node  $k$  is a function of slope and intercept of inverse demand function, cost function, its estimation about other rivals reactions in the market, lagrangian multiplier  $\lambda_{ik}$  and the sum of transmission cost over the injection in node  $k$ . Further case study of this model will be conducted in Chapter 5.



Instructions on scarce transmission capacity allocation will be given to avoid congestion in an efficient manner.

### **4.3 Oligopsonistic Electricity Market Modeling**

This section focuses on the modelling of retailers of bilateral electricity market. Theoretical analysis and mathematical formulations have been presented to study the market behaviors and output of retailers in the oligopsonistic electricity market.

In the past a lot of research has been focusing on generation companies. Little attention has been paid to the retailers in the electricity market. However, the retailers play a significant role in the electricity market, such is the case in China, where the two giant transmission companies with the integration of transmission, distribution and retail functions, dominate the electricity market as single buyer. A lot of the problems of Chinese electricity market are caused by the single dominant buyer and this is the key reason in this round of power industry reform to introduce competition in retail market.

Bilateral market is a double-sided market, where both generation companies and retailers have permission and willingness to participate in the market; the retailers can have an active role in the market and try to maximize their profits alongside the generation companies. Thus, in this research the oligopsonistic market with a small number of Retailers dominating the whole market is also investigated in detail.

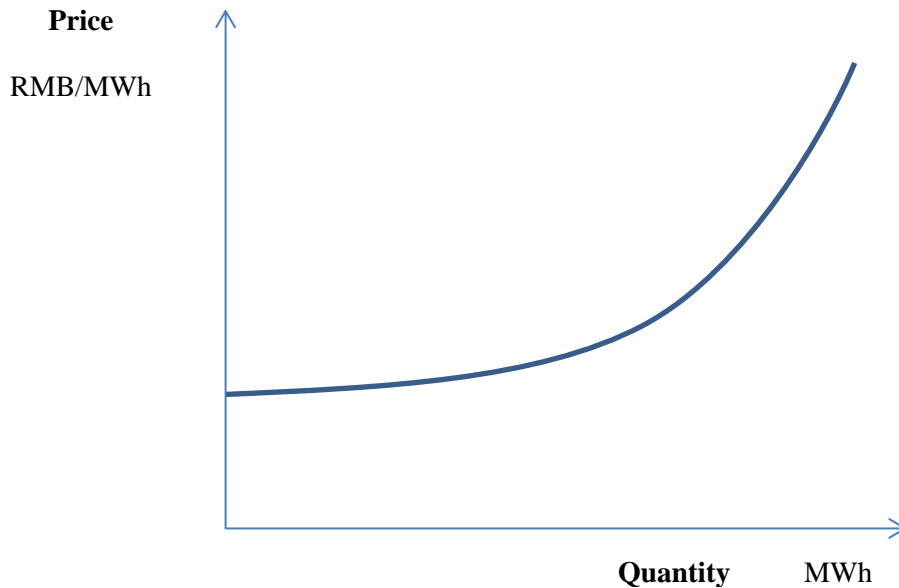
#### **4.3.1 Retailers' Behaviors**

From 2002 to 2015, the Chinese electricity market is a single buyer market. The transmission grid is the single buyer and single retailer. Most of the generation companies sell electricity to the grid company at on-grid price which is decided by the NDRC. While in some piloting provinces, there is competitive bidding for the generation companies. However, the transmission grid is strictly regulated by the government. The grid company can choose to buy different quantity of electricity from different generation companies at different prices, while power plants have no choice but to sell to the single grid company. One side is the competition to sell; the other side is the monopoly to purchase, resulting in electricity oversupply, bidding price going down all the way, while the retail price for end-users increase in the opposite way.

The power grid company is in monopoly operation, in fact, is a monopoly of the electricity market.

With the introduction of competition to the retail market, more retailers will be established, and the transaction quantity and price can be negotiated with the generation companies through bilateral contracts, which brings liquidity and liberalization to the supply side of the bilateral electricity market. However, due to the entry barrier and high quality requirement, the potential number will be relatively small. Retailers can play active roles in the bilateral electricity market. In such an oligopsonistic market the Retailers can dominate the bilateral market. They can put one Generation company against another Generation company so they can lower their costs. They can also push the market towards their preferable quantity and price and transfer some sources of risks like demand variation, overproduction, to the generation side [9][10]. All these can be enhanced especially when the generation capacity exceeds the demand, which is exactly the situation of Chinese electricity market. The future Chinese electricity market will be a typical buyers' market.

The primary objective of the retailer is to maximize its profit in the bilateral trading. In the bilateral electricity market, the behaviors and strategies of retailers are mainly affected by the electricity price and quantity of bilateral contract, which are the main factors of the generation function. According to the inverse generation curve, the quantity of electricity production will go up with the price. This is mainly because with the generation output going up, the cost will decrease as a result of economy of scale. The gap between price and cost will be larger, which guarantees the profit of generation companies.



**Figure 4.4 Inverse generation curve**

### **4.3.2 Oligopsonistic Electricity Market Modeling Using CVE Model**

To fully present the characteristics of bilateral electricity market, where both generation companies and retailers have certain market power in negotiating the bilateral contracts, modelling of the strategic behaviors of retailers to maximize their profit is needed. In the research of *Alikhanzadeh* (2011, 2012), oligopsonistic electricity market model with the application of CVE model has been developed to maximize the profit of retailers [9][10]. In this research we adopt the model developed by *Alikhanzadeh* to study the behaviors of retailers in the bilateral electricity market in China. The model is summarized in this section. The main sets and parameters are:

M: Number of retailers

$\pi_{id}$ : Retailer  $i$ 's profit

$P_r$ : Retail price of electricity

$q'_{id}$ : Amount of electricity sold to the end-users by retailer  $i$

$q_{id}$ : Purchased value of retailer  $i$

$q_{jd}$ : Purchased value of the retailer  $j$

$q_{-id}$ : The total purchased value of all the other retailers except retailer  $i$

$f_{ci}$ : Fixed cost of retailer  $i$

$p_g$ : Price at which retailer  $i$  buys electricity from generation companies

$e_g$ : Intercept of inverse generation curve

$f_g$ : Slope of inverse generation curve

$CV_{ijd}$ : Conjectural variation value of retailer  $i$  about the rival company  $j$ 's reaction to the change of its purchased value of electricity

$CV_{id}$ : Conjectural variation value of retailer  $i$  about all the rival companies' reaction to the change of its purchased value of electricity

To carry out the modeling of oligopsonistic electricity market, three assumptions have been made:

First, all the electricity purchased by a retailer from generation companies has been sold to the end-users, that is to say no energy holding is permitted in this model, which prevents participants from abusing the market.

$$q'_{id} = q_{id} \quad (4.60)$$

Second, the retail price  $P_r$  is assumed to be fixed for all the retailers in the case of oligopsonistic market. In the case study of market equilibrium, different retail price for different company will be adopted.

At last, the retailers' fixed costs,  $f_{ci}$ , have been assumed not to be a function of quantity in order to simplify the calculations. The fixed cost includes cost of physical assets, cost of renting the location, cost of human resources and other overhead costs. All the above costs are not in direct relation with quantity of purchased or sold electricity.

Hence, retailer  $i$ 's profit maximization problem can be defined as follow:

$$\text{Max } \pi_{id} = P_r q'_{id} - p_g q_{id} - f_{ci} \quad (i = 1, \dots, M) \quad (4.61)$$

where  $p_g$  is an initial inverse generation function and represents the price with which the retailer buys electricity from generation company. Similar to the situation in oligopolistic

market, due to the features of bilateral electricity market, it is not possible to obtain the inverse generation function for each company based on historical data, as the price and amount of traded electricity in bilateral trading is not disclosed. The same problem happens with the use of residual generation function to denote the generation information, it is hard to estimate the competitors' demand and demand function, especially when most of the trade in bilateral electricity market is in the form of forward contracts.

To simplify, the general generation function  $p_g$  is adopted. This is very practical in the study of the generation companies and the internal reactions between generation companies. While in the case of market equilibrium, since genetic algorithm is used, the intercept and slope of generation function will be updated step by step to obtain an accurate and realistic shape of generation curve and will result in calculating the purchased electricity of each retailer in the bilateral electricity market.

Hence, to maximize the profit:

$$\text{Max } \pi_{id} = P_r q_{id} - p_g q_{id} - f_{ci} = (P_r - p_g) q_{id} - f_{ci} \quad (i = 1, \dots, M) \quad (4.62)$$

Like  $p_d$  in the case of oligopolistic market, the inverse generation function  $p_g$  can be formulated as a linear curve to simplify the calculations:

$$p_g = e_g + f_g Q \quad (4.63)$$

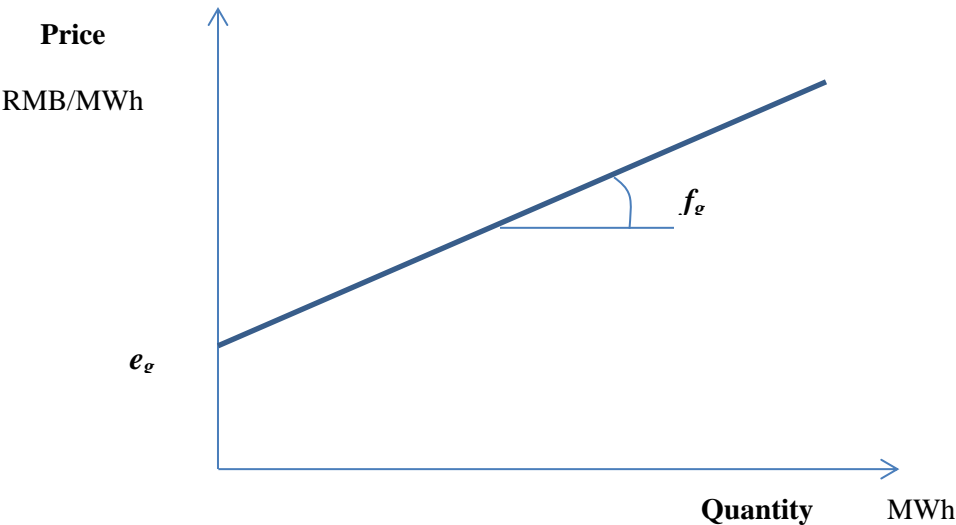


Figure 4.5 Linear generation curve

Thus, the profit of retailer in the oligopsonistic market is:

$$\text{Max } \pi_{id} = (P_r - e_g - f_g Q)q_{id} - f_{ci} \quad (4.64)$$

According to the market equilibrium condition, the total generation should match the total demand, hence:

$$D = Q = \sum_{i=1}^M q_{id} \quad (4.65)$$

In order to maximize the retailer's profit

$$\frac{\partial \pi_{id}}{\partial q_{id}} = 0 \quad (i = 1, 2, \dots, M) \quad (4.66)$$

Therefore, the optimized solution will be:

$$\frac{\partial \pi_{id}}{\partial q_{id}} = \frac{\partial (P_r q_{id})}{\partial q_{id}} - \frac{\partial (e_g q_{id})}{\partial q_{id}} - \frac{\partial (f_g q_{id} \sum_{i=1}^M q_{id})}{\partial q_{id}} = 0 \quad (4.67)$$

To simplify the above equation:

$$\frac{\partial \pi_{id}}{\partial q_{id}} = P_r - e_g - f_g (2q_{id} + \sum_{\substack{j=1 \\ j \neq i}}^M q_{jd} + q_{id} \sum_{\substack{j=1 \\ j \neq i}}^M \frac{\partial q_{jd}}{\partial q_{id}}) = 0 \quad (4.68)$$

The Conjectural Variation (CV) for retailers in oligopsonistic market can be identified as follow:

$$CV_{ijd} = \frac{\partial q_{jd}}{\partial q_{id}} \quad (i, j = 1, 2, \dots, M)(i \neq j) \quad (4.69)$$

The  $CV_{ijd}$  is the estimation from retailer  $i$  about the response of its rival, retailer  $j$  to the changes in its strategies. More precisely, the CV value is defined as the change of purchasing quantity of retailer  $j$  over the change of purchasing quantity of retailer  $i$ . Different CV values represent different strategies of retailers and will result in different market models.

Thus, by substituting Equation 4.69 into 4.68:

$$\frac{\partial \pi_{id}}{\partial q_{id}} = P_r - e_g - f_g(2q_{id} + \sum_{\substack{j=1 \\ j \neq i}}^M q_{jd} + q_{id} \sum_{\substack{j=1 \\ j \neq i}}^M CV_{ijd}) = 0 \quad (4.70)$$

Hence, the above equation can be transformed into:

$$q_{id} = \frac{P_r - e_g - f_g \sum_{\substack{j=1 \\ j \neq i}}^M q_{jd}}{f_g(2 + \sum_{\substack{j=1 \\ j \neq i}}^M CV_{ijd})} \quad (4.71)$$

It is very hard to estimate the purchased value by other companies and their specific CV value.

To simplify, the total value of electricity of other rival companies is aggregated as bellow:

$$q_{-id} = \sum_{\substack{j=1 \\ j \neq i}}^M q_{jd} \quad (4.72)$$

Similarly, the summed value of  $CV_{ijd}$  can be introduced as:

$$CV_{id} = \sum_{\substack{j=1 \\ j \neq i}}^M CV_{ijd} \quad (4.73)$$

Therefore, the purchased value of each retailer considering the reactions of other rivals can be calculated as:

$$q_{id} = \frac{P_r - e_g - f_g q_{-id}}{f_g(2 + CV_{id})} \quad (4.74)$$

It can be seen from the above equation, the purchased value by a retailer depends on the inverse generation function, retail price and the reactions of the rivals. Therefore, the preferred purchased value by each Retailer, considering their rivals' behaviors, has been identified.

#### 4.4 Analysis of Conjectural Variations in Bilateral Electricity Markets

The key improvement of CVE model is to conjecture the rivals' strategies and reactions, as response to the change of output. This section will focus on the study of conjectural variations and the specifications of CVs in both oligopolistic and oligopsonistic electricity market. The

basic idea behind the CVE method for both oligopolistic and oligopsonistic bilateral electricity markets is to examine, if one firm changes its output or purchased electricity value, how much it should expect others to increase or decrease their quantities in response to the change. The basic concepts and value range of CV has been discussed by *Alikhanzadeh* (2011, 2012) in his research [9][10]. In this research, the ideas of *Alikhanzadeh* are briefly summarized and important factors that affect CV value are further described.

#### 4.4.1 Generation Companies' Conjectural Variations Boundaries

According to Equation 4.19, the conjectural variation value of generation company  $i$  can be formulated as below:

$$\begin{aligned}
 CV_{ig} &= \frac{e_d - f_d q_{-ig} - b_i - 2f_d q_{ig} - c_i q_{ig}}{f_d q_{ig}} = \frac{e_d - f_d Q + f_d q_{ig} - b_i - 2f_d q_{ig} - c_i q_{ig}}{f_d q_{ig}} \\
 &= \frac{e_d - f_d Q - f_d q_{ig} - (b_i + c_i q_{ig})}{f_d q_{ig}} = \frac{e_d - f_d Q - (b_i + c_i q_{ig})}{f_d q_{ig}} - 1 \\
 &= \frac{p_d - MC_{ig}}{f_d q_{ig}} - 1
 \end{aligned} \tag{4.75}$$

As indicated in Equation 4.75, with the assumption of uniform demand function  $p_d$ , the conjecture value for generation company  $i$  is only a function of the quantity and cost function of generation company  $i$ . Thus, cost functions of competitive companies are needed.

In the case of perfect competition, the marginal revenue equals to the marginal cost, as indicated in Equation 4.4, the wholesale price and marginal costs are equal. Thus, the value of  $CV_{ig}$  for the perfect competition is:

$$CV_{ig} = \frac{p_d - MC_{ig}}{f_d q_{ig}} - 1 = -1 \tag{4.76}$$

In the case of oligopolistic electricity market, it is not perfect competition, generation companies will try to sell at a wholesale price higher than the marginal cost.

$$p_d \geq MC_{ig} \tag{4.77}$$



Therefore, the value of  $CV_{ig}$ , is equal or bigger than -1. The upper limit is set to 0 to represent the case where generation companies have no reaction to other companies' output. Hence:

$$-1 \leq CV_{ig} \leq 0 \quad (4.78)$$

As long as the value is close to its lower limit, the competition is close to the perfect environment, since as one generation company or retailer decreases the quantity, the others will act aggressively and step in the market and fill in the gap caused by that reduction in the quantity.

Several factors will affect the reaction of generation companies to their rivals' output, mainly the specific technology they are using for power production. For instance coal fired and natural gas fired power plants are more feasible in changing output, while nuclear power plants almost always run at fixed power rate and renewable power plants are affected by the intermittency due to variable available time each day. Demand elasticity is also very important in the fact that if the demand is inelastic, the energy produced by the generation companies will be always consumed by customers, which makes the increase of output less risky, otherwise the generation companies have to bear the risk of generation loss. Other characteristics, like ramp rate, start up, shut down time, transmission constraints and whether they deliver base load or they only follow the peak load also restrict the reaction of generation companies.

#### 4.4.2 Retailers' Conjectural Variations Boundaries

Based on Equation 4.74, the conjectural variation value of retailer can be formulated as below:

$$\begin{aligned} CV_{id} &= \frac{P_r - e_g - f_g q_{-id} - 2f_g q_{id}}{f_g q_{id}} = \frac{P_r - e_g - f_g(Q - q_{id}) - 2f_g q_{id}}{f_g q_{id}} \\ &= \frac{P_r - e_g - f_g Q + f_g q_{id} - 2f_g q_{id}}{f_g q_{id}} = \frac{P_r - e_g - f_g Q - f_g q_{id}}{f_g q_{id}} \\ &= \frac{P_r - p_g}{f_g q_{id}} - 1 \end{aligned} \quad (4.79)$$

Similar to the case of oligopolistic electricity market, assuming uniform generation function  $p_g$ , the  $CV_{id}$  value for retailers in oligopsonistic electricity market is only dependent on the retail

price and the purchased quantity from the wholesale market. Likewise, the value of  $CV_{id}$  in perfect electricity market, is -1. Normally in the case of imperfect competition, the retail price is higher than the wholesale market price, which guarantees the profit of retailers. The upper limit is set to 0 to represent the case where retailers have no reaction to other companies' output. Hence:

$$P_r \geq p_g \quad (4.80)$$

$$CV_{id} \geq -1 \quad (4.81)$$

$$-1 \leq CV_{id} \leq 0 \quad (4.82)$$

Similarly, when the CV value is close to -1, the competition is moving towards perfect competition. Compared with generation companies, the retailers are facing the end-users, which means that the demand required by retailers will have less volatility, because this is directly influenced by the load demand of end-users and retailers have to match the quantity of energy they buy from generation companies to the demand of end-users. The main factors that will affect the reaction of retailers to their rivals' output are: retail price and demand elasticity of end-users.

#### **4.5 Market Equilibrium Modelling**

In the research of market equilibrium, the most basic rules of market clearing conditions should be satisfied. Since electricity cannot be stored in big quantity, the amount of electricity produced by generation companies should be equal to the demand of retailers and the selling price should be the same as the buying price, as indicated in Figure 4.6. Thus, the first step is to seek the output of generation companies in the bilateral electricity market.

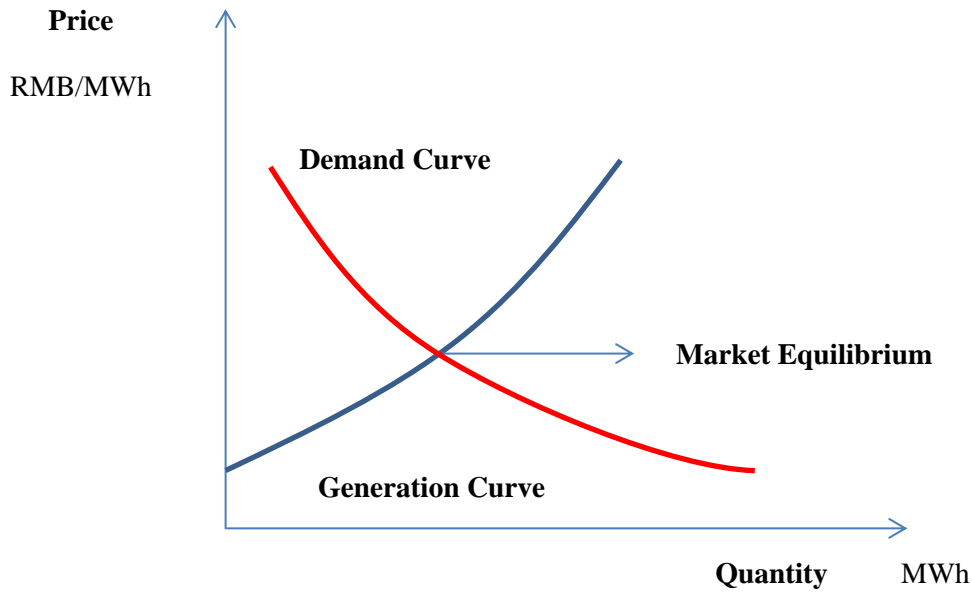


Figure 4.6 Market equilibrium

#### 4.5.1 Market Equilibrium Modelling with CVE model

In the research of *Alikhanzadeh* (2011, 2012), a framework in which the final equilibrium point of the bilateral electricity market represents the strategies of all market participants on both sides of the market is constructed [9][10]. To build the platform for both sides of the bilateral electricity market, the equations of output of generation companies and purchased value of retailers are expressed in matrix form. By transforming Equation 4.16, the following equation is achieved:

$$q_{ig} \times (f_d(2 + CV_{ig}) + c_i) = e_d - f_d q_{-ig} - b_i \rightarrow$$

$$2q_{ig}f_d + q_{ig}f_dCV_{ig} + c_iq_{ig} + f_dq_{-ig} = e_d - b_i \quad (i = 1, \dots, n) \quad (4.83)$$

The production of each generation company is expressed in the form of matrix. It gives a better view of the output of generation company and the relation with generation companies' strategies, slope and intercept of the inverse demand curve.

$$\begin{bmatrix} f_d(2 + CV_{1g}) + C_1 & f_d & f_d & \dots & f_d \\ f_d & f_d(2 + CV_{2g}) + C_2 & f_d & \dots & f_d \\ f_d & f_d & f_d(2 + CV_{3g}) + C_3 & \dots & f_d \\ \vdots & \vdots & \vdots & \dots & \vdots \\ f_d & f_d & f_d & \dots & f_d(2 + CV_{ng}) + C_n \end{bmatrix} \times \begin{bmatrix} q_{1g} \\ q_{2g} \\ q_{3g} \\ \vdots \\ q_{ng} \end{bmatrix} \\
= \begin{bmatrix} e_d - b_1 \\ e_d - b_2 \\ e_d - b_3 \\ \vdots \\ e_d - b_n \end{bmatrix} \quad (4.84)$$

Likewise, the purchased value by retailers is transformed into a matrix format as well:

$$q_{id} \times f_g(2 + CV_{id}) = P_r - e_g - f_g q_{-id} \rightarrow \\
2q_{id}f_g + q_{id}f_g CV_{id} + f_d q_{-id} = P_r - e_g \quad (i = 1, \dots, M) \quad (4.85)$$

The matrix format gives a better view of the purchased value of retailers with relation to retailers' strategies and intercept of the inverse generation curve.

$$\begin{bmatrix} f_g(2 + CV_{1d}) & f_g & f_g & \dots & f_g \\ f_g & f_g(2 + CV_{2d}) & f_g & \dots & f_g \\ f_g & f_g & f_g(2 + CV_{3d}) & \dots & f_g \\ \vdots & \vdots & \vdots & \dots & \vdots \\ f_g & f_g & f_g & \dots & f_g(2 + CV_{Md}) \end{bmatrix} \times \begin{bmatrix} q_{1d} \\ q_{2d} \\ q_{3d} \\ \vdots \\ q_{Md} \end{bmatrix} = \begin{bmatrix} P_{r1} - e_g \\ P_{r2} - e_g \\ P_{r3} - e_g \\ \vdots \\ P_{rM} - e_g \end{bmatrix} \quad (4.86)$$

Matching the two matrixes of Equations 4.84 and 4.86 together, a virtual pool structure is formed. The output of each generation company and purchased value by each retailer can be calculated through this co-ordination algorithm. The algorithm tries to maximize the profits of both generation companies and retailers while matching the total quantity and price in both oligopoly and oligopsony matrices. This is achieved by changing the slopes and intercepts, which are variables in both left and right sides of these matrices.

Equation 4.84 can be simplified as below:

$$[B_G] = [A_G]^{-1}[C_G] \quad [B_G] \text{ is the matrix of output } q_{ig} \quad (4.87)$$

Equation 4.86 can be simplified as below:

$$[B_D] = [A_D]^{-1}[C_D] \quad [B_D] \text{ is the matrix of purchased value } q_{id} \quad (4.88)$$

As can be seen from the equations above, several parameters such as  $e_d$ ,  $e_g$ ,  $f_d$ ,  $f_g$  and  $P_r$ , are playing very important roles in determining the market equilibrium. To respect the reality and have feasible solutions, some restrictions are set:

- According to Equation 4.84, the intercept value of inverse demand function,  $e_d$ , should be bigger than the maximum linear coefficient of generators' cost function,
- According to Equation 4.86, the intercept value of inverse generation function,  $e_g$ , should be sufficiently less than the retail price,  $P_r$ .
- To have feasible solution, the intercept value of inverse generation curve,  $e_g$ , is less than the intercept of inverse demand curve,  $e_d$ .
- Because of the demand inelasticity, the slope of inverse demand curve,  $f_d$ , should be high.

If all these are satisfied, the calculated equilibrium point can be assumed as the actual values for the real market quantity and price.

In this research, the model for generation company with different generation resources and the model of bilateral electricity market with integration of transmission constraints are developed. The specific output of generation companies in these two new models is expressed in the matrix form as well to build the platform for bilateral electricity market. Similar to the case of single technology company, the production of each generation company with multi-generation resources can be also expressed in the form of matrix.

$$q_{ig} \times (f_d(2 + CV_{ig})) = e_d - f_d q_{-ig} - \lambda_i \rightarrow$$

$$\lambda_i + f_d(2 + CV_{ig})q_{ig} + f_d q_{-ig} = e_d \quad (i = 1, \dots, n) \quad (4.89)$$

Different from the case where generation companies have single generation resource, the lagrangian multiplier  $\lambda_i$  is also presented in the matrix together with  $q_{ig}$ .

$$\begin{bmatrix} 1 & 0 & 0 & \dots & 0 & f_d(2 + CV_{1g}) + C_1 & & & f_d & & & \\ 0 & 1 & 0 & \dots & 0 & f_d & f_d(2 + CV_{2g}) + C_2 & \dots & & & & f_d \\ 0 & 0 & 1 & \dots & 0 & f_d & & & f_d & & & \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & & & \vdots & & & \\ 0 & 0 & 0 & \dots & 1 & f_d & & & & \dots & f_d(2 + CV_{ng}) + C_n & \end{bmatrix} \times \begin{bmatrix} \lambda_1 \\ \vdots \\ \lambda_n \\ q_{1g} \\ \vdots \\ q_{ng} \end{bmatrix} = \begin{bmatrix} e_d \\ \vdots \\ e_d \\ \vdots \\ e_d \end{bmatrix} \quad (4.90)$$

To solve the market equilibrium in this case,  $[B_G]$  with lagrangian multiplier  $\lambda_i$  included can be solved first. Then part of the result, with only  $q_{ig}$  can be used to match the demand calculated by Equation 4.88. The following steps will be the same as the case of companies with single generation resource. Hence, the market equilibrium point for multi-technology companies can be achieved.

The production of each generation company in the model of transmission constraints is also expressed in the form of matrix. By transforming Equation 4.58, the following equation is achieved:

$$f_{dk}(2 + CV_{ci}^{j \rightarrow k})q_{ci}^{j \rightarrow k} + f_{dk}q_{ci}^{-(j \rightarrow k)} + \lambda_{ij} = e_{dk} - b_{ci}^j \quad (4.91)$$

Express the above equation in the form of matrix:

$$\rho^* \begin{bmatrix} f_{dk}(2 + CV_{c1}^{1 \rightarrow k}) & \dots & f_{dk} & \dots & f_{dk} & \dots & f_{dk} & \dots & f_{dk} & \dots & f_{dk} & 10 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & 0 & 1 & 0 & \dots & 0 \\ f_{dk} & \dots & f_{dk}(2 + CV_{c1}^{k \rightarrow k}) & \dots & f_{dk} & \dots & f_{dk} & \dots & f_{dk} & \dots & f_{dk} & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ f_{dk} & \dots & f_{dk} & \dots & f_{dk}(2 + CV_{c1}^{m \rightarrow k}) & \dots & f_{dk} & \dots & f_{dk} & \dots & f_{dk} & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ f_{dk} & \dots & f_{dk} & \dots & f_{dk} & \dots & f_{dk}(2 + CV_{ci}^{1 \rightarrow k}) & \dots & f_{dk} & \dots & f_{dk} & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ f_{dk} & \dots & f_{dk} & \dots & f_{dk} & \dots & f_{dk} & \dots & f_{dk}(2 + CV_{cn}^{m \rightarrow k}) & \dots & 0 & 0 & 0 & \dots & 1 \end{bmatrix} \times \begin{bmatrix} q_{c1}^{1 \rightarrow k} \\ \vdots \\ q_{c1}^{k \rightarrow k} \\ \vdots \\ q_{c1}^{m \rightarrow k} \\ \vdots \\ q_{cn}^{1 \rightarrow k} \\ \vdots \\ q_{cn}^{m \rightarrow k} \\ \vdots \\ \lambda_1^1 \\ \vdots \\ \lambda_1^m \\ \vdots \\ \lambda_n^m \end{bmatrix} =$$

$$\rho^* \begin{bmatrix} e_d^k - b_1^1 \\ \vdots \\ e_d^k - b_1^k \\ \vdots \\ e_d^k - b_1^m \\ \vdots \\ e_d^k - b_i^1 \\ \vdots \\ e_d^k - b_n^m \end{bmatrix} \quad (j = 1 \dots m, k = 1 \dots m, i = 1 \dots n; \rho = 1, j \neq k; \rho = 0, j = k) \quad (4.92)$$

By transforming Equation 4.59, the following equation is achieved:

$$f_{dk}(2 + CV_{ci}^{k \rightarrow k})q_{ci}^{k \rightarrow k} + f_{dk}q_{ci}^{-(k \rightarrow k)} + \lambda_{ik} = e_{dk} - b_{ci}^k + \sum_{xy=1}^{n_l} |t_{xy} \cdot PTDF_{xy}^k| \quad (4.93)$$



To solve the market equilibrium in such a case,  $q_{ci}^{j \rightarrow k}$  is solved first. Then the total output of generation companies on each node and the corresponding price can be calculated to match the demand at each node, which is achieved through Equation 4.88. The following steps will be the same as the case of companies with single generation resource. Therefore, the market equilibrium point with integration of transmission constraints can be achieved.

#### 4.5.2 Summary of the Models in this Research

For generation companies with single generation resource, the profit maximization problem is defined as:

$$\text{Max } \pi_{ig} = p_d q_{ig} - C_{ig}(q_{ig}) \quad (i = 1, \dots, n) \quad (4.96)$$

The output of generation company  $i$  is:

$$q_{ig} = \frac{e_d - f_d q_{-ig} - b_i}{f_d(2 + CV_{ig}) + c_i} \quad (4.97)$$

The production of each generation company expressed in the form of matrix is:

$$\begin{bmatrix} f_d(2 + CV_{1g}) + C_1 & f_d & f_d & \dots & f_d \\ f_d & f_d(2 + CV_{2g}) + C_2 & f_d & \dots & f_d \\ f_d & f_d & f_d(2 + CV_{3g}) + C_3 & \ddots & f_d \\ \vdots & \vdots & \vdots & \ddots & f_d \\ f_d & f_d & f_d & \dots & f_d(2 + CV_{ng}) + C_n \end{bmatrix} \times \begin{bmatrix} q_{1g} \\ q_{2g} \\ q_{3g} \\ \vdots \\ q_{ng} \end{bmatrix} = \begin{bmatrix} e_d - b_1 \\ e_d - b_2 \\ e_d - b_3 \\ \vdots \\ e_d - b_n \end{bmatrix} \quad (4.98)$$

For retailers, the profit maximization problem is defined as:

$$\text{Max } \pi_{id} = P_r q'_{id} - p_g q_{id} - f_{ci} \quad (i = 1, \dots, M) \quad (4.99)$$

The purchased value of retailer  $i$  is:

$$q_{id} = \frac{P_r - e_g - f_g q_{-id}}{f_g(2 + CV_{id})} \quad (4.100)$$



The purchased value of retailer expressed in the form of matrix is:

$$\begin{bmatrix} f_g(2 + CV_{1d}) & f_g & f_g & \dots & f_g \\ f_g & f_g(2 + CV_{2d}) & f_g & \dots & f_g \\ f_g & f_g & f_g(2 + CV_{3d}) & \dots & f_g \\ \vdots & \vdots & \vdots & \dots & \vdots \\ f_g & f_g & f_g & \dots & f_g(2 + CV_{Md}) \end{bmatrix} \times \begin{bmatrix} q_{1d} \\ q_{2d} \\ q_{3d} \\ \vdots \\ q_{Md} \end{bmatrix} = \begin{bmatrix} P_{r1} - e_g \\ P_{r2} - e_g \\ P_{r3} - e_g \\ \vdots \\ P_{rM} - e_g \end{bmatrix} \quad (4.101)$$

For generation companies with different generation resources, the profit maximization problem is defined as:

$$\text{Max } \pi_{ig} = q_{ig} \cdot p_d - \sum_{k=1}^v b_{ik} q_{igk} \quad (i = 1, \dots, n, k = 1, \dots, v) \quad (4.102)$$

The output of generation company  $i$  is:

$$q_{ig} = \frac{e_d - f_d q_{-ig} - \lambda_i}{f_d(2 + CV_{ig})} \quad (4.103)$$

The production of each generation company expressed in the form of matrix is:

$$\begin{bmatrix} 10 \ 0 \ \dots \ 0 & f_d(2 + CV_{1g}) + C_1 & f_d & \dots & f_d \\ 01 \ 0 \ \dots \ 0 & f_d & f_d(2 + CV_{2g}) + C_2 & \dots & f_d \\ 00 \ 1 \ \dots \ 0 & f_d & f_d & \dots & f_d \\ \vdots \ \vdots \ \ddots \ \vdots & \vdots & \vdots & \dots & \vdots \\ 00 \ 0 \ \dots \ 1 & f_d & f_d & \dots & f_d(2 + CV_{ng}) + C_n \end{bmatrix} \times \begin{bmatrix} \lambda_1 \\ \vdots \\ \lambda_n \\ q_{1g} \\ \vdots \\ q_{ng} \end{bmatrix} = \begin{bmatrix} e_d \\ \vdots \\ e_d \\ e_d \\ \vdots \\ e_d \end{bmatrix} \quad (4.104)$$

For generation companies in the bilateral electricity market with the integration of transmission constraints, the profit maximization problem is defined as:

$$\pi_{ci} = \sum_{j=1}^m (\pi_{ci}^j) = \sum_{j=1}^m \sum_{k=1}^m p_k \cdot q_{ci}^{j \rightarrow k} - \sum_{j=1}^m \sum_{k=1}^m b_{ci}^j q_{ci}^{j \rightarrow k} - \sum_{j=1}^m \sum_{xy=1}^{n_i} (|t_{xy} \cdot PTDF_{xy}^j| \cdot (q_{ci}^j - q_{ci}^{j \rightarrow j})) \quad (4.105)$$

The amount of electricity of generation company  $i$  sold to node  $k$  from node  $j$  is:

$$q_{ci}^{j \rightarrow k} = \frac{e_{dk} - f_{dk} q_{ci}^{-(j \rightarrow k)} - b_{ci}^j - \lambda_{ij}}{f_{dk}(2 + CV_{ci}^{j \rightarrow k})} \quad (4.106)$$

The amount of electricity of generation company  $i$  sold to node  $k$  from node  $k$  is:

$$q_{ci}^{k \rightarrow k} = \frac{e_{dk} - f_{dk}q_{ci}^{-(k \rightarrow k)} - b_{ci}^k - \lambda_{ik} + \sum_{xy=1}^{n_l} |t_{xy} \cdot PTDF_{xy}^k|}{f_{dk}(2 + CV_{ci}^{k \rightarrow k})} \quad (4.107)$$

The amount of electricity sold to node  $k$  expressed in the form of matrix is:

$$\begin{bmatrix} f_{dk}(2 + CV_{c1}^{1 \rightarrow k}) & \dots & f_{dk} & \dots & f_{dk} & \dots & f_{dk} & \dots & f_{dk} & 10 & 0 & \dots & 0 \\ \vdots & & \vdots & & \vdots & & \vdots & & \vdots & 0 & 1 & 0 & \dots & 0 \\ f_{dk} & \dots & f_{dk}(2 + CV_{c1}^{k \rightarrow k}) & \dots & f_{dk} & \dots & f_{dk} & \dots & f_{dk} & 0 & 0 & 1 & \dots & 0 \\ \vdots & & \vdots & & \vdots & & \vdots & & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ f_{dk} & \dots & f_{dk} & \dots & f_{dk}(2 + CV_{c1}^{m \rightarrow k}) & \dots & f_{dk} & \dots & f_{dk} & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & & \vdots & & \vdots & & \vdots & & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ f_{dk} & \dots & f_{dk} & \dots & f_{dk} & \dots & f_{dk}(2 + CV_{cn}^{1 \rightarrow k}) & \dots & f_{dk} & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & & \vdots & & \vdots & & \vdots & & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ f_{dk} & \dots & f_{dk} & \dots & f_{dk} & \dots & f_{dk} & \dots & f_{dk}(2 + CV_{cn}^{m \rightarrow k}) & 0 & 0 & 0 & \dots & 1 \end{bmatrix} \times \begin{bmatrix} q_{c1}^{1 \rightarrow k} \\ \vdots \\ q_{c1}^{k \rightarrow k} \\ \vdots \\ q_{c1}^{m \rightarrow k} \\ \vdots \\ q_{cn}^{1 \rightarrow k} \\ \vdots \\ q_{cn}^{m \rightarrow k} \\ \vdots \\ \lambda_1^1 \\ \vdots \\ \lambda_1^m \\ \vdots \\ \lambda_n^m \end{bmatrix}$$

$$= \begin{bmatrix} e_d^k - b_1^1 \\ \vdots \\ e_d^k - b_1^k \\ \vdots \\ e_d^k - b_1^m \\ \vdots \\ e_d^k - b_n^1 \\ \vdots \\ e_d^k - b_n^m \end{bmatrix} + \begin{bmatrix} T_{c1}^{1 \rightarrow k} \\ \vdots \\ T_{c1}^{k \rightarrow k} \\ \vdots \\ T_{c1}^{m \rightarrow k} \\ \vdots \\ T_{cn}^{1 \rightarrow k} \\ \vdots \\ T_{cn}^{m \rightarrow k} \end{bmatrix} \quad (T_{ci}^{j \rightarrow k} = 0, j \neq k; T_{ci}^{j \rightarrow k} = \sum_{xy=1}^{n_l} |t_{xy} \cdot PTDF_{xy}^k|, j = k; j = 1 \dots m, k = 1 \dots m, i = 1 \dots n) \quad (4.108)$$

### 4.5.3 Market Equilibrium Solving with Genetic Algorithm

In the study of *Alikhanzadeh* (2011, 2012), the Hierarchical Optimization Algorithm through using Matlab Pattern Search Toolbox is adopted to solve the market equilibrium problem. And the market clearing conditions are defined as the objective function of the optimization problem.

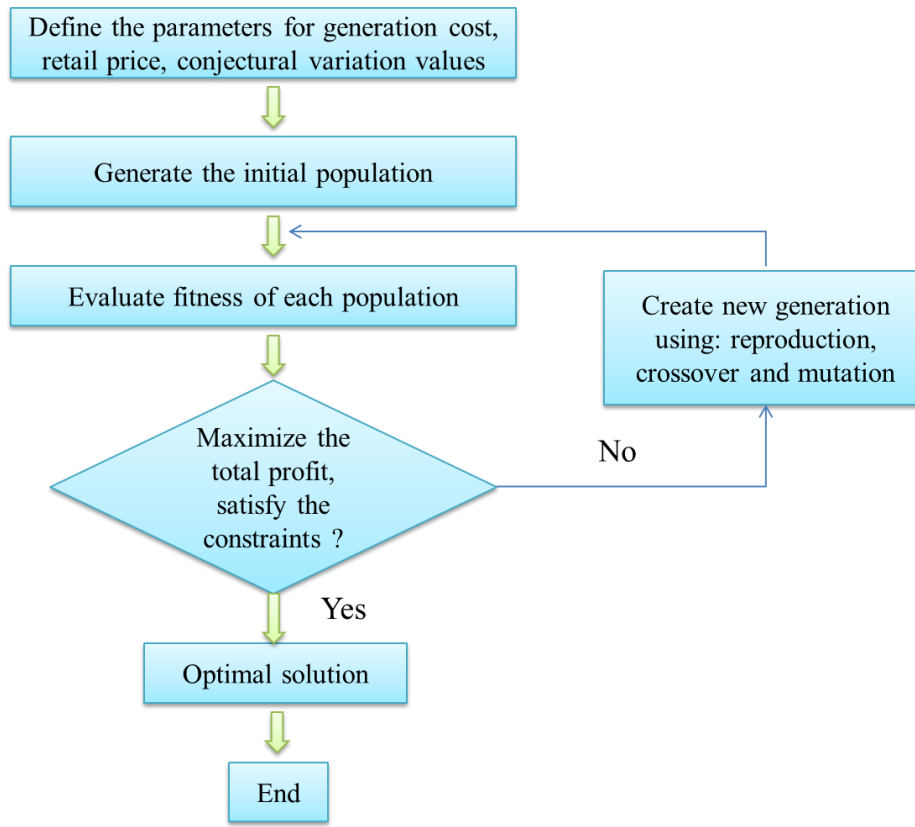
$$\text{Min} (\sum_{i=1}^n q_{ig} - \sum_{i=1}^M q_{id})^2 + (p_g - p_d)^2 \quad (4.109)$$

The initial value of demand and generation functions,  $e_d, e_g, f_d, f_g$ , are given by the author and the values of these four parameters will update with the iterations until the objective function is minimized. Then the market equilibrium point can be calculated. Otherwise, the optimizer keeps increasing the number of iterations and replaces the slopes and intercepts parameters with updated values. However, there is one main drawback with this optimization approach. With the variation of the initial values of the four parameters  $e_d, e_g, f_d, f_g$ , different market

equilibrium points are reached. This is mainly because the local optimal solution is found instead of global optimal solution. As a matter of fact, the objective function of market clearing conditions can be satisfied with different combinations of the four parameters of demand and generation functions.

To overcome the disadvantage of resulting in local optimal solution in Pattern Search, Genetic Algorithm (GA) has been adopted to solve the optimization problem in this research. As a stochastic method applied to solve both constrained and unconstrained optimization problems based on a natural selection process that mimics biological evolution, Genetic Algorithm (GA) has several advantages in global convergence, strong ability, etc. GA has been widely implemented in the field of electric power system analysis [55][56][57][58].

The traditional genetic algorithm operation process consists of several iterative processes: define fitness function; determine genetic strategy; create initial population of randomly generated candidates, each candidate is called a chromosome; calculate the fitness function of individuals in the population; form the next generation population according to the genetic strategy; determine whether to continue iteration or not. A set of candidate solutions are retained in each GA iteration process. A portion of the existing population is selected to breed a new generation through individual evaluation and comparison. Normally a fitness-based process is adopted and fitter solutions measured by the fitness function are selected. By using selection, crossover and mutation to combine the selected individuals, new generation will be produced and the processes above will be repeated until convergence. The process of genetic algorithm for this research is briefly indicated in Figure 4.5.



**Figure 4.7 Genetic Optimization Algorithm**

In this research, the primary objective is to maximize the total profit of the market participants. Thus the profit maximization problem is defined:

$$Max \pi = \pi_g + \pi_d \quad (4.110)$$

$\pi$  : Total profit of market participants

$\pi_g$ : Profit of generation companies

$\pi_d$ : Profit of retailers

Equivalently the maximization problem can be written as the following minimization problem, which is the objective function of the model:

$$Min - \pi = -\pi_g - \pi_d \quad (4.111)$$

This can be used as the fitness function in the genetic algorithm. Therefore, the fitness value of each chromosome can be determined by Equation 4.111.

The market clearing conditions and the basic rules of parameter ranges discussed above for  $e_d$ ,  $e_g$ ,  $f_d$ ,  $f_g$ , have been set as constraints. Since the values of  $e_d$ ,  $e_g$ ,  $f_d$ ,  $f_g$  will update with the iteration and  $Q_g$ ,  $Q_d$ ,  $p_g$ ,  $p_d$  will be calculated under each iteration. The market clearing conditions are defined as nonlinear equality constraints:

$$Q_g - Q_d = 0 \quad (4.112)$$

$$p_g - p_d = 0 \quad (4.113)$$

The generation balance will be set as linear equality constraints:

$$q_{ig} - \sum_{k=1}^v q_{igk} = 0 \quad (k = 1 \dots v) \quad (4.114)$$

$$q_{ci}^j - \sum_{k=1}^m q_{ci}^{j \rightarrow k} = 0 \quad (j = 1 \dots m, k = 1 \dots m) \quad (4.115)$$

Besides, generation capacity limit and transmission constraints can be included as nonlinear inequality constraints, as defined below:

$$q_{ig \min} \leq q_{ig} \leq q_{ig \max} \quad (4.116)$$

$$q_{igk}^{\min} \leq q_{igk} \leq q_{igk}^{\max} \quad (k = 1 \dots v) \quad (4.117)$$

$$q_{ci}^{j \min} \leq q_{ci}^j \leq q_{ci}^{j \max} \quad (j = 1 \dots m) \quad (4.118)$$

$$T_{xy}^{\min} \leq T_{xy} = \sum_{j=1}^m PTDF_{xy}^j \left( \sum_{i=1}^n q_{ci}^j \right) - D^j \leq T_{xy}^{\max} \quad (i = 1 \dots n, j = 1 \dots m) \quad (4.119)$$

The parameter range for  $e_d$ ,  $e_g$ ,  $f_d$ ,  $f_g$  are set as linear inequality constraints. The Matlab Genetic Algorithm is adopted as the optimization tool. The optimization process of generation companies with single generation resource is specifically described as below:

Step 1) Define the generators' cost function variables:  $a_i$ ,  $b_i$ ,  $c_i$ , for generation companies and retail price,  $P_r$  for retailers.

Step 2) Define the  $CV_{ig}$  and  $CV_{id}$  based on historical data and technical characteristics of each generation company and retailer respectively.

Step 3) Generate an initial random population of chromosomes ( $e_d, e_g, f_d, f_g$  for demand and generation functions). In this research, double vector is adopted as the population type and different values of the population size are selected at first. After the comparison of the calculation results and sensitivity analysis, the population size is fixed as 200. Since there are nonlinear constraints and no integer constraints, the Nonlinear Feasible population is adopted as the creation function.

Step 4) Compute the output of each generation company,  $q_{ig}$ , and the purchased amount of electricity by each retailer,  $q_{id}$ , using Equations 4.97 and 4.100. Calculate the total demand  $Q_d$  and total generation  $Q_g$ . Compute the price values for oligopolistic and oligopsonistic markets respectively, based on inverse demand and inverse generation functions respectively.

Step 5) Evaluate the fitness function in Equation 4.111 using the values obtained in the previous step. The fitness of the individuals is evaluated and the individuals are ranked according to their fitness. Scaling function Top with the value of 0.5 is adopted as fitness scaling function. 50% of the population will be fittest individuals that produce offspring. Each of these individuals has an equal probability of reproducing.

Step 6) Recording the objective function values and best individuals of this generation. If there is an optimal solution or stop criteria is met then the program terminates else the program continue to step 7.

Step 7) While the termination criteria are not satisfied, selection, crossover and mutation are carried out to produce a new generation of population.

The selection function chooses parents for the next generation based on their scaled values from the fitness scaling function. In this research the selection function Tournament is adopted and the Tournament size is 5. This function selects each parent by choosing 5 individuals at random, and then choosing the best individual out of the 5 individuals to be a parent.

Reproduction determines how the genetic algorithm creates children at each new generation. Elite count specifies the number of individuals that are guaranteed to survive to the next generation. In this research Elite count is set as 5% of population size. Crossover fraction

specifies the fraction of the next generation that crossover produces. In this research the value is set as 90%. Mutation produces the remaining individuals in the next generation.

Crossover combines two individuals to form a new child for the next generation. In this research, crossover function Heuristic is adopted. It creates children that randomly lie on the line containing the two parents, a small distance away from the parent with the better fitness value, in the direction away from the parent with the worse fitness value. The Heuristic value is set as the default value 1.2.

Mutation functions make small random changes in the individuals in the population, which provide genetic diversity and enable the genetic algorithm to search a broader space. In this research, mutation function Adaptive feasible is adopted. It randomly generates directions that are adaptive with respect to the last successful or unsuccessful generation. A step length is chosen along each direction so that linear constraints and bounds are satisfied.

Step 8) Go for next iteration. If the total profit is maximized, linear and nonlinear constraints in Equation 4.112, 4.113, 4.116 are satisfied, the equilibrium point can be calculated, if not, the optimizer keeps increasing the number of iterations, and replaces the slopes and intercepts parameters with updated values, then goes to step (4). The maximum generation size is set as 500 and the constraint tolerance is set as  $1e-8$ .

As for the market equilibrium in the model of generation companies with different generation resources and transmission constraints, the basic optimization processes are similar. Only the variables, linear and nonlinear constraints are changed in each case according to the specific constraints defined in each model.

In the model of generation companies with different generation resources, the fitness function is Equation 4.111, the linear constraint is Equation 4.114, and nonlinear constraints are Equation 4.112, 4.113 and 4.117. Apart from  $e_d, e_g, f_d, f_g$  for demand and generation functions, electricity output from each generation resource and each company, and lagrangian multipliers are all included as variables.

In the model of bilateral electricity market with integration of transmission constraints, the fitness function is Equation 4.111, the linear constraint is Equation 4.115, and nonlinear

constraints are Equation 4.112, 4.113, 4.118 and 4.119. Except  $e_d$ ,  $e_g$ ,  $f_d$ ,  $f_g$  for demand and generation functions, amount of electricity of generation company  $i$  sold to node  $k$  from node  $j$ , and lagrangian multipliers are set as variables.



## **5. Simulation and Test**

### **5.1 Introduction**

In chapter 4, the development of a bilateral electricity market model is described in detail. Both sides of the bilateral electricity market are investigated and market equilibria under different situations are calculated in detail with mathematical formulations.

In this chapter, case study will be conducted to test the above developed models. Sensitivity analysis will be conducted to study the effect of some important factors on oligopolistic and oligopsonistic markets as well as market equilibrium.

First sensitivity analysis of inverse demand curve slope, intercept and conjecture variation values for generation companies are conducted. Meanwhile, generation companies with capacity of different resources, impact of transmission constraints and price on generation companies are tested.

Similarly, sensitivity analysis of inverse generation curve slope, intercept and conjecture variation values for retailers are conducted. Impact of retail price on retailers is tested.

Besides, market equilibria under three different situations are tested respectively: market equilibrium in single nodal market; market equilibrium for generation companies with capacity of different resources; market equilibrium with fixed transmission price.

Finally, a specific case of Chinese electricity market is analyzed with a focus on Shanxi province. The market equilibrium price in bilateral electricity market solved in this model is compared with the former on-grid price to see the progress and advantages of the new market mechanism. And the effect of integration of more renewable energy is tested as well.

### **5.2 Oligopolistic Electricity Market Case Study**

This section is focused on the case study of oligopolistic electricity market. Different number of generation companies, energy resources and strategies will be tested to see the basic behaviors of generation companies.

### 5.2.1 Impact of Inverse Demand Curve Slope and Intercept on Generation Companies

As analyzed in chapter 4, the main behaviors of generation companies are their internal interactions and their response to the demand function. Thus sensitivity analysis of demand curve slope and intercept is conducted to test the oligopolistic electricity market model summerized in 4.2.2. The output of each generation company and the electricity price are calculated. The basic parameters are listed in Table 5.1. To simplify, the  $CV_{ig}$  values for all the companies are the same and no limits have been set to the generation capacity.

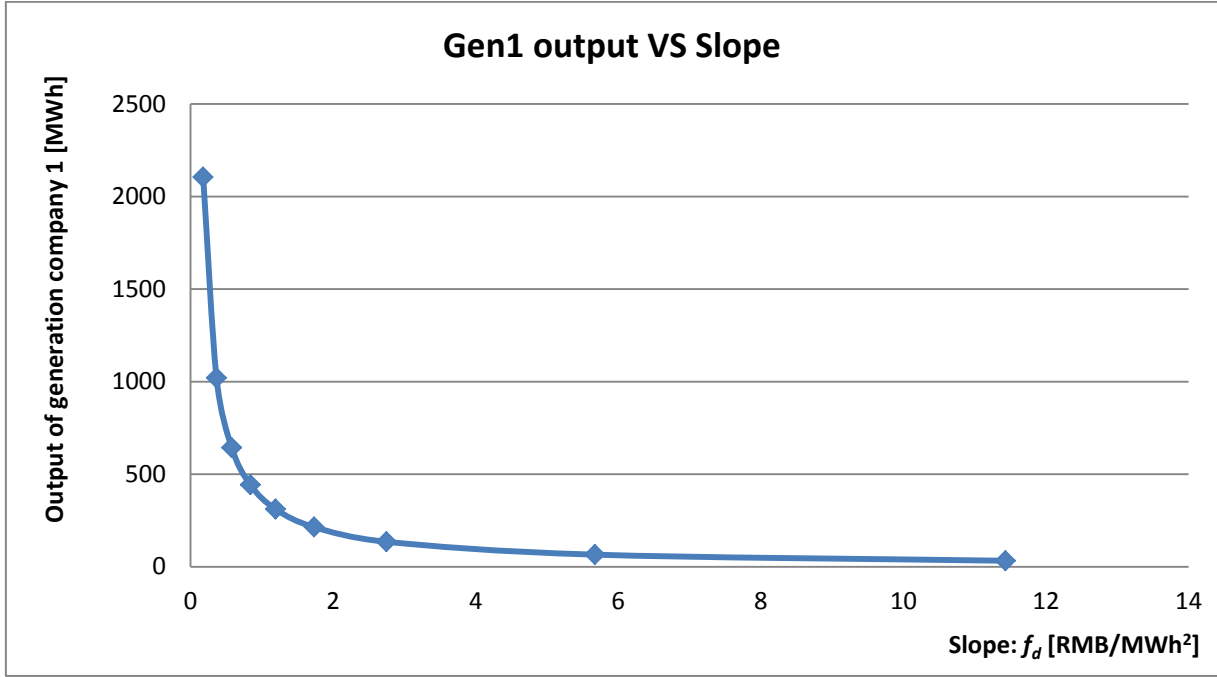
Company	ai [RMB]	bi [RMB/MWh]	ci [RMB/MWh <sup>2</sup> ]	$CV_{ig}$
1	0	150	0	-0.4
2	0	160	0	-0.4
3	0	170	0	-0.4
4	0	250	0	-0.4
5	0	260	0	-0.4
6	0	270	0	-0.4

**Table 5.1 Basic parameters for generation companies**

First, the intercept of inverse demand function is set as 2000 RMB/MWh, and the value of slope is changed. The value of slope ranges from 0.1763 RMB/MWh<sup>2</sup> (10%) to 11.43 RMB/MWh<sup>2</sup> (85%). Different values of slope indicate different demand elasticity. The outputs of all the generation companies are listed in Table 5.2. **(Intercept: 2000 RMB/MWh)**

Slope [RMB/MWh <sup>2</sup> ]	Gen1 [MWh]	Gen2 [MWh]	Gen3 [MWh]	Gen4 [MWh]	Gen5 [MWh]	Gen6 [MWh]	Total output [MWh]	Price [RMB/MWh]
0.17632698	2105.2	2010.7	1916.2	1160	1065.5	971	9228.6	372.7273
0.36397023	1019.9	974.1	928.3	562	516.2	470.4	4470.9	372.7273
0.57735027	642.958	614.091	585.223	354.283	325.416	296.548	2818.519	372.7273
0.83909963	442.393	422.531	402.668	243.768	223.905	204.043	1939.3082	372.7273
1.19175359	311.484	297.499	283.514	171.634	157.649	143.664	1365.444	372.7273
1.73205081	214.319	204.697	195.074	118.094	108.472	98.8494	939.5064	372.7273
2.74747742	135.110	129.044	122.978	74.4485	68.3823	62.3161	592.2789	372.7273
5.67128182	65.4547	62.5159	59.5771	36.0669	33.1281	30.1893	286.932	372.7273
11.4300523	32.4769	31.0187	29.5606	17.8954	16.4373	14.9791	142.368	372.7273

**Table 5.2 Impact of slope of inverse demand function on the output of generation companies**

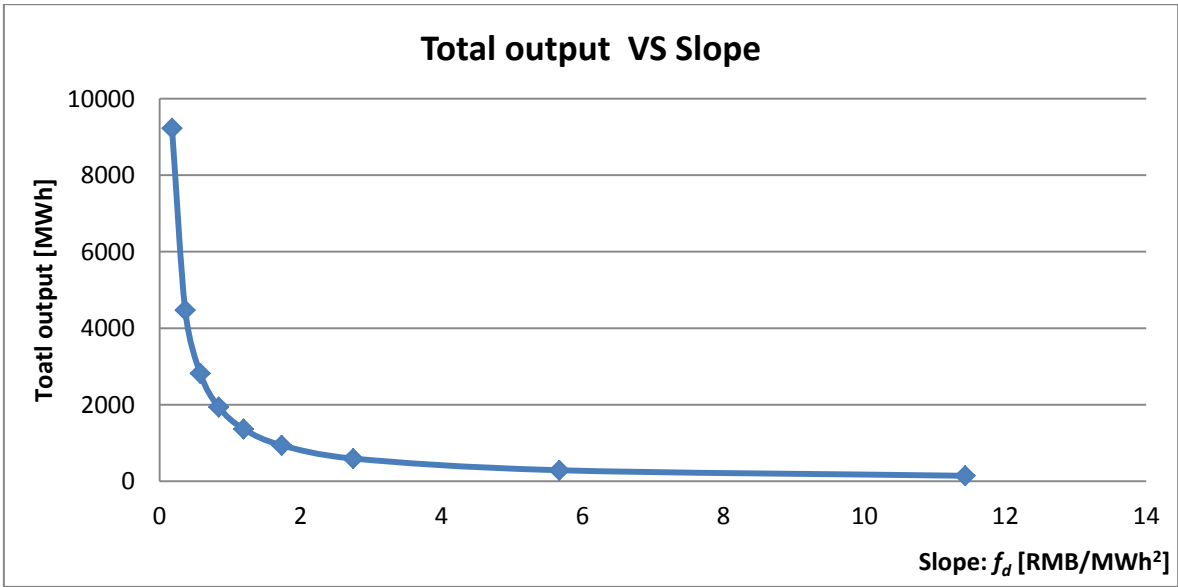


**Figure 5.1 Impact of slope of inverse demand function on the output of generation company 1**

As can be seen from Figure 5.1, with the increase of the slope of demand function, the output of generation company 1 keeps on going down. This indicates that the generation company is experiencing market power in the oligopolistic electricity market. Another very interesting phenomenon is that in the region of small value of slope, the output of generation company 1 changes very fast, while in the region of big value of slope, the output of generation company 1 changes slowly. This is mainly because, with big value of slope of inverse demand function, the demand is inelastic and relatively stable compared with the case of demand elastic region. The real electricity market is featured with inelastic demand function. Since the cost coefficient  $c_i$  value is fixed as 0 for all the companies and the  $CV_{ig}$  values for all the companies are the same, by substituting Equation 4.11, 4.12 and 4.19, Equation 5.1 can be achieved. As it can be seen from Equation 5.1, the price is a function of intercept of demand function,  $CV_{ig}$  value and cost coefficient  $b_i$ . Once all the three parameters are fixed, the price is fixed.

$$p_d = \frac{e_d(1 + CV_{ig}) + \sum_{i=1}^n b_i}{n + CV_{ig} + 1} \quad (5.1)$$

Therefore, the electricity price does not change with the slope of demand function in this case study, as shown in Table 5.2



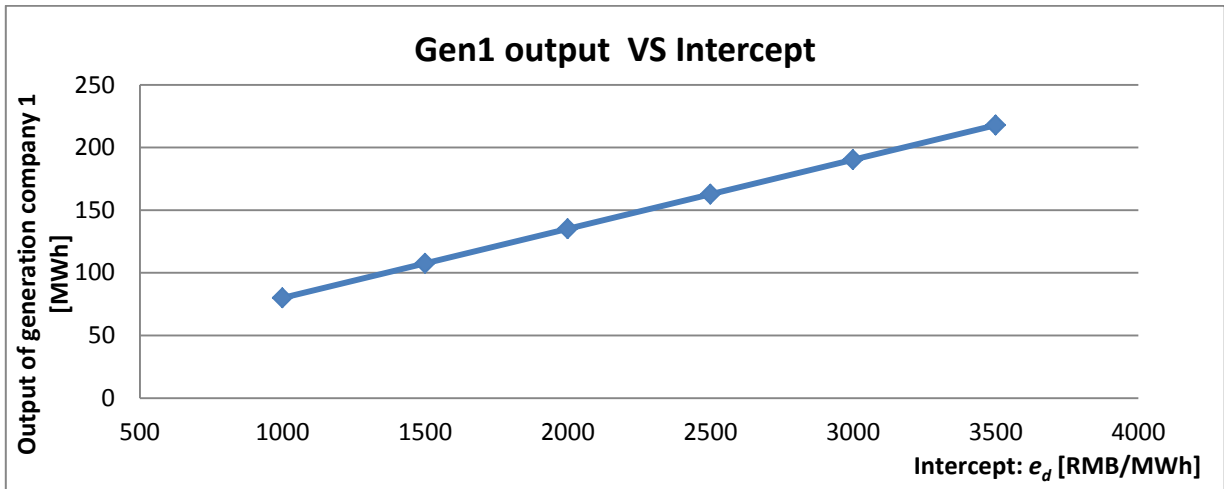
**Figure 5.2 Impact of slope of inverse demand function on the total output**

As is shown in Figure 5.2, with the increase of the slope of inverse demand function, the total output of generation companies decreases, which is similar to the trend of single generation company 1.

Second, the slope of inverse demand function is fixed as 2.7475 RMB/MWh<sup>2</sup> (70 %), and the value of intercept ranges from 1000 RMB/MWh to 3500 RMB/MWh. Different values of intercept indicate different willingness of retailers to pay. The outputs of all the generation companies are listed in Table 5.3. (Slope: 2.7475 RMB/MWh<sup>2</sup>)

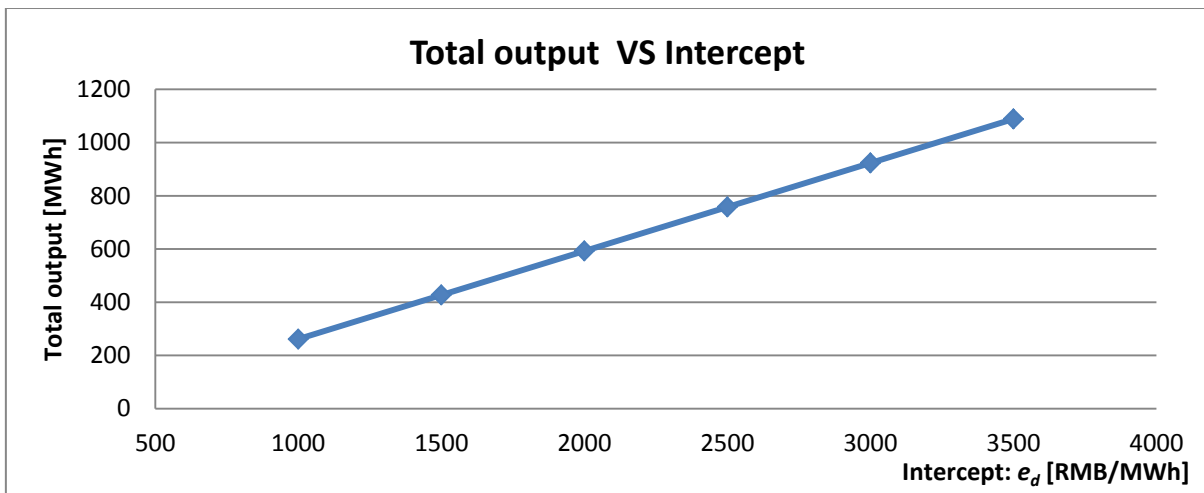
Intercept [RMB/MWh]	Gen1 [MWh]	Gen2 [MWh]	Gen3 [MWh]	Gen4 [MWh]	Gen5 [MWh]	Gen6 [MWh]	Total output [MWh]	Price [RMB/MWh]
1000	79.96	73.9	67.83	19.3	13.24	7.17	261.4	281.8182
1500	107.54	101.47	95.4	46.87	40.81	34.74	426.83	327.2727
2000	135.11	129.04	122.98	74.45	68.38	62.32	592.28	372.7273
2500	162.68	156.62	150.55	102.02	95.96	89.89	757.72	418.1818
3000	190.26	184.19	178.12	129.59	123.53	117.46	923.15	463.6364
3500	217.83	211.76	205.7	157.17	151.1	145.04	1088.6	509.0909

**Table 5.3 Impact of intercept of inverse demand function on the output of generation companies**

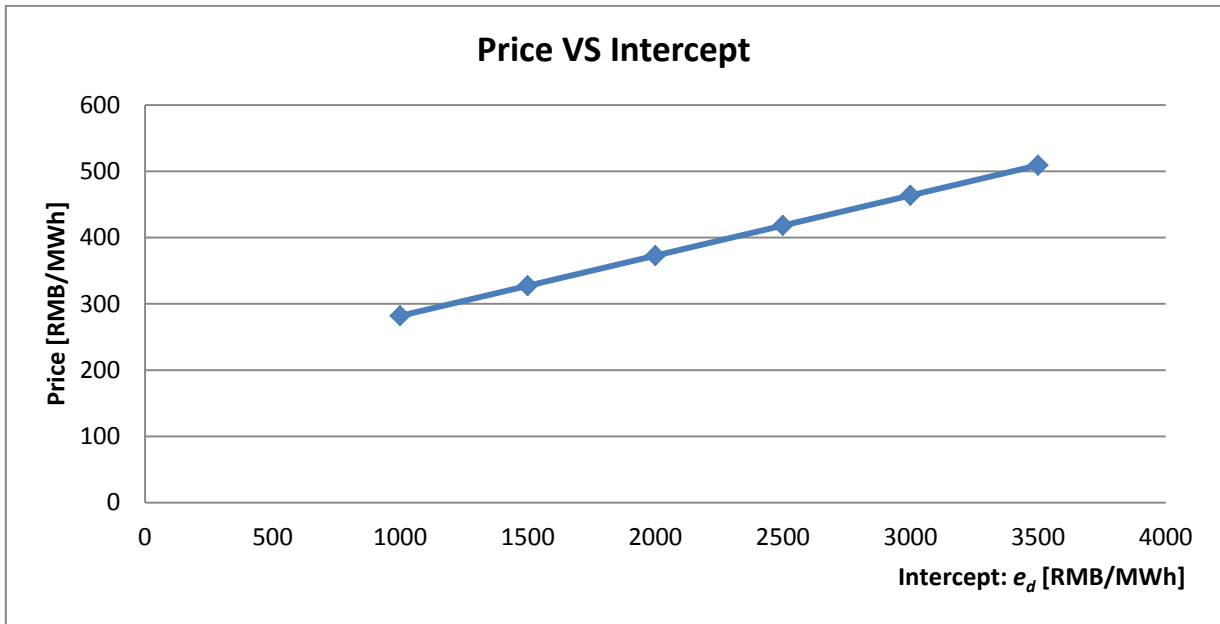


**Figure 5.3 Impact of intercept of inverse demand function on the output of generation company 1**

As it can be seen from Figure 5.3, the output of generation company 1 increases nearly linearly with the growth of the intercept. The total output shares similar trend as shown in Figure 5.4. This is mainly because with larger value of intercept of demand function, the demand is higher and the willingness to pay of retailers is stronger. So it is unsurprisingly to see the transaction price increases with the value of intercept. The price over the increase of intercept is shown in Figure 5.5. The price grows linearly with the increase of intercept. This can be explained with Equation 5.1, with uniform  $CV_{ig}$  value and fixed cost for each company, the price  $p_d$  turns a linear function of the intercept value. Thus, the price is directly decided by the intercept of demand function.



**Figure 5.4 Impact of intercept of inverse demand function on the total output**



**Figure 5.5 Impact of intercept of inverse demand function on price**

To summarize, the increase of slope of inverse demand function will have a negative effect on the output of the generation companies, while the increase of intercept of inverse demand function will affect the output of generation companies positively. Meanwhile generation companies are experiencing market power in oligopolistic market.

### 5.2.2 Impact of $CV_{ig}$ Values on Generation Companies

As discussed in Chapter 4,  $CV_{ig}$  is the conjecture variation value of all the rivals' reaction over the change of output of company  $i$ . Different values of  $CV_{ig}$  indicates different strategies and market competitiveness. In this research the range of  $CV_{ig}$  is between -1 and 0. When the value goes towards -1, the oligopolistic electricity market will move towards perfect competition. To see more specifically the effect of  $CV_{ig}$ , sensitivity analysis has been conducted based on the model in 4.2.2. The output of each generation company and the electricity price are calculated. The slope and intercept of demand function are fixed at  $f_d=2.7475$  RMB/MWh<sup>2</sup> and  $e_d=2000$  RMB/MWh. The results are listed in Table 5.4.

Company	Case 1		Case 2		Case 3		Case 4	
	$CV_{ig}$	Output [MWh]	$CV_{ig}$	Output [MWh]	$CV_{ig}$	Output [MWh]	$CV_{ig}$	Output [MWh]
1	-0.4	135.1091	-0.7	234.6631	-0.7	216.1878	-0.7	203.4497
2	-0.4	129.0429	-0.4	111.2654	-0.6	153.0416	-0.6	143.4881
3	-0.4	122.9768	-0.4	105.1993	-0.5	115.154	-0.5	107.5111
4	-0.4	74.4478	-0.4	56.6703	-0.4	47.4327	-0.4	41.0636
5	-0.4	68.3817	-0.4	50.6042	-0.4	41.3666	-0.3	29.9979
6	-0.4	62.3156	-0.4	44.5381	-0.4	35.3004	-0.8	86.7942
<b>Total output [MWh]</b>		592.2739		602.9404		608.4831		612.3046
<b>Price [RMB/MWh]</b>		372.7273		343.4211		328.1928		317.6934

**Table 5.4 Impact of  $CV_{ig}$  values on generation companies**

Compare the results of case 2 with the basic case 1, with  $CV_{ig}$  value of company 1 becoming smaller, the output of this company grows up, meanwhile the total output of all the generation companies increases and the price goes down. This is mainly because, with the  $CV_{ig}$  value moving towards -1, the market environment will be more competitive, the generation company will react fast to fill in the gap, once the other companies decrease their output. Since the market moving towards perfect competition, the total output increases and the market price goes down, which are the common phenomena in case 2, 3, 4. On the contrary, if the  $CV_{ig}$  value increases, the output of this company will decrease, indicating more modest reaction over the rivals' strategy change, which is the case of company 5 in case 4.

### 5.2.3 Generation Companies with Capacity of Different Resources

In this section, case study of generation companies with capacity of different resources will be studied to test the model developed in 4.2.3. The output of each generation resource, the electricity price and profit are calculated. Different costs of resources are adopted to see the strategies of generation companies in capacity allocation. Generation capacity limits are set to match the real market situation and test the effect of generation limits on the behaviors of generation companies. Different methodologies are applied in simulation, namely GA, Linear Complementary Problem (LCP) methodology and pure game methodology.

First, the generation capacity for each company and resource is set to a very big value 150 MW, which will not limit the output of the generation companies. The parameters and results are listed in Table 5.5. The index  $qg1\_1$  represents output of generation resource 1 in company

1. It is clear that when the generation capacity is big enough, the generation companies always choose to produce electricity from the cheaper resource. With higher generation cost, the output will be lower and the corresponding selling price will be higher. In some extreme cases (Table 5.5, data with light blue background color), where the cost of one resource is extremely low, and the others are relatively high, only the cheap resource has output, the outputs of all the rest remain zero.

Second, generation capacity of some technology is set to lower value to see if the smaller capacity can be fully used or not. The parameters and simulation results are listed in Table 5.6. When the capacity is limited, the generation companies always choose to produce electricity from the cheaper technology firstly. If the limit is reached, then produce electricity from the more expensive technology. However, most of the profit goes to the lower cost generators. An example is listed in Table 5.6 (the data with yellow background color). with the generation cost of each resource equaling to 50 RMB/MW, 250 RMB/MW, 500 RMB/MW and 500 RMB/MW respectively, the profit for company 1 is 32609RMB, while the profit for company 2 is 1057RMB, only 3.14% of the total profit.

In table 5.7 and 5.8, cost of technologies are fixed, different generation capacity limits combinations are set. As can be seen from Table 5.7, due to the generation capacity limit of lower cost technology, technologies with higher cost can produce more. Sensitivity analysis of the capacity of one technology is conducted as shown in table 5.8. With all the other capacities fixed, only the capacity of generation company 2 resource 1 is changing. At first when the capacity of generation company 2 resource 1 is relatively big, only resource 1 has production. With the decrease of the capacity to 55MW, the higher cost resource starts to produce. This means 55MW is the critical point for generation, which can be a useful instruction in practical operation and the future planning of generation capacity expansion.

Besides, sensitivity analysis of technology cost is conducted and the results are listed in Table 5.9. With the generation cost of three resources fixed at very high value, only the lower cost resource (the cost ranges from 0 to 50 RMB/MWh] has output. However, with the cost further increasing, the other technologies start to have output. Despite the fact that the cost of company 1 resource 2 is lower than the cost of both resources in company 2, the output of



company 1 resource 2 still remains 0. Due to the fact that generation capacity of company 1 resource 1 is big enough, the company chooses to produce all the electricity from lower cost technology. The price keeps on going up all the way with the increasing of generation cost.

Comparison between linear complementary methodology and pure game methodology is conducted to test the results. The  $CV_{ig}$  values are set to 0 to simulate the non-competitive market. In the case of linear complementary methodology, the constraints of Equation 4.30, 4.31, 4.32 are linear complementary problems and can be solved with TOMLAB [53][54]. In the pure game methodology, first fix the output of company 1, change the output of company 2 to find the value which maximizes the profit of company 2. Keep this optimal value fixed for company 2, and similarly change the output of company 1 to find the value which maximizes the profit of company 1. Then repeat the above steps until the output of each company keeps constant. The optimal output and profit of both companies are found in this way. In GA, the constraints of Equation 4.30, 4.31, 4.32 are defined as nonlinear equality constraints.

The comparison results of these three methodologies are listed in Table 5.10 and 5.11. All the results of different methodologies are the same. This indicates that the model is robust and feasible optimal results can be achieved through applying different methodologies.

ed [RMB/MWh]	fd [RMB/MWh <sup>2</sup> ]	CVig1	CVig2	Generation capacity [MW]			
1000	5	-0.1	-0.1	150	150	150	150

Cost of resource [RMB/MWh]				Lagrangian multipliers										Output [MWh]				Price	Profit
b11	b12	b21	b22	lamda1	lamda2	r11	r11	r12	r12	r21	r21	r22	r22	qg1_1	qg1_2	qg2_1	qg2_2	[RMB/MWh]	[RMB]
150	250	160	260	150	160	0	0	100	0	0	0	100	0	59.387	0	57.1648	0	417.2414	30576
100	250	110	260	100	110	0	0	150	0	0	0	150	0	62.8352	0	60.613	0	382.7586	34300
50	250	60	260	50	60	0	0	200	0	0	0	200	0	66.2835	0	64.0613	0	348.2759	38238
150	150	160	160	150	160	0	0	0	0	0	0	0	0	29.6935	29.6935	28.5824	28.5824	417.2414	30576
30	30	30	30	30	30	0	0	0	0	0	0	0	0	33.4483	33.4483	33.4483	33.4483	331.0345	40276
30	30.1	30.1	30	30	30	0	0	0.1	0	0.1	0	0	0	66.8966	0	0	66.8966	331.0345	40276
50	250	500	500	50	499.9998	0	0	200	0	0.0002	0	0.0002	0	100	0	0	0	499.9999	45000
50	250	600	700	50	500	0	0	200	0	100	0	200	0	100	0	0	0	500	45000
30	250	500	500	30	489.4737	0	0	220	0	10.5263	0	10.5263	0	102.1053	0	0	0	489.4737	46915

**Table 5.5 Generation companies with capacity of different resources 1**

ed [RMB/MWh]	fd [RMB/MWh <sup>2</sup> ]	CVig1	CVig2	Generation capacity [MW]			
1000	5	-0.1	-0.1	50	100	50	100

Cost of resource [RMB/MWh]				Lagrangian multipliers										Output [MWh]				Price	Profit
b11	b12	b21	b22	lamda1	lamda2	r11	r11	r12	r12	r21	r21	r22	r22	qg1_1	qg1_2	qg2_1	qg2_2	[RMB/MWh]	[RMB]
150	250	160	260	250	260	0	100	0	0	0	100	0	0	50	2.4904	50	0.2682	486.2069	33770
150	350	160	360	275	275	0	125	75	0	0	115	85	0	50	0	50	0	500	34500
50	250	60	260	250	260	0	200	0	0	0	200	0	0	50	2.4904	50	0.2682	486.2069	43770
150	150	160	160	150	160	0	0	0	0	0	0	0	0	14.3514	45.0356	13.465	43.6997	417.2414	30576
30	30	30	30	30	30	0	0	0	0	0	0	0	0	17.9611	48.9355	17.9611	48.9355	331.0345	40276
30	30.1	30.1	30	30.1	30	0	0.1	0	0	0.1	0	0	0	50	16.882	0	66.9042	331.069	40277
50	250	500	500	250	500	0	200	0	0	0	0	0	0	50	20.8812	7.8456	7.4801	568.9655	33666
250	50	500	500	50.0004	499.9993	199.9996	0	0	0.0004	0.0007	0	0.0007	0	0	99.9999	0.0001	0.0001	499.9998	45000
30	250	500	500	250	500	0	220	0	0	0	0	0	0	50	20.8812	7.7925	7.5332	568.9655	34666

**Table 5.6 Generation companies with capacity of different resources 2**

ed [RMB/MWh]	fd [RMB/MWh <sup>2</sup> ]	CVig1	CVig2	b11 [RMB/MWh]	b12 [RMB/MWh]	b21 [RMB/MWh]	b22 [RMB/MWh]
1000	5	-0.1	-0.1	30	50	150	250

Generation capacity [MW]				Lagrangian multipliers										Output [MWh]				Price [RMB /MWh]	Profit [RMB]
qg1_1	qg1_2	qg2_1	qg2_2	lamda1	lamda2	r11	r11	r12	r12	r21	r21	r22	r22	qg1_1	qg1_2	qg2_1	qg2_2		
150	150	150	150	30	150	0	0	20	0	0	0	100	0	76.092	0	49.4253	0	372.4138	37048
50	150	50	150	50	156.5789	0	20	0	0	0	6.5789	93.4211	0	50	23.6842	50	0	381.5789	37011
50	150	40	150	50	225.2632	0	20	0	0	0	75.2632	24.7368	0	50	28.9474	40	0	405.2632	39258
40	150	40	150	50	225.2632	0	20	0	0	0	75.2632	24.7368	0	40	38.9474	40	0	405.2632	39058
40	30	40	150	124.4737	250	0	94.4737	0	74.4737	0	100	0	0	40	30	40	2.1053	439.4737	40041
40	30	50	150	85	175	0	55	0	35	0	25	75	0	40	30	50	0	400	37800
40	30	150	150	71.8421	150	0	41.8421	0	21.8421	0	0	100	0	40	30	52.6316	0	386.8421	36844

**Table 5.7 Generation companies with capacity of different resources 3**

ed [RMB/MWh]	fd [RMB/MWh <sup>2</sup> ]	CVig1	CVig2	b11 [RMB/MWh]	b12 [RMB/MWh]	b21 [RMB/MWh]	b22 [RMB/MWh]
1000	5	-0.1	-0.1	150	250	160	260

Generation capacity [MW]				Lagrangian multipliers										Output [MWh]				Price [RMB /MWh]	Profit [RMB]
qg1_1	qg1_2	qg2_1	qg2_2	lamda1	lamda2	r11	r11	r12	r12	r21	r21	r22	r22	qg1_1	qg1_2	qg2_1	qg2_2		
50	100	60	100	225	180	0	75	25	0	0	20	80	0	50	0	60	0	450	32400
50	100	56	100	245	218	0	95	5	0	0	58	42	0	50	0	56	0	470	33360
50	100	55	100	249.9992	227.4996	0	99.9992	0.0008	0	0	67.4996	32.5004	0	50	0.0001	55	0	474.9996	33575
50	100	50	100	250	260	0	100	0	0	0	100	0	0	50	2.4904	50	0.2682	486.2069	33770

**Table 5.8 Generation companies with capacity of different resources 4**

ed [RMB/MWh]	fd [RMB/MWh <sup>2</sup> ]	<i>CVig1</i>	<i>CVig2</i>	Generation capacity [MW]			
1000	5	-0.1	-0.1	150	150	150	150

Cost of resource [RMB/MWh]				Lagrangian multipliers										Output [MWh]				Price	Profit
b11	b12	b21	b22	lamda1	lamda2	r11	r11	r12	r12	r21	r21	r22	r22	qg1_1	qg1_2	qg2_1	qg2_2	[RMB/MWh]	[RMB]
0	100	500	500	0	473.6842	0	0	100	0	26.3158	0	26.3158	0	105.2632	0	0	0	473.6842	49861
10	100	500	500	10	478.9474	0	0	90	0	21.0526	0	21.0526	0	104.2105	0	0	0	478.9474	48869
30	100	500	500	30	489.4737	0	0	70	0	10.5263	0	10.5263	0	102.1053	0	0	0	489.4737	46915
50	100	500	500	50	499.9999	0	0	50	0	0.0001	0	0.0001	0	100	0	0	0	500	45000
60	100	500	500	60	500	0	0	40	0	0	0	0	0	98.5441	0	0.3831	0.3831	503.4483	43702

**Table 5.9 Generation companies with capacity of different resources 5**

ed [RMB/MWh]	fd [RMB/MWh <sup>2</sup> ]	<i>CVig1</i>	<i>CVig2</i>	Generation capacity [MW]			
1000	5	0	0	100	100	100	100

Linear Complementary

Cost of resource [RMB/MWh]				Output [MWh]						
b11	b12	b21	b22	qg1_1	qg1_2	qg2_1	qg2_2	qg1	qg2	Profit [RMB]
150	250	160	260	57.3333	0	55.3333	0	57.3333	55.3333	31744
150	350	160	360	57.3333	0	55.3333	0	57.3333	55.3333	31744
50	150	60	160	64	0	62	0	64	62	39700
150	150	160	160	28.6667	28.6667	27.6667	27.6667	57.3333	55.3333	31744
50	250	500	500	93.3333	0	1.6667	1.6667	93.3333	3.3333	43611

Pure Game

Cost of technology [RMB/MWh]				Output [MWh]		Profit [RMB]		
b11	b12	b21	b22	qg1	qg2	Profit	Profit1	Profit2
150	250	160	260	57.3333	55.3334	31745	16436	15309
150	350	160	360	57.3333	55.3334	31745	16436	15309
50	150	60	160	64	62	39700	20480	19220
150	150	160	160	57.3333	55.3334	31745	16436	15309
50	250	500	500	93.3333	3.3334	43611.56	43556	55.5561

**Table 5.10 Linear complementary methodology VS Pure game methodology**

ed [RMB/MWh]	fd [RMB/MWh <sup>2</sup> ]	CVig1	CVig2	Generation capacity [MW]			
1000	5	0	0	100	100	100	100

Linear Complementary

Cost of resource [RMB/MWh]				Output [MWh]						Profit [RMB]
b11	b12	b21	b22	qg1_1	qg1_2	qg2_1	qg2_2	qg1	qg2	
150	250	160	260	57.3333	0	55.3333	0	57.3333	55.3333	31744
150	350	160	360	57.3333	0	55.3333	0	57.3333	55.3333	31744
50	150	60	160	64	0	62	0	64	62	39700
150	150	160	160	28.6667	28.6667	27.6667	27.6667	57.3333	55.3333	31744
50	250	500	500	93.3333	0	1.6667	1.6667	93.3333	3.3333	43611

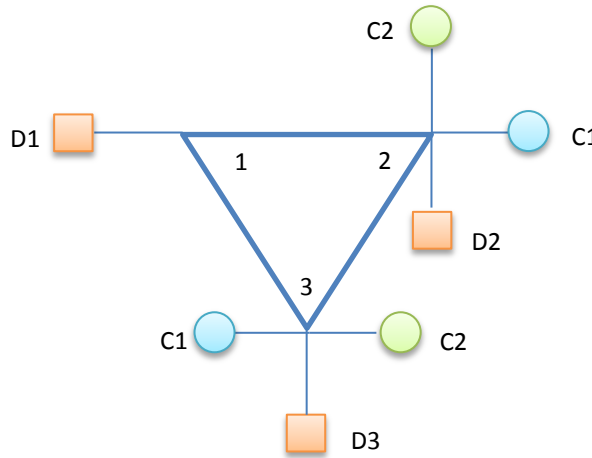
GA

Cost of technology [RMB/MWh]				Output [MWh]		Profit [RMB]
b11	b12	b21	b22	qg1	qg2	
150	250	160	260	57.3333	55.3333	31744
150	350	160	360	57.3333	55.3333	31744
50	150	60	160	64	62	39700
150	150	160	160	57.3333	55.3333	31744
50	250	500	500	93.3333	3.3333	43611

**Table 5.11 Linear complementary methodology VS Genetic algorithm**

### 5.2.4 Impact of Transmission Constraints on Generation Companies

The transmission constraints will have vital effect on the behaviors of generation companies. Theoretical analysis of transmission constraints and transmission capacity allocation has been conducted in Chapter 3 and Chapter 4. In this section case study of oligopolistic electricity market with integration of transmission constraints has been conducted to test the model developed in 4.2.4. A three nodes network is adopted, as shown in Figure 5.6. There is demand in all the three nodes. Company 1 has two branches and each is located in node 2 and node 3. The two branch companies are represented as company 1\_2 and company 1\_3 respectively. Company 2 has two branches and each is located in node 2 and node 3. The two branch companies are represented as company 2\_2 and company 2\_3.



**Figure 5.6 Network for transmission constraints**

To study mainly the behaviors and reactions of generation companies, all the electricity produced by generation companies is assumed to be consumed by retailers. The demand function on each node is given. The basic parameters are given in Table 5.12 and 5.13.

Node	Intercept of demand function $e_d$ [RMB/MWh]	Slope of demand function $f_d$ [RMB/MWh <sup>2</sup> ]	Transmission line	Transmission price $t_{xy}$ [RMB/MWh]	PTDF Value		
1	2800	10	12	10	0	-0.7510	-0.5005
2	3000	6.8	13	10	0	-0.2503	-0.5008
3	3200	6	23	10	0	0.2505	-0.5010

**Table 5.12 Basic parameters for impact of transmission constraints on generation companies 1**

Generation company	Cost [RMB/MWh]	Min_capacity [MW]	Max_capacity [MW]	$CV_{ig}$
1_2	60	0	300	-0.1
1_3	50	0	300	-0.11
2_2	70	0	300	-0.12
2_3	40	0	300	-0.14

**Table 5.13 Basic parameters for impact of transmission constraints on generation companies 2**

In the first simulation, we set both generation and transmission capacity very large. So there are no generation capacity limits or transmission constraints. The simulation results are listed in Table 5.14.

Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Sum [MWh]	$\lambda_{ij}$	$r_{ij}$	$r_{ij}$	$\Sigma(txyPTDFxyj)$
1_2	245.3629	54.7447	87.1409	103.4773	245.3629	7.508	0	0	7.508
1_3	250.8477	55.639	87.29	107.9187	250.8477	15.023	0	0	15.023
2_2	246.2379	54.8525	87.4502	103.9352	246.2379	7.508	0	0	7.508
2_3	264.409	58.7427	92.045	113.6212	264.4089	15.023	0	0	15.023
Sum	1006.858	223.9789	353.9261	428.9524	1006.857				

**Table 5.14 Impact of transmission constraints on generation companies 1**

As can be seen from the lagrangian multipliers value in Table 5.14, constraints set by Equation 4.47, 4.51, 4.52, 4.53 are all satisfied. To further analyze the effect of transmission cost, different transmission costs are set. The simulation results are listed in 5.15.

Transmission line	txy [RMB/MWh]	Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Sum of all the lines [MWh]
12	10	1_2	245.3629	54.7447	87.1409	103.4773	245.3629
13	10	1_3	250.8477	55.639	87.29	107.9187	250.8477
23	10	2_2	246.2379	54.8525	87.4502	103.9352	246.2379
		2_3	264.409	58.7427	92.045	113.6212	264.4089
		Sum	1006.8575	223.9789	353.9261	428.9524	1006.8574

Transmission line	txy [RMB/MWh]	Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Sum of all the lines [MWh]
12	50	1_2	246.8939	55.5217	91.1977	100.1745	246.8939
13	50	1_3	244.7131	53.0472	81.4632	110.2027	244.7131
23	50	2_2	247.8037	55.6472	91.5993	100.5573	247.8038
		2_3	258.0603	56.0605	86.0149	115.985	258.0604
		Sum	997.471	220.2766	350.2751	426.9195	997.4712

Transmission line	txy [RMB/MWh]	Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Sum of all the lines [MWh]
12	100	1_2	248.8077	56.4929	96.2687	96.0461	248.8077
13	100	1_3	237.0448	49.8074	74.1796	113.0578	237.0448
23	100	2_2	249.761	56.6404	96.7855	96.335	249.7609
		2_3	250.1246	52.7077	78.4772	118.9397	250.1246
		Sum	985.7381	215.6484	345.711	424.3786	985.738

Transmission line	txy [RMB/MWh]	Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Sum of all the lines [MWh]
12	150	1_2	250.7215	57.4641	101.3398	91.9176	250.7215
13	150	1_3	229.3765	46.5676	66.896	115.9129	229.3765
23	150	2_2	251.7182	57.6337	101.9718	92.1127	251.7182
		2_3	242.1888	49.3549	70.9395	121.8944	242.1888
		Sum	974.005	211.0203	341.1471	421.8376	974.005

Transmission line	txy [RMB/MWh]	Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Sum of all the lines [MWh]
12	200	1_2	252.6352	58.4353	106.4108	87.7891	252.6352
13	200	1_3	221.7082	43.3278	59.6124	118.768	221.7082
23	200	2_2	253.6755	58.627	107.1581	87.8904	253.6755
		2_3	234.253	46.0021	63.4019	124.849	234.253
		Sum	962.2719	206.3922	336.5832	419.2965	962.2719

**Table 5.15 Impact of transmission constraints on generation companies 2**

As can be seen from Table 5.15, with the increase of transmission cost, the total output of generation companies decreases. Meanwhile, more electricity will be sold to local market and less will be sold through transmission line due to the increasing cost of line use, which is the practical response of real electricity market, where the primary objective of the market



participant is profit maximization. More specifically trend of contracted quantity over the change of transmission cost is shown in Figure 5.7, 5.8, 5.9.

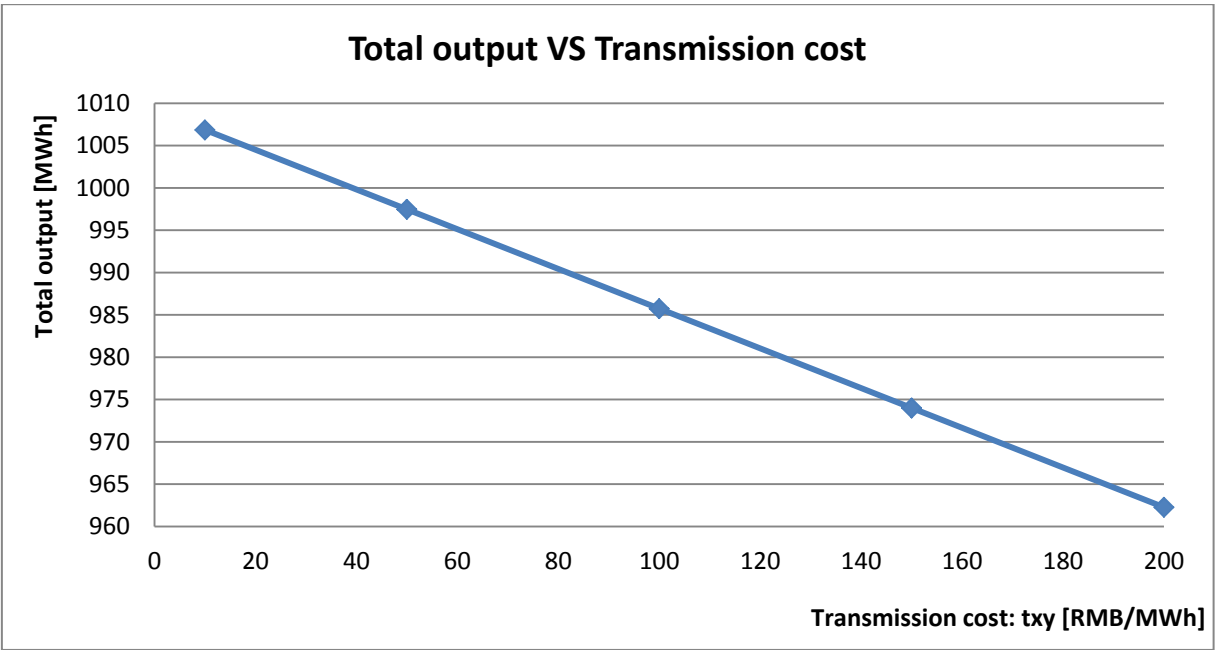


Figure 5.7 Impact of transmission price on total output of generation companies

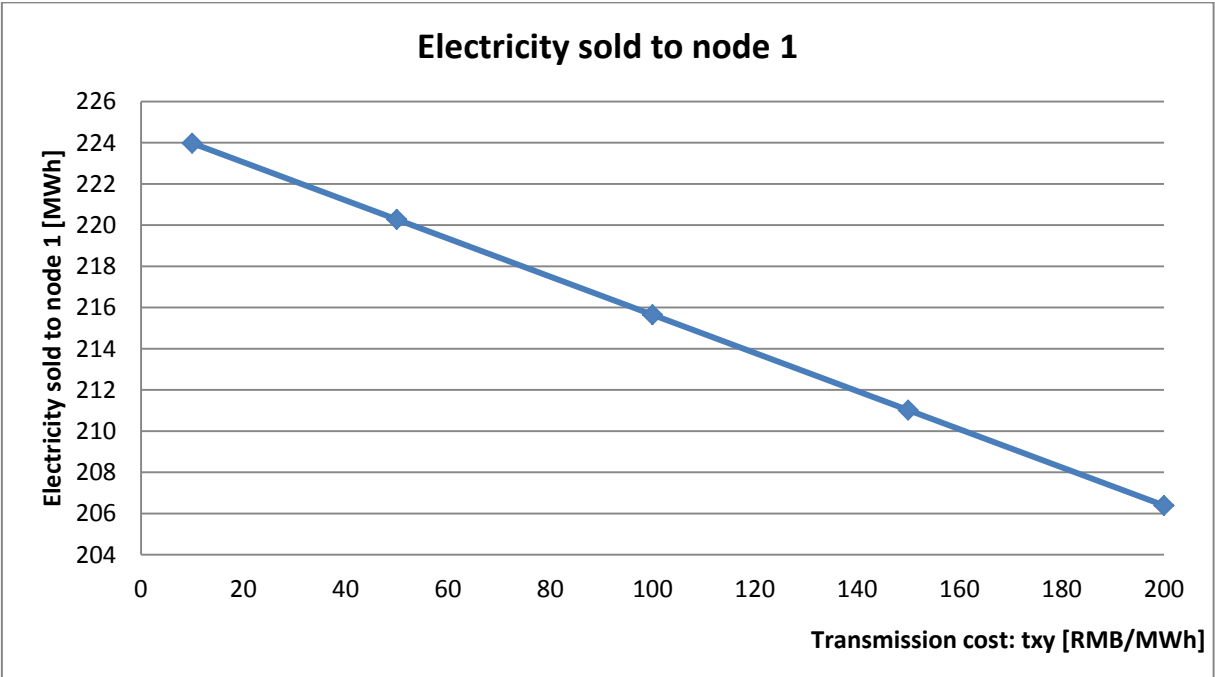


Figure 5.8 Impact of transmission price on electricity sold to node 1

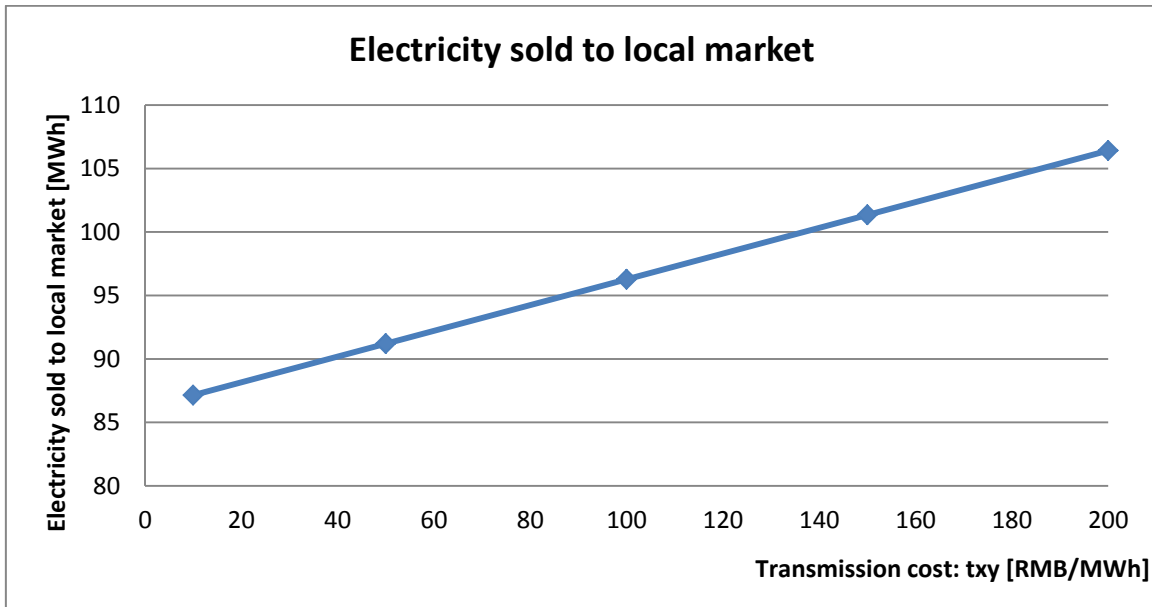


Figure 5.9 Impact of transmission price on electricity sold to local market

### 5.3 Oligopsonistic Electricity Market Case Study

This section is focused on the case study of oligopsonistic electricity market. Sensitivity analysis of inverse generation curve slope and intercept will be conducted. Effects of retail price and CV values on retailers are analyzed as well.

#### 5.3.1 Impact of Inverse Generation Curve Slope and Intercept on Retailers

As analyzed in chapter 4, the main behaviors of retailers are their internal interactions and their response to the generation function and retail price. Thus sensitivity analysis of generation curve slope and intercept is conducted based on the model summarized in 4.3.2. The purchased amount of electricity and purchasing price are calculated. The basic parameters are listed in Table 5.16. To simplify, the retail price for all the companies is the same and no purchasing limits have been set to the retailers.

Company	$CV_{id}$	$Pr$ [RMB/MWh]
1	-0.3	650
2	-0.4	650
3	-0.5	650
4	-0.6	650

Table 5.16 Basic parameters of oligopsonistic electricity market

The intercept of inverse generation function is first set to 200 RMB/MWh, and the value of slope is changed. The value of slope ranges from 0.1763 RMB/MWh<sup>2</sup> to 11.43 RMB/MWh<sup>2</sup>. Different values of slope indicate different competitiveness of generation companies. The purchased value of the retailers are listed in Table 5.17. **(Intercept: 200 RMB/MWh)**

Slope [RMB/MWh]	Retail1 [MWh]	Retail2 [MWh]	Retail3 [MWh]	Retail4 [MWh]	Total purchased value [MWh]	Price [RMB/MWh]
0.176326981	424.168	494.863	593.835	742.294	2255.16	597.6454
0.363970234	205.49	239.738	287.686	359.608	1092.522	597.6454
0.577350269	129.544	151.135	181.3616	226.702	688.7426	597.6454
0.839099631	89.134	103.99	124.7875	155.984	473.8955	597.6454
1.191753593	62.758	73.218	87.8614	109.827	333.6644	597.6454
1.732050808	43.181	50.378	60.4539	75.567	229.5799	597.6454
2.747477419	27.222	31.759	38.111	47.639	144.731	597.6454
5.67128182	13.188	15.386	18.463	23.079	70.116	597.6454
11.4300523	6.544	7.634	9.1609	11.451	34.7899	597.6454

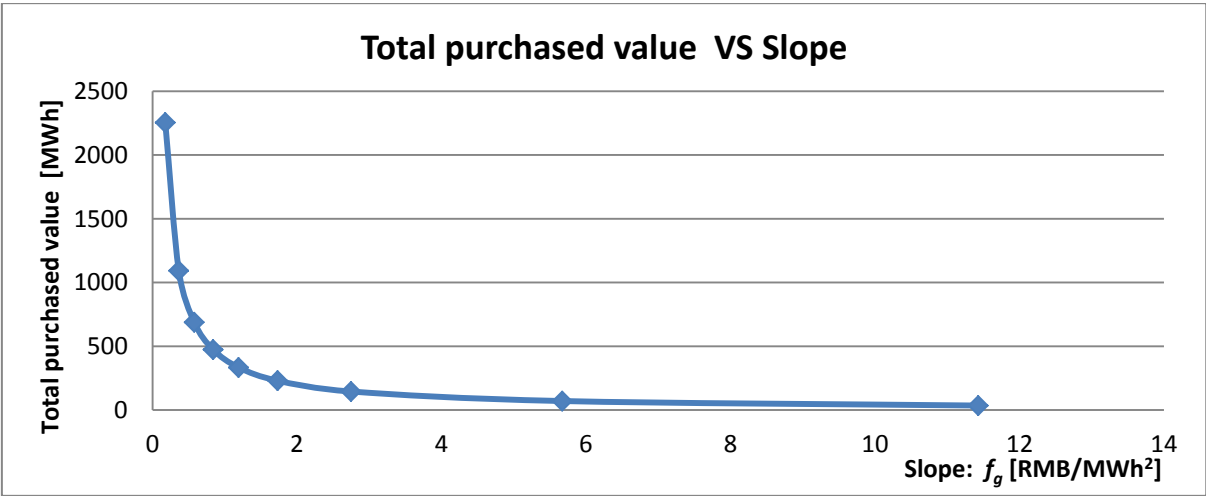
**Table 5.17 Impact of slope of inverse generation function on the purchased value of retailers**

Similar to the analysis in 5.2.1, the purchasing price is a function of intercept of generation function,  $CV_{ig}$  value and retail price  $Pr$ . Once all the three parameters are fixed, the purchasing price is fixed.



**Figure 5.10 Impact of slope of inverse generation function on the purchased value of retailer 1**

As it can be seen from Figure 5.10, the purchased value of company 1 decreases with the increase of the slope of inverse generation function. The purchased value changes fast in the low slope region, while in the large slope region, the purchased value changes more modestly. This is mainly because with higher slope, the generation market will be more competitive. The output will tend to be more stable when the market is moving towards perfect competition. The total purchased quantity of electricity has similar decreasing trend with the increase of slope, as shown in Figure 5.11.



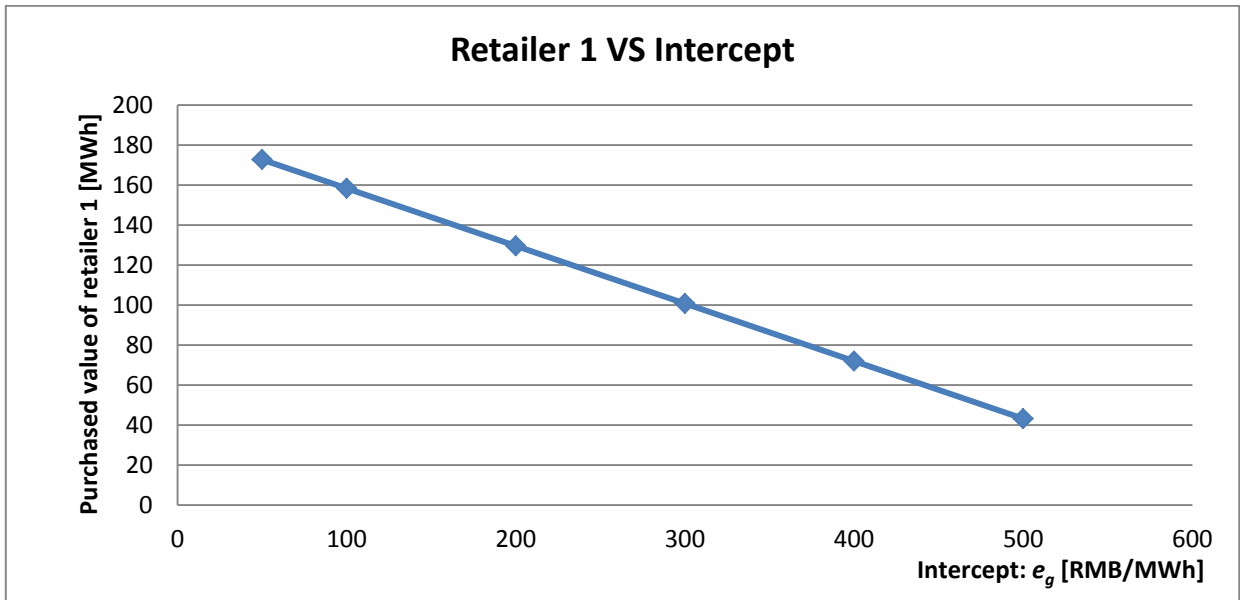
**Figure 5.11 Impact of slope of inverse generation function on the total purchased value**

Secondly the slope of inverse generation function is fixed as 0.57735 RMB/MWh<sup>2</sup> (30 %), and the value of intercept is changed. The value of intercept ranges from 50 RMB/MW to 500 RMB/MWh. Different values of intercept indicate different willingness of generation companies to sell. The purchased values of all the retailers are listed in Table 5.18.

**(Slope: 0.57735 RMB/MWh<sup>2</sup>)**

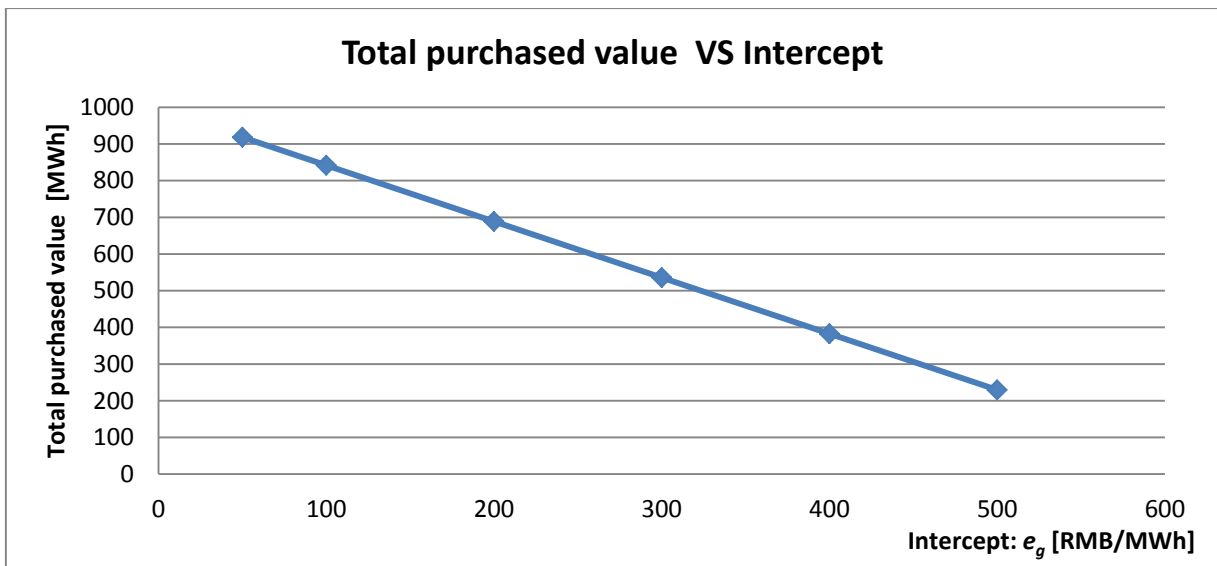
Slope [RMB/MWh]	Retail1 [MWh]	Retail2 [MWh]	Retail3 [MWh]	Retail4 [MWh]	Total purchased value [MWh]	Price [RMB/MWh]
50	172.725	201.513	241.815	302.269	918.322	580.194
100	158.332	184.72	221.664	277.08	841.796	586.011
200	129.544	151.135	181.362	226.702	688.743	597.645
300	100.756	117.549	141.059	176.324	535.688	609.28
400	71.969	83.964	100.756	125.946	382.635	620.914
500	43.181	50.378	60.454	75.567	229.58	632.549

**Table 5.18 Impact of intercept of inverse generation function on the purchased value of retailers**

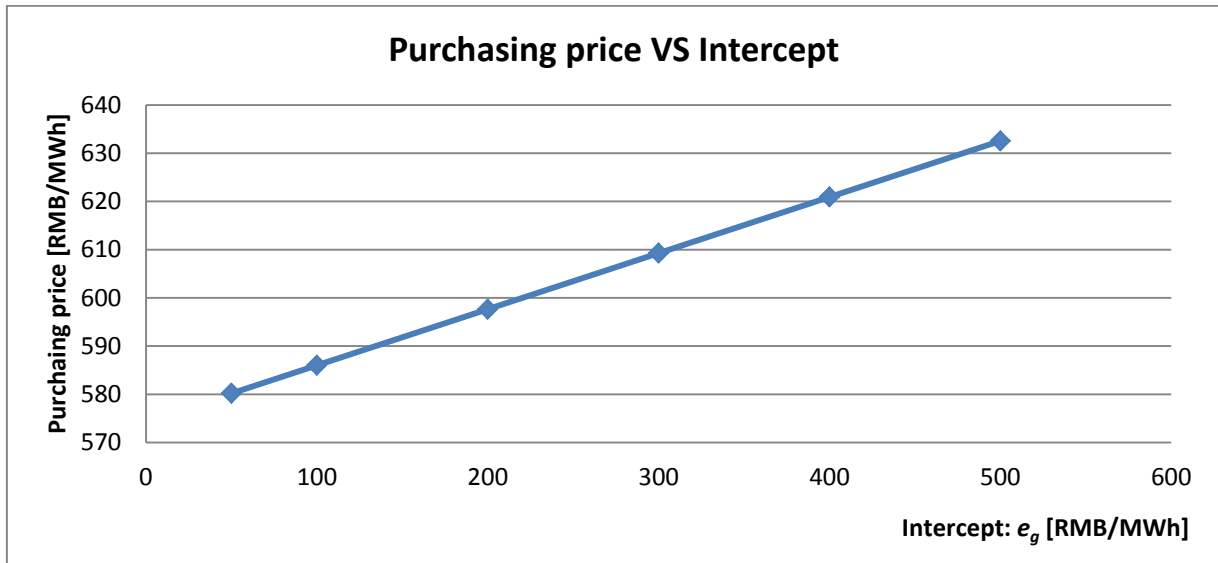


**Figure 5.12 Impact of intercept of inverse generation function on the purchased value of retailers**

It is obvious that the purchased value of retailers will decrease with the increase of the intercept of inverse generation curve, as shown in Figure 5.12 and 5.13. This is due to the fact that with a larger intercept, the generation companies will sell at higher prices, thus the purchasing willingness of retailers will be weaker. The purchasing price of retailers will grow alongside the increase of the inverse generation curve intercept, as shown in Figure 5.14.



**Figure 5.13 Impact of intercept of inverse generation function on the total purchased value**



**Figure 5.14 Impact of intercept of inverse generation function on the purchasing price**

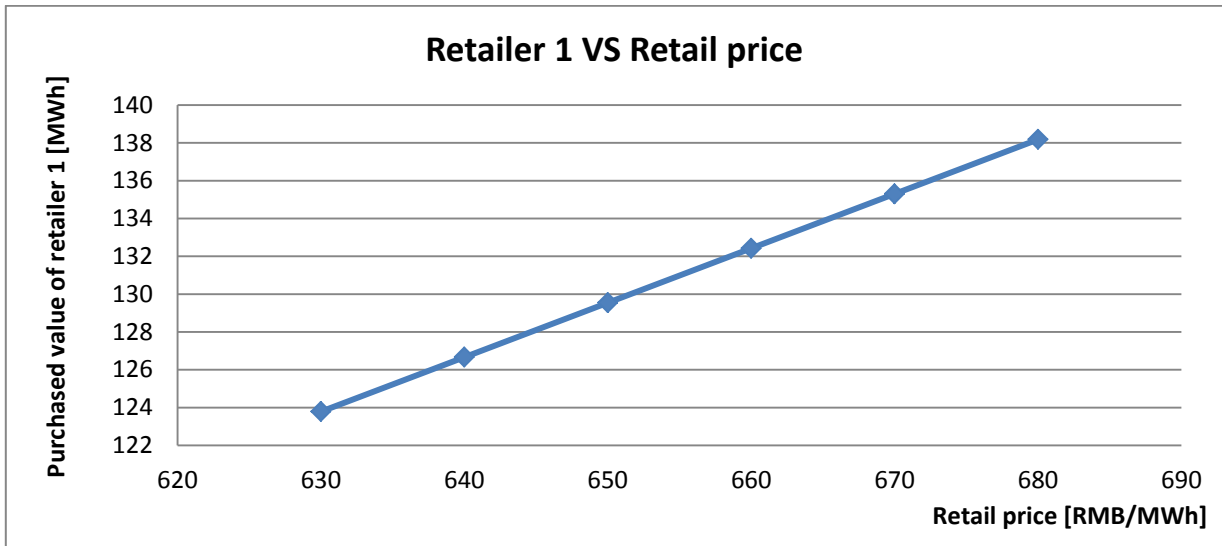
Therefore, unlike the case of oligopolistic electricity market, the increase of slope and intercept of inverse generation function will both have negative effects on the purchased value of retailers.

### 5.3.2 Impact of Retail Price on Retailers

As one of the most important factors of oligopsonistic electricity market, the retail price will affect the willingness of retailers to purchase and the profit of retailers. Hence, in this section, sensitivity analysis of retail price is conducted based on the model in 4.3.2 to see the specific effect of retail price on retailers' behaviors. The purchased amount of electricity and purchasing price are calculated. The results are listed in Table 5.19.

Retail price [RMB/MWh]	Retail1 [MWh]	Retail2 [MWh]	Retail3 [MWh]	Retail4 [MWh]	Total purchased value [MWh]	Purchasing price [RMB/MWh]
630	123.787	144.418	173.301	216.626	658.132	579.9723
640	126.665	147.776	177.331	221.664	673.436	588.8089
650	129.544	151.135	181.362	226.702	688.743	597.6454
660	132.423	154.493	185.392	231.74	704.048	606.482
670	135.302	157.852	189.422	236.778	719.354	615.3186
680	138.18	161.21	193.452	241.815	734.657	624.1551

**Table 5.19 Impact of retail price on retailers**



**Figure 5.15 Impact of retail price on retailers**

As can be seen from Figure 5.15 and 5.16, both the purchased value and purchasing price of retailers increase with the growth of retail price. The main reason is that with higher retail price, the revenue of retailers will be better guaranteed. Therefore the retailers will have more incentive to buy more electricity at higher price.



**Figure 5.16 Impact of retail price on retailers' purchasing price**

### 5.3.3 Impact of $CV_{id}$ Values on Retailers

As discussed in Chapter 4,  $CV_{id}$  is the conjecture variation value of all the rivals' reaction over the change of purchased value of retailer  $i$ . Different values of  $CV_{id}$  indicates different strategies and market competitiveness. In this research the range of  $CV_{id}$  is between -1 and 0. When the value goes towards -1, the oligopsonistic electricity market will move towards perfect competition. To see more specifically the effect of  $CV_{id}$ , sensitivity analysis has been conducted to test the model in 4.3.2. The purchased value of electricity and purchasing price are calculated. The results are listed in Table 5.20. The slope and intercept are fixed at the value of  $f_g=0.57735$  RMB/MW<sup>2</sup> and  $e_g=200$  RMB/MW.

Company	Case 1		Case 2		Case 3		Case 4	
	$CV_{id}$	Purchased amount [MWh]	$CV_{id}$	Purchased amount [MWh]	$CV_{id}$	Purchased amount [MWh]	$CV_{id}$	Purchased amount [MWh]
1	-0.4	169.4398	-0.7	278.3654	-0.7	255.5486	-0.7	261.6769
2	-0.4	169.4398	-0.4	139.1827	-0.6	191.6614	-0.6	196.2576
3	-0.4	169.4398	-0.4	139.1827	-0.4	127.7743	-0.4	130.8384
4	-0.4	169.4398	-0.4	139.1827	-0.4	127.7743	-0.3	112.1472
<b>Total purchased amount [MWh]</b>		677.7592		695.9135		702.7586		700.9201
<b>Purchasing price [RMB/MWh]</b>		591.3043		601.7857		605.7377		604.6763

**Table 5.20 Impact of  $CV_{id}$  Values on retailers**

As can be seen from the results of case 2, with  $CV_{id}$  value of company 1 becoming smaller, the purchased value of this company grows up, meanwhile the total purchased value of all the retailers increases and the price goes up. This is mainly because, with  $CV_{id}$  moving towards -1, the competition is close to the perfect environment, as one retailer decreases the quantity, the others will act aggressively, step in the market and fill in the gap caused by that reduction in the quantity. Due to higher competitiveness, the total purchased value increases and the market purchasing price goes up, which are the common phenomena in case 2, 3, 4. On the contrary, if the  $CV_{id}$  value increases, the purchased quantity of this company will decrease,



indicating more modest reaction over the rivals strategy change, which is the case of company 4 in case 4.

## 5.4 Market Equilibrium Case Study

In this session, market equilibrium case study has been conducted to test the market equilibrium developed in 4.51. The contract quantity, price and total profit of all the market participants are calculated. At first basic case of single nodal market has been analyzed to solve the optimal market equilibrium. Besides, generation companies with multi-resources are investigated to see their behaviors and market strategies in capacity allocation to maximize the profits. Meanwhile, the effect of transmission constraints on the market equilibrium has been analyzed. In this case, several nodal markets coexist at the same time. The profits of all the market participants are summed together as the objective function. Sensitivity analysis on transmission price has been conducted.

### 5.4.1 Market Equilibrium in Single Market

The basic parameters for single market case study are listed in Table 5.21. The software Matlab is adopted and Genetic Algorithm (GA) has been applied as the optimization toolbox. The calculated results after three repeating times are listed in Table 5.22. As can be seen from Table 5.22, the optimal solution of the market equilibrium arrives at the point  $e_d=2482.2$  RMB/MWh,  $e_g=30$  RMB/MWh,  $f_d=6.1$  RMB/MWh<sup>2</sup>,  $f_g=1.5$  RMB/MWh<sup>2</sup> and the corresponding profit is 145080 RMB. The demand slope is relatively big, indicating demand inelastic, which is the practical case in real electricity market. The slope of generation function is 1.5 RMB/MWh<sup>2</sup>, a medium value, indicating that with six generation companies, certain competition can be achieved in the oligopolistic electricity market.

Generation Company	Cost [RMB/MWh]	Capacity [MWh]	$CV_{ig}$	Retailer	Retail Price [RMB/MWh]	$CV_{id}$
1	150	100	-0.015	1	640	-0.09
2	160	100	-0.02	2	650	-0.12
3	170	100	-0.03	2	660	-0.2
4	250	50	-0.1			
5	260	50	-0.15			
6	270	50	-0.2			

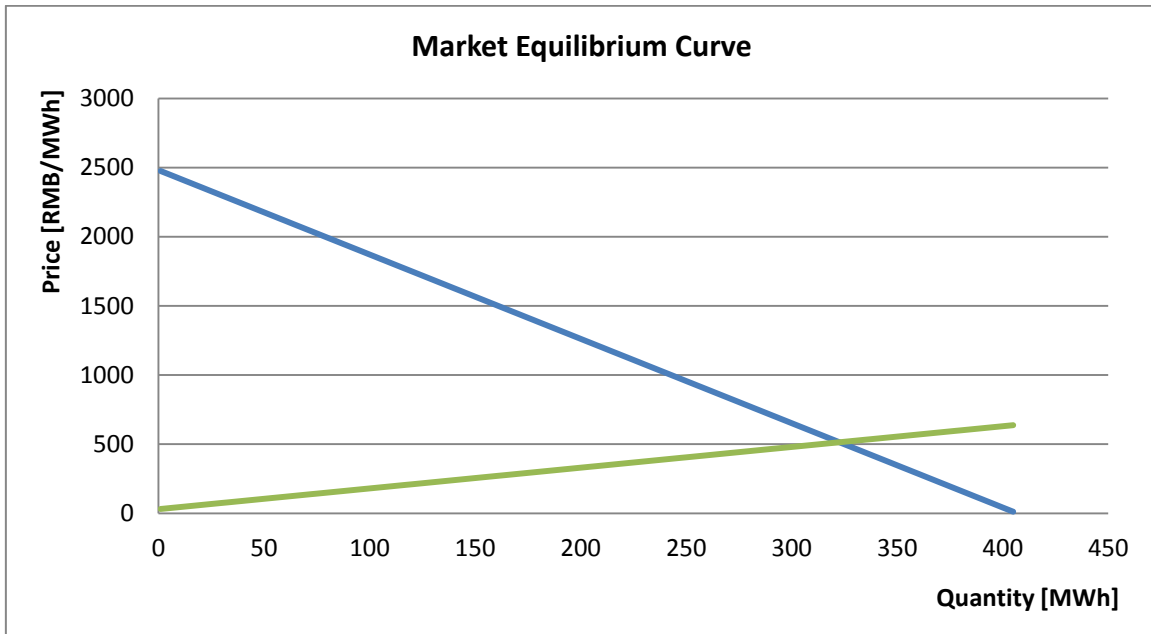
**Table 5.21 Basic parameters for market equilibrium**

Intercept of demand curve $e_d$ [RMB/MWh]	Intercept of generation curve $e_g$ [RMB/MWh]	Slope of demand curve $f_d$ [RMB/MWh <sup>2</sup> ]	Slope of generation curve $f_g$ [RMB/MWh <sup>2</sup> ]	Total profit [RMB]	$Q_d$ [MWh]	$Q_g$ [MWh]	$P_d$ [RMB/MWh]	$P_g$ [RMB/MWh]	$q_d$ [MWh]	$q_g$ [MWh]
2482.2	30	6.1	1.5	145080	325.4863	325.4863	512.1065	512.1065	94.8849	60.737
									105.7916	59.361
									124.8099	58.2697
										48.1159
										49.0025
										50

Intercept of demand curve $e_d$ [RMB/MWh]	Intercept of generation curve $e_g$ [RMB/MWh]	Slope of demand curve $f_d$ [RMB/MWh <sup>2</sup> ]	Slope of generation curve $f_g$ [RMB/MWh <sup>2</sup> ]	Total profit [RMB]	$Q_d$ [MWh]	$Q_g$ [MWh]	$P_d$ [RMB/MWh]	$P_g$ [RMB/MWh]	$q_d$ [MWh]	$q_g$ [MWh]
2482.2	30	6.1	1.5	145080	325.4863	325.4863	512.1065	512.1065	94.8849	60.737
									105.7916	59.361
									124.8099	58.2697
										48.1159
										49.0025
										50

Intercept of demand curve $e_d$ [RMB/MWh]	Intercept of generation curve $e_g$ [RMB/MWh]	Slope of demand curve $f_d$ [RMB/MWh <sup>2</sup> ]	Slope of generation curve $f_g$ [RMB/MWh <sup>2</sup> ]	Total profit [RMB]	$Q_d$ [MWh]	$Q_g$ [MWh]	$P_d$ [RMB/MWh]	$P_g$ [RMB/MWh]	$q_d$ [MWh]	$q_g$ [MWh]
2482.2	30	6.1	1.5	145080	325.4863	325.4863	512.1065	512.1065	94.8849	60.737
									105.7916	59.361
									124.8099	58.2697
										48.1159
										49.0025
										50

**Table 5.22 Market equilibrium with GA**



**Figure 5.17 Market equilibrium curve**

The market equilibrium curve is shown in Figure 5.17. To further confirm the result is global optimal solution, the Matlab Pattern Search Optimization Toolbox is adopted as comparison. The methodology is briefly described in the end of Chapter 4. First three random combinations of initial values of slope and intercept for inverse demand and generation functions,  $e_d$ ,  $e_g$ ,  $f_d$ ,  $f_g$ , are set, and different results of equilibrium points are achieved. However, none of the profits in these three cases is equal to or bigger than the optimal equilibrium point solved with GA. Then, the optimal result achieved with GA is used as the initial input values of  $e_d$ ,  $e_g$ ,  $f_d$ ,  $f_g$  in Pattern Search and the calculated optimal solution is the same as the initial input values. This enhances the probability that the result achieved with GA is to be the global optimal solution.

The portable PC HP Probook 440 G1 with Intel® Core™ i5-4200M CPU @2.50GHz, RAM 3.88GB and Windows 7, 64 bit system, is used for the implementation of the model. The simulation time in GA is 19.09 s and simulation time in Pattern Search is 192.48 s. The calculation with GA is much faster than Pattern Search. Thus, GA has advantages in finding global optimal solution and calculation speed. The results are shown in Table 5.23.

Intercept of demand curve ed [RMB/MWh]	Intercept of generation curve eg [RMB/MWh]	Slope of demand curve fd [RMB/MWh <sup>2</sup> ]	Slope of generation curve fg [RMB/MWh <sup>2</sup> ]	Total profit [RMB]	Qd [MWh]	Qg [MWh]	Pd [RMB/MWh]	Pg [RMB/MWh]	qd [MWh]	qg [MWh]
Initial input				105279.2675	236.7609	236.7609	572.3036	572.3036	64.68163	42.87346
3000	300	10	1						76.76707	42.07179
Final result									95.3122	41.4746
2939.9	300	10	1.2							35.81151
										36.7416
										37.78795
Intercept of demand curve ed [RMB/MWh]	Intercept of generation curve eg [RMB/MWh]	Slope of demand curve fd [RMB/MWh <sup>2</sup> ]	Slope of generation curve fg [RMB/MWh <sup>2</sup> ]	Total profit [RMB]	Qd [MWh]	Qg [MWh]	Pd [RMB/MWh]	Pg [RMB/MWh]	qd [MWh]	qg [MWh]
Initial input				99193.23312	223.0955	223.0955	599.9185	599.9185	55.81322	39.96238
2000	40	3	0.5						72.11557	39.27352
Final result									95.16672	38.77646
3149.9	423.9	11.4	0.8							34.0156
										34.98723
										36.08032

Intercept of demand curve ed [RMB/MWh]	Intercept of generation curve eg [RMB/MWh]	Slope of demand curve fd [RMB/MWh <sup>2</sup> ]	Slope of generation curve fg [RMB/MWh <sup>2</sup> ]	Total profit [RMB]	Qd [MWh]	Qg [MWh]	Pd [RMB/MWh]	Pg [RMB/MWh]	qd [MWh]	qg [MWh]
Initial input				87031.82352	195.6156	195.6156	552.3581	552.3581	55.11602	35.73801
3500	100	5	2						63.49815	35.0276
Final result									77.00144	34.48676
2788.2	210.5	11.4	1.7							29.39226
										30.09193
										30.87906

Intercept of demand curve ed [RMB/MWh]	Intercept of generation curve eg [RMB/MWh]	Slope of demand curve fd [RMB/MWh <sup>2</sup> ]	Slope of generation curve fg [RMB/MWh <sup>2</sup> ]	Total profit [RMB]	Qd [MWh]	Qg [MWh]	Pd [RMB/MWh]	Pg [RMB/MWh]	qd [MWh]	qg [MWh]
Initial input				143260	321.4043	321.4043	512.1065	512.1065	93.6949	59.97533
2482.2	30	6.1	1.5						104.4648	58.61658
Final result									123.2446	57.53898
2482.2	30	6.1	1.5							47.51249
										48.388
										49.37294

**Table 5.23 Market equilibrium with Pattern Search**

With the introduction of competition to retail market, more retailers will be encouraged to establish. Thus, in this research, the sensitivity analysis of retail price and the number of retailers are conducted and the effect on market equilibrium is studied as well. First the retail

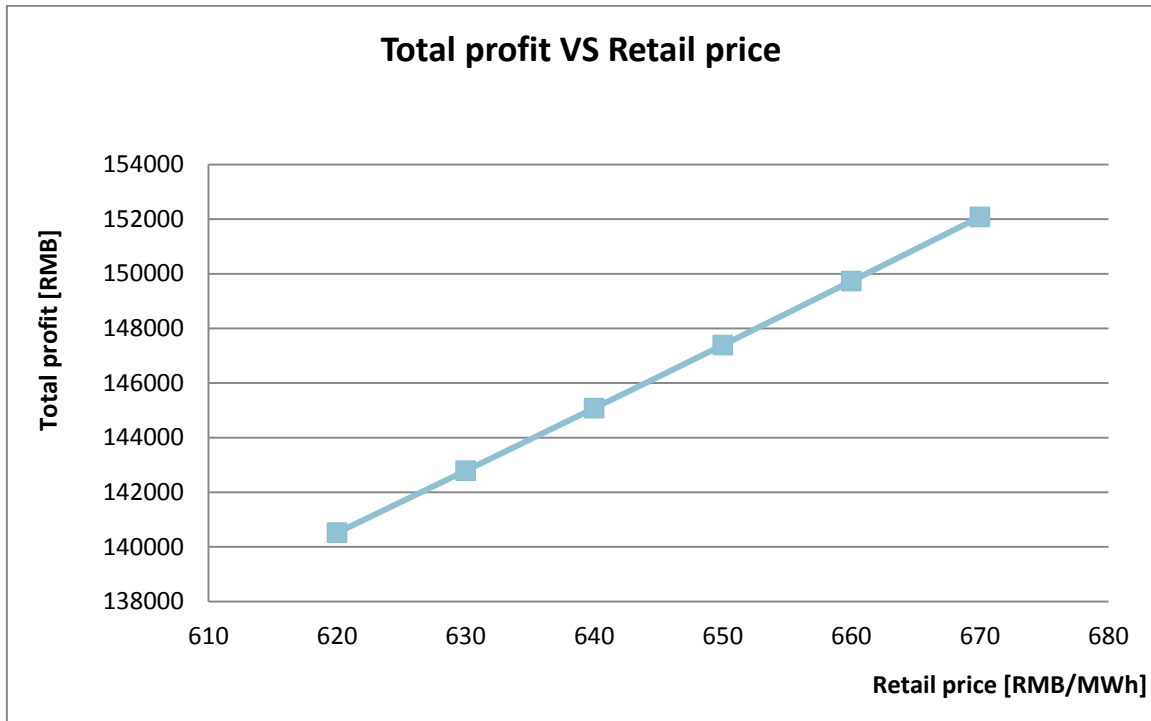
price is changed and the corresponding results are listed in Table 5.24. It is obvious that both the contract price and total profit increase with the retail price. With higher retail price, the profit of retailers is better guaranteed and they are willing to buy at higher price to have more market share. This can be seen from the increasing of the intercept and slope of demand function. More specifically the trend of contract price and total profit over retail price is shown in Figure 5.18 and 5.19.

Retail price [RMB/MWh]			Intercept of demand curve ed [RMB/MWh]	Intercept of generation curve eg [RMB/MWh]	Slope of demand curve fd [RMB/MWh <sup>2</sup> ]	Slope of generation curve fg [RMB/MWh <sup>2</sup> ]	Quantity [MWh]	Price [RMB/MWh]	Profit [RMB]
com1	com2	com3							
620	630	640	2364	30	5.7	1.4	329.6925	496.57	140520
630	640	650	2423.1	30	5.9	1.4	327.5197	504.34	142790
640	650	660	2482.2	30	6.1	1.5	325.4863	512.11	145080
650	660	670	2541.3	30	6.2	1.5	323.5794	519.88	147390
660	670	680	2600.3	30	6.4	1.5	321.7875	527.65	149730
670	680	690	2659.4	30	6.6	1.6	320.1006	535.42	152080

Table 5.24 Impact of retail price on market equilibrium



Figure 5.18 Impact of retail price on the contract price



**Figure 5.19 Impact of retail price on total profit**

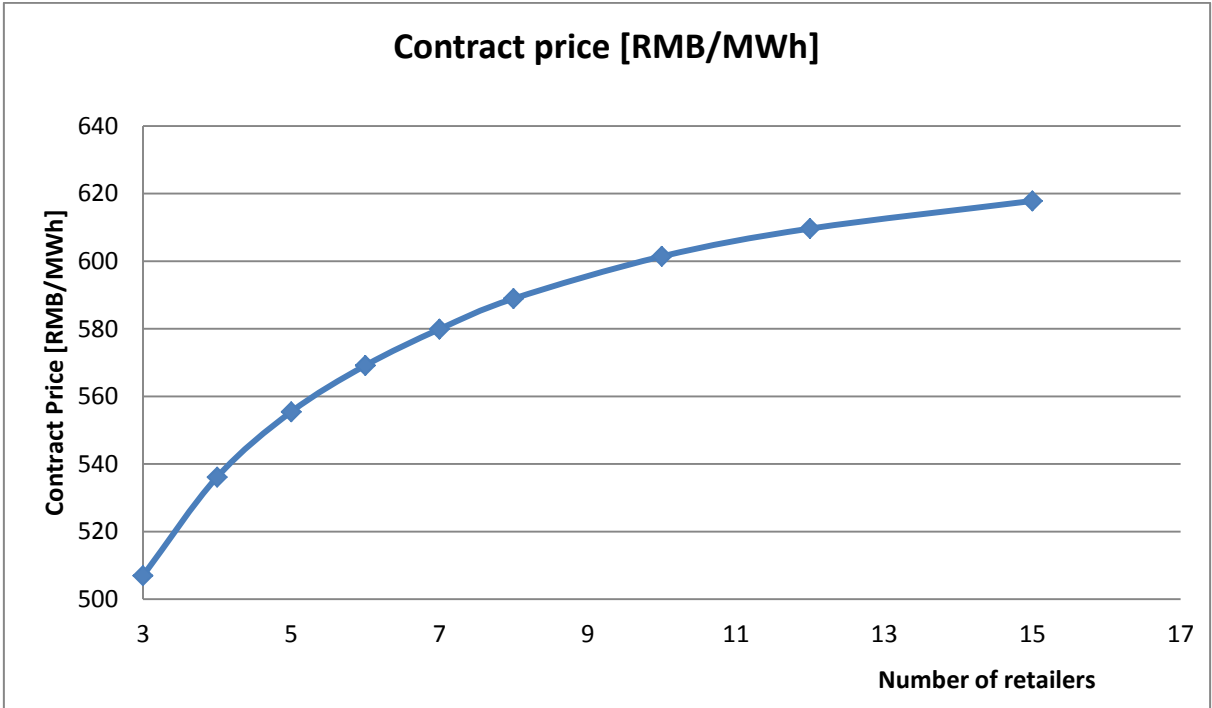
Second the number of retailers is changed and the corresponding results are listed in Table 5.25. The parameters for all the retailers are set as the same value, with retail price equals to 650 RMB/MW,  $CV_{id}$  equals to -0.1.

NO. of companies	Intercept of demand curve $e_d$ [RMB/MWh]	Intercept of generation curve $e_g$ [RMB/MWh]	Slope of demand curve $f_d$ [RMB/MWh <sup>2</sup> ]	Slope of generation curve $f_g$ [RMB/MWh <sup>2</sup> ]	Quantity [MWh]	Price [RMB/MWh]	Profit [RMB]
3	2442.70	30.00	5.90	1.50	326.83	506.92	145430
4	2664.80	30.00	6.70	1.60	319.95	536.12	142120
5	2811.60	30.00	7.10	1.70	316.18	555.42	140300
6	2915.80	30.00	7.50	1.70	313.80	569.13	139150
7	2997.60	34.60	7.70	1.70	312.07	579.89	138320
8	3066.30	46.00	8.00	1.70	310.72	588.92	137660

**Table 5.25 Impact of number of retailers on market equilibrium**

With more retailers, there will be more competition in the oligopsonistic electricity market. The purchasing price will be higher due to more competition between retailers. The

corresponding intercept and slope of demand function will be higher as well, indicating stronger willingness to pay and more demand inelastic.



**Figure 5.20 Impact of number of retailers on contract price**

The trend of contract price over the increase of the number of retailers is shown in Figure 5.20. Apart from the increasing trend due to more competition, the price increasing speed will decrease. As more retailers exist in the market, the market will move towards perfect competition environment and the contract price will turn stable.

**5.4.2 Market Equilibrium for Generation Companies with Capacity of Different Resources**

Generally a big generation company normally has generation capacity of different resources. Case study of generation companies’ behaviors and strategy in capacity allocation over given demand function is analyzed in detail in Chapter 5.2.3. This section is focused on the case study of market equilibrium for generation companies with capacity of different resources. The contract quantity, price and total profit of all the market participants are calculated. First a comparison between multi-resource model and single resource model is conducted by setting the generation cost of different resources at the same value in one generation company. In this

case, the multi-resource model turns to be a single resource model. The costs of resources are 150 RMB/MWh and 250RMB/MWh for the two companies respectively. The input parameters are listed in Table 5.26 and simulation results are listed in Table 5.26. The index company 1\_1 represents generation company 1 resource 1 and qg1\_1 represents output of generation resource 1 in company 1. It is clear that the results solved by the two models are exactly the same, as shown in Table 5.27. It demonstrates the accuracy of the multi-resource model.

To further study the market equilibrium situation for multi-resource companies, more generation companies are introduced. The basic parameters for generation companies and retailers are shown in Table 5.28. The results are shown in Table 5.29. When the company has multiple generation resources, priority is always given to cheap resources. And the capacity of cheaper resource will be fully used first. After the capacity of cheaper resources is fully used, if the demand is still high, the company will start to produce from more expensive resources. This is the case of company 3 resource 1. At first the generation capacity is big enough and there is no output from resource 2 in company 3 due to its high generation cost. However when the capacity of resource 1 is limited to 100 MW, to satisfy the demand, the company has a full output from technology 1 and an extra 22.287MWh from technology 2. The results of limited capacity are shown in Table 5.30.

Another very ample phenomenon is that the total output decreases when more expensive technologies are adopted. And the corresponding contract price increases. This is mainly because with the objective of profit maximization, the consumption tends to be lower due to the higher generation cost. This can be confirmed with the comparison of profits in the two cases. The profit is 512337.9 RMB in case 1 and decreases to 475368.9 RMB when the generation cost increases in case 2.

Generation company	Cost [RMB/MWh]	Min_capacity [MW]	Max_capacity [MW]	CVig	Retailer	Retail price [RMB/MWh]	Cvid
1_1	150	0	500	-0.1	1	640	-0.09
1_2	150	0	500	-0.1	2	650	-0.12
2_1	250	0	500	-0.1	3	660	-0.2
2_2	250	0	500	-0.1			

**Table 5.26 Basic parameters for generation companies and retailers 1**



Multi-resource model														
ed [RMB /MWh]	eg [RMB /MWh]	fd [RMB /MWh <sup>2</sup> ]	fg [RMB /MWh <sup>2</sup> ]	profit [RMB]	qg1_1 [MWh]	qg1_2 [MWh]	qg2_1 [MWh]	qg2_2 [MWh]	qg1 [MWh]	qg2 [MWh]	Qg [MWh]	Qd [MWh]	Pg [RMB /MWh]	Pd [RMB /MWh]
1205.7	30	0.9	0.6	368140	225.6987	239.643	54.1352	282.6969	465.3417	336.8321	802.1738	802.1738	512.1065	512.1065
1205.7	30	0.9	0.6	368140	325.7448	139.5969	47.9865	288.8456	465.3417	336.8321	802.1738	802.1738	512.1065	512.1065
1205.7	30	0.9	0.6	368140	306.6834	158.6579	228.2923	108.5395	465.3413	336.8318	802.1731	802.1731	512.1066	512.1066
1205.7	30	0.9	0.6	368140	455.7477	9.594	312.5506	24.2815	465.3417	336.8321	802.1738	802.1738	512.1065	512.1065

Single resource model														
ed [RMB /MWh]	eg [RMB /MWh]	fd [RMB /MWh <sup>2</sup> ]	fg [RMB /MWh <sup>2</sup> ]	profit [RMB]	qg1 [MWh]	qg2 [MWh]	Qg [MWh]	Qd [MWh]	Pg [RMB /MWh]	Pd [RMB /MWh]				
1205.7	30	0.9	0.6	368140	465.3419	336.8322	802.1741	802.1736	512.1065	512.1064				
1205.7	30	0.9	0.6	368140	465.342	336.8322	802.1742	802.1738	512.1065	512.1062				
1205.7	30	0.9	0.6	368140	465.337	336.8288	802.1658	802.1659	512.1069	512.1069				
1205.7	30	0.9	0.6	368140	465.3405	336.8314	802.1719	802.1724	512.1065	512.1071				

**Table 5.27 Market equilibrium for generation companies with capacity of different resources 1**

Generation company	Cost [RMB/MWh]	Min Capacity [MW]	Max capacity [MW]	$CV_{ig}$	Supply company	Retail Price [RMB/MWh]	$CV_{id}$
1_1	60	0	150	-0.1	1	640	-0.1
1_2	5	0	30	-0.1	2	650	-0.11
2_1	63	0	150	-0.12	3	655	-0.12
2_2	7	0	40	-0.12	4	660	-0.13
3_1	65	0	200	-0.14			
3_2	240	0	30	-0.14			
4	6	0	50	-0.03			
5	9	0	50	-0.04			
6	64	0	100	-0.15			
7	27	0	100	-0.01			

**Table 5.28 Basic parameters for generation companies and retailers 2**

qg1_1 [MWh]	qg1_2 [MWh]	qg2_1 [MWh]	qg2_2 [MWh]	qg31 [MWh]	qg32 [MWh]	qg4 [MWh]	qg5 [MWh]	qg6 [MWh]	qg7 [MWh]	Profit [RMB]
149.5083	30	142.4377	40	185.8958	0	50	50	100	100	512337.9

qg1 [MWh]	g2 [MWh]	qg3 [MWh]	qg4 [MWh]	qg5 [MWh]	qg6 [MWh]	qg7 [MWh]	Qg [MWh]	Pg [RMB/MWh]	Profit_g [RMB]	ed [RMB/MWh]	fd [RMB/MWh <sup>2</sup> ]
179.50	182.43	185.89	50	50	100	100	847.8	538.79	416501.3	3051.4	2.9635

Case 1	qd1 [MWh]	qd2 [MWh]	qd3 [MWh]	qd4 [MWh]	Qd [MWh]	Pd [RMB/MWh]	Profit_s [RMB]	eg [RMB/MWh]	fg [RMB/MWh <sup>2</sup> ]
	187.33	208.1	220.0	232.1	847.8	538.79	95836.59	30	0.6001

**Table 5.29 Market equilibrium for generation companies with capacity of different resources**

Generation company	Cost [RMB/MWh]	Min Capacity [MW]	Max capacity [MW]	$CV_{ig}$
1	60	0	150	-0.1
1	5	0	30	-0.1
2	63	0	150	-0.12
2	7	0	40	-0.12
3	65	0	100	-0.14
3	240	0	30	-0.14
4	6	0	50	-0.03
5	9	0	50	-0.04
6	64	0	100	-0.15
7	27	0	100	-0.01

qg1_1 [MWh]	qg1_2 [MWh]	qg2_1 [MWh]	qg2_2 [MWh]	qg31 [MWh]	qg32 [MWh]	qg4 [MWh]	qg5 [MWh]	qg6 [MWh]	qg7 [MWh]	Profit [RMB]
150	30	149.1455	40	100	22.287	50	50	100	100	475368.9314

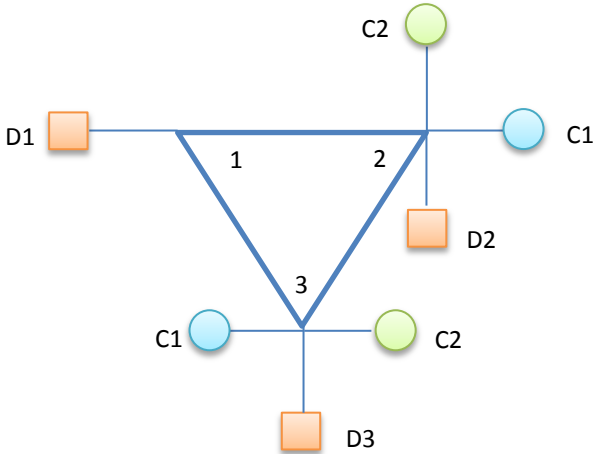
qg1 [MWh]	g2 [MWh]	qg3 [MWh]	qg4 [MWh]	qg5 [MWh]	qg6 [MWh]	qg7 [MWh]	Qg [MWh]	Pg [RMB/MWh]	Profit_g [RMB]	ed [RMB/MWh]	fd [RMB/MWh <sup>2</sup> ]
180	189.14	122.29	50	50	100	100	791.4	543.76	389823.4	2829.6	2.8883

Case 2	qd1 [MWh]	qd2 [MWh]	qd3 [MWh]	qd4 [MWh]	Qd [MWh]	Pd [RMB/MWh]	Profit_s [RMB]	eg [RMB/MWh]	fg [RMB/MWh <sup>2</sup> ]
	174.0	194.2	205.7	217.4	791.4	543.76	85545.5	57.430	0.6144

**Table 5.30 Market equilibrium for generation companies with capacity of different resources 3**

**5.4.3 Market Equilibrium with Fixed Transmission Price**

Case study for impact of transmission constraints on generation companies has been conducted in Chapter 5.24 with given demand function. In this section case study of market equilibrium with transmission constraints is conducted. A three nodes network is adopted, as shown in Figure 5.21. Generation company 1 has two branches and each is located in node 2 and node 3. The two branch companies are represented as company 1\_2 and company 1\_3 respectively. Generation company 2 has two branches and each is located in node 2 and node 3. The two branch companies are represented as company 2\_2 and company 2\_3. There is 1 retailer in node 1, 3 retailers (retailer 2\_1, 2\_2 and 2\_3) in node 2 and 3 retailers (retailer 3\_1, 3\_2 and 3\_3) in node 3.



**Figure 5.21 Network for transmission constraints**

First sensitivity analysis of different transmission capacity is given. The input parameters are shown in Table 5.31. At first the transmission capacity is fixed at relatively big value, there is no transmission congestion. With the decrease of transmission capacity, the electricity sold to node 1 decreases correspondingly and the transmission capacity is fully used as well. The results are listed in Table 5.32 and Figure 5.22. The quantity of electricity sold to node 1 tends to be more stable over the increase of transmission capacity. This is mainly because there is an upper limit for the demand in node 1.

Generation company	Cost [RMB/MWh]	Min_capacity [MW]	Max_capacity [MW]	$CV_{ig}$	Bus	Transmission price txy [RMB/MWh]	PTDF Value		
1_2	60	0	300	-0.1	1	10	0	-0.751	-0.5005
1_3	50	0	300	-0.11	2	10	0	-0.2503	-0.5008
2_2	70	0	300	-0.12	3	10	0	0.2505	-0.501
2_3	40	0	300	-0.14					

Retailer	Retail price [RMB/MWh]	$CV_{id}$
1	650	-0.11
2_1	650	-0.11
2_2	655	-0.12
2_3	660	-0.115
3_1	660	-0.105
3_2	655	-0.12
3_3	660	-0.115

**Table 5.31 Basic parameters for market equilibrium with fixed transmission Price**

Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Line	Transmission cost txy [RMB/MWh]	Transmission capacity [MW]	Power flow [MW]
1_2	300	65.7	153.6	80.7	12	10	200	-126.7213
1_3	300	65	151.5	83.5	13	10	200	-132.8328
2_2	300	64.8	154.4	80.8	23	10	200	-138.9183
2_3	300	63.7	152.6	83.7				
Sum	1200	259.2	612.1	328.7				

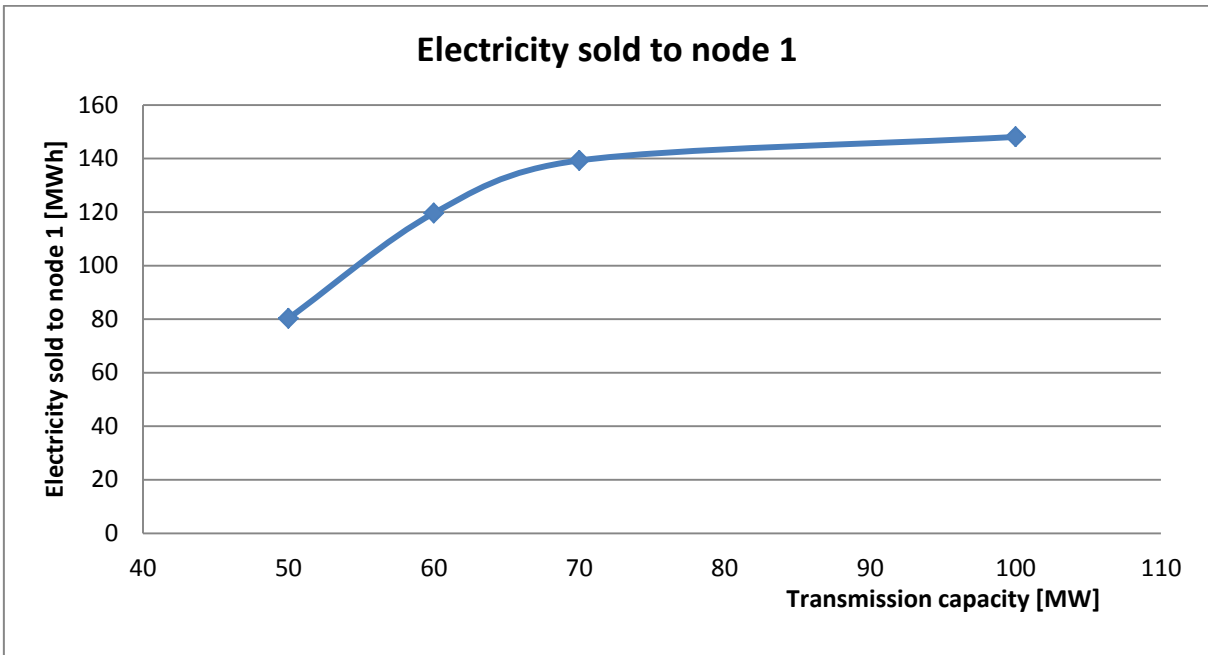
Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Line	Transmission cost txy [RMB/MWh]	Transmission capacity [MW]	Power flow [MW]
1_2	300	37.5	125.3	137.2	12	10	100	-99.98527
1_3	300	36.9	122.6	140.5	13	10	100	-48.28544
2_2	300	37.2	125.7	137.1	23	10	100	3.429182
2_3	300	36.5	123.1	140.4				
Sum	1200	148.1	496.7	555.2				

Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Line	Transmission cost txy [RMB/MWh]	Transmission capacity [MW]	Power flow [MW]
1_2	300	35.2	151.4	113.4	12	10	70	-69.62830
1_3	300	34.8	148.5	116.7	13	10	70	-69.82111
2_2	300	34.9	151.6	113.5	23	10	70	-70
2_3	300	34.4	148.8	116.9				
Sum	1200	139.3	600.3	460.5				

Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Line	Transmission cost txy [RMB/MWh]	Transmission capacity [MW]	Power flow [MW]
1_2	300	30.3	151.5	118.3	12	10	60	-59.99908
1_3	300	29.9	148.2	121.9	13	10	60	-59.74431
2_2	300	30	151.6	118.4	23	10	60	-59.47758
2_3	300	29.4	148.2	122.4				
Sum	1200	119.6	599.5	481				

Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Line	Transmission cost txy [RMB/MWh]	Transmission capacity [MW]	Power flow [MW]
1_2	300	20.4	156.2	123.4	12	10	50	-36.95017
1_3	300	19.9	149.5	130.6	13	10	50	-43.47860
2_2	300	20.3	156.9	122.8	23	10	50	-49.99900
2_3	300	19.7	150.4	129.9				
Sum	1200	80.3	613	506.7				

**Table 5.32 Market equilibrium with different transmission constraints**



**Figure 5.22 The effect of transmission capacity on electricity sold to node1**

To further analyze the effect of transmission price, different transmission prices are set and the simulation results are shown in Table 5.33 and Figure 5.23, 5.24. The maximum generation capacity is increased to 400MW. As it can be seen from the table, with the increase of transmission price, more electricity is preferred to be sold in the local market rather than through the transmission lines. The transmission cost (revenue for TSO) increases first with the transmission price and reaches a peak at the point around 250 RMB/MWh. After the peak, the transmission cost decreases. This indicates that the TSO cannot always increase the revenue through increasing the transmission price. Meanwhile the total profit goes down first with the increase of transmission cost and increases after the valley.

Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Profit [RMB]	Transmission cost [RMB]	txy [RMB/MWh]	Electricity sold through line [MWh]	Electricity sold to local [MWh]
1_2	400	53.8	295.5	50.7	998270	11995	10	902.8	697.3
1_3	400	54.2	293.1	52.8					
2_2	400	53.2	296	50.8					
2_3	400	53.2	293.8	53					
Sum	1600	214.4	1178.4	207.3					

Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Profit [RMB]	Transmission cost [RMB]	txy [RMB/MWh]	Electricity sold through line [MWh]	Electricity sold to local [MWh]
1_2	400	48.6	208.6	142.8	920460	49126	50	845.3	742.6
1_3	387.9	44.4	183.6	159.9					
2_2	400	47.8	209.1	143.1					
2_3	400	45.7	189.3	165					
Sum	1587.9	186.5	790.6	610.8					

Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Profit [RMB]	Transmission cost [RMB]	txy [RMB/MWh]	Electricity sold through line [MWh]	Electricity sold to local [MWh]
1_2	400	60.7	174.9	164.4	878040	88825	100	816	784
1_3	400	49.5	134.7	215.8					
2_2	400	59.8	175.9	164.3					
2_3	400	47.7	134.9	217.4					
Sum	1600	217.7	620.4	761.9					

Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Profit [RMB]	Transmission cost [RMB]	txy [RMB/MWh]	Electricity sold through line [MWh]	Electricity sold to local [MWh]
1_2	400	65.1	141.6	193.3	853030	113110	150	759.9	840.1
1_3	400	38	85.2	276.8					
2_2	400	64.4	142.7	192.9					
2_3	400	36	85	279					
Sum	1600	203.5	454.5	942					

Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Profit [RMB]	Transmission cost [RMB]	txy [RMB/MWh]	Electricity sold through line [MWh]	Electricity sold to local [MWh]
1_2	400	39.8	186.5	173.7	832770	126130	200	632.8	967.3
1_3	400	21.7	83.1	295.2					
2_2	400	39.6	187.8	172.6					
2_3	400	20.7	81.6	297.8					
Sum	1600	121.8	539	939.3					

Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Profit [RMB]	Transmission cost [RMB]	txy [RMB/MWh]	Electricity sold through line [MWh]	Electricity sold to local [MWh]
1_2	400	38.7	190.2	171.1	799880	129670	250	574.8	1002
1_3	376.9	14.9	59.9	302.1					
2_2	400	38.4	191.6	170					
2_3	400	16.6	65.2	318.1					
Sum	1576.9	108.6	506.9	961.3					

Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Profit [RMB]	Transmission cost [RMB]	txy [RMB/MWh]	Electricity sold through line [MWh]	Electricity sold to local [MWh]
1_2	400	50.7	259.4	89.9	814890	121680	300	409.4	1125.1
1_3	352.9	3.2	56.2	293.5					
2_2	400	49.8	261.9	88.3					
2_3	381.6	7.1	64.2	310.3					
Sum	1534.5	110.8	641.7	782					

Company	Total output [MWh]	Electricity sold to node 1 [MWh]	Electricity sold to node 2 [MWh]	Electricity sold to node 3 [MWh]	Profit [RMB]	Transmission cost [RMB]	txy [RMB/MWh]	Electricity sold through line [MWh]	Electricity sold to local [MWh]
1_2	400	31.6	313.6	54.8	822560	61798	300	202.5	1252.2
1_3	313.6	0	11.1	302.4					
2_2	400	31.1	316.5	52.4					
2_3	341.2	2.3	19.2	319.7					
Sum	1454.8	65	660.4	729.3					

**Table 5.33 Market equilibrium with different transmission prices**



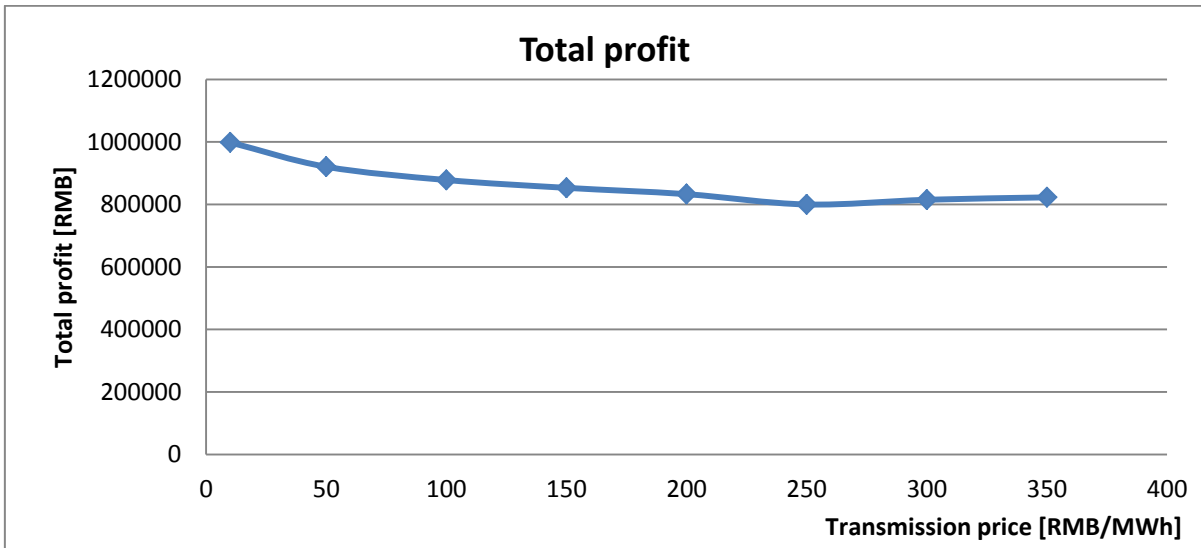


Figure 5.23 The effect of transmission price on total profit

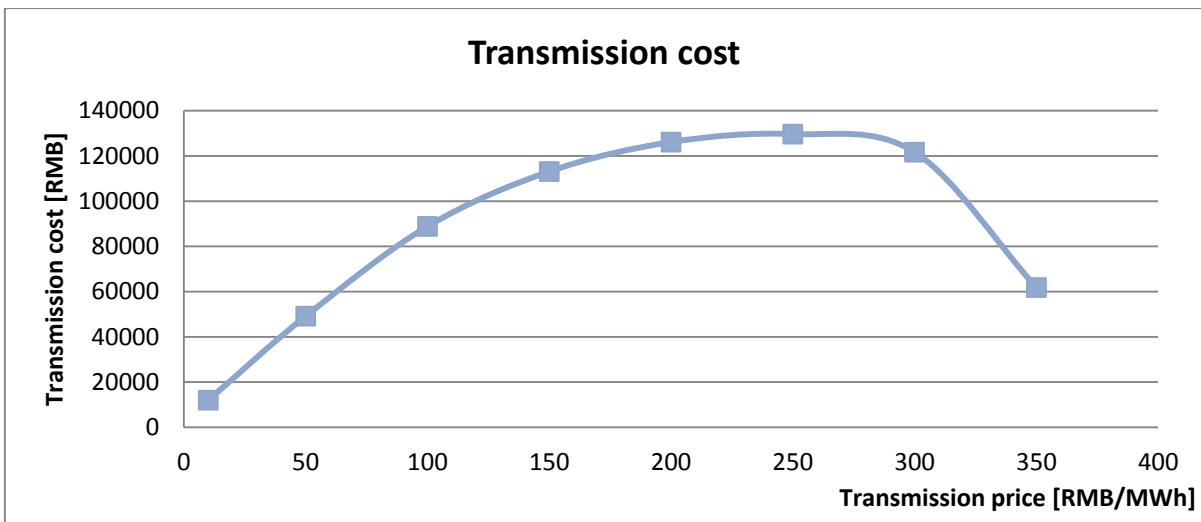


Figure 5.24 The effect of transmission price on transmission cost

### 5.5 Specific Case Study of Chinese Electricity Market

In this section, case study of a specific case of electricity market in Shanxi province, China, is conducted. In Shanxi province the majority of electricity is produced by thermal power plants. The electricity consumption in 2014 is 122.6 TWh and the total generation is 132.6 TWh [48]. The generation exceeds the demand, this province can be self-supplied. The basic information about generation and demand of Shanxi province is listed in Table 5.34.

Technology	Generation [TWh]	Installed capacity [MW]	Annual operating hours [h]	Available capacity [MW]	Total annual generation [TWh]	Total annual demand [TWh]	Cost of coal [RMB/t]	Coal consumption [g/kWh]
Thermal	124	24980	4828	13767.52	132.6	122.6	364	318
Hydro	7.1	2530	4253	1228.32				
Wind	1.35	840	1085	104.04				
Solar	0.09	63	1097	7.9				

**Table 5.34 Basic information of Shanxi Province [48] [51] [59]**

In terms of market share, six big generation companies have relatively large thermal capacity compared with other companies. The main companies and their thermal capacities are listed in Table 5.35. The data is summarized from [48] and the official website of all these companies.

Company	Thermal capacity [MW]	Available thermal capacity [MW]
Datang	7155	3943.4
Huadian	4020	2215.6
Shenhua	3600	1984.1
Guodian	2520	1388.9
Huaneng	2520	1388.9
Shanxitou	1951	1075.3
Sum	21766	11996.2

**Table 5.35 Main generation companies in Shanxi province [48]**

Except for these six big companies, the remaining thermal power plants are all small ones. To simplify, the rest available thermal capacity 1771.3 MW is divided into five small companies, each has a capacity of 354.26 MW. The hydro capacity is divided into two companies, each has 614.2 MW. For wind and solar, due to the small quantity, each of them are represented by a single company. The variable cost for thermal power plants is calculated from data in Table 5.34 as 115.752 RMB/MWh and the variable cost for hydro and renewables are assumed as little value as 10 RMB/MWh and 5 RMB/MWh respectively. The summarized information is listed in Table 5.36.

Technology	Company	Available capacity [MW]	Cost [RMB/MWh]	$CV_{ig}$
Thermal	Datang	3943.4	115.752	-0.7
	Huadian	2215.6	115.752	-0.5
	Shenhua	1984.1	115.752	-0.4
	Guodian	1388.9	115.752	-0.3
	Huaneng	1388.9	115.752	-0.3
	Shanxitou	1075.3	115.752	-0.3
	7	354.26	115.752	0
	8	354.26	115.752	0
	9	354.26	115.752	0
	10	354.26	115.752	0
	11	354.26	115.752	0
Hydro	12	614.2	10	-0.1
	13	614.2	10	-0.1
Wind	14	104	5	0
Solar	15	7.9	5	0

**Table 5.36 Summarized information of generation companies in Shanxi**

First the demand function is solved. The price is set as the on-grid price of thermal power plants in Shanxi province, which is 359 RMB/MWh [51]. Information of typical summer day load and winter day load from the year 2006 to 2009 is described in [60]. However, the data of base load after 2009 is not available. In this research, the quantity of base load is assumed to be 9000MW as inspired by the information available in [60]. After solving with the CVE model developed in paragraph 4.2.3, the intercept value  $e_d$  of demand function is 4488.5 RMB/MWh and the slope value  $f_d$  of demand function is 0.4588 RMB/MWh<sup>2</sup>.

The calculated slope of demand function is not typical value. Normally the slope of demand function is relatively large due to demand inelasticity. The main reason why this value is achieved is the assumptions adopted in this model. First, the uniform linear demand function is adopted which simplifies the model and calculation, but the real demand curve is not well represented. Second, since the historical trading data is not available, the CV values are assumed based on the generation resource and capacity of each company. Normally big thermal power plants are more feasible in changing output, while renewable power plants are affected by the intermittency due to variable available time each day. Thus, the  $CV_{ig}$  values for

large power plants are relatively small, while the  $CV_{ig}$  values for small thermal power plants and renewable power plants are bigger and close to 0, as they are normally price takers and experience less market power compared with big thermal power plants. The primary task of this case study is to analyze the effect of  $CV_{ig}$  values on the output of generation companies. The calculated intercept and slope will be used to represent the demand function. The  $CV_{ig}$  values for base case are listed in Table 5.36. Sensitivity analysis of  $CV_{ig}$  value is conducted and the results are listed in Table 5.37.

As it can be seen from the results, with  $CV_{ig}$  value of one company becoming larger, the output of this company goes down. Meanwhile the total output of all the generation companies decreases and the price grows up. This is mainly because, with the  $CV_{ig}$  value moving towards 0, the market environment will be less competitive, the generation company will be more moderate in reacting to the rivals' change in generation output. This is the phenomenon in case 2 and 3, when compared with the base case 1.

In case 4, the  $CV_{ig}$  value is decreased for generation company Shenhua, the output of this company grows up. The total output of all the generation companies increases and the price goes down correspondingly. With the  $CV_{ig}$  value moving towards -1, the market environment will be more competitive, the generation company will react fast to fill in the gap, once the other companies decrease their output. Since the market moving towards perfect competition, the total output increases and the market price goes down.

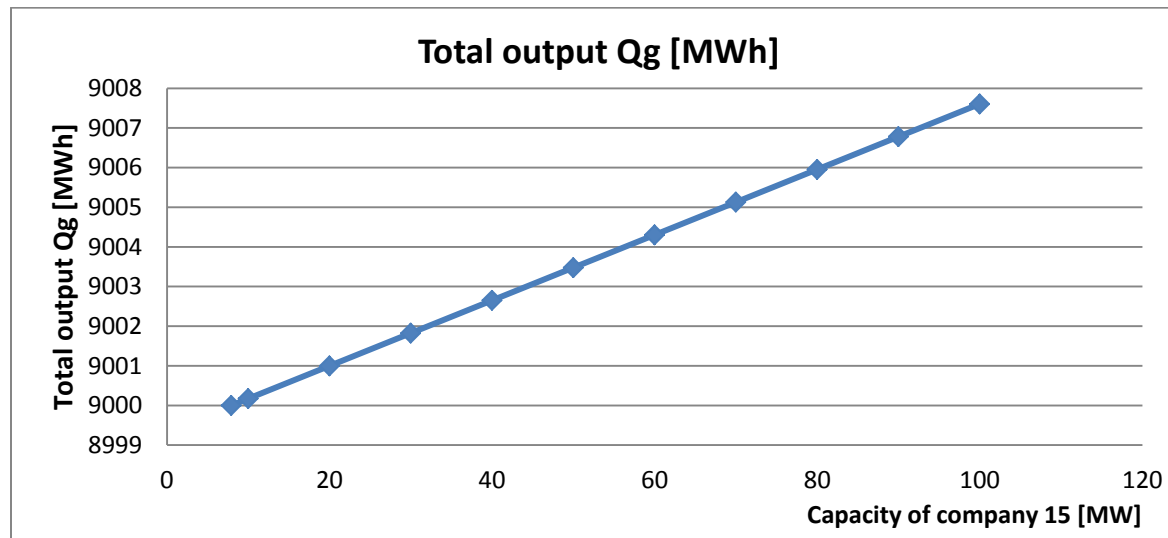
Thus, the  $CV_{ig}$  value has very important effect on the contract quantity and price in bilateral electricity market. It is evident that the  $CV_{ig}$  value is the key element in the implementation of this model, which highlights the direction of future work in improving the value of  $CV_{ig}$  to indicate the real market behaviors.

Technology	Company	Case 1		Case 2		Case 3		Case 4	
		$CV_{ig}$	Output [MWh]	$CV_{ig}$	Output [MWh]	$CV_{ig}$	Output [MWh]	$CV_{ig}$	Output [MWh]
Thermal	Datang	-0.7	1767.1511	-0.6	1423.3310	-0.6	1466.6969	-0.7	1653.3511
	Huadian	-0.5	1060.2906	-0.5	1138.6648	-0.4	977.79798	-0.5	992.01068
	Shenhua	-0.4	883.57556	-0.4	948.88737	-0.4	977.79798	-0.6	1240.0133
	Guodian	-0.3	757.35048	-0.3	813.3320	-0.3	838.11255	-0.3	708.57906
	Huaneng	-0.3	757.3504812	-0.3	813.33203	-0.3	838.11255	-0.3	708.57906
	Shanxitou	-0.2	662.68167	-0.2	711.66553	-0.2	733.34848	-0.2	620.00667
	7	0	354.26	0	354.26	0	354.26	0	354.26
	8	0	354.26	0	354.26	0	354.26	0	354.26
	9	0	354.26	0	354.26	0	354.26	0	354.26
	10	0	354.26	0	354.26	0	354.26	0	354.26
	11	0	354.26	0	354.26	0	354.26	0	354.26
Hydro	12	-0.1	614.2	-0.1	614.2	-0.1	614.2	-0.1	614.2
	13	-0.1	614.2	-0.1	614.2	-0.1	614.2	-0.1	614.2
Wind	14	0	104	0	104	0	104	0	104
Solar	15	0	7.9	0	7.9	0	7.9	0	7.9
		Total output	9000	Total output	8960.8129	Total output	8943.4665	Total output	9034.1399
		Price [RMB/MWh]	358.9999	Price [RMB/MWh]	376.98031	Price [RMB/MWh]	384.93939	Price [RMB/MWh]	343.33545

**Table 5.37 Impact of  $CV_{ig}$  value on the bilateral electricity market**

qg1 [MWh]	qg2 [MWh]	qg3 [MWh]	qg4 [MWh]	qg5 [MWh]	qg6 [MWh]	qg7 [MWh]	qg8 [MWh]	qg9 [MWh]	qg10 [MWh]	qg11 [MWh]	qg12 [MWh]	qg13 [MWh]	qg14 [MWh]	qg15 [MWh]	Total output Qg [MWh]	Contract price Pg [RMB/MWh]
1546.5	1288.8	1288.8	1104.7	1104.7	1104.7	624.8	624.8	624.8	624.8	624.8	1265	1265	840	63	13995.4	359
1539.6	1283.0	1283.0	1099.7	1099.7	1099.7	624.8	624.8	624.8	624.8	624.8	1265	1265	840	100	13998.8843	357.9039815
1530.2	1275.1	1275.1	1093.0	1093.0	1093.0	624.8	624.8	624.8	624.8	624.8	1265	1265	840	150	14003.59282	356.4228748
1520.7	1267.3	1267.3	1086.2	1086.2	1086.2	624.8	624.8	624.8	624.8	624.8	1265	1265	840	200	14008.30134	354.9417683
1511.3	1259.4	1259.4	1079.5	1079.5	1079.5	624.8	624.8	624.8	624.8	624.8	1265	1265	840	250	14013.00986	353.4606619
1501.9	1251.6	1251.6	1072.8	1072.8	1072.8	624.8	624.8	624.8	624.8	624.8	1265	1265	840	300	14017.71838	351.9795556
1492.5	1243.7	1243.7	1066.1	1066.1	1066.1	624.8	624.8	624.8	624.8	624.8	1265	1265	840	350	14022.4269	350.4984491
1483.1	1235.9	1235.9	1059.3	1059.3	1059.3	624.8	624.8	624.8	624.8	624.8	1265	1265	840	400	14027.13542	349.0173427
1473.7	1228.0	1228.0	1052.6	1052.6	1052.6	624.8	624.8	624.8	624.8	624.8	1265	1265	840	450	14031.84394	347.5362363
1464.2	1220.2	1220.2	1045.9	1045.9	1045.9	624.8	624.8	624.8	624.8	624.8	1265	1265	840	500	14036.55246	346.0551299
1439.8	1199.8	1199.8	1028.4	1028.4	1028.4	624.8	624.8	624.8	624.8	624.8	1265	1265	840	630	14048.79461	342.2042533

**Table 5.38 Impact of integration of more renewable energy on the bilateral electricity market**



**Figure 5.25 Impact of integration of more renewable energy on the total output**

Besides, sensitivity analysis will be conducted to see the effect of integration of more renewable energy in the electric power system. The basic input is listed in Table 5.36. The capacity of company 15 is increased from 7.9 MW to 100 MW and the corresponding change in outputs and contract price is achieved. The results are shown in Table 5.38 and Figure 5.25, 5.26, 5.27.

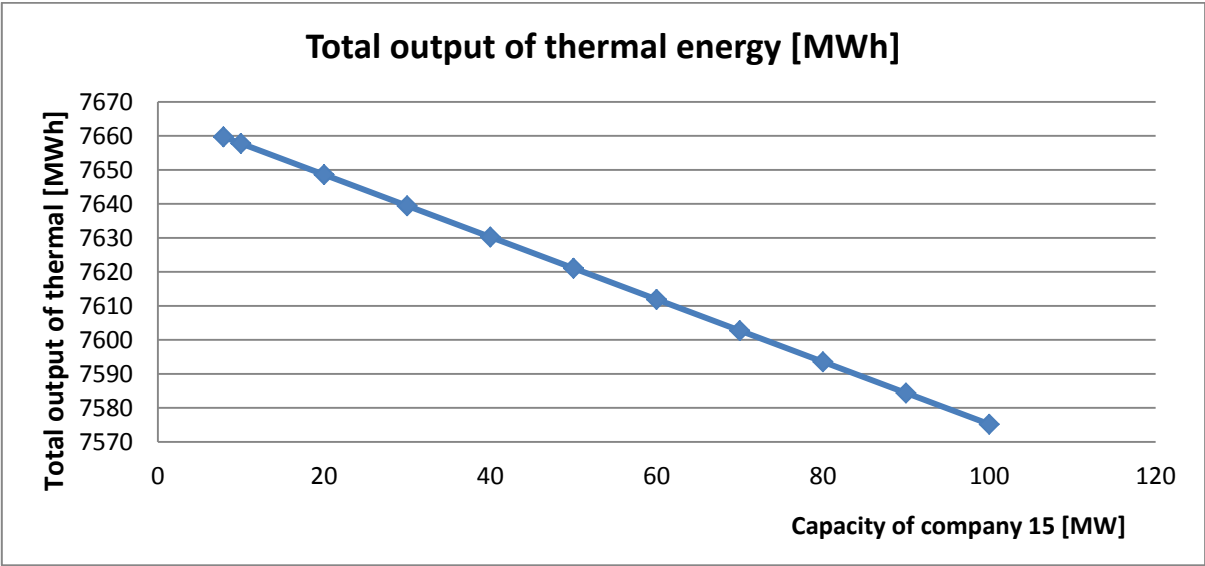


Figure 5.26 Impact of integration of more renewable energy on the output of thermal energy

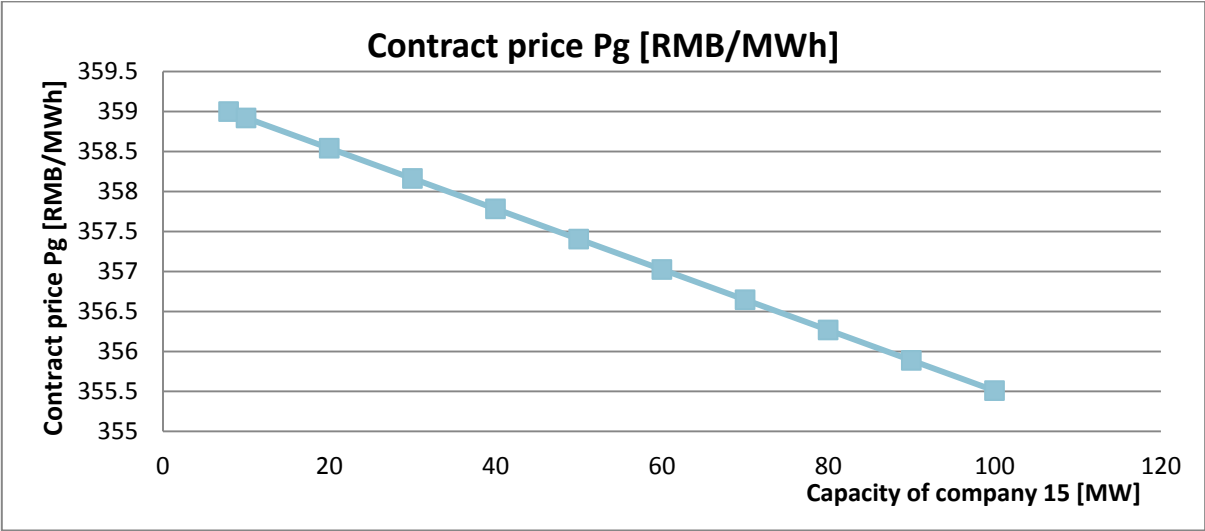


Figure 5.27 Impact of integration of more renewable energy on the contract price

As it can be seen from Figure 5.25, the total output of generation companies increases with the integration of more renewable energy. This is mainly because the renewable energy has lower variable cost compared with thermal power plants. Meanwhile, the output of thermal power plants decreases with the increase of renewable energy as shown in Figure 5.26. As it can be seen from Figure 5.27, the market contract price will decrease thanks to the lower cost of renewable energy. However, in real electricity market the development of renewable energy is limited by the high investment cost and intermittency caused by variable available time each day. Thus incentives or subsidies are needed to help the renewable energy power plants to recover the investment and further enhance the technology innovation to lower the generation cost.



## **6. Conclusions and Future Works**

### **6.1 Introduction**

In Chapter 5 many different case studies have been conducted to test the models developed in this thesis. Sensitivity analysis for both generation companies and retailers is conducted to check the effect of slope and intercept of demand and generation functions. Besides, the effect of conjecture variations, number of companies and transmission constraints are tested. Furthermore, behaviors and strategies of companies with multi-technologies are studied. Similarly, market equilibria under the above situations are tested as well. Specific case in real Chinese electricity market has been tested. In this section the summary and conclusions of this thesis is presented based on all the developed models and simulation results.

### **6.2 Conclusions**

This thesis presents an electricity market model for analyzing the bilateral electricity market. Through adopting the CVE model, behaviors of market participants are analyzed and market equilibrium is solved with the objective of profit maximization. A detailed literature survey on electricity market models are presented in Chapter 2 and comparisons have been conducted to specify the advantages of CVE model in modelling bilateral electricity market. Brief analysis of transmission constraints and congestion management strategies has been conducted. In Chapter 3, detailed description of the development history of Chinese electricity market has been presented. The present situation and existing problems have been analyzed. The on-going reform policy has been described in detail and future development has been discussed briefly. Based on the reform target, a bilateral electricity market model for Chinese electricity industry is described in detail in Chapter 4. Simulation and case study by applying the developed model is presented in Chapter 5.

To summarize, the following are the findings of this research:

- 1) The bilateral electricity market mechanism helps to improve the power industry efficiency in China and mitigate the problems caused by former single buyer market mechanism due to the change in price mechanism. The former on-grid price which is

decided by NDRC will be replaced by transaction price which is negotiated between generation companies and eligible users or retailers.

- 2) The intercept and slope of demand and generation functions have important effect on the contract quantity and price of bilateral electricity market. With different values of these four parameters, different market environments are represented.
- 3) The interactions among generation companies and retailers can be represented by the CVs. Different CV values indicate different market competitiveness. The sensitivity analysis of CV values shows that the CV values have vital effect on the contract price and quantity of bilateral electricity market.
- 4) The increase of retail price will increase the contract price in the bilateral electricity market due to the fact that the profit of retailers is better guaranteed.
- 5) The model in [9][10] is further extended to take into account generation companies with capacity of different resources. The simulation results show that generation companies with capacity of different resources will always produce from the cheaper resource as the first choice. The contract price will increase with the generation cost, while both the contract quantity and total profit will go down with the increase of generation cost.
- 6) The bilateral electricity market model with the integration of transmission constraints is developed. The simulation results show that the transmission capacity will limit the electricity sold through transmission lines. With the increase of transmission price, more electricity will be sold in the local market rather than to the distant areas.
- 7) When transmission price is considered, the revenue for TSO will grow first with the increase of transmission price. After a peak value at a certain point, the revenue will decrease. This critical point can be an instruction in the setting of transmission price.
- 8) Optimal market equilibrium can be achieved by applying the CVE model with the maximization of total profit of the market participants.
- 9) With the increase of the number of retailers, the contract price will increase. But the increasing speed has a decreasing trend. This indicates that under the new policy, with the establishment of more retailers, the market will move towards more competitive

environment and the contract price will increase and approach a stable value when perfect competition is reached.

- 10) The specific case study in Shanxi, China, shows that with the integration of more renewable energy in the electric power system, the contract price will decrease.
- 11) Genetic algorithm has been adopted to implement all the developed models in the research. The calculation results show that the genetic algorithm can solve the market equilibrium for bilateral electricity market and has clear advantages in finding optimal solution and higher calculation speed with respect to Pattern Search.
- 12) This study is primarily focused on the development of more realistic electricity market model for the bilateral electricity market and a number of assumptions have been made in applying this model to Chinese market due to lack of data. These assumptions should be managed carefully when trying to compare the simulation results with the real market data.

### **6.3 Future Works**

As described in the research, some basic parameters like CV values are based on assumptions. So the primary job in the future is to collect more historical trading data and achieve practical values for the basic parameters in this model so that simulation of more realistic cases can be conducted. Besides, more precise demand function can be developed to fit the real characteristics of demand curve.

Furthermore, the future work can follow the development of the electricity market in China. With the upcoming of ETS mechanism in 2017, the effect of ETS on electricity market can be studied. Since the majority of electricity generation coming from coal power plants, the emission trading market and electricity market will be closely related and interactions between these two markets will be very complicated. Thus the model needs to be improved to integrate the cost associated with emission trading to better simulate the bilateral electricity market in China.

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