Oligopolistic and Oligopsonistic Bilateral Electricity Market Modeling Using Hierarchical Conjectural Variation Equilibrium Method

Submitted in fulfillment of the requirement for the degree of Doctor of Philosophy

by

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Abstract

An electricity market is very complex and different in its nature, when compared to other commodity markets. The introduction of competition and restructuring in global electricity markets brought more complexity and major changes in terms of governance, ownership and technical and market operations.

In a liberalized electricity market, all market participants are responsible for their own decisions; therefore, all the participants are trying to make profit by participating in electricity trading. There are different types of electricity market, and in this research a bilateral electricity market has been specifically considered.

This thesis not only contributes with regard to the reviewing UK electricity market as an example of a bilateral electricity market with more than 97% of long-term bilateral trading, but also proposes a dual aspect point of view with regard to the bilateral electricity market by splitting the generation and supply sides of the wholesale market. This research aims at maximizing the market participants' profits and finds the equilibrium point of the bilateral market; hence, various methods such as equilibrium models have been reviewed with regard to management of the risks (e.g. technical and financial risks) of participating in the electricity market.

This research proposes a novel Conjectural Variation Equilibrium (CVE) model for bilateral electricity markets, to reduce the market participants' exposure to risks and maximize the profits. Hence, generation companies' behaviors and strategies in an imperfect bilateral market environment, oligopoly, have been investigated by applying the CVE method. By looking at the bilateral market from an alternative aspect, the supply companies' behaviors in an oligopsony environment have also been taken into consideration.

At the final stage of this research, the 'matching' of both quantity and price between oligopolistic and oligopsonistic markets has been obtained through a novel-coordinating algorithm that includes CVE model iterations of both markets. Such matching can be achieved by adopting a hierarchical optimization approach, using the Matlab

Patternsearch optimization algorithm, which acts as a virtual broker to find the equilibrium point of both markets.

Index Terms-- **Bilateral electricity market, Oligopolistic market, Oligopsonistic market, Conjectural Variation Equilibrium method, Patternsearch optimization, Game theory, Hierarchical optimization method**

Declaration

I AmirHessam Alikhanzadeh declare that this research, its idea, analysis, findings, and conclusions that are included in this PhD thesis are entirely developed by me for the purpose of this program only and have not been submitted for another qualification.

Acknowledgements

The accomplishment of this investigation was only possible by the guidance, professional supervision, and encouragement that have been offered by my supervisors Prof. Malcolm Irving and Prof. Gareth Taylor. I am grateful for the devoted time, effort, constructive feedback, and thoughts and creativity provoking ideas you both have honored me.

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Finally, special thanks to my family and every person who loved to see the successful accomplishment and achievement of this work.

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List of Abbreviations

ABM Agent – Based Model

ATC Available Transfer Capabilities

BM Balancing Mechanism

BMU Balancing Mechanism Unit

BSC Balancing and Settlement codes

CALISO California Independent System Operators

CGE Computable General Equilibrium

CV Conjectural Variation

CVE Conjectural Variation Equilibrium

EC European Council

EU European Union

ETSO European Transmission Operators

ENTSO-E European Network of Transmission Systems Operators for Electricity

EMCAS Electricity Market Complex Adaptive Systems

ERCOT Electric Reliability Council of Texas

FCM Fuzzy Cognitive Maps

FIPA Foundations for Intelligent Physical Agents

FERC Federal Energy Regulation Committee

GA Genetic Algorithm

GPS Generalized Patternsearch

IS Imbalanced Settlement

ISO Independent System Operators

ISO-NE Independent System Operators New England

IEM Internal Electricity Market

IPP Independent Power Producers

JADE Java Agent DEvelopment Framework

KKT Karush-Kuhn-Tucker

LMP Local Marginal Pricing

MC Marginal Cost

MW Megawatt

MAS Multi Agent System

MO Market Operator

MISO Midwest Independent System Operators

MABS Multi Agent Based Systems

NEM National Electricity Market

NEMMCO National Electricity Market Management Company

NYISO New York Independent System Operators

NG National Grid

NGC National Grid Company

OFGEM Office of Gas and Electricity Markets

OASIS Open Access Same-time Information System

OTC Over The Counter

PX power exchange

PJM Pennsylvania-New Jersey-Maryland

RO Renewable Obligation

RTO Regional Transmission Organizations

REC Regional Electricity Companies

SAA Settlement Administration Agent

SSP System Sell Price

SBP System Buying Price

SMP System Marginal Price

SO System Operator

SoS Security of Supply

SPP Southwest Power Pool

Supply Co Supply Company

TSO Transmission System Operators

TransCo Transmission Company

UK United Kingdom

US United States

Chapter 1: Introduction

1.1 Introduction

Electricity utility systems around the world continue to evolve from vertically integrated monopoly structure to a competitive environment market, which provides all the customers with the choice of services. The electricity markets liberalization combines the unbundling vertically integrated utilities, introduction of competition in the market and the limitation of central and governmental control.

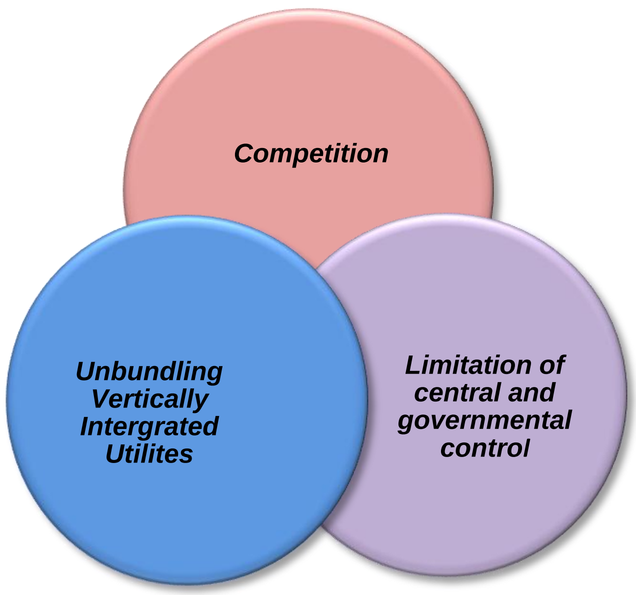


Figure 1.1: Liberalized Electricity Market Components

For instance, the electricity market in UK has seen major changes since the Electricity Act in 1989, which introduced a competitive environment and began the privatization in all sections of the market [1] in order to bring transparency and liquidity into electricity trading. These changes resulted in the electricity Pool; afterwards the New Electricity Trading Arrangement (NETA) appeared in 2001, which included England and Wales and was a bilateral electricity market. In 2005 NETA reformed into British Electricity Trading and Transmission Arrangement (BETTA) covering England, Wales and Scotland [2]. In such a market structure, as it will be investigated in details in Chapter 3, most of the energy trading are long-term bilateral contracts (Figure 1.2) and the general principles of these changes have been the unbundling of the market into separate areas of generation, transmission, distribution and supply.

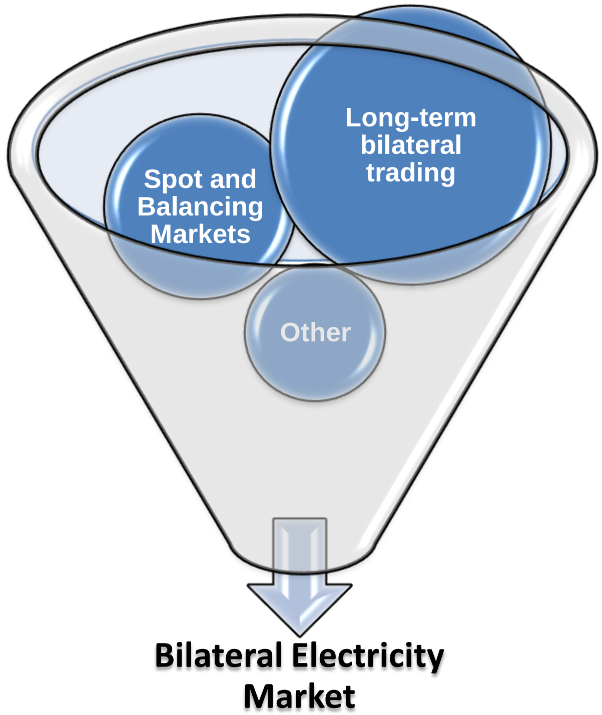


Figure 1.2: Bilateral Long-Term Trading Share

In bilateral electricity markets, each market participant has its own and unique business, aims, strategy, and technical and financial risks. Decentralizing decision-makers is one of the significant goals of restructured bilateral markets. 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; which seems challenging for all market participants.

The volatility exhibited by markets restructuring (e.g. UK electricity market evolutions), several market failures (e.g. California electricity market crisis) and different behaviors of restructured markets (e.g. various electricity market structures in different countries) have highlighted the need for a better understanding of market structure and its complexity.

Advance modeling approaches are needed to demonstrate the complication of this kind of market structure and model the behaviors of market participants over a period of time and show how they react to the economic, financial and technical changes in the power system. One of these approaches is Conjectural Variation Equilibrium (CVE) method, which brings robustness to the market modeling comparing to other applied approaches. This research investigates imperfect bilateral electricity market modeling based on equilibrium method for profit maximization on both sides of the market and finding equilibrium point of the market.

1.2 Significance of this Research

Electricity, and more generally the energy, has become a significant and key issue in developed and even developing countries around the world and plays an important role in forming their medium and long-term macro economical and financial strategies. Electricity has also an impact on economic environment. Restructuring can bring different policies in the electricity markets and change the objectives of market participants. Far from the advantages that these deregulations can bring to the electricity market and power system, there will also be some challenging environment and conditions for participants.

One of the key impacts of deregulation is increasing exposure to the risks. By the nature of power system and electricity market, certain risks exist, such as: operational and technical failures, demand variations, volatilities in price of fuel based on international policies (e.g. recent Middle East crisis). However, in a monopoly industry, which is regulated and vertically integrated, carrying different strategies like excessing capacity can easily cover all these risks. On the other hand deregulation do not only accentuate the inherent market risks but also brings additional risk sources like the complexity of market structure, lack of time, complex pricing procedure and etc. These risk resources can cause imperfect competition in the market.

Therefore, it is essential to consider both sides of the bilateral electricity market and consider the reactions and behaviors of market participants on both sides of the market in order to monitor the market power.

1.3 Scope of this Research

The current research covers bilateral electricity market modeling considering the impacts of long-term contracts on the equilibrium point of the market. According to Figure 1.3 the majority of electricity trading in the bilateral electricity markets are long-term contracts [2]; therefore their influences on the decision makers in the market should be taken into consideration. Figure 1.3 provides an overview about different functions of electricity market within the time period.

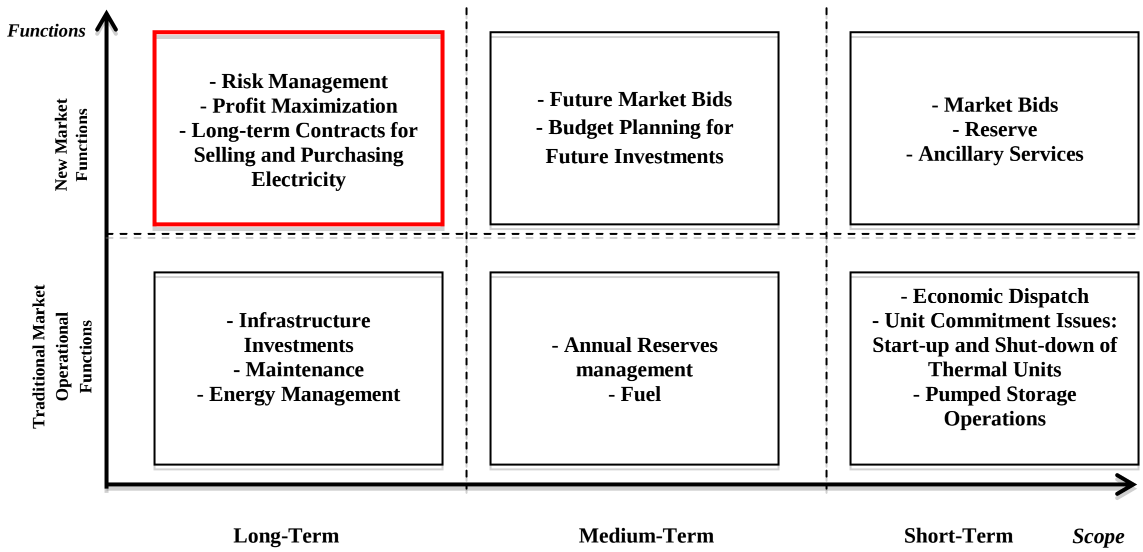


Figure 1.3: Electricity Market Functionalities

According to the figure above, long-term electricity market can bring profit maximization and also risk management. However, by considering only generation side of the market, achieving to a competitive and stable bilateral electricity market is impossible, since the impacts of demand side behaviors have not been considered. In such a market structure both generation and demand sides of the market should be considered and the impacts of each firm’s strategic decision on the equilibrium of the market need to be studied. The market participants should be modeled as decision makers that consider their rivals’ strategies base on any changes in their decisions. In this method all the firms can learn from their decisions and other market participants behaviors, simultaneously.

After reviewing several approaches, equilibrium model will be applied in this research, and among different equilibrium models, Conjectural Variation Equilibrium method [2] has been selected based on its investigated specifications in Chapter 4.

According to Figure 1.4, both sides of the market have been considered in this research and since it is a double-sided environment, it is essential to consider the link between generation and supply sides and influences of these two edges on each other in an imperfect environment. Therefore two market terms have been introduced: *oligopolistic* electricity market and *oligopsonistic* electricity market. This research is observing these two types of market individually and furthermore, by building and developing a novel algorithm, which looks at the common aspects of these two types of market, the equilibrium point of the whole bilateral market can be investigated.

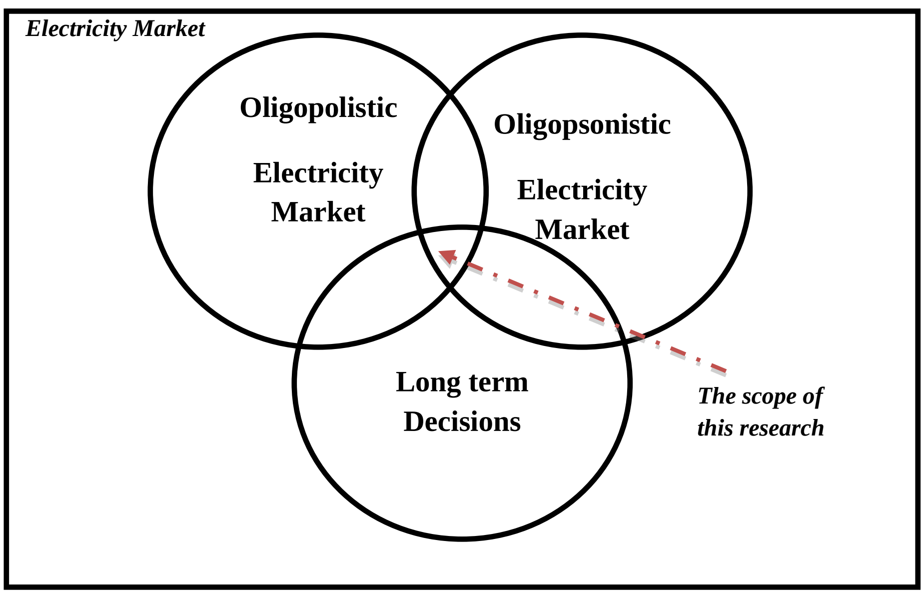


Figure 1.4: Scope of this Research

1.4 Aim and Objectives

The principle aim of this research as mentioned in the scope of this research is modeling market participants' behaviors in bilateral electricity market in order to find out the equilibrium point of the market, while all market participants are making profit. Hence, the followings would be the objectives of this research:

- Detailed investigations on BETTA structure as a bilateral electricity market example, in order to understand the market participants' behaviors and clarify the necessity of considering both sides of the market.
- Identifying different types of risks and uncertainties in bilateral electricity market.
- Detailed investigations on different electricity market modeling techniques. This covers the following aspects:
  - Why is it required to model bilateral electricity markets?
  - Why has equilibrium modeling been chosen?
  - Why has the Conjectural Variation Equilibrium method been selected?
- Considering imperfect competitions in generation side of the market, looking at oligopolistic electricity market modeling.
- Considering imperfect competitions in supply side of the market, looking at oligopsonistic electricity market modeling.
- Investigating the impacts of generation companies (GenCos) and supply companies (SupplyCos) strategies on both sides of the market.
- Calculating equilibrium point of the market considering both sub-markets, while all market participants are making profit by taking part in electricity trading.

1.5 Outline of this Research

This section provided an overview of this research. The following chapters provide a more exhaustive picture of the relevant applications of the research.

Chapter 2 provides different concepts of electricity market and demonstrates how electricity market has been evolved from vertically integrated structure to a competitive and transparent environment. In order to clarify market revolutions toward deregulations, market structures in several countries have been investigated. One of these reviewed markets is UK electricity market. The appearance of electricity Pool structure has been reviewed and the reasons of transforming into bilateral electricity market have been highlighted. Furthermore, different types of market modeling techniques have been investigated and Equilibrium method has been selected as a modeling approach based on its specifications.

In Chapter 3, the UK electricity market, BETTA, structure has been investigated in details as an example of bilateral market in order to clarify the importance of modeling bilateral electricity market. The reasons behind bilateral market modeling will be explained based on different facts such as price volatility in Balancing Mechanism (BM) and spot market; hence, the impacts of such a market structure on market participants' behaviors and strategies will be presented.

Exercising market power in bilateral electricity market will be reviewed in Chapter 4, by investigating some concepts such as perfect competition and monopoly. It will be explained that in order to model bilateral electricity market, it is essential to split it into generation and supply sides. In Chapter 4, the imperfect competition in generation side will be studied and GenCos' strategies in oligopolistic electricity market will be highlighted. In order to monitor market power, different techniques will be reviewed and equilibrium method, particularly Conjectural Variation Equilibrium (CVE) approach will be selected. A presented case study in this chapter, illustrates that the inverse demand curves parameters such as slope and intercept and also GenCo's conjectures about their rivals' have strong impacts on the market.

SupplyCos' behaviors will be taken into consideration in chapter 5 by investigating and modeling oligopsonistic electricity market. In this chapter the boundaries of GenCos' and SupplyCos' conjectures will be studied and the impacts of inverse generation curve parameters and the retail price on SupplyCos' strategies will be highlighted.

Chapter 6 looks at the bilateral electricity market at a higher level in order to find the equilibrium point of the market. The co-ordination between oligopolistic and oligopsonistic electricity markets will be highlighted and a novel hierarchical optimization algorithm will introduced By performing this algorithm the equilibrium point of the market can be calculated, in which all market participants are making profits and the proposed case study in this chapter can validate this algorithm.

Finally Chapter 7 provides various concluding remarks about this research.

1.6 Publications

A. H. Alikhanzadeh, M. Irving, G.A. Taylor, "Oligopolistic and Oligopsonistic Bilateral Electricity Market Modeling Using Hierarchical Conjectural Variation Equilibrium Methods," European Transaction on Electrical Power, 2013, Submitted for Publication.

A. H. Alikhanzadeh, M. Irving and G.A. Taylor, "Combined Oligopoly and Oligopsony Bilateral Electricity Market Model Using CV Equilibria,"2012 *IEEE Conference on Power and Energy Society General meeting*, San-Diego, California, USA.

A. H. Alikhanzadeh and M. Irving, "Bilateral Electricity Market Theory Based on Conjectural Equilibria," 2011 *8th International Conference on the European Energy Market (EEM),* Zagreb, Croatia, pp. 99-104.

A. H. Alikhanzadeh, M. Irving and G.A. Taylor, "UK electricity market modeling using combined Conjectural Variation equilibrium method and hierarchical optimization algorithm", *2012 47th International Universities Power engineering Conference (UPEC),* London, UK.

A. H. Alikhanzadeh, M. Irving and G.A. Taylor, "Bilateral Electricity Market Model using Conjectural Variation Equilibria and Hierarchical Optimization", ", *2011 46th International Universities Power engineering Conference (UPEC),* Soest, Germany.

Chapter 2: Literature Review

2.1 Introduction

Electricity market deregulation has changed the power industry from a centralized structure into a competitive market environment. Over the past two decades many changes have been made in the power industry in order to make a new economical structure. There are several commodity markets around the world, which almost have the same structure and mechanism. In all of them, supply should meet the demand and market equilibrium should be found; however, there are several factors that make the electricity market different and more complex compared to others such as:

- Method of delivery (Generated electricity from one generator cannot be directed to a specific costumer).
- Date of delivery (Electricity demand should be met on real time basis).
- Complex regulations (The existence of several governance regulations make the market structure complex).
- Transactions conditions (Complex market structure brings complication into transaction conditions e.g. forward, future and option contracts).
- Limitations on storage (Electricity can not be stored like other comedies in large scale)
- Governmental obligations (existence of several governmental and renewable obligation bring complexity into the market).
- Demand prediction (Unlike other comedies the demand profile predictions is challenging).
- Fast market operations (e.g. in the UK electricity market the System Operator has got only 1 hour in order to match the generation and demand for each settlement period).

Liberalization, climate policy and promotion of renewable energy are challenges to players in the electricity sector in many countries. Policy makers have to consider issues like market power, bounded rationality of players and appearance of fluctuating energy sources in order to provide adequate legislation. Furthermore, interactions between markets and environmental policy instrument become an issue of increasing importance. A viable approach for the scientific analysis of these developments is equilibrium methods, the goals of this chapter is to provide an overview on the market concept and its evolution towards a competitive environment, this evolution of the power market leads to a new electricity market that is an ‘electricity pool’. Yet the pool concept suffered from a number of disadvantages. Those problems led the UK government to announce New Electricity Trading Arrangement (NETA) as a new power market in 2001 and developed into British Electricity Trading and Transmission Arrangement (BETTA) in 2005 that covers England, Wales and Scotland. BETTA specification leads us toward understanding the concepts of oligopoly and oligopsony market conditions and investigations of this market structure.

In order to achieve a clear understanding of the UK electricity market operation, as a bilateral electricity market, and to find out how this market can be modeled in a way to create an environment to help all market participants make profit, an overview of electricity market revolutions from vertically integrated utilities to a competitive market environment in the UK and other countries is presented in this chapter. Pool structure electricity markets will be described and a brief introduction about the appearance of NETA and BETTA will be discussed. However, a more detailed review of BETTA and the risks of participating in such a market will be provided in Chapter 3. Considering deregulated electricity markets’ risks, this chapter correspondingly evaluates different market study methods, which have been studied. Further details with respect to the proposed modeling method will be discussed comprehensively in Chapter 4.

2.2 Concept of Electricity Market

Several governance structures and market designs have been proposed to reflect regional and national requirements. Like other competitive markets, numerous evolutions have occurred and still there are some ongoing revolution processes; however unlike other markets the governance, regulations and pricing arrangements for this kind of market are very complicated. It took years for policy makers to find out that markets for transmission and energy cannot be introduced without any linkage between them and after several trial investigations some appropriate and established structures have been introduced [2].

Several years ago, when customers wanted to buy and use electricity they had no choice since the structure of the electrical industry was a monopoly. Thus, they had to buy electricity from the utilities, which was vertically integrated and held the monopoly [1]. Those utilities managed generation, transmission, distribution, infrastructure supervisions and electric services to the individual large or small customers. They also coped with the maintenance and future developments of their own assets to meet the future demand level and also maintained both high voltage transmission lines and low voltage distribution network. Therefore, the security of supply, which is one of the most important pillars in national strategies, could not be met properly since it was shared among all these vertically integrated utilities. Some of these utilities were government agencies, while others were regulated private companies. Figure 2.1 demonstrates the monopoly model of electricity market [1]. In (a) the utility is completely vertically integrated; however in (b) the distribution handled by two or more companies.

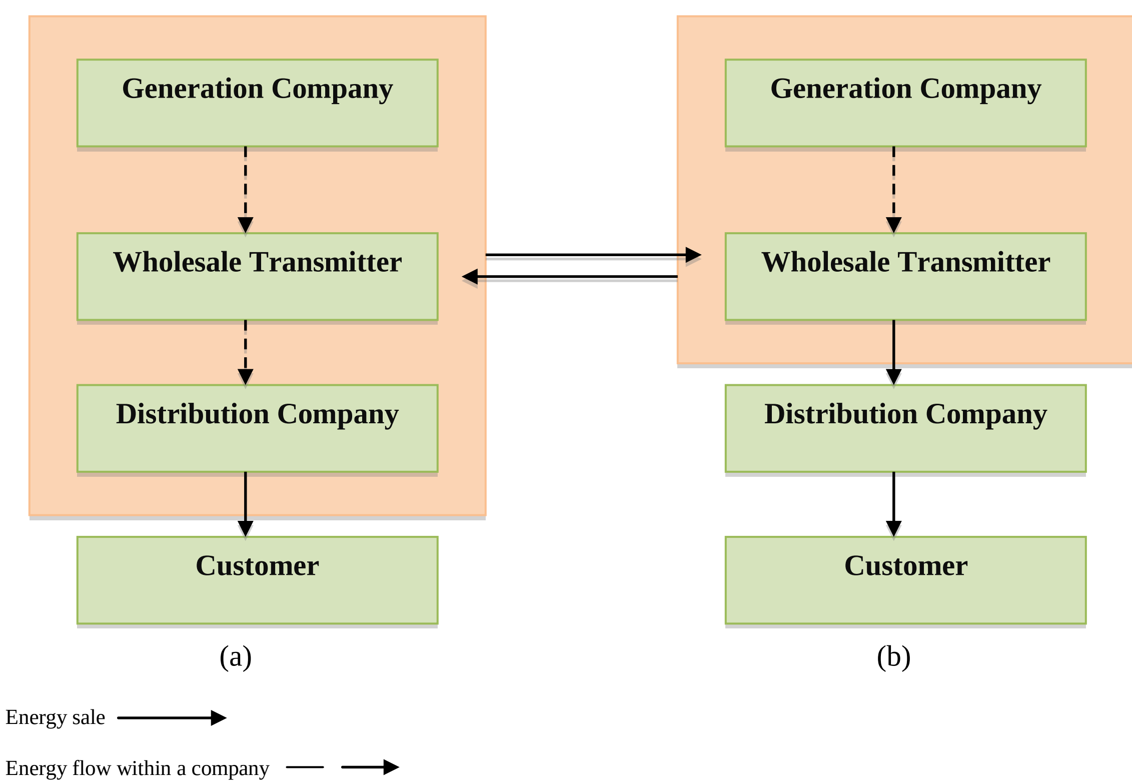


Figure 2.1: Monopoly of Electricity Market [1]

In the 1980's engineers, customers and economists realized that this kind of structure could remove the incentives to operate, participate and make investment efficiently in the electrical industry. The public utilities were so close to the government and these policies could interfere with the power market [2]. Besides, the regulated private utilities passed on the cost of their mistakes to the customers and that made the price of the electricity unreasonably high.

In order to introduce more incentives to the market participants and make the quality of supply higher and the electricity price low, the existence of competition in the market and among the participants of the electricity industry is an essential issue to consider. In most cases the introduction of competition leads into privatization. In the privatization process some public utilities are sold to the private sector by the government [1].

Figure 2.2 shows the double dimension of the restructuring process. The vertical axis shows the reforms related to the ownership and the horizontal axis displays the market structure [3]. By moving towards left, the level of completion increases.

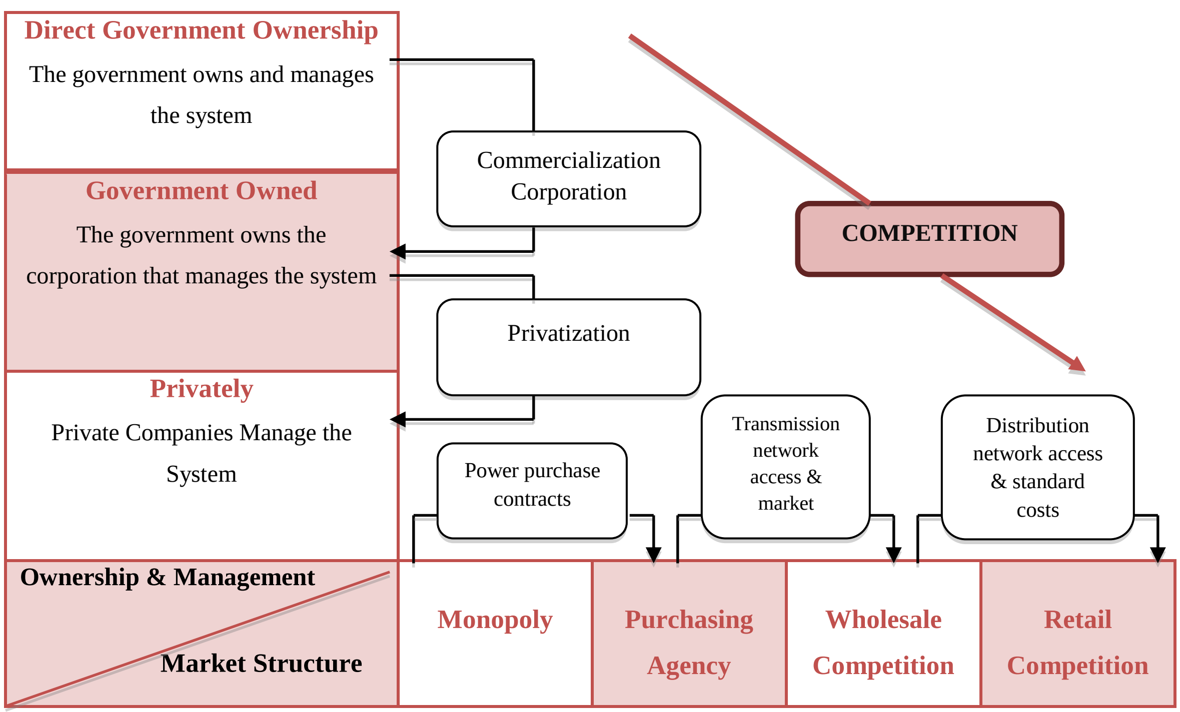


Figure 2.2: Restructuring Dimensions and Possibilities [3]

2.3 Models for Electricity Sector

According to the Figure 2.2, four electricity models combining the types from Hunt and Schuttleworth (1996) and Tenenbaum, Lock and Barker (1992) can be considered. The level of competition at each stage has distinguished these models, presented as below.

2.3.1 Monopoly

Generation, transmission and distribution in this model are vertically integrated, although in the distribution section there may be different distribution companies, which have local monopoly conditions (Figure 2.1). This can happen commonly in the wholesale market even for bilateral trading [4,5].

2.3.2 Purchasing Agency

This is a first step around a competitive environment in the electricity market. In this model the utility no longer owns all the generations. Here the Independent Power Producers (IPP) plays an important role and sells their electricity as purchasing agents [1]. Figure 2.3 illustrates the purchasing model, in which IPPs are also participating in the electricity trading and have brought competition into the generation side.

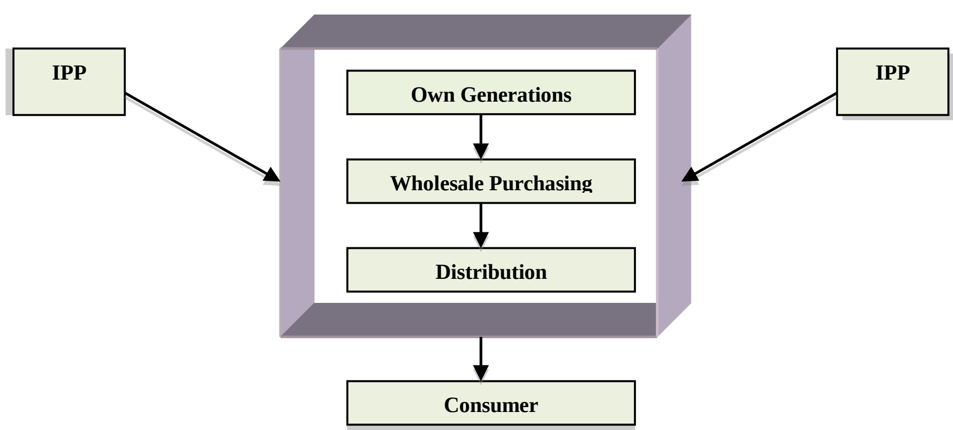


Figure 2.3: Purchasing Agency Model of Electricity Market [3]

One of the advantages of this model is introducing some competitive environments in the generation side. However, this model cannot be an appropriate one especially for a bilateral market since there are still some monopoly and monopsony powers among the participants.

2.3.3 Wholesale Competition Model

There is no central organization in this kind of model. All the Distribution Companies (DisCos) purchase the electricity directly from the Generation Companies (GenCos) and distribute among their customers. As shown in Figure 2.4, large customers are allowed to buy the electricity directly from the wholesale market [1,2,5-7]. At the wholesale level, only the operation of the transmission network and the Spot market remain centralized [1]. On the other hand, at the retail level the system is still centralized, since each DisCo purchases electricity on behalf of customers that are located in that area.

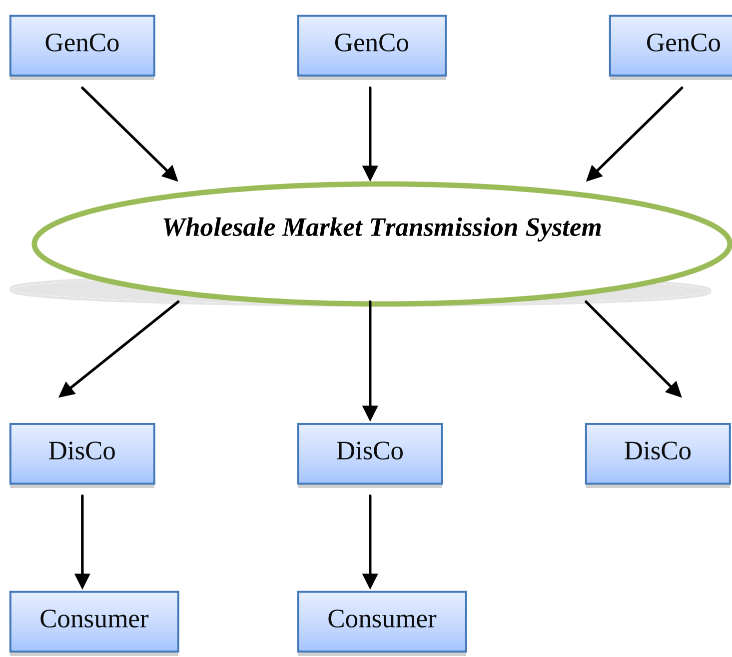


Figure 2.4: Wholesale Competition Model [3]

It is noticeable that the wholesale market can take the form of Pool or bilateral transactions [2]. This model creates a more competitive environment at the generation level because the wholesale price can be determined by the bidding strategies of the GenCos. On the other side, the retail price of electricity should be regulated based on the fact that there is no chance for small customers to select their suppliers if the prices are too high. This is even challenging for DisCos since they cannot reduce their exposures to the risk of increases in the wholesale price.

2.3.4 Retail Competition

In this model customers have been given the chance to choose their suppliers in full retail competition [7-9]; therefore there is no need for the retail price to be regulated any more. In this model, because of transaction charges some large customers can purchase electricity directly from the wholesale market. Figure 2.5 demonstrates the structure of this model.

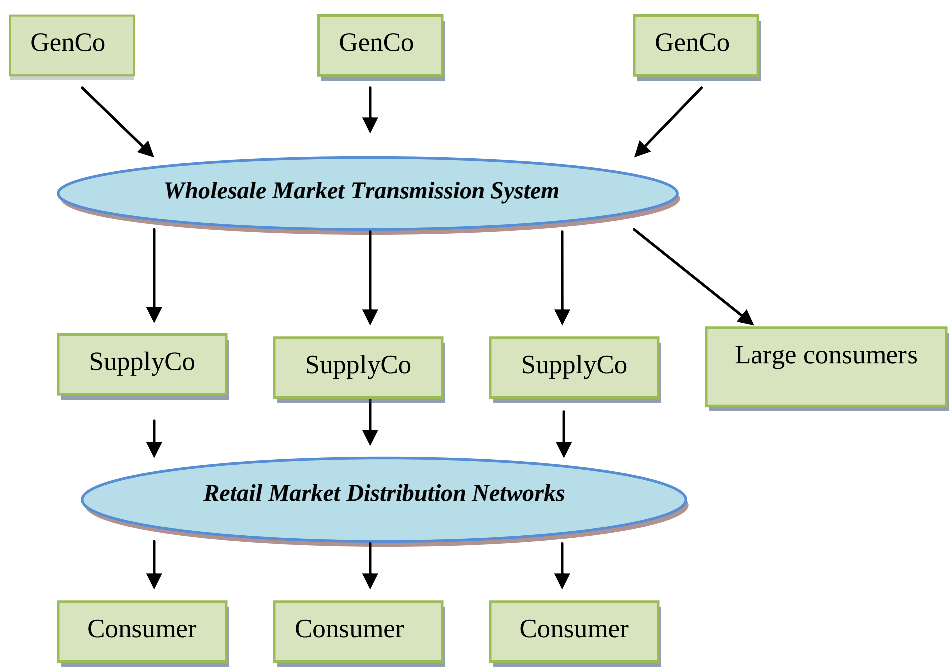


Figure 2.5: Retail Competition Model [3]

It is also noticeable that Distribution Companies' physical activities are totally separate from their retail activities to avoid any local monopoly for supplying the electricity to the end users [2]. The only concern that remains is the monopoly in operation of transmission and distribution networks, so it is expected that the charges for using these networks would be shared among all the market participants. Hence, differences in these models are whether there is competition among generation companies, supply companies and also whether the final consumers can choose whom to buy their power from, e.g. comparing to wholesale model, in retail completion the end-users have been provided the chance of choosing their suppliers.

2.4 Global Movements towards Market Restructuring

In the late 1970s, one of the earliest introductions to the privatizations in the market structure took place in Chile. Argentina also tried to build a market and privatize existing generation companied and provide capital investments for reintegration of assets and for transmission expansions. Other Latin countries like Brazil, Peru and Colombia were among those followers who tried to establish a competitive market in 1990s [2].

Economic crisis forced other countries around the world to restructure their market into a completive one in order to bring transparency and remove market power from wholesale trading. Nordic countries, Continental Europe, New Zealand, North America, Australia and Great Britain were among those pioneers [2]. Brief summary of these market revolutions are described below.

2.4.1 Nordic Countries

Nordic countries consist of Norway, Sweden, Finland and Denmark. Norway was the first country that introduced market restructuring by the Energy Act of 1990. Following Norway, Sweden tried to establish a competitive market in 1995, which resulted in establishing Norwegian-Swedish Exchange (Nord Pool) in 1996. Later on Finland joined this market in 1998, West Denmark in 1999 and East Denmark in 2000. There are five System Operators (SO) in this market, one for each country except Denmark with two SOs; therefore the Nord Pool can be considered as the only existing international market [10].

2.4.2 Continental Europe

Since electricity markets in each European Union (EU) states have weak points in terms of cross-border electricity exchanges the idea of single Internal Electricity Market (IEM) was introduced in 1996 [11-13].

The majority of trading would be bilateral contacts including forward and future arrangements; only a small fraction of trading would take place in daily and hourly contracts in the spot markets in order to help all participants to fine-tune their positions.

The IEM would be divided into submarkets in order to help Transmission System Operators (TSOs) monitoring and controlling each zone. In 1999, European Transmission System Operator (ETSO) was established in order to implement IEM. Also in 2009, European Network of Transmission Systems Operators for Electricity (ENTSO-E) was founded to insure co-operation among European TSOs and implement regulations and rules in line with European Union legislation [12].

However, it is obvious that further investigations required establishing a single IEM for all EU states, with the purpose to fulfill all three European Union pillars, which are as follow:

- Security of supply
- Sustainability and environment
- Competition

European Council (EC) has set a target as 2014 to achievement of the Internal Electricity Market. By this time electricity would be traded freely in Europe [11].

2.4.3 New Zealand

New Zealand used to have a monopoly electricity market until 1994. Since then several deregulations took place in both generation and retail sides to bring competition into the market. The wholesale electricity market, called NZEM, brought transparency and regulated prices by using pool and spot markets. NZEM in considered as the first international market based on nodal pricing, which brings Local Marginal Pricing (LMP) in the market. M-co is a company who administrates the market on behalf of government and a state-owned company is the owner of transmission networks and plays the role of TSO [14].

2.4.4 Australia

Altered commercial solutions and restructures were introduced in the early 1990s to eliminate the monopoly from wholesale and retail markets and bring functionality into transmission and distribution network operations. In 1998 the major reform took place in southern and eastern Australia where the National Electricity Market (NEM) was established. The market operator for this market is called National Electricity Market Management Company (NEMMCO).

The NEM involves pool structure where all the electricity sold at wholesale level is traded in this market. NEM covers one of the longest interconnected power systems since there are six zones in this market and constraints on interconnectors can cause distinct marginal spot prices among these regions [2,15].

2.4.5 United States

The emerge of Independent System Operators (ISOs) in United States happened in 1996 after launching the Energy Policy Act of 1992. The Federal Energy Regulatory Commission (FERC) introduced ISOs including Pennsylvania-New Jersey-Maryland (PJM), ISO New England (ISO-NE), New York ISO (NYISO), California ISO

(CalISO), Midwest ISO (MISO), Southwest Power Pool (SPP) and Electric Reliability Council of Texas (ERCOT) [2].

Each ISO covers one or more than one area and is responsible for reliability and security of supply for those areas. The procedure of this market is based on two elements: Available Transfer Capabilities (ATC), provided by ISOs, and Open Access Same-time Information System (OASIS). These ATCs would be published on OASIS and based on bilateral trading; transmission requests can be addressed within those specified areas [16].

However diversity in a number of ISOs in United States caused divergence problems. Some ISOs had pool market background, which resulted in creation of several voluntary spot markets like 1997 PJM and 1999 ISO-NE markets [17,18]. In order to establish a top-level organization to ensure the reliability of all transmission networks and security of supply, FERC founded Regional Transmission Organizations (RTO) in 2000, which was responsible for market operations and regulations and supervising the ISOs. Finally, this complex structure of electricity market and partial deregulations caused market manipulation and in 2000 California Market had several crises, which resulted in multiple blackouts and economic fall out [19].

The California electricity market crisis was a good case that demonstrated the importance of considering market reliability in designing electricity market structure.

2.5 Great Britain

As discussed earlier, one of the main reasons of market deregulation was to make electricity, as a commodity in such a market, analyzable in economical and financial frameworks. UK electricity industry has seen major changes since Electricity Act in 1989 [5] in order to make it one of the most advanced electricity market in Europe. The following sections represent these evolutions.

2.5.1 Electricity Pool in UK

The UK introduced a new electricity market that started on April 1st 1990. The electricity was sold through the Electricity Pool, which had become the wholesale market for trading electricity. In 1990 before the privatization, there were three major companies in England and Wales and National Power, Powergen and Nuclear Electric supplied approximately 75% of the UK's power generation [5].

2.5.1.1 Competition at Generation Level

In the 1990s, the competition on the generation side created an environment in which there were nearly 40 major generation companies selling electricity into the Pool in England and Wales. However, the Pool was still dominated by the 5 largest companies – British Energy, PowerGen, National Power, BNFL Magnox Generation and Eastern Merchant Generation – that produced 50% of the generated electricity from October 1999 to September 2000. 2% of the generated electricity was provided by the France-England and Scotland-England interconnections and the remaining 48% from other medium and small size generation companies [20]. Also there were four large generation companies in Northern Ireland owned by Premier Power, Nigen and Coolkeeragh Power. In contrast to England and Wales and Northern Ireland, Scotland had a monopoly market dominated by ScottishPower and Hydro-Electric. Later Privatizations and deregulations covered National Power, PowerGen and Scottish Power in 1991, National Grid in 1995 and finally British Energy in 1996 [20].

2.5.1.2 Competition at Transmission Level

Before BETTA, there are four transmission operators in the UK. National Grid Company (NGC) is operating in England and Wales, which is the largest transmission network. Northern Ireland Electricity is operating the transmission network in Northern Ireland and similarly there are two transmission operators in Scotland: ScottishPower and Hydro – Electric. All these transmission networks are connected through several interconnections. However, after 1990 in order to bring flexibility and competition in to the market these transmission networks are open to licensed suppliers based on a Grid Code [5,20].

2.5.1.3 Competition at Distribution Level

There were 15 privatized Regional Electricity Companies (RECs) in the UK from 1990 to 2001. Each distribution grid operated by one REC. RECs were responsible for both distribution and supply the electricity before the privatization however, after market deregulation these two tasks unbundled. 12 RECs covered England and Wales and distribution grid in Scotland was operated by 2 RECs alongside generation and transmission companies and Northern Ireland was vertically integrated with only one company [20].

2.5.1.4 Competition among Suppliers

Before privatization, distribution companies were responsible for supplying the customers in their regions. However, after Pool establishment the supply market became open for competition and RECs could participate in trading. There were two types of RECs in the market described as follow [5,20]:

- **First Tier RECs**: These were the local responsible companies for distributing electricity in their designated area. Alongside their responsibilities for connecting end-users to the grid, they were constrained to supply electricity to any small customers within their licensed area as well. They were regulated by public electricity supply (PES) license. Since they were providing physical connections and playing the role of supplier they can easily dominate the market and their market share for each area would be high.
- **Second Tier RECs**: Other supply companies were considered as Second Tier RECs. They were regulated by a private license. These supplier provided electricity for the customers, which were outside their regions.

Table 2.1 demonstrates the market share for each REC in each region. It can be found that the First Tier RECs were dominating the supply market.

Table 2.1: Domestic Market Share of Local REC (June 2000) [20]

Region	REC (owner of supply business)	Market share by number of customers (%)	Market share by volume (%)
Eastern	Eastern Energy (TXU)	81	82
South	Southern Electric (SSE)	83	85
East Midlands	East Midlands Electricity (PowerGen)	79	79
Midlands	Midlands Electricity (Innogy)	82	85
Northwest	Norweb (TXU)	83	81
South Scotland	Scottish Power	84	86
Yorkshire	Yorkshire Electricity (Innogy)	84	85
Southeast	Seeboard	83	84
London	London Electricity (EdF)	84	85
Merseyside	Manweb (Scottish power)	81	86
Northeast	Northern Electric	78	75
Southwest	Sweb (EdF)	89	91
South Wales	Swalec (SSE)	84	88
North Scotland	Hydro-Electric (SSE)	89	93

Correspondingly, Figure 2.6 has been provided in order to achieve to a comprehensive understanding of UK electricity Pool structure.

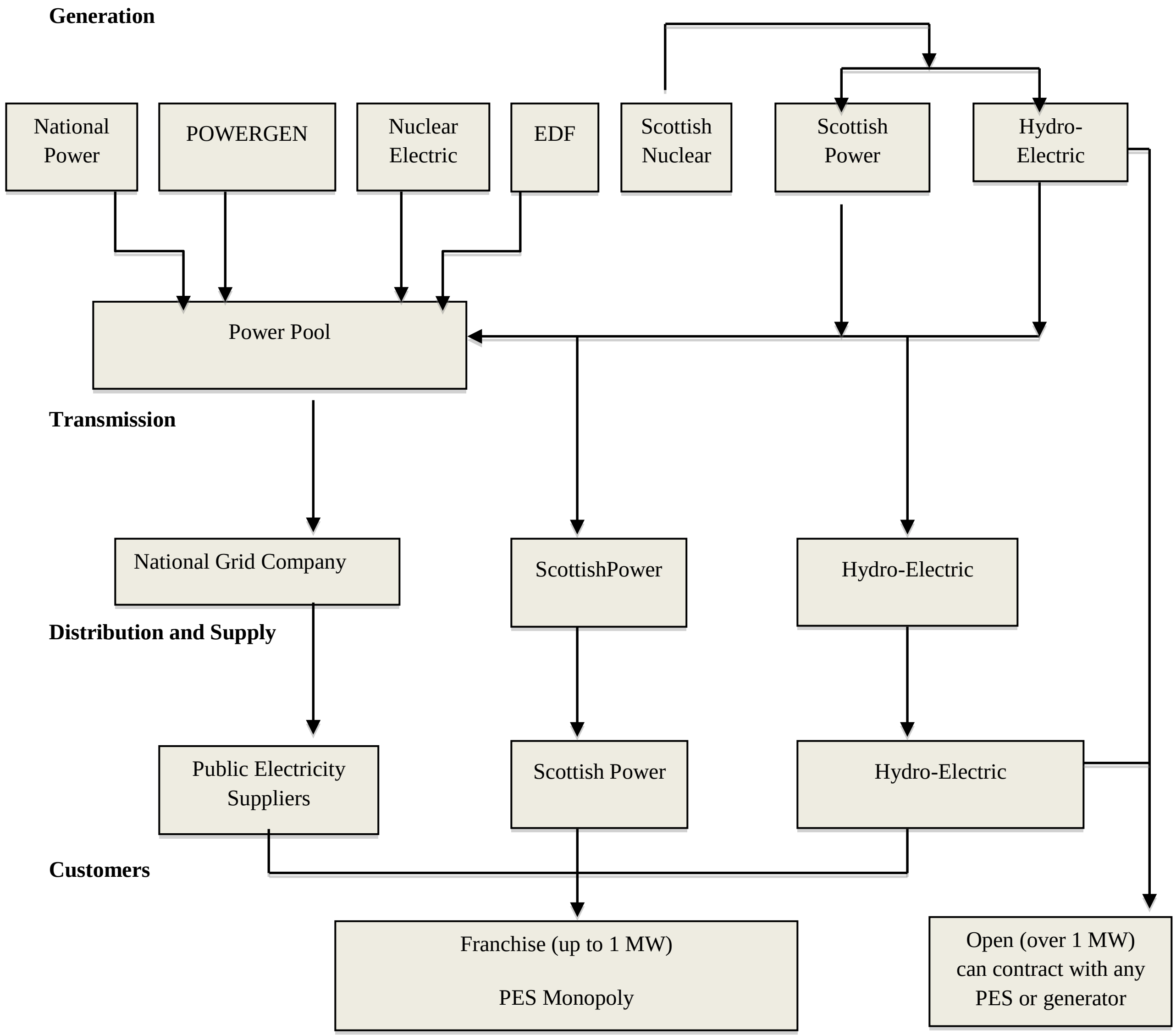


Figure 2.6: Privatized UK Electricity Industry Structure [5]

2.5.1.5 Electricity Pool General Structure

The Pool was a centralized market and designed to allow National Grid (NG), as the System Operator (SO), to be responsible for making sure that there is enough generation capacity in the system to meet the end-users' demand. Figure 2.7 demonstrates an overview of Pool's procedures.

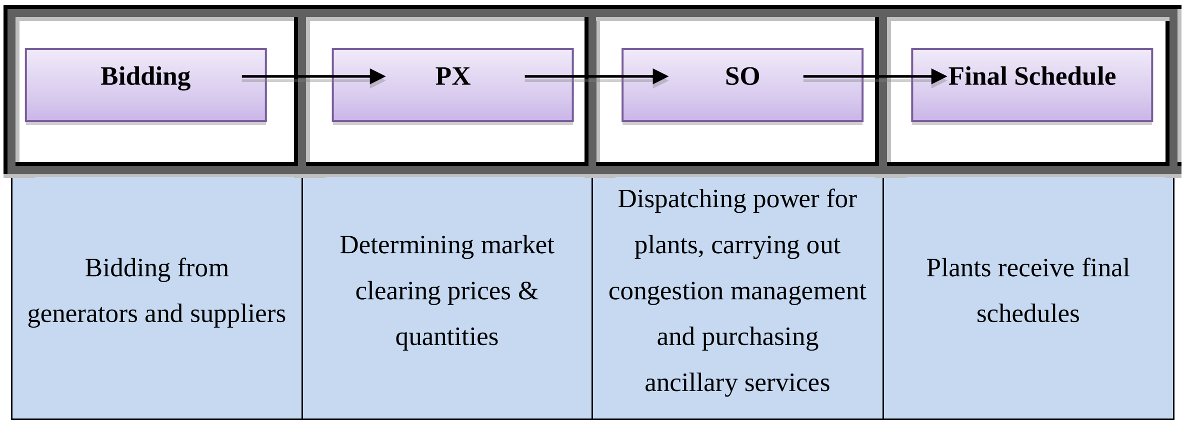


Figure 2.7: Overview of Pool's Procedures

Based on above discussion, the Pool does not buy or sell electricity. It just provides a framework, within which all sales and purchases of the electricity made between producers, and consumers took place. Bids submitted by the generation companies are ranked by the market operator in order of increasing price. This is called ''merit order''. Figure 2.8 below illustrates the merit order ranking.

Figure 2.8: Electricity Pool Market Merit Order Ranking

The SO carries out a *centralized dispatch*, which decides which generation company run in order to meet the demand. Marginal generator is the last generator that is scheduled to meet the demand from either demand cost curve or demand forecast and System Marginal Price (SMP) is based on marginal cost of marginal generator [21,22]. Generators selling price into the Pool was based on the price of marginal generation in each half – hour.

Under this scheme generation companies have an incentive to offer a price which is equal to their marginal costs which implies:

- Individual generators cannot increase the market price by raising their own offer prices unless they know that their power plant is at the margin.

- There is insufficient competition and some players would practice market power because:
  - If they offer a price that is too high, they may not be dispatched at the times when the spot price is above their real costs according to the merit order ranking and SMP.
  - If they offer a price that is too low, they may be dispatched at times when the spot market price is below their real costs.
  - For some generation companies, the priority is to get their units running, so market manipulation would happen and they may submit zero bids, but still get paid at SMP, which is not fair [22].

Since the beginning of the Pool until 1998 only the 50,000 largest customers had been given the opportunity to switch between the suppliers; however, from September 1998 all end-users were given this permission to make the demand side more active [21]. However the Pool was not able to make the demand side fully active in the market trading.

Although this restructuring brought some competition in the market that caused 30% reduction in electricity bills [21,23] in the first few years, after a while the Pool started to be suffering from some problems and discriminations.

Accordingly, the Pool suffered from number of key problems, such as:

- Complexity of bids, since no-load price and average marginal cost should be taken into account for submitting merit order price
- Pool capacity payment, since all customers were paying for capacity payment, which was not reasonable
- One sided market, since the demand side did not have an active role
- Market power, since some GenCos could submit zero bids to get paid at SMP
- Marginal pricing
- Lack of transparency in submitting bids
- Lack of competition

These began a process to make fundamental changes in the market and led to NETA appearance.

2.5.2 Appearance of NETA and BETTA

The New Electricity Trading Arrangement (NETA) appeared in March 2001. NETA took four years to develop from its beginning of 1997, to implementation in 2001. This new arrangement covered England and Wales and reformed into British Electricity Trading and Transmission (BETTA) in 2005, which besides England and Wales, covers Scotland [24-30]. One of the most significant principles of BETTA is that the market should provide a free environment to bring the capability of meeting all electricity demand in the system. To achieve this goal BETTA abolished the electricity Pool as a *centralized market* in which the National Grid Company (NGC) as the system operator according to the bids and offer of the market participants and the security issues of the system, determines which units of the GenCos should generate electricity and which generators and suppliers are permitted to sell and buy electricity in the Pool.

On the opposite side, BETTA has created a market framework in which all units of GenCos are free to *self-dispatch* and decide to generate electricity according to their objectives. They can enter bilateral contracts with suppliers. The key point of BETTA is based on a series of bilateral contract traded ahead of real time. These contracts can be in the form of forward and future trading several months or even one year ahead of real time. According to the main specifications of BETTA, unlike the electricity Pool that was *centralized-dispatched*, here all generators are *self-dispatched.* It means that each generation company according to its maintenance schedule, marginal cost, cost of fuel, etc., decides to generate the electricity or buy from the market. Therefore, all units of a power plant can generate within a wide range, they can generate at their full rated level or nothing. Also demand side plays an active role through the retail market (Figure 2.9). More about this new trading arrangement will be discussed in Chapter 3.

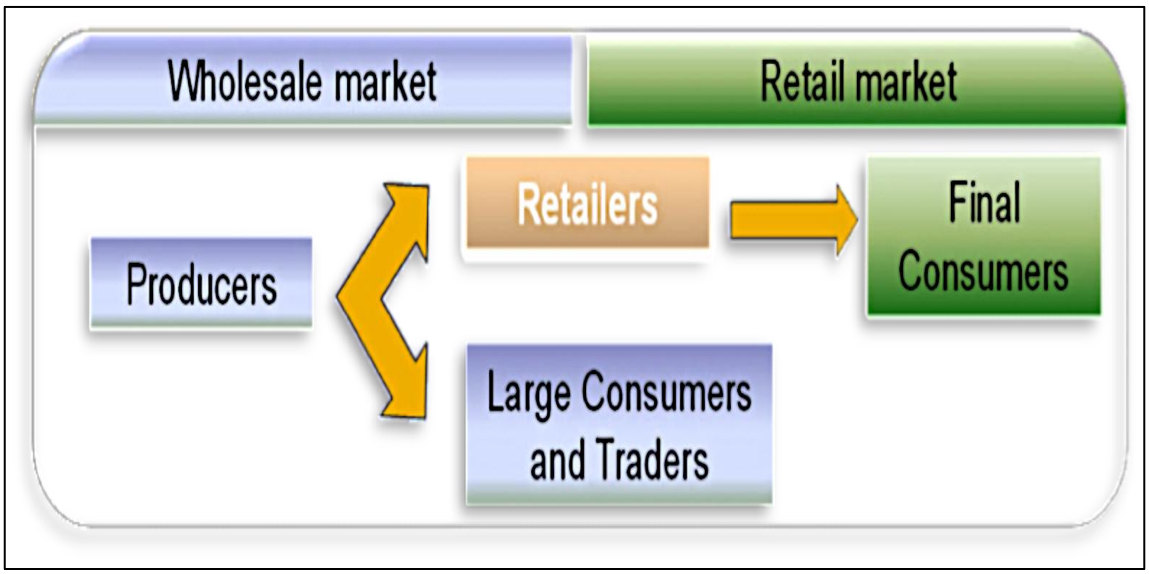


Figure 2.9: Including Wholesale and Retail Markets

These significant specifications can lead us to find that all electricity market participants have various specifications as follow:

- Heterogeneous; they are have various specifications
- Autonomous; they are acting independently
- Have their own objectives and their own strategies to reach them
- They interact among themselves in a dynamic changing environment

Therefore, all these factors direct us to an investigation into a proper model in order to develop an algorithm that acts as a tool to support decisions and obtain knowledge about market behaviors to model this environment and maximize all market participants' profits.

2.6 Concerns and Consequences of Market Deregulation

The electricity sector in both UK and Europe is experiencing considerable changes. The privatization of electricity market, climate policy, proposed Renewable Obligations (ROs), CO_2 emissions and renewable targets are some factors to be addressed now and near future.

According to these issues new question arises:

- How to simplify the structure of deregulated markets and the process of bidding?
- How to model each market component to find out its objectives and strategies?
- How can liberalized markets be developed without endangering the security of supply?
- How to implement a method in a way that all market participants would make profit?
- How to hedge the risk of market participations and reduce the exposures to the risks?

- How to make a competitive market environment reducing market power?

Considering the above questions and concern, the following are various impacts and consequences of deregulation, specifically BETTA appearance:

1. Electricity prices: pricing mechanism is one of the most important and key issues in the power market. Keeping the price of electricity at the lowest level is the main goal of a restructured market. To achieve this goal, existence of a competitive environment is necessary. In such an environment all generators try to monitor their competitors' prices and based on their historical data close their prices to their marginal costs.

2. Reasonable costs: In a regulated market the capital cost of assets is to be reflected in the electricity prices. So, there is a chance for private utilities to recover the cost of their facilities.

3. Risks: There are some inherent risks in electricity markets like demand variation, variation of fuel price based on international policies equipment failure, input prices, etc. However, in a monopoly vertically integrated utilities by excessing capacity or choosing different kinds of strategies these risks can be covered easily. On the other hand, deregulated market not only contains these inherent risks but also introduces additional risk sources such as the structure complexity, complex pricing structure and significantly in BETTA lack of time to balance the demand and generation and keeping the security of supply at a reasonable level.

4. Investment: Enough investment in the power system will bring a high level of reliability to the system. In a public utility the government will take this responsibility to make more investment. But in the deregulated market, private companies do not have any obligation to make more investments, however lack of investment will decrease the reliability and increase the prices. This investment issue and lack of incentives for market participants can cause situations that electricity market is dominated by small amount of market participants.

In order to deal with questions above and impacts of a deregulated market, several scientific research have been carried out followed by various approaches and tools have been suggested and developed.

2.7 Electricity Market Modeling Trends

This section attempts to introduce and classify main approaches of modeling and compare them based on their properties and practice. This classification would reveal their advantages, disadvantages, properties and clarify the reasons for choosing Conjectural Variation Equilibrium (CVE) model as a promising approach to model bilateral electricity market i.e. BETTA. Accordingly, Figure 2.10 below demonstrates a proper overview of all these approaches examined in this research including their sub-methods.

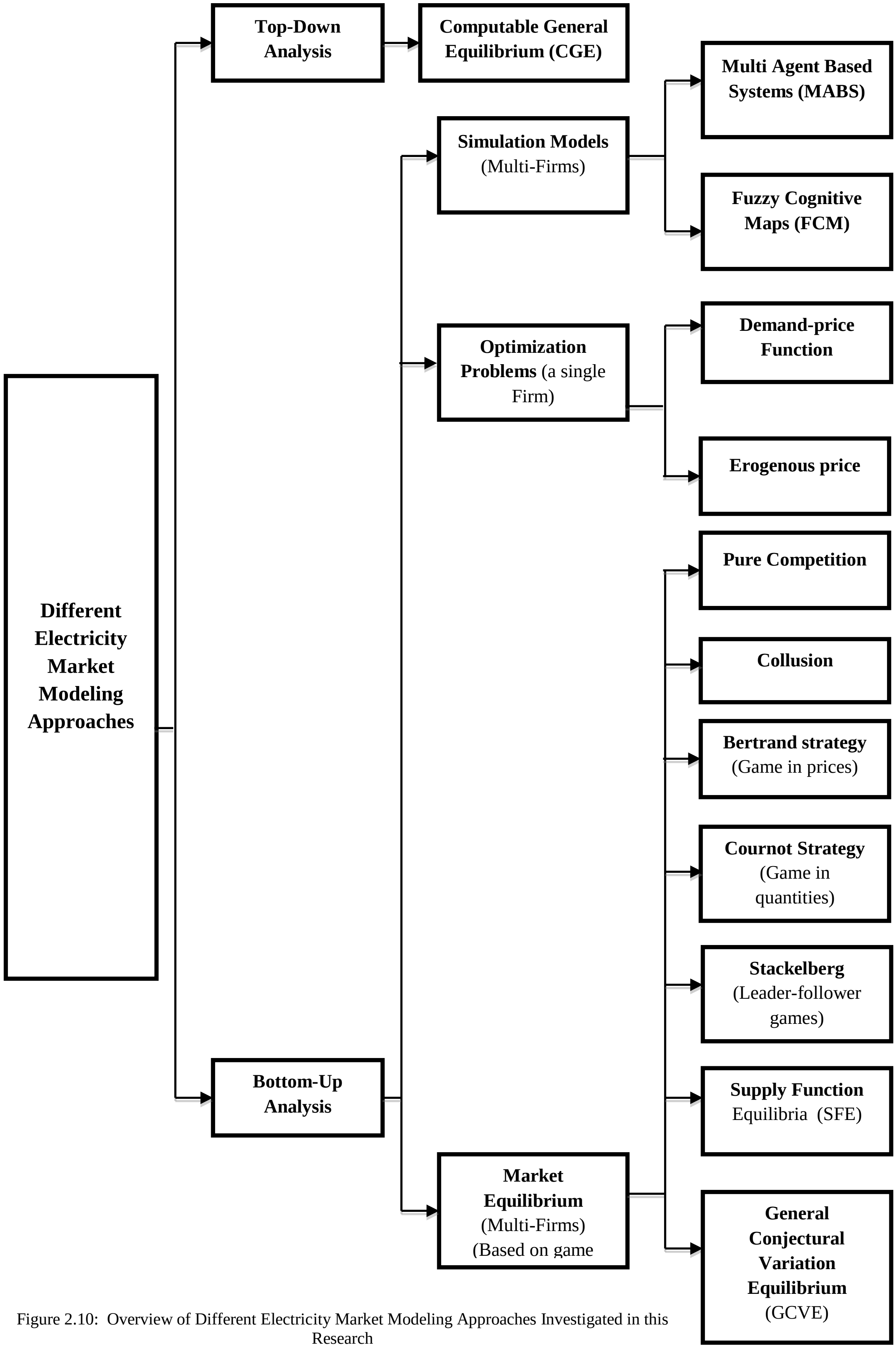


Figure 2.10: Overview of Different Electricity Market Modeling Approaches Investigated in this Research

2.7.1 Top – Down Analysis

2.7.1.1 Computable General Equilibrium (CGE)

Top – down analysis includes Computable General Equilibrium (CGE) models or other macroeconomic modeling [31-34]. They apply a high level of aggregation that lacks the detail level necessary to analyze the short-term changes in the power market, which result from participants' strategies and technical issues [31]. One of the main problems of this approach is to make an adaption between the classical pure financial modeling techniques and a complex novel market like BETTA, because many principles and assumptions used in this approach are not valid in electricity market and ignore the realistic side of the market [32]. In order to model bilateral electricity market, it is significantly vital to take into consideration all market participants' behaviors and try to model them based on their own and rivals' properties; however in such an environment macroeconomic approaches which focus on cross-country and national level modeling cannot be an appropriate approach [33,34]. Furthermore, CGE models are based on perfect competition information, therefore, it would be unrealistic to use this model since there is no perfect competition in bilateral electricity market and most markets suffer from market power.

2.7.2 Bottom – Up Analysis

Bottom – up analysis is a combination of power system limitations and technical characteristics with a realistic modeling of market participants' behaviors. This analysis consists of three major approaches as follow [31,32]:

- Simulation Methods (for multi firms);
- Optimization Methods (for a single firm);
- Equilibrium Methods (for multi firms)

The detailed classifications of this analysis have been provided in the following sections.

2.7.2.1 Simulation Methods

This model has experienced an increasing popularity to model a range of applications including electricity markets. Since these methods do not consider fundamental issues such as market equilibrium point and perform the analysis based on iterative simulations, most of them can suffer from lack of convergence [35, 36]. On the contrary, simulation methods have some advantages over optimization methods in terms of mathematical structure since simulation methods provide a platform where the profit maximization would be performed for all market participants instantaneously.

2.7.2.1.1 Multi Agent Based Systems (MABS)

Agent – Based Model (ABM) is one the main types of simulation methods. This model has experienced an increasing popularity in order to model different environments such as electricity markets [31, 37-45]. In this method market participants can be modeled as agents. Wooldridge and Jennings (1995) defined an appropriate and the most popular definition of a system agent as:

"An agent is a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objectives."

Selection of several agents can create a Multi Agent System (MAS) in which those agents are interacting with each other in order to fulfill their goals. However, there are several disadvantages about Multi Agent Based Systems (MABS) that should be considered.

In order to implement MABS within electricity market some general issues require to be considered [37, 40, 43, 44]:

1. **Platforms:** The platform should be established based on a standard to provide a flexible, extensible and open architecture environment, however the conjunction of different platforms is required. The Foundation for Intelligent Physical Agents (FIPA) defined a range of standard open architectures. The platform provides a message transport system that enables agents to communicate. Message Transport System is equipped with standard protocols like HTTP and IIOP. One of the first Agent Communication Languages (ACL) was Knowledge Query and Manipulation Language or KQML. The language (KQML) was introduced in 1990's; in recent years it is replaced by FIPA – ACL.
2. **Agent communication languages and ontology:** Social ability of the agents requires them to have communication languages. FIPA has introduced four different content languages: FIPA – Semantic Language (FIPA – SL); Knowledge Interchange Format (KIF); Resource Definition Framework (RDF); Constraint Choice Language (CCL). The content language can shape the ontology that describes the concept of the domain and the predicates and agent actions.
3. **Security:** If agents want to communicate with each other, there should be an appropriate level of trust between them and the security of messaging.

Therefore, these issues bring complexity into the market in two aspects:

- Computational analysis
- Communication resources

Since MABS is an appropriate approach to model large systems with large amount of market participants, this model would reflect several weaknesses in modeling bilateral electricity market considering market power. [40] attempts to model NETA and manage the risks involved in this market using MABS. This study can be considered in among of those few research that effort to model NETA as a bilateral market; however, multi agent based simulation covers consequences of market interactions among large number of market participants, therefore it would not be possible to consider market power and oligopolistic and oligopsonistic markets. Moreover, the learning process in this paper is based on merely historical data, which ignores the flexibility and aliveness of market participants.

In addition, the majority of MABS deployed to model electricity markets are modeling Pool structure rather than bilateral electricity markets. For instance, agents in [42] are modeling the electricity Pool market.

As mentioned above, building an agent is a complex task since it consists of several layers. Figure 2.11 demonstrates the layered structure of an agent.

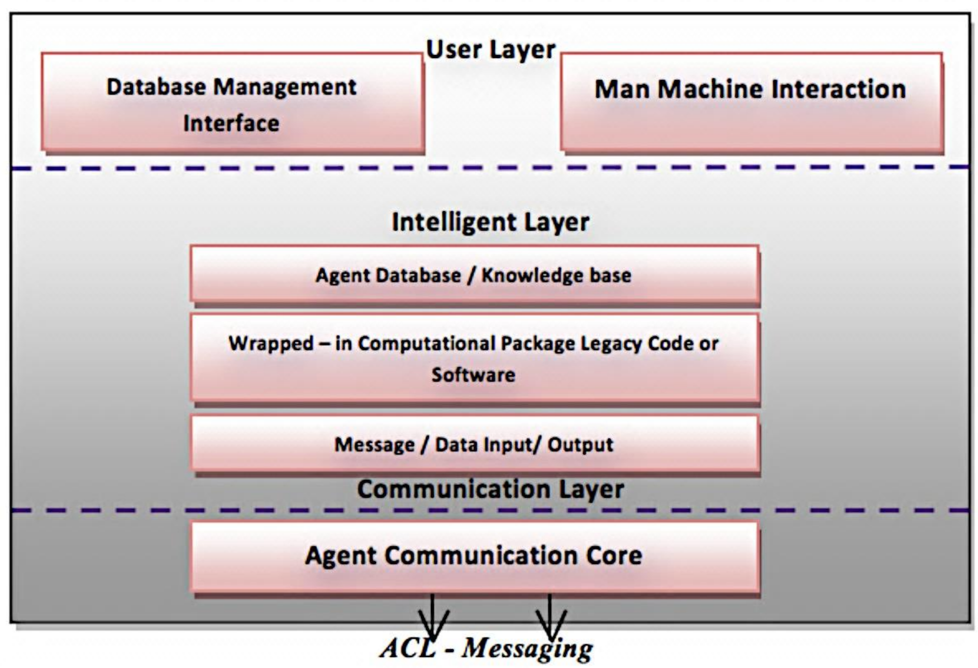


Figure 2.11: Layered Structure of an Agent

In recent years, many implementation tools have been developed. Java Agent DEvelopment framework (JADE) has become a firm favorite. JADE supports FIPA standards and is a suitable platform for implementing layered – architecture agents. However, deploying Java might need further requirements and knowledge and would bring complexity to the mode; therefore, several software packages have been developed and several researches have been carried out based on these software [39]. [41] and [46] are using Electricity Market Complex Adaptive Systems (EMCAS) tool to model wholesale markets and like other previous researches, they are modeling Pool structure and do not fully cover bilateral electricity trading. Also a weakness of this tool is that it does not provide a predictive capability for market participants. In [38] another multi agent tool has been deployed; *PowerWeb*, however this tool does not consider any long term trading which is in contradiction to bilateral contracts.

2.7.2.1.2 Fuzzy Cognitive Maps (FCM)

Fuzzy Cognitive Maps (FCMs) were introduced by Kosko in 1986 [47]. FCM is a combination of Neural Network and Fuzzy logic [48]. FCMs present the knowledge and behavior of a system by using several nodes interacting in a network and also weighted edges. These nodes describe main characteristics of the system and represent the concepts used to describe the market participants' behaviors and weighted edges represent the causal-effect relations among concepts. [49].

FCMs have been deployed in some research to model electricity markets [49-51]. However, as a simulation approach, it suffers from lack of convergence. [49] has deployed FCM to model and monitor a deregulated electricity market; however it is not clear how these weighted edge factors which play significant roles in modeling can be set. Without any distinguished algorithm to identify these weighed edges, FCM cannot represent the causal relation between the nodes.

[50] and [51] are using this method to model electricity markets however there are several weaknesses regarding this approach. Firstly, FCM does not consider long-term planning and only focus on causal relations. Secondly, since bilateral electricity market is a dynamic environment, so it is essential for participants to take into consideration their rivals' behaviors iteration by iteration; however FCM does not provide any robust dynamic mechanism so it restricts its applications. Thirdly, and more importantly is that, this method does not follow Nash equilibrium method characteristics, so market participants might change their behaviors in order to make more profit and play market power. Another flaw is that the concepts in fuzzy cognitive maps are usually binary. Based on binary concepts, a fuzzy cognitive map is unable to model the strength of

cause and degree of effect. Therefore this method cannot fulfill the requirements to model oligopoly and oligopsony electricity markets.

2.7.2.2 Optimization Methods

Optimization methods constitute concepts of a problem in real world and the challenge is finding the concepts, which constitute appropriate representations of problems considering associated constraints. In contrast to the simulation methods, optimization methods are solving an optimization problem for a single firm in the electricity market, however in both simulation and equilibrium methods the objective functions of all market participants, which are normally profit maximization problems, would be considered. This method can be classified in two categories as follow [32]:

2.7.2.2.1 Exogenous Price

In this approach the System Marginal Price (SMP) is an input for the optimization method, which means the market clearing process is an exogenous procedure for this method. In this case the revenue of generation companies (GenCo), $'R_{ig}'$, would be a linear function of GenCo's output:

$$R_{ig} = P_{SMP} \times q_{ig} \tag{2.1}$$

Where the $'P_{SMP}'$ is the system marginal price and $'q_{ig}'$ is the output of GenCoi. Therefore:

$$R_{ig} \propto q_{ig} \tag{2.2}$$

According to Equation 2.2, it is apparent that the behavior of other generation companies in the market, as rivals for GenCo i, is not considered. Therefore this method cannot be an appropriate approach to model electricity markets.

Consequently this approach can be only applicable for a quasi-perfect competition [32], which is not the case for electricity markets since it neglects the market power of each market participant, specifically in bilateral markets.

2.7.2.2.2 Demand-Price Function

In the previous method the system marginal price was calculated exogenously, therefore the quantity of each generation company does not have any influence on this calculation; however in this approach the price is based on the output of generation companies [32].

This approach, which is based on microeconomic theory is called leader-in-price model [52], (cited in [32]). Here, each generation company is given the demand function and also the supply function of its rivals, which is called *residual demand function* in order to maximize its profit. The residual demand function can be calculated by subtracting the aggregation of all rivals' supply functions from the whole demand side bids. However, calculating the residual demand function would be a challenging issue for all market participants specifically in the case of bilateral market, since all the forward and future contracts are not disclosed and market participants do not have any knowledge about their rivals' bilateral trading, therefore in bilateral market generation companies can not compute the aggregation of rivals' selling offers.

These mathematical optimization methods can be combined with other approaches, which can results in better and more robust solutions for solving complex problems. For instance in this research one type of equilibrium method has been combined with an originally proposed hierarchical optimization algorithm in order to find the equilibrium point of the bilateral market. Further details will be discussed in Chapters 4, 5 and 6.

2.7.2.3 Equilibrium Methods

One of the most appropriate approaches to model electricity market behavior is equilibrium method. These methods have several advantages over previously mentioned approaches in several different aspects [32]:

- **Market Modeling**: Compared to optimization methods where only one firm's objective function is minimized, equilibrium methods consider all market participants behaviors simultaneously therefore by employing this approach more robust overview of the market environment will be provided and furthermore it will provide market monitoring features which act a significant role in market power analysis.
- **Mathematical Assembly:** Figure 2.12 demonstrates the fundamental difference between optimization methods and equilibrium methods. Equilibrium methods consist of several profits maximization problems optimized in parallel considering relative economical and technical constraints.

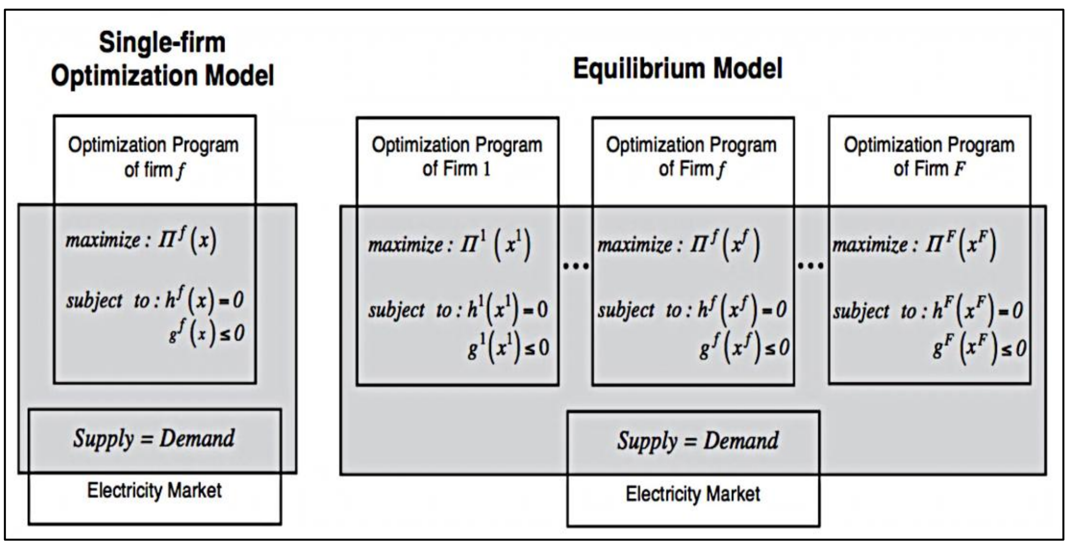


Figure 2.12: Differences between Optimization Model and Equilibrium Model [32]

- **Computational Exploration:** Optimization methods can deal with heavy mathematical problems therefore considering these methods can be combined with other existing methods in order to bring more flexibility into the modeling.

Comparing to equilibrium methods, simulation approaches are appropriate for large-scale systems; however, for considering the imperfect conditions in bilateral trading in an electricity market, equilibrium methods can be an excellent choice.

- **Major Usage:** In contrast to simulation and optimization approaches, equilibrium methods are appropriate for modeling long term decisions, like forward and future contracts which can be made years ahead of delivery time in bilateral markets. Also, they can analyze market power since they consider all market participants.

Based on these four aspects, it can be concluded that equilibrium methods are desirable for both regulators and market participants [35]. It helps regulators to monitor market power and assists market participants to get knowledge about their rivals' strategies and behaviors in case of any changes in strategies of each market participants; furthermore it supports market players in long-term planning and participation in bilateral electricity market, which is within the scope of this research.

2.7.2.3.1 Game Theory and Equilibrium Methods

Game theory is a branch of applied mathematics, which has been employed in several fields like economics, engineering, science, etc. This theory assists us to have an adequate understanding about decision makers in the market and their interactions in a competitive environment [53]. Game theory tries to model the behavior of market participants mathematically in order to illustrate that each decision maker's success in the market, e.g. profit maximization, is based on the decisions of other market participants.

Game theory, which can be considered as a decision theory, was developed in 1920s by Emil Borel and John von Neumann [2]. It has been widely applied in economic fields [54] specifically modeling competitive energy markets [55-58]. In 1950s John F. Nash developed a significant concept in the game theory by introducing *Nash Equilibrium (NE)* [2].

Game theory predicts how a game will be played and these predications will be solutions for each decision maker in order to provide it with adapting appropriate strategies. Consequently, strategies constitute the interaction behaviors of each market participants and each player decides to perform a specific action by choosing a specific strategy. In a *non-cooperative* market, a condition that usually happen specially in bilateral electricity markets, if a decision maker chooses a *dominant strategy* it would get the best possible payoff, which is normally profit maximization, irrespective of other rivals' actions [59]. It is possible that all market participants have dominant strategies, also it can happen that none of them have any dominant strategies; therefore reaching to dominant equilibria is not guaranteed in every game. However, Nash equilibria are wider concept comparing to dominant equilibria. It is assumed that as all market participant are rational and interactive, therefore it can be a set of strategies for each player that help to achieve the best possible payoff by considering other rivals' strategies [59]. The Nash equilibrium point is stable since by approaching to that point no party will deviate from its strategies since it will not make any further profit. Consequently, the primary feature of game theory is to calculate the Nash equilibrium point of the market.

Game theory includes three decision variables, which can result in different equilibrium methods. These variables are:

- Price
- Quantity
- Combination of price and quantity

According to these variables and also considering the reactions among market participants and their abilities to response to these reactions, several market equilibrium conditions can be proposed as follow:

- Pure Competition
- Collusion
- Bertrand Model (Game in prices)
- Cournot Model (Game in quantities)

- Stackelberg Model (Leader – follower games)
- Supply Function Equilibrium Model (SFE)
- Conjectural Variation Equilibrium Model (CVE)

In Chapter 4, detailed discussion concerning these models including their advantages, disadvantages and applications will be presented, considering various research that have been carried out on this topic. It will be shown why Conjectural Variation Equilibrium (CVE) model has been preferred as a promising approach to model bilateral electricity market in this research.

2.8 Summary

This chapter is divided into two main sections. In the first section the concept of electricity market has been discussed, and different types of competitive electricity market models have been reviewed. According to these studies, various electricity market structures in different countries introduced. Importantly, this research aims to focus on bilateral electricity market, such as UK electricity market, the background of UK electricity market since 1990, where electricity Pool structure appeared, and its revolutions towards NETA and BETTA have been investigated.

In the second section, effects of market deregulation process have been examined, and according to those consequences the need for electricity market modeling has been discovered. Various methods of electricity market modeling examined and Equilibrium method as a promising approach was selected to model imperfect bilateral electricity market based on its indicated specifications.

Chapter 3: BETTA, Balancing Mechanism and Risk Management

3.1 Introduction

Energy is produced in a technically complex industry; therefore facing large uncertainties while participating in electricity market will be inevitable since there is always a chance of gaining balanced position in the market with a chance of loss as well. Risks in the electricity market reflect not only the losses but also the volatility of revenue, which can fragile market participants' positions in the market. Participating in such a market successfully requires that firstly the structure of this market should be considered in detail; secondly all risk resources should be identified and properly managed since there is a relationship between risk management effectiveness and company performance.

Chapter 2 described the concept of an electricity market and its evolutions from vertically integrated structure to a competitive environment. It was demonstrated briefly how UK alongside other countries moved towards restructuring electricity market. A brief overview of British Electricity Trading and Transmission Arrangement (BETTA) was covered in Chapter 2, however in this chapter more detailed study will be provided and the purpose of market modeling especially in bilateral electricity markets like BETTA will be demonstrated. Furthermore, the impacts of these deregulations on market participants' behaviors and various aspects of risk resources, which may be caused and affect market participants strategies, will be investigated.

3.2 Motivations for Transformation from Pool to Bilateral Market

Since the electricity physically flows from the generation side to the end users in a pool structure, firstly it was thought that in order to model the market, the same type of structure could be employed. Therefore Pool is a *centralized market*, which constitutes centralized transactions in the market and also centralized transmission network operation. Considering these two factors makes the Pool structure more complex in which it is hard to distinguished market responsibilities [2]. Also the system operator (National Grid in the UK) within the Pool employs a merit order, however in bilateral electricity market the system operator is constrained in arrangements by the provided negotiated contract price and volumes between generation companies and supply companies.

Also in the Pool structure most small and medium size demands do not have any willingness to participate in the market and enter into bilateral negotiations since they do not have any incentives to play active roles in the market, thus the price determination process in the Pool market does not affect the demand. On the contrary, price determination process in bilateral market (like BETTA in the UK) represents a proper overview of trading process considering the *market equilibrium*. Economist believe that in order to make Pool market more transparent and demand side more active bilateral negotiations can help and also will reduce the price of electricity where there are no trading administrations needed.

3.3 Stakeholders in Restructured Electricity Markets

A liberalized electricity market has been divided into several individuals as follow [2]:

- **Generation Companies (GenCos):** These units are responsible for maintaining and supplying electricity into the grids. GenCos participate in the market by entering into bilateral contracts or they may sell electricity to an organized electricity market. Compared to Pool structure these units are not price regulated.
- **Transmission Companies (TransCos):** These companies are responsible for building, maintaining and operating the transmission network within their region. They own the transmission network and in some cases like UK, National Grid (NG) as the Transmission System Operator (TSO) and network owner is the Independent System Operator (ISO) as well.
- **Distribution Companies (DisCos):** These companies are the asset owners in the distribution level. They dispatch the transferred electricity to the end users within their authorized area and control power quality.
- **Supply Companies (SupplyCos):** These individual are responsible for purchasing electricity from wholesale market and sell to the customers. These market participants play an important role in the bilateral electricity market,

e.g. BETTA, where they are active in both wholesale and retail markets. Like GenCos they can play market power; therefore it is essential to model the behavior of these strategic entities in the market.

- **Independent System Operator (ISO):** Ensuring the security of supply in the electricity grid is one of the significant roles of ISO. NG as the system operator in UK tries to balance the generation and demand for each settlement period by performing Economic Dispatch (ED). Congestion management is another responsibility of ISO. In some countries the system operator also acts as a Market Operator (MO) playing as a nonprofit company to function the market.

According to the discussion above, GenCos and SupplyCos play significant roles in the electricity market. They can bring competiveness to the market or on the other hand they can play market power that causes imperfect competition in electricity market. Thus, modeling these market players is essential. Chapter 4 and 5 demonstrate how to model these market participants in order to model imperfect market. Figure 3.1 illustrated a competitive electricity market structure containing several stakeholders.

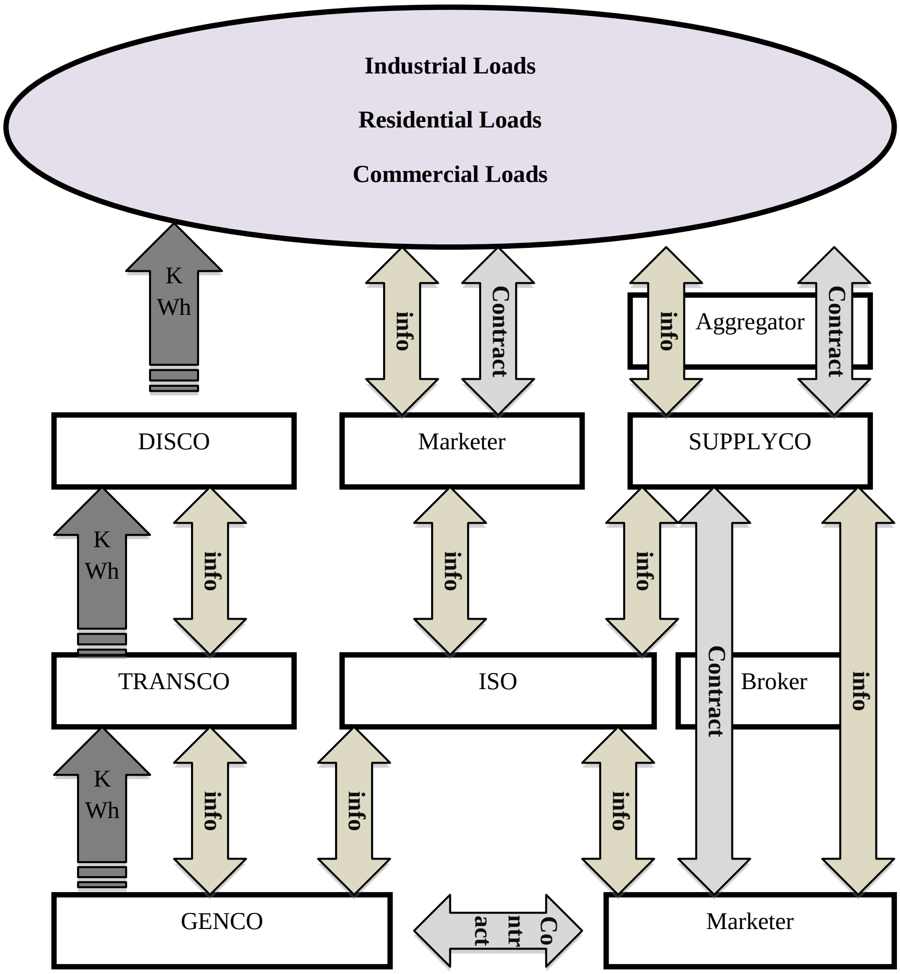


Figure 3.1: A Competitive Electricity Market Structure [2]

3.4 Operation of BETTA

BETTA implemented in 2005 [2], affected transformation of the wholesale electricity market. The basic premise of BETTA is that the free environment should cover the market; therefore BETTA established a free market in which parties may contract for selling or buying electricity in a way they prefer. The philosophy of BETTA is not to dictate how energy should be bought and sold, nevertheless to provide mechanisms for almost real time clearing and settlement of imbalances between contractual and actual positions for different parties.

Unlike electricity Pool, BETTA has some main objectives:

- Focusing on firm forward and future contracts;
- Increasing the transparency of the market;

- Providing more incentive for System Operator (SO);
- Making electricity like other commodities; and
- Keeping the price lower.

According to its goals and objectives, BETTA is based and designed around bilateral contracts and trading between generation companies (GenCos), supply companies (SupplyCos), traders and consumers. So, all the market participants can choose the way they want to play.

BETTA incorporates the following features:

- Forward and future contracts
- Short term power exchange (PX)
- Balancing Mechanism (BM)
- Imbalanced Settlement (IS)

More details about these features have been discussed in the following sections. Figure 3.2 demonstrates the time line of BETTA operation and structure.

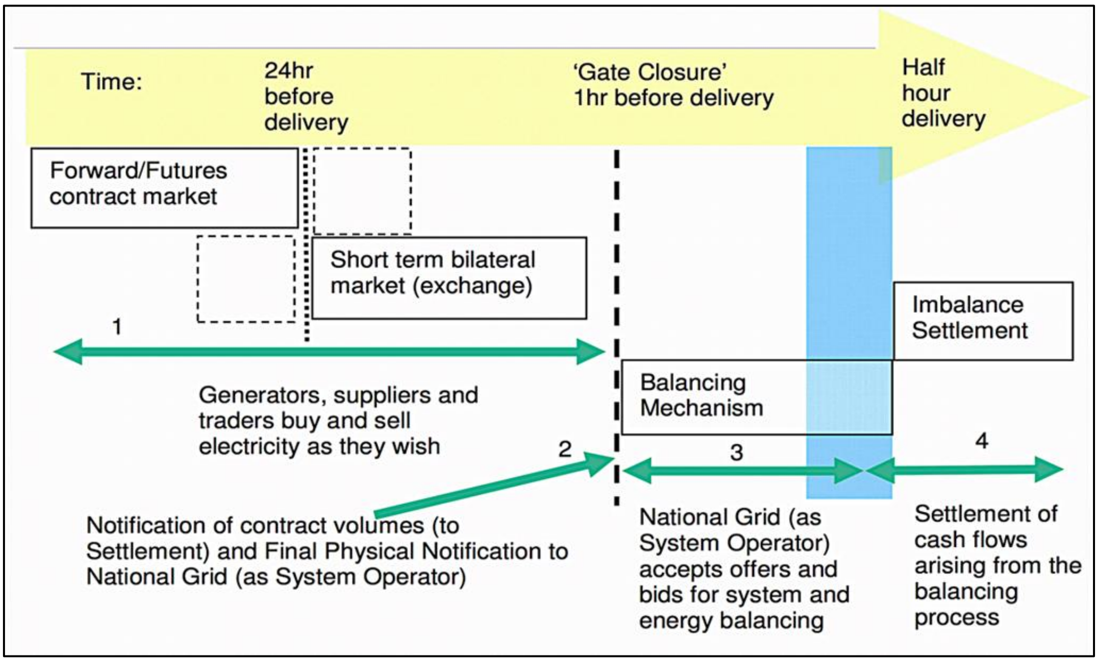


Figure 3.2: Time Line of BETTA Operations

3.4.1 Long-term Bilateral Contracts

The intention of BETTA is that the majority of electricity should be traded through several long-term bilateral contracts. Bilateral contracts involve two parties: a buyer and a seller. In such a market there is no *official price* since the price of traded electricity is set independently by the seller and buyer [2]; therefore the traded price and quantity will be private in these types of contracts. However general information about the Over The Counter (OTC) contracts, which constitute less trading volume and price in order to help market participants to fine tune their positions close to delivery time, normally published by reporting organizations. Considering this fact, modeling bilateral electricity market is much more complex compared to the Pool structure.

These long-term bilateral contracts can be in the following forms [1,20]:

- **Long-term negotiated contracts:** A significant proportion of generation and consumption are traded through these kinds of contracts. Terms of the contracts are usually opaque and the volume of the traded energy is very large. These contracts are usually about 1-5 years ahead of real time.
- **Forward trading:** Although these contracts are standardized, but the counter parties may agree with additional conditions like delivery point, duration, volume and other issues. They operate from a year ahead of real time (Figure 3.2). These contracts provide an opportunity for all generation companies to choose the quantity, price and date of delivery with specified supply companies, so forward contracts are differentiator between BETTA and the electricity Pool.
- **Future trading:** future contracts are so similar to forward contracts, because they enable parties to trade electricity in the future at a price agreed now. On the other hand future contracts are more financial rather than physical settlement and can be traded in PX.

According to the above bilateral contracts all market participants are free to determine how they prefer to participate in the market. They may participate in the long term bilateral contract or they may even decide to only participate in Power Exchange (PX) or Balancing Mechanism (BM); however by joining only in PX or

BM they will face more risks therefore both GenCos and SupplyCos desire to enter bilateral contracts for much more of their capacity.

3.4.2 Power Exchange (PX)

The main concept of BETTA is the establishment of Power Exchange (PX) as a short time market close to the real time, to bring liquidity and transparency to the market by giving a last chance to generation companies and supply companies as market participants to fine tune their actual positions to their contractual positions.

BETTA is very much related to the long term bilateral contracts, therefore it is essential to have a short term market very close to the delivery time in order to secure the GenCos and SupplyCos positions in the market and assist the standardized trading. It can be one or several PXs in the electricity market.

Actually PX has two main features [20]:

- **Self balancing:** Because of the nature of the BETTA which is based on long term bilateral contracts to reduce the *price risk* in the spot market, market participants face another kind of risk which is related to their ability to fine tune their contractual position close to the real time. Demand variations for SupplyCos, changes in supply capacity for GenCos, unanticipated technical problems and etc. put market participants more in the composure of the risk very close to the real time. PX helps participants to recover this type of risk.

- **Assisting trading:** BETTA intends to make a wide ranging electricity trading market, and PX brings high liquidity to the market and help participants to become closer to their position without changing the price of the electricity very seriously, unlike a normal spot market. This happens because of the fact that the volume of the electricity traded in the PX is not so huge and is just for fine-tuning. Figure 3.3 shows the exchange clearing process in the PX.

PX can involve future contracts as a form of Over The Counter (OTC) or it can be in form of a spot market to delivery electricity on the day. Spot market is a short-term market close to the delivery period. In BETTA it is 24-48 hours to the Gate Closure, which is 1 hour before the delivery time. Although this spot market helps market participants to fine-tune their positions against any possible imbalances, still by participating in this market they may face price volatility and this will increase the exposures to the financial risks. Furthermore, the PX participants will remain anonymous.

3.4.2.1 Power Exchange Charges

Besides the price volatility issue in the PX, there are several relative charges and costs for participating in the PX, such as [20]:

- **Membership charges:** These are the charges of using PX market, which can be debited monthly for each market participant.
- **Transaction fees:** PX charges a specific rate according to each transaction happened on PX.
- **Connection charges:** These charges are related to costs of telecommunication links and Internet, etc.
- **Support service charge:** These include the charges of maintaining and hiring trading hardware and software.
- **Credit margins:** These are related to the costs of covering risk of counterparty.
- **Contract notification fees:** These fees include the cost of using third party contract notification services.

Considering the above charges, market participants try to position themselves in a balanced position as much as possible; thus they use long-term bilateral contracts to avoid these further charges, which reduce their profits. Consequently the requirement of employing a proper modeling approach to exemplary the market participants’ behaviors has been revealed.

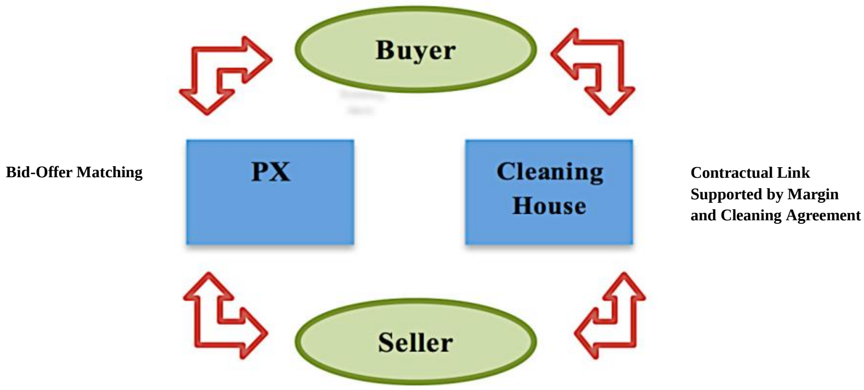


Figure 3.3: Exchange Clearing [20]

According to the Figure 3.3, offers and bids can be posted based on their contractual information; PX matches these bids and offers. PX usually performs about 24 – 48 hours before the real time and contributes just around 1-2 % of electricity trading [20].

3.4.3 Balancing Mechanism (BM)

Balancing Mechanism (BM) is the heart of the BETTA. It provides a key role in maintaining security of supply on the transmission grid. In BETA, parties who generate electricity are expected to enter into direct sale contracts with the consumers and perform *self-dispatching* market clearing procedure. Similarly, supply companies are required to enter into electricity supply contracts with the generation companies to meet their own demand and provide a secure and continuous supply. Bilateral contracts, Over The Counter (OTC) and PX markets can assist in matching buyers and sellers close to real time. Although these bilateral contracts should assist parties to balance their positions in the market and find the market equilibrium point between the consumption and generation, in reality it is unlikely to be assured because bilateral trading do not continue up to real time, which can cause imbalances on the electricity grid. In order to ensure the security of supply, as one of the 3 main European pillars for future Electricity Highway Systems (EHS), the existence of BM is essential.

3.4.3.1 Operation of Balancing Mechanism

BETTA as a bilateral market abolished the Pool as a centralized electricity market and introduced a new structure in which all market participants are *self-dispatched* and the majority of traded electricity is long-term bilateral contracts, more than 97% [20,60]. A BM Unit (BMU) is designed to inform National Grid Company (NGC) about the services of particular flexible party. Generation and supply companies who wish to participate in Balancing Mechanism are required to register as a BMU. Each BMU has a half-hourly metering capability in order to measuring the unit's participation in the Balancing Mechanism. Also they are provided by a special communication links to NGC, which allow the NGC as a System Operator (SO) manage the contribution of each unit in the BM.

In the generation side, each generation company is considered as a BMU, also on the other side of the market each supply company, as a BMU, is expected to enter supply bilateral contracts in order to provide electricity for its end users. Consequently this kind of market is a *double-sided* market where demand side plays an active role in the market decisions.

As discussed later, electricity is not like other commodities and cannot be stored on a large scale; therefore real time balancing will be a challenging issue for both market participants and also System Operator. In theory it is expected that both GenCos and SupplyCos can meet their bilateral contracts completely however in reality it is highly unlikely to happen owing to two unpredictabilities in two sides of the market:

- **Generation side of the bilateral market:** GenCos may face several uncertainties that cause them not to be able to balance themselves before the gate closure and face penalties. These uncertainties can include:

    - Fuel supply issues, like fuel supply interruptions, fuel price surge, etc.
    - Human error in terms of technical and market operations
    - Equipment failure
    - Inappropriate money-making decisions made by a GenCo
    - Etc.

- **Supply side of the bilateral market:** SupplyCos also may face several uncertainties, which cause losses in their profits. These uncertainties are based on:

  - Sudden changes in their end-users consumptions pattern as a consequence of several issues like popular TV show, etc.
  - Weather conditions
  - Inappropriate money-making decisions made by a SupplyCo
  - Etc.

According to the above discussion it can be realized that it is essential to model both sides of the market especially in bilateral electricity market, e.g. BETTA. In Chapter 4 and 5 it will be discussed that one the main contributions of this research is that the supply side of the market has been taken into consideration and modeled in order to calculate an accurate market equilibrium point while both sides of the market are making profit.

3.4.3.1.1 Gate Closure

According to the previous section it can be realized that BETTA has created two kinds of markets:

1. **Free market**: Most electricity trading occurs in free market. Over 97% of trading that includes long-term bilateral contracts; OTC and PX can be done before the real time. This research focuses on this market and tried to assist market participants to fine-tune their positions in this market to avoid any penalties and imbalanced positions in Balancing Mechanism and Imbalanced Settlement (IS) period.
2. **Balancing Mechanism**: This market can help the SO to meet the demand in the real time and most importantly maintain security of supply.

Gate closure, which is 1 hour ahead of the half-hour settlement period [30], is a boundary between these two markets. By the gate closure all parties should submit their contractual data in terms of the volume of the electricity, which is going to be generated or consumed to the central settlement of BETTA. Further to the gate closure, no physical trading is permitted for sellers and buyer outside the BM and their contractual positions will be compared to their actual positions, which can be determined by the assistance of metering facilities, afterwards the volume of imbalanced energy can be recognized. Next, NGC as the SO of the market takes the responsibility of balancing the generation and demand for a specific period of time [60].

All BM Units who are greater than 50MW are required to notify the SO about their levels of operation. BMUs for any settlement units must submit Initial Physical Notifications (IPNs) to the SO by 11:00 a day before the delivery, also submit their Final Physical Notifications (FPNs) at the gate closure [20,60]. FPNs show the production or consumption of each generator and supplier during each settlement period. FPNs for generators are positive and demand's FPNs are negative. Figure 3.4 illustrates an example of FPNs values for both sides of the market.

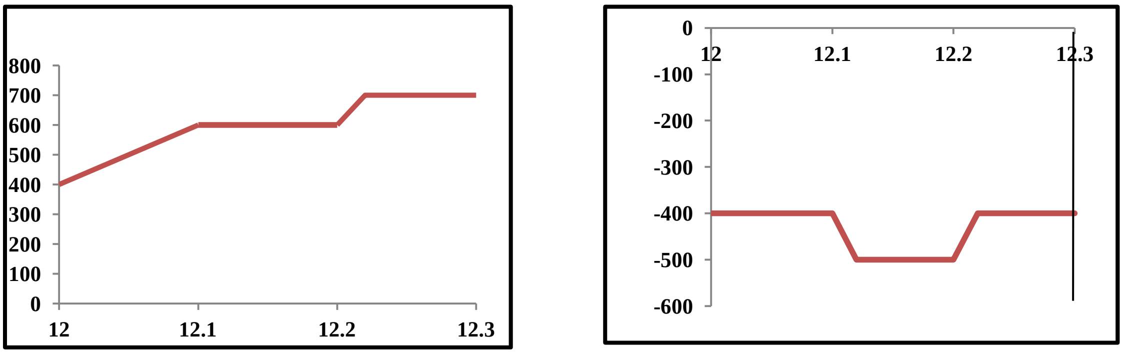


Figure 3.4: Typical GenCo' and Demand' FPNs, Left FPN for a GenCo, Right FPN for a Demand [20]

3.4.3.1.2 BM Bids and Offers

Circumstances may arise which lead BM Units to vary their actual generation or consumption from the level mentioned in their FPNs by submitting bids and offers to the SO.

Biding in BM means, parties want to operate below the level of FPN, generation companies will reduce their generation and supply companies will increase their consumptions. Offering in BM means, parties want to operate above the level of FPN, generation companies will increase their generation and supply companies will decrease their consumptions. Bids and offers should be submitted in pairs and once accepted by the SO they become firm and cannot be cancelled. Bid-offer pairs above the FPN are numbered positive and bid-offer pairs below the FPN are numbered negative. Figure 3.5 demonstrates a typical bid-offer pair for a GenCo.

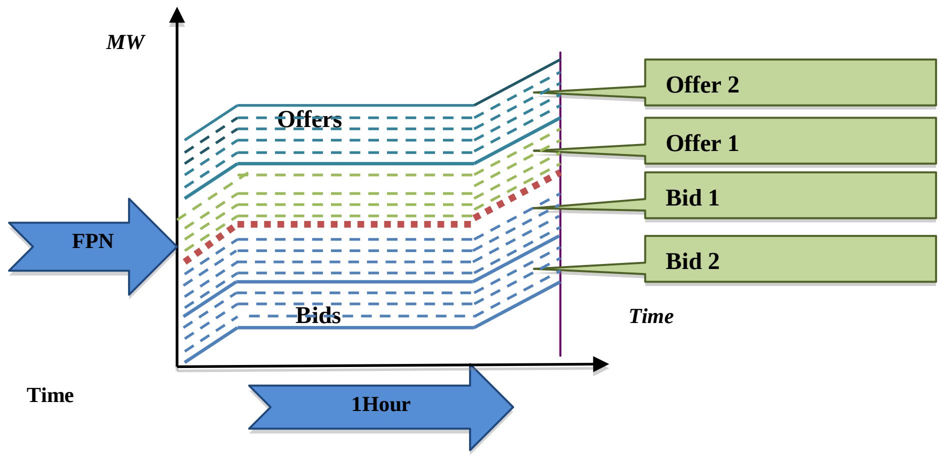


Figure 3.5: A Typical Bid – Offer Pair for a GenCo

3.4.3.1.3 Real Time Balancing

NGC as the SO, at gate closure takes the responsibility to monitor the generation, consumption and the electricity transmission network, and make sure there is a balance environment in the real time. During the BM and each settlement period the SO efforts to communicate market participants to provide *ancillary services* such as, frequency response, voltage response, black start and etc.

When the SO decides to accept the bid-offer pair of a BMU, it will send the acceptance to that BMU’s control centre. Figure 3.6 illustrates the acceptance of different bids and offers for a generation unit.

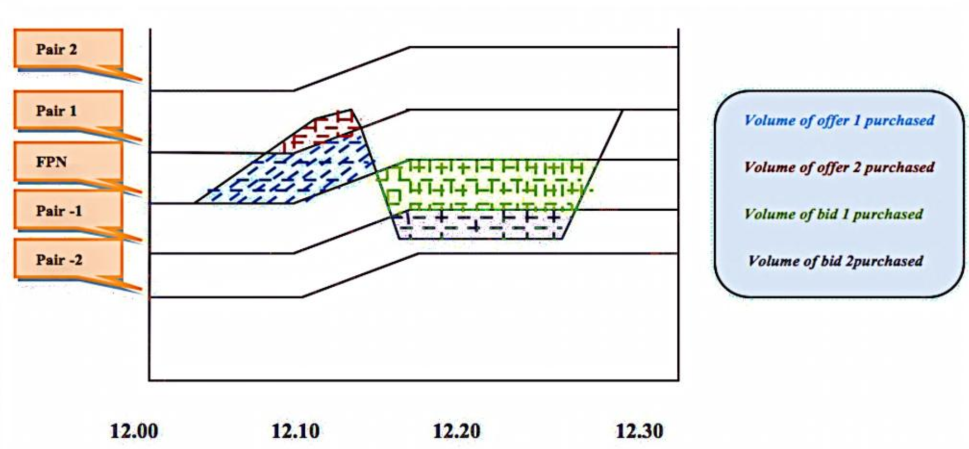


Figure 3.6: Acceptance of Bid – Offer Pair of a Generator Unit [20]

Furthermore, Figure 3.7 illustrates a simple example that how NGC as the SO performs real-time balancing in the system. This figure demonstrates that how the imbalances in both sides of the market make the SO react to equalize the market.

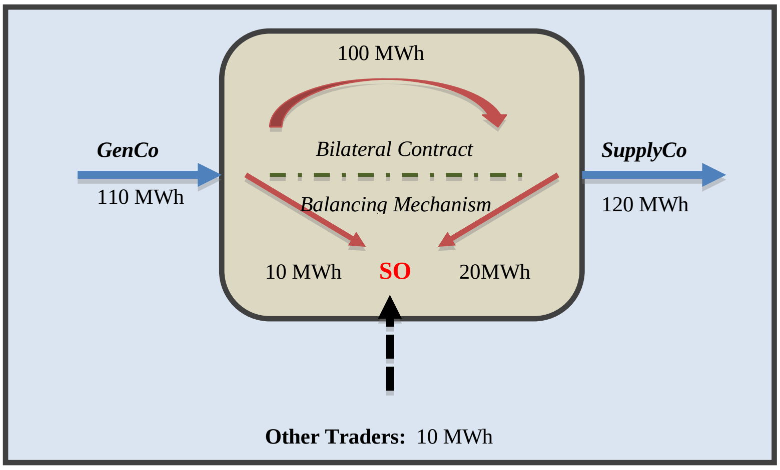


Figure 3.7: SO's Real Time Balancing

3.4.3.1.4 Bid and Offer Payment

When the system operator accepts BMU's bids and offers, they make or receive a payment in £/MWh. Normally, BMUs receive payment for accepted offers and should make payment for their accepted bids. In reality the BM bids and offers may be accepted at excessive prices. At these cases the BM is making money from flexible large GenCos or SupplyCos and increase small companies' exposure to the risks. In this case the importance of modeling bilateral electricity market considering both sides of the market can be revealed in order to encourage market participants to fine tune their position before the gate closure and reduce the market power.

3.4.3.1.5 Importance of Balancing Mechanism

As mentioned, the electricity market system operator requires to be informed of the capacity of generation to adjust the level of production and consumption, taking into account the transmission network capacity in order to maintain the security of supply. If the system is short, SO will select the BMUs' offers to increase the generation, whereas if the system is long, SO decides to accept BMUs' bids to increase the consumption in order to deal with that surplus generation.

Therefore NGC plays a significant role in BM, which is maintaining local balances in the real time. Despite of SO's key role, duration of Balancing Mechanism is just 1 hour [61], which is too short, and its contribution in the BETTA structure is about 2% [20]. Figure 3.8 demonstrates the BETTA market structure by its volume.

Figure 3.8: BETTA Structure by Volume

3.4.4 Imbalanced Settlement (IS)

One of the key specification of BETTA as a bilateral market is that it companies BM and Imbalanced Settlement (IS) [61] in order to reward those market participants that assist the SO to balance the system and penalize those ones that cause imbalanced conditions. In order to assure the link between BM and IS, Balancing and Settlement Codes (BSCs) are required [20]. BSCs are in from of legal frameworks that all licensed market participants, e.g. GenCos and SupplyCos, who want to trade electricity, should agree with and sign them up. These frameworks enable the SO to apply charges for parties who cause imbalances on the market.

Therefore, it is crucial to model both sides of the market in order to assist them to establish long-term bilateral contracts in order to avoid facing Imbalanced Settlement period penalties. These imbalanced charges have three factors in common:

- IS in the BETTA is based on net imbalances rather than the whole system flow. This feature will make the central settlement much more smaller compare to the Pool however increase the market participants' exposures to the risks.

- Since BETTA is a bilateral market, imbalances of generation side and demand side of the market are divided. According to this feature those market participants who are active in both sides of the market (they are more electricity producers and suppliers) will be at risk since they need to have a balanced position in the market and this will avoid them to play market power.

- IS chargers must reflect the cost of balancing the system

One of the fundamental issues in the BETTA structure is how to refer payments of the electricity generation and consumption to different parties. Imbalanced Settlement (IS) has three key principles as follows [20,30]:

1. Net imbalances*:* Imbalanced settlement is based on the differentiation between the contractual volume of electricity and players' actual metered consumption or production. This method makes the settlement part much smaller compare to the Pool.

2. Double accounting*:* In BETTA structure the production or consumption accounts are separated. Therefore parties interested in both generation and supply will be provided by separate accounts.

3. Cost trading*:* If there are any net imbalances in the system the SO should take balancing actions to make a balanced condition, which is costly. This can be done through dual-cash out pricing system by creating incentives to some parties in order to reducing the cost of balancing by penalizing the parties who cause these imbalances. Parties that spill electricity to the system will be paid a price and parties that have a power deficit will be penalized.

Once imbalance volumes determined, the Settlement Administration Agent (SAA) calculates the cash-out [60]. It is noticeable that by the gate closure all market participants are required to notify the SO of their contractual volume of electricity and the trading prices can remain confidential.

Any surpluses are cashed out at System Sell Price (SSP) which is a payment made to parties in return to the excess electricity. SSP is based on the price of accepted bids on the BM. On the other hand, differences should be cashed out at System Buying Price (SBP) [30]. Parties will be charged based on the deficit energy that the system has bought on behalf of them. SBP is based on the accepted BM offers. Figure 3.9 shows the imbalanced settlement exposure.

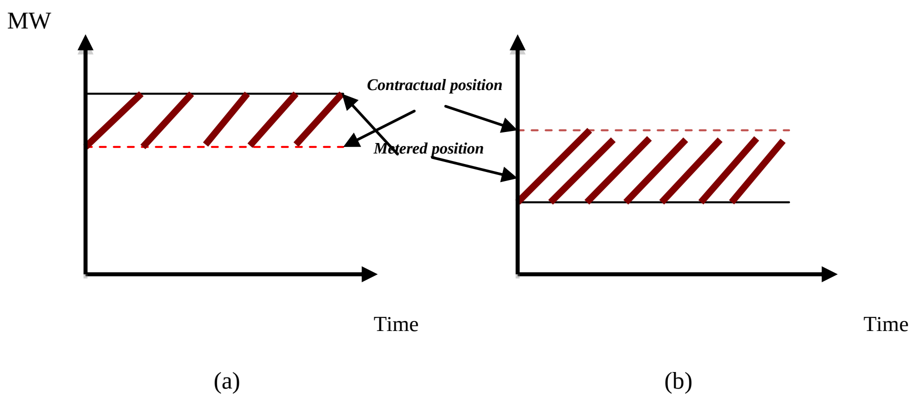


Figure 3.9: Imbalanced Settlement Exposure, (a) Spills are paid at SSP, (b) Shorts must be paid at SBP

Further to imbalanced cash out charges, other charges can also be introduced in the IS, such as *Non-delivery charges* [20]. These charges may be applied to the failure of providing BM bid-offer pair and further to the imbalanced charges these kinds of penalties may be added.

These charges are:

- For non-delivered offers = Accepted offer price – SBP
- For non-delivered bids = SSP – accepted bid price

Figure 3.10 demonstrates an overview of settlement process, which is performed by Elexon in the UK.

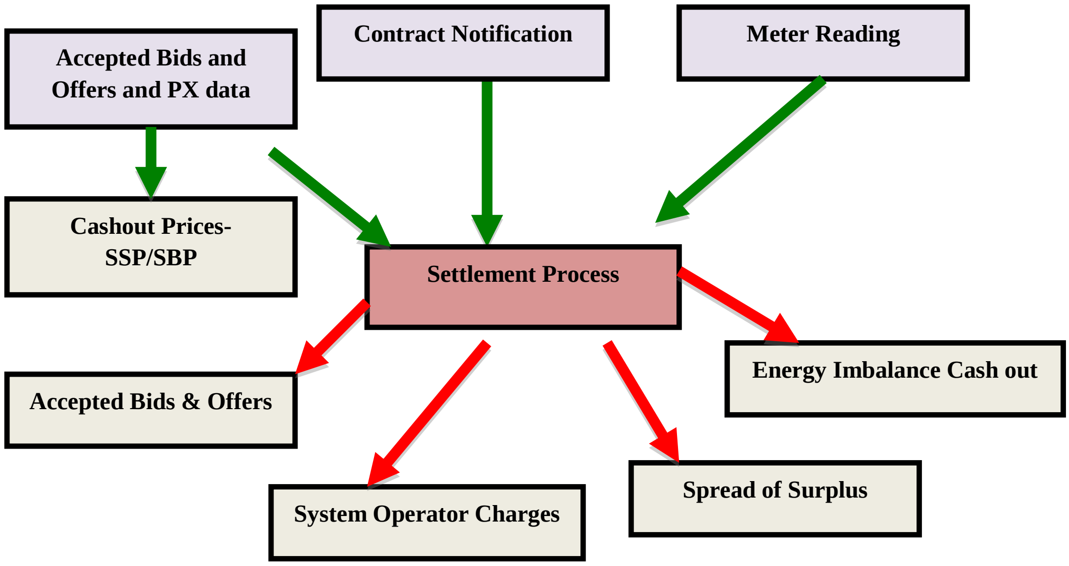


Figure 3.10: Overview of Settlement Process

3.5 Comparing BETTA with other Major Electricity Markets

It has been discussed in Chapter 2 that the electricity market in the UK is BETTA while in Australia it is called NEMMCO, in Norway, Denmark, Sweden and Finland is NordPool and in the USA there are several markets such as PJM. Table 3.1 (developed and modified based on [62] for purpose of this study) gives consolidated overview of these world's most established power markets and compare them with BETTA through some key aspects such as: type of bidding, balancing mechanism, risk management, participants, market offerings, Adjustment, Pricing rule, Pricing type and Active demand side.

3.5.1 Operational Comparisons between Competitive Electricity Markets

Competitive electricity markets around the world are diverse according to the methods of processing Unit Commitment (UC). These electricity markets can be considered in three main types [62]:

- Pure centralized spot market,
- Combination of spot market and pre-signed bilateral transactions; and
- Combination of bilateral electricity market and centralized balancing mechanism.

In centralized spot markets, like UK electricity Pool in 1990s, the System Operator performs the Unit Commitment. On the contrary, PJM and NYISO [62] as markets in which the spot market and pre-signed bilateral transactions are combined, the market participants have got this chance to choose whether they prefer the SO to perform the UC or they want to be self-committed. Compare to these two types of market, bilateral electricity markets combined with BM, e.g. BETTA, all market participants are self-dispatched and self-committed and the SO is no longer responsible for UC.

According to the above discussion all the GenCos and SupplyCos in BETTA are responsible for their decisions therefore, these market participants' behaviors should be modeled in order to make their profits maximized and reduce their exposures to the risks.

Table 3.1: Overview of World's Most Established Power Markets Compared With BETTA

	BETTA	***NEMMCO***	***NordPool***	***PJM***
Participation	Voluntary for PX & Balancing Mechanism	Compulsory for day ahead spot	Voluntary for day ahead and adjustment market	Compulsory day ahead market
Market offerings	Long-term bilateral contracts, PX, Balancing market	Day ahead spot	Day ahead spot, hour ahead, Forwards, Futures	Day ahead spot, real time spot, capacity credit market
Type of bidding	Double sided Including Retail market	Double sided	Double sided	Double sided
Adjustment market	Bids and offers called for adjustments payment	-	Intra – day auction market	Bid quantities can be changed till gate closure
Real time/ Balancing Mechanism	Penalty for deviation from schedule	Through purchase of ancillary services	Counter trade for real time – participants are given MCP	Deviations are traded in real time
Pricing rule	Confidential prices for bilateral contracts, Single price for Balancing market	Zonal pricing	Zonal pricing	Locational Marginal Pricing – Nodal pricing
Pricing type	Ex - post	Ex - post	Ex - post	Ex - post
Risk management	UKPX, Bilateral OTC	OTC, Derivatives on Sydney Future exchange	Forwards, Futures on NordPool	FTRs –Bilateral OTC, Multi – settlement market, virtual bidding, financial trading at NYMEX
Congestion management	Locational signals for transmission tariff	Locational signals for transmission tariff	Area splitting and zonal pricing	Security constrained economic dispatch
Transmission Losses	To be purchased by the consumers	To be purchased by generators	Included in zonal price	Included in LMP
Time frame	Gate closure before one hour of real time operation	Half – hourly; time weighted average price of six five minute blocks	One hour time blocks	Hourly blocks

Figure 3.11 demonstrates an overview of a general framework of electricity market consisting of wide-range of different electricity sub-markets:

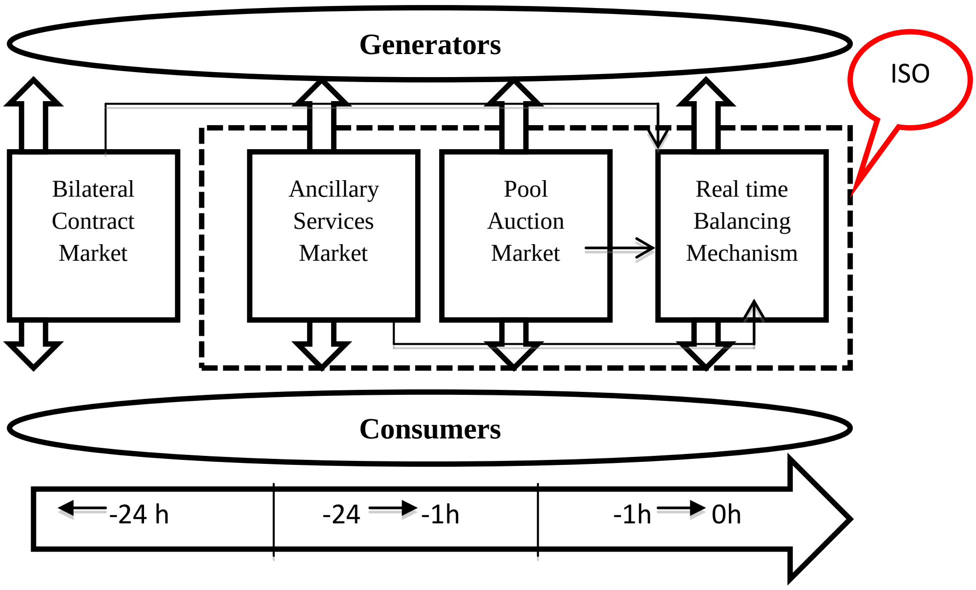


Figure 3.11: General Framework of Electricity Market [62]

In addition, California, PJM and NordPool electricity markets are based on single cash-out settlement price; on the other hand, UK electricity market is based on dual cash-out settlement pricing. This dual cash-out pricing method incentivizes market participants in both sides of the market to be active in long-term contracts, since these prices will be volatile and can increase the exposure to the risks. More details have been discussed in the following sections. Figure 3.12 illustrates categorized comparisons between different market structures:

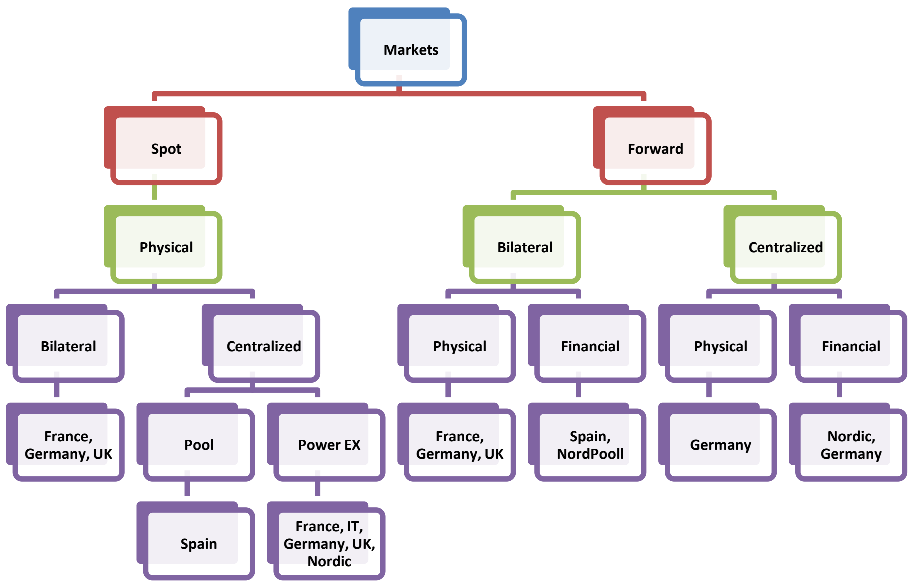


Figure 3.12: `Categorized Comparisons between Different Market Structures

3.6 Risk Management

Trading energy is usually a risky business with a chance of gaining balanced position or a chance of making loss. There are different types of risks. Most of the risks can be categorized into two main types:

- Technical risks
- Financial risks

Technical risks are related to the structure of the market and the system conditions. They are usually referred to the technical abilities of the market participants in order to reach their tasks and objectives.

Financial risks are related to the losses, which can be caused by any changes in the values of the financial assets in the market. These kinds of risks are so significant especially in the market environment where parties are competing with each other in order to make more profit. Generally there are five different types of financial risks in any types of market [63]:

- Market risk related to the price variation;
- Credit risk related to contractual conditions;
- Liquidity risk related to the lack of competition and activity in the market;
- Legal risk related to losses based on failures of a company because of law or regulatory changes;
- Operational risk related to the financial losses on technical problems.

The first three types of risks are associated with the liquidity and efficiency of the market. A liquid market provides an environment that allows additional parties to enter the market without any changes to the price of the electricity. In a liquid market players will not have a chance to play market power. Furthermore, an efficient market will not suffer from the lack of predictions about the future conditions of the market, including uncertainties and price volatility in BM and spot market.

3.6.1 Why Risk?

As a commodity, electricity can be traded in the market. The development of the electricity market has arisen so many issues. Risks in this market have become a major concept because of the nature of the market and the specifications of the electricity.

There are some important and significant differences between electrical energy and other commodities in different markets. These differences can lead us to find why electricity market is totally different from other markets and recognize its probable risks.

Some of these differences are as follows:

- Electricity as a commodity in the electricity market has a strong link to the physical system. The power system is one of the most complex systems and covers a huge geographical area including millions of participants with different strategies, objectives and risks.
- In the power system electricity generation and consumption should be balanced second by second; therefore, the time duration of balancing process and meeting the demand is too short.
- Storing the electricity as a commodity in power market is a complex and expensive process. Electricity is not like other commodities, which can be easily stored and used. As soon as the electricity generated, it should be transferred and consumed; therefore, the generation and consumption of the electricity should be balanced in the real-time.
- The electricity demand profile is so volatile and difficult to predict it. As mentioned, this can be so challenging to parties and increase their exposure to the risks.
- The energy produced by a GenCo cannot be transferred to a specific customer.

The above dissimilarities between electricity and other commodities in other markets bring some kinds of risks into the electricity market. Figure 3.13 illustrates a BSC’s actions in the BETTA, as a bilateral electricity market. According to this figure a

BSC unit should have a trade off between various movements while participating in the electricity market.

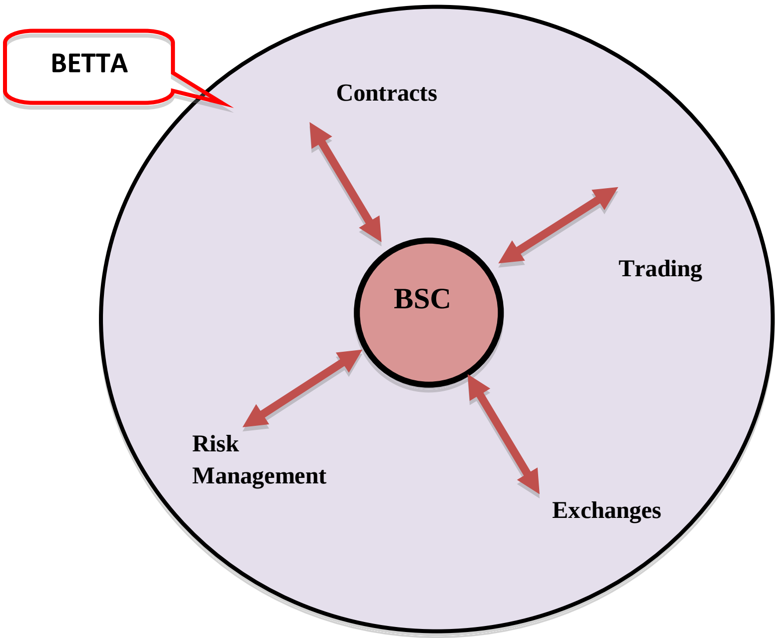


Figure 3.13: BSC's Actions in BETTA

3.6.1.1 Impact of Restructuring on the Market Participation Risks

One of the main purposes of electricity market deregulation is to reduce the risks in the market; nevertheless, these deregulations have even brought different types of risks into the market.

In the previous case, vertical integrated systems were providing an insured electricity supply chain through a non-privatized, centrally regulated market; however, vertical integration buffered price volatility, which was a main risk in a monopoly system for parties.

Restructuring results in redistribution of risks and brings different challenges to the market:

- Utilities become a financial broker, using long-term contracts and financial instruments (like BETTA structure).
- Existing system obligations need to be restructured.

- Development of price-responsive demand so that some risks can be shifted to retail customers, especially this occurred when the electricity Pool reformed into BETTA and the demand side becomes more active.

Figure 3.14 demonstrates the condition of a SupplyCo in a restructured market.

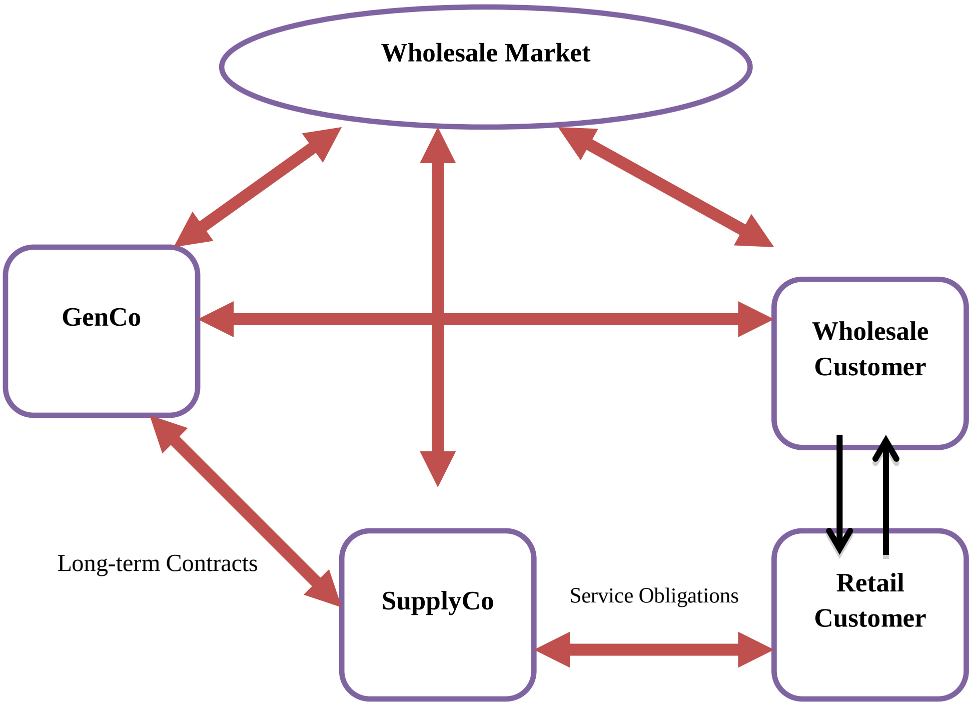


Figure 3.14: SupplyCo in a Restructured Market

According to the Figure 3.14, restructuring causes utility's cost and risks to rise because:

- The structure of deregulated market dictates that the utility is vulnerable to lose its position by a wrong load shape forecasting.
- Large base-load customers find bilateral contracts more attractive and by entering into these types of contracts; they will take some risks for fine-tuning their positions. This is an important issue in the BETTA structure.
- The cost of service will rise.

Consequently, the above issues will result in:

- Increasing business risk and put market participants in loss positions
- Increasing the cost of capital
- Increasing effects on utilities obligation like:

- Inability in meeting service quality standards
- Inability in making investments in transmission network in future planning
- Inability in following regulatory price procedures made by the watchdog
- Inability in providing equal services to all customers
- Inability in operating efficiency on both technical and market operations

3.6.1.2 Impact of BETTA on the Market Participation's Risks

BETTA has created a market in which the responsibility of balancing the generation and consumption has been switched from the centralized Pool to the market participants.

One of the significant concerns of the BETTA refers to the long-term bilateral contracts. Because of the price volatility in the spot market, economists suggest to establish a market in which about 97% consists of long-term bilateral contracts. According to the economists' points of view energy financial derivatives like future, forward and option contracts can be used to manage the energy market risks.

On the other hand because bilateral contracts are a long time ahead of real time, it can be hard for both GenCos and SupplyCos to fine-tune their positions and they may face risks especially close to real time. GenCos may become faulty due to different reasons during this long period and need to be off for essential maintenance. Also it is so challenging for SupplyCos to be sure how much electricity they need in order to meet their demands.

Therefore the market designers have given a last chance to parties to fine-tune their positions by trading in the PX, 24-48 hours ahead of real time and recover the risks caused by bilateral contracts.

In theory, those bilateral contracts and PX should make a perfect balance between generation and consumption but in reality there is always an imbalance on the electricity grid. Balancing Mechanism is a real time market, which can help the SO to balance the market. In BM parties try to reduce their exposures to the risks by not participating in it as far as possible and fine-tune their positions before the BM in order to avoid experiencing the price volatility. These instabilities can have impacts especially on SupplyCos, since they undoubtedly cannot predict their demand profile accurately.

BM contribution in the market is not so much, at about 2%; however, it is a key stage from the power engineers' point of view since its duration is just one hour. It is very challenging for NGC to not only balance the system but also ensure the security of supply. In Figure 3.15 the temporal sequence of the BETTA structure and the price volatility in the existing market has been presented.

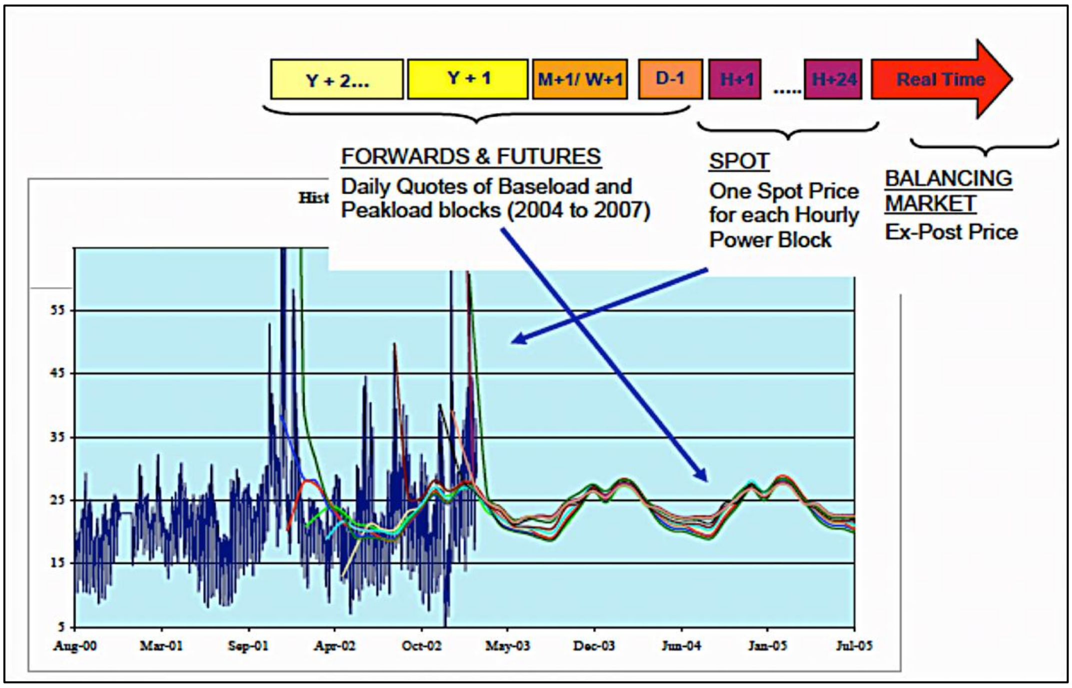


Figure 3.15: Price Volatility in BETTA

In BETTA structure, the SO has various and significant responsibilities as follow:

- Balancing the demand and generation: the SO should cover differences between the GenCos 'and SupplyCos' contractual and actual positions. These imbalances are because of the uncertainties of demand profile and also generation variations.
- Correcting net errors.
- Providing resource for the system.

- Providing ancillary services, such as frequency response and reactive power (voltage support)

Performing these tasks by the SO in the short duration of BM sounds challenging and introduces new kinds of risks.

One of the main risk sources in the electricity market, which is related to Balancing Mechanism offers and bids, is the imbalance cashing-out process. There are two imbalance cash-out prices, SBP is the price that is paid by parties whose positions are short, and SSP is the price received by parties whose positions are long. Both of these cash-out prices are based on Balancing Mechanism participants and the bids and offers that are accepted. Usually SBP exceeds SSP [20, 60].

The outcome is a set of imbalance prices which are quite volatile and give incentive to market participants to balance their positions before Gate closure and reduce their exposures to the risks. These prices can be very variable, and the demand or generation may face some unpredictable failure close to the real time, such as an unexpected surge in the demand side or loss of main generation on the system. Figures 3.16 and 3.17 demonstrate how the imbalances arise near real time [30].

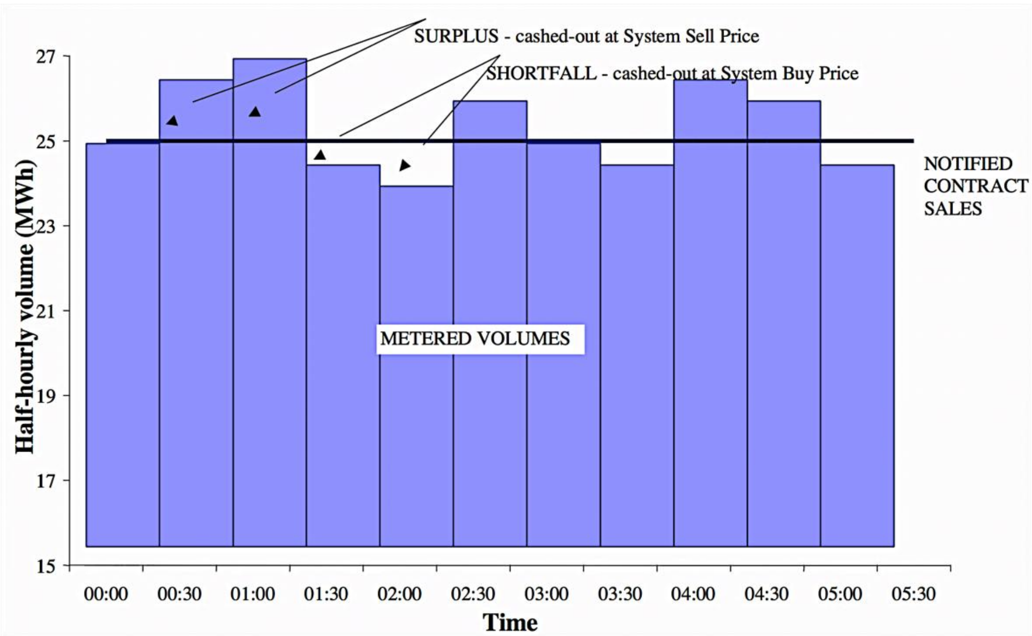


Figure 3.16: Imbalance arising from variable generation [30]

Figure 3.16 illustrates an appropriate view about the imbalances that each generation in the power system may experience. As mentioned these shortfalls and surpluses that cause imbalance cash-out prices, will bring some risks to the market.

On the other hand, the effect of unexpected failure on the generation side has been demonstrated in Figure 3.17. A 25 MW genset failure has causes a forced outage and makes a significant imbalance in the system and increases parties' exposures to the risks. These generation shortfalls are based on any outages occurring close to the Gate closure, a time at which all parties are prohibited to enter into new bilateral contracts.

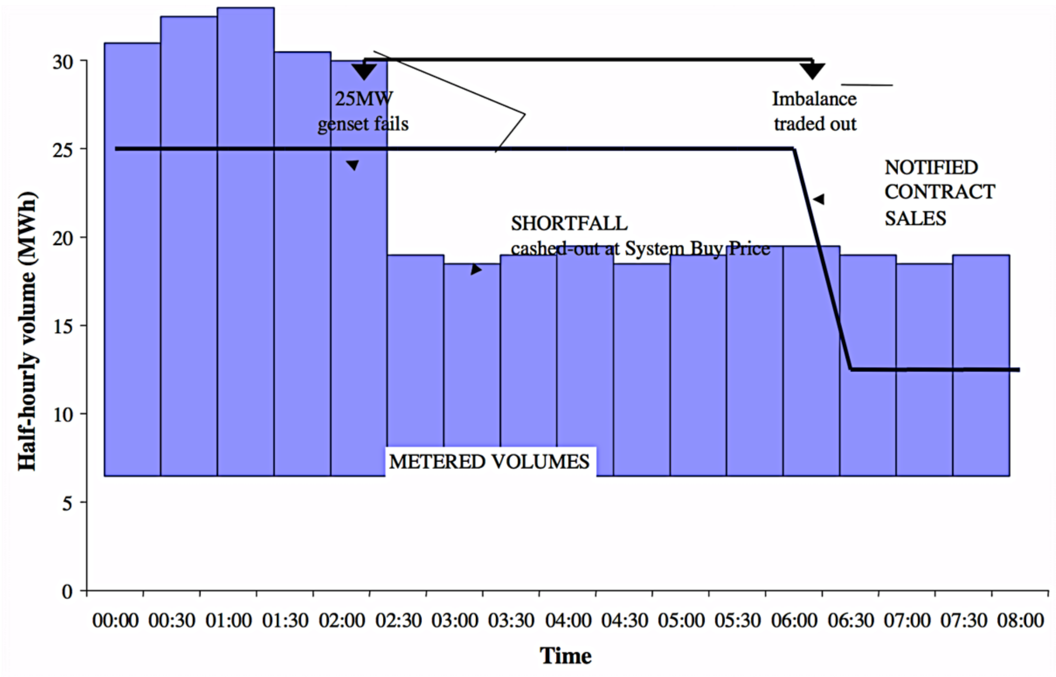


Figure 3.17: Imbalance arising from unexpected generation failure on 25MW capacity [30]

3.6.2 Other Aspects of Risks in Electricity Markets

According to the description of BETTA and its impact on the market risks there are various types of risks that must be managed under BETTA [20]:

- **Price**: The demand of the electricity cannot be predicted very accurately. It has a variable nature and this causes the electricity to be volatile. The demand profile is always changing due to different reasons like weather, national events and technical issues; on the other hand, there should be a second by second balance in the power system.

- **Volume**: One of the main stages in BETTA is Imbalance Settlement which brings significant volume risk to market participants. Generation and supply companies should try to make a balance between their actual and contractual positions, or they be penalized by imbalance cash-out prices. In addition the BM offers and bids reflect the cost of imbalance charges.
- **Credit**: BETTA is a free market and unlike the Pool all parties are self-dispatched; thus, credit and counterparty risks are important. All parties should have the ability to deliver and meet their contracts' terms and be able to pay for it. The existence of power exchange can help to remove the risks.

3.6.2.1 Electricity Market Risks Associated with Renewable Obligations (ROs)

Currently, UK alongside European countries have set up several legislations and Renewable Obligations (ROs) in order to increase the proportion of renewable energy sources in short and long term futures and reduce the dependency on conventional energy sources such as oil, natural gas and coal.

The Climate Change Act 2008 established an ambitious binding target for the UK to reduce its greenhouse gas emissions by 80% compare to the 1990 level by the year 2050 [64]. Furthermore, in order to make it feasible to achieve to this target, UK should gradually reduce its greenhouse gas emissions by 37% by 2020 and 60% by 2030 [64].

Additionally, all the European Union (EU) member states have agreed on a target that 20% of all EU energy should come from renewable sources by 2020. In order to achieve to this target each member state has set a national legal target, e.g. the UK's target is 15%. However, presently, only 3% of UK energy is coming from renewable sources [65].

On the other hand, in order to meet this 15% target, three main UK sectors – electricity, heat and transport – should be involved in the process. The largest contribution is likely to come from the electricity sector, about 30% of the generated electricity should come from renewable sources and only about 12% of heat and 10% of transport energy will be provided by renewable sources [64].

According to above, three main pillars should be considered for future electricity markets regulations, structures and modeling:

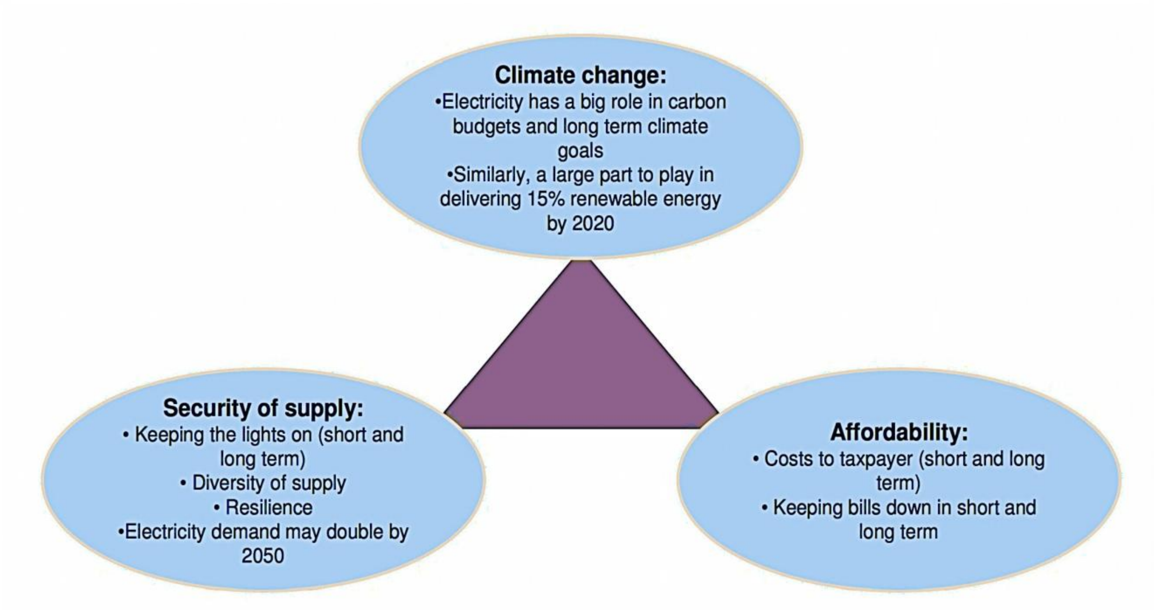


Figure 3.18: Three Main Future Electricity Markets Pillars

In order to have a low carbon economy and consider the climate change targets, electricity markets, especially bilateral markets, need to consider the other two main pillars:

- **Affordability**: To keep electricity bills down.
- **Security of Supply (SoS)**: To keep lights on.

To the purpose of achieving to these three pillars, electricity market modeling is essential since the establishment of electricity market will have some impact on sustainable generation and will introduce some new risks into the renewable energy field. Market regulations and legislations can reduce the profitability of GenCos and

SupplyCos, since most of the renewable resources are unpredictable such as wind and solar energy. For instance, GenCos having wind farms are able to predict their output with 60-70% accuracy. This results in a 30-40% imbalance [20] and they will face severe differences between their contractual and actual positions and their exposures to the risks will increase. Consequently, it is necessary to model electricity markets to reduce these kinds of risks and also avoid market participants from playing market power owing to lack of market players in both sides of the market. More detailed discussion has been provided in Chapters 4 and 5.

Europe is currently in the process of designing and developing a top-down methodology to support the planning of a future pan-European transmission system that potentially includes prioritized corridors or electricity highways that have the capability to address pan-European electricity transmission and market requirements from 2020 and up to 2050 [66]. The proposed top-down methodology supports the planning of a pan-European Electricity Highways System (EHS) [67] by providing a modular and robust expansion plan that will be in line with the previously mentioned three pillars. This means that more interconnections between EU members will be constructed and in purpose of trading electricity in such a network, bilateral electricity market will play a significant role.

3.7 Summary

This chapter investigated operation of UK electricity market structure, BETTA, as a bilateral electricity market in details and concluded that by participating in bilateral electricity markets, in which major electricity trading are conducted years ahead of gate closure bilaterally, the exposure to the risks can increase. Several aspects of risks that can be introduced by participating in such a market structure have been reviewed. According to these aspects, the need for bilateral electricity market modeling exposed. Furthermore, the impacts of other market obligations have been examined.

Chapter 4: Oligopolistic Electricity Market Modeling

4.1 Introduction

In Chapter 2, it was demonstrated how vertically integrated electricity markets in different countries transformed to more competitive structures. For instance, it was discussed how electricity market reforms in the UK caused market revolution from a vertical structure to the electricity Pool and afterwards to BETTA. In deregulated electricity market structures more private companies will be involved in electricity trading and all of them are targeting to maximize their profits and reduce their exposures to risks. Additionally, Chapter 3 discussed further on BETTA structure in detail, as a bilateral electricity market, in which all market participants should fine-tune their positions before Gate Closure in order to avoid facing any imbalances and penalties in the settlement period. In such conditions, market participants on both sides of the market may try to abuse the market to the purpose of making their own profits maximized and put other market participants in loss positions.

This chapter will then discover the reasons behind playing market power in electricity markets. In addition, several techniques for measuring market power will be discussed, hereafter will be explained the reason why Equilibrium methods have been selected as a promising approach in this research.

In the next step, different equilibrium models will be reviewed in detail and Conjectural Variation Equilibrium (CVE) approach will be introduced as a proposed approach to model imperfect bilateral electricity market in this thesis.

Furthermore, it will be examined how the generation side of a bilateral electricity market, which is suffering from market power, can be modeled. Since bilateral electricity markets are double-sided markets, in order to model them it is essential to break them up into two sub-markets:

- Generation side market
- Demand side market

Considering the bilateral electricity market and separating the two sides of an imperfect bilateral electricity market have been introduced as novel aspects of this research.

In this chapter, the generation side of an imperfect bilateral electricity market will be modeled, formulated and further in Chapter 5 the other side of the market, named ‘demand side’, will be taken into consideration.

4.2 Perfect Competition

In a perfect electricity market all market participants will act as a price takers and both GenCos and SupplyCos co-ordinate against each other in order to find the market clearing price. In such an environment the marginal value of the electricity is equal to the marginal cost (MC) [68]. Therefore, GenCos generate electricity in order to cover their marginal costs and this will be the most efficient solution of the market.

The revenue, $'R_i'$, of GenCo i can be calculated as follow:

$$R_i = pq_i \tag{4.1}$$

Where, $'q_i'$ is the output of GenCo i and $'p'$ is the market price, which is fixed in this case and equal to the marginal cost of GenCo i, $'MC_i'$:

$$MC_i = p \tag{4.2}$$

Therefore, in order to maximize the profit, the marginal revenue of GenCo i, MR_i, can be calculated as:

$$MR_i = \frac{\partial pq_i}{\partial q_i} = p = MC_i \tag{4.3}$$

There is no economic advantage in participating in a perfect competition, and all market participants enter fair trading contracts in order to match the generation and demand. In order to have a perfect competition, the existence of a large number of market players on both sides of the market (generation and demand sides) is essential. In this case, those companies who want to withhold electricity for the purpose of making higher profit will be eliminated by other rivals' actions. In other words, GenCos who ask for a higher electricity price and SupplyCos who offer less than market price will be ignored in such a market, since there are other players who can fill their positions.

However, in reality these conditions are very far from the existing electricity markets and it is almost impossible to have such a market, considering solid system constraints.

4.3 Market Power in Electricity Markets

Although decentralized and restructured electricity markets have brought transparency, market liquidity, price minimization, competition, etc. to electricity trading; however, exercising market power has been always a main challenge for these deregulated markets.

As a result of complex market structure, complicated regulations, financial crisis, complex bidding, lack of incentives, etc., less market participants will be involved in the electricity markets and this will cause price volatility and the exercising of market power. Generally, market power refers to the ability of excluding other market participants from trading electricity in the market and control the total output of electricity in order to drive electricity price above the competitive level [7].

As an example, as discussed in Chapter 3, Balancing Mechanism (BM) is a market in BETTA, which allows the System Operator to balance the energy in the market and increase the security of supply in the power system. The prices in this market will be high and volatile and will sometimes cause market participants to make a loss. In such a market structure, some market participants may take advantage and cause other market participants to face these high prices in the BM. In such a condition, utilities will increase the final price of electricity in order to offset their losses and this will be against the price reduction strategy as one of the market restructuring goals.

Exercising market power is a result of several issues that distinguish electricity markets from other markets around the world:

1. Complex market assembly.
2. Complex regulations.
3. Lack of storage (no economically and operationally feasible storage options have been introduced as yet).
4. Continuous and real time balancing.
5. Renewable energy integration considering their inherent uncertainties.

As discussed in section 2.4.5 in Chapter 2, the California electricity market failure can be listed as one the market power effects on the electricity market [69, 70] as a result of demand inelasticity, absence of a bilateral market and inability of market participants in balancing their positions. Therefore, market power monitoring is a crucial issue for electricity markets in order to bring more transparency to the market and avoid large companies to abusing the market.

In general, market power is exercised when there is lack of market participants in both sides of the market and few companies have influence on major proportion of traded electricity. These companies, which can be called strategic companies, dominate the market aiming to approach a higher profit.

Although in most cases exercising market power refers to the number of market participants, there are some other factors that have impacts on imperfect competitions:

- **Demand elasticity:** In an electricity market with inelastic demand side, all generation companies can raise their prices, since they are aware of the fact that their generated electricity is absolutely needed. In such a case, GenCos can make huge profits.

- **Market participants' incentives:** In a competitive electricity market there are several market participants with different economic backgrounds. Therefore, electricity market regulations should incentivize them in order to participate in the market. For instance, wind farms may face uncertainties, which cause them to end up with imbalanced positions and face penalties in the market; consequently, there should be several investment and risk management initiatives being applied in the market.

- **Existence of potential competitors considering system constraints:** Availability of adequate market participants considering system constraints in a specific region will have impacts on level of imperfect competition.

4.3.1 Monopolistic Electricity Market

A Monopolistic market has a strong conflict against perfect completion. In such a market, which is the extreme case of an oligopolistic market, only one player is selling its product to the market. In such a condition the GenCos sells the generated electricity to the SupplyCos via the wholesale market at a certain price, which is much higher than its marginal cost in order to make a huge profit. In order to avoid higher prices in a monopolistic market, the regulator should play a significant role since the electricity watchdog should set the market price to the value of marginal cost of that GenCo, which is a challenging task since the marginal cost of these types of companies are confidential. Transmission and distribution companies in particular areas can be examples of monopoly in the market.

4.3.2 Oligopolistic Electricity Markets

As discussed in section 4.1, one of the novelties of this research is considering bilateral electricity markets as structures that will be leading in market trading in future competitive electricity markets in different countries and also at the pan-European level. Furthermore, since these bilateral electricity markets may suffer from imperfect competition, they have been split into two electricity sub-markets in this research.

Several research efforts have been carried out in order to model imperfect electricity markets [71,72,73]; however most of them have reviewed electricity Pool structure or they have just modeled one side of the electricity market, which is the generation side.

Since in the bilateral electricity market, e.g. BETTA, both sides of the market are active and market players' behaviors will have impacts on market equilibrium point; it is essential to consider and model both sides of the market. Since the scope of this study, which has been discussed in Chapter 1 Figure 1.1, this chapter will primarily consider on oligopolistic electricity market as shown in Figure 4.1.

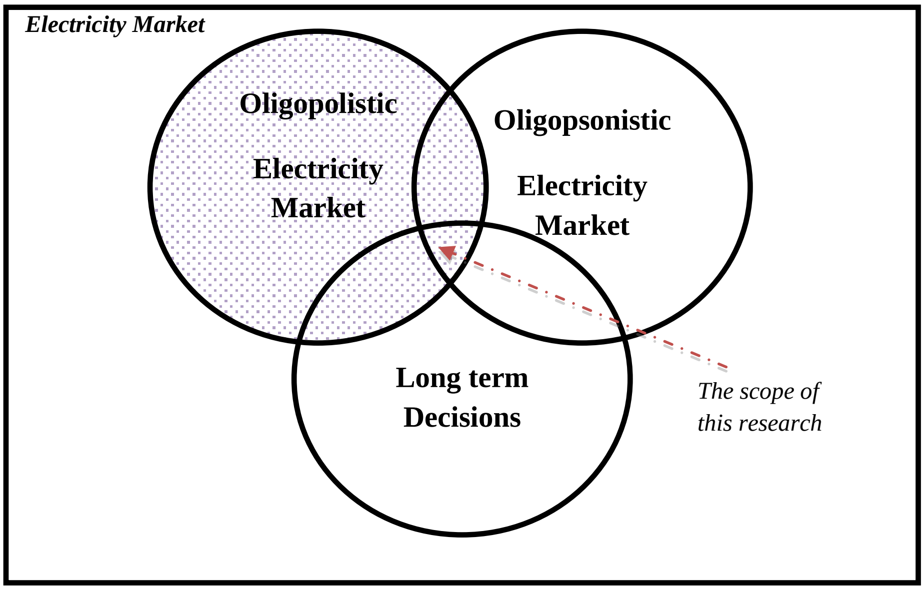


Figure 4.1: Oligopolistic Electricity Market Boundary

In this chapter, the generation side of an imperfect bilateral electricity market has been modeled. In realistic bilateral electricity markets, the number of generation firms will be limited as a result of capital; regulatory and operational constraints and all of these GenCos try to maximize their own profits. Such a market in which GenCos are acting in an uncompetitive manner in order to sell their production above the market price and have control of a major share of produced electricity is called *oligopolistic competition* [71]. An oligopolistic market is an environment in which small numbers of sellers (in this case GenCos) are dominating the market and cause high costs for consumers. It is essential to mention that previously explained monopolistic market is different from the oligopolistic market since in monopoly conditions only one market player is dominating the market environment.

Generally, there are three main factors with cause oligopoly in the generation side of the bilateral electricity markets:

- **Small number of firms:** As explained above, lack of generation firms will have major impacts on exercising market power in bilateral electricity markets.

- **Barriers to entry to the market:** These can be categorized into two main barriers:
  - Legal barriers: National and European Renewable Obligations (ROs), Carbon reduction targets, lack of investment incentives, complex market regulations
  - Natural barriers: Renewable energy sources, such as wind power can be source of uncertainty due to the unpredictable nature of the energy source.

- **Dependent behaviors:** Generation firms have dependent behaviors in an oligopolistic bilateral market, meaning that when one firm decides to raise or low its price or quantity, the other firm is going to change its decision making as well, so they have to consider what and when the other firms have planned to do. This characteristic is unique compare to perfect completion and also monopolistic electricity markets, since in perfect competition the firms are price takers and in monopolistic market there is only one firm whose concern is its own amount of generated electricity. This factor will lead us to the game theory concept, which was explained in section 2.7.2.3.1, and assist us to select an appropriate method to model imperfect bilateral electricity market in the next sections.

In an oligopolistic electricity market GenCos exercise market power in two different ways:

- Economical withholding
- Physical withholding

Economical withholding means GenCos will take advantage of their positions in order to increase the prices in the market. Moreover, they can dominate the market by withholding their production in order to make deficiency of electricity. In this case SupplyCos will be forced to participate in Balancing Mechanism and spot markets in order to purchase electricity to fulfill their demand; thus they will face price volatility. Generally, in an oligopolistic electricity market, those GenCos who exercise market power try to monitor the impacts of their decisions on the market conditions and other participants' behaviors in order to follow their strategy or switch to another one. Furthermore, in oligopoly those large generation companies may coalesce together and share the profits among themselves to eliminate small-scale companies who generate electricity from renewable sources. Further explanations will be provided in the following sections.

4.3.3 Market Power Measurement Techniques

The existence of strategic generation companies in the imperfect bilateral electricity markets can have destructive impacts on the competitiveness of the market; therefore, it is crucial to identify and measure the market power in electricity markets. Several market power techniques have been introduced in order to measure the imperfectness of the electricity market, such as [74]:

- Price-Cost Margin Index
- Herfindhal-Hirschen Index (HHI)
- Simulation Analysis
- Equilibrium Methods

4.3.3.1 Price-Cost Margin Index

According to the previous sections, exercising market power in the generation side will result in selling electricity to the SupplyCos at much higher than market competitive price and marginal cost (MC). This approach, which also called Lerner Index, is based on formula below [75]:

$$L = \frac{P_{cp} - MC_i}{P_{cp}} \tag{4.4}$$

Where, $'P_{cp}'$ is the market competitive price.

In order to measure the market power using this method, knowledge about marginal cost of strategic companies in the electricity market is essential; however, these information are confidential and generation companies in oligopolistic market do not have any willingness to disclose these information with other market participants, therefore applying this method is practically challenging in this research. Furthermore, this method is suffering from lack of interaction between market participants in the market compare to the CVE method.

4.3.3.2 Herfindhal-Hirschen Index (HHI)

The Hirschmann-Herfindahl Index can be identified by the following formula:

$$HHI = \sum_{i=1}^{n} S_i^2 \tag{4.5}$$

Where the $'S_i'$ is the market share of each strategic market participant in the bilateral electricity market [76].

The reason for squaring the market share in Equation 4.5 is that, the impact of large generation companies will be strongly taken into consideration compare to small-scale companies.

According to Federal Energy Regulation Committee (FERC) in the US, if the value of HHI is ′0′, it will be prefect competition, and when it is below 1000 the market power will be exercised less and higher than 1800 the market power will be exercised strongly. Furthermore, FERC believes that the application of HHI belongs to the past and other approaches can bring more accurate analysis of market power in the bilateral electricity market [74].

However, this method cannot be an appropriate approach for modeling bilateral electricity market, since:

1. The behaviors of other rivals' reactions to each generation company's strategies cannot be modeled.

2. There is no strong fundamental background behind this method compare to other approaches, such as equilibrium methods.

3. Since this approach is unable to consider all market participants' behaviors in the market; therefore, it is incapable of considering demand elasticity in the market power measurement. Nevertheless, in order to model bilateral electricity market, it is crucial to consider demand side and this can be one of the greatest weaknesses of this approach.

4. This index does not consider the structure of a bilateral electricity market.

5. Balancing the generation and demand which is the main goal of a bilateral electricity market has not been considered in this approach.

4.3.3.3 Simulation Analysis

Through simulation analysis the behavior of strategic generation companies will be estimated based on a series of studies that gradually measure the market power [74]. The traded price and quantity will be compare to estimated perfect competition price and quantity in order to have an idea about the level of market power; therefore, this analysis will be based on historical data which cannot be reliable since bilateral electricity market is a dynamic environment and it is essential to consider rivals' reactions to any changes in the strategies of each market participants.

4.3.3.4 Equilibrium Methods

Equilibrium method has been applied into several studies as a promising approach to measure market power in electricity markets. As discussed in section 2.7.2.3, the equilibrium method has several advantages over other approaches.

In order to model double-sided bilateral electricity market, it is essential to satisfy both sides of the market, which means the equilibrium point of the market should be identified while:

1. Generation meets demand and market is cleared.
2. All market participants in both sides of the market will maximize their profits by satisfying their first-order conditions, Karush-Kuhn-Tucker (KKT), for raising their own benefits.

$$Maximizing \quad f(x) \tag{4.6}$$

Subject to:
$$g_i(x) \leq 0$$
$$h_j(x) = 0$$

While: $'f(x)'$ is the objective function, $'g_i \ (i = 1, \ldots, m)'$ are the inequality constraints and $'h_j \ (j = 1, \ldots, n)'$ are the equality constraints.

Therefore, the equilibrium point of the market will be a stable point for both sides of the market and all generation companies' profits, in an oligopolistic market, will be maximized and the market cleared price and the output of each generation company will be identified. In this case, the Nash Equilibrium (NE) 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. Furthermore, equilibrium methods are capable of considering long-term strategies; therefore they can be appropriate for modeling bilateral electricity markets.

Figure 4.2 illustrates an overview of market power measurement tools and the unique structure, which has been introduced in this research, in order to model imperfect bilateral electricity market. It is demonstrated in Figure 4.2 that the bilateral electricity market has been divided into to sub-markets as discussed previously.

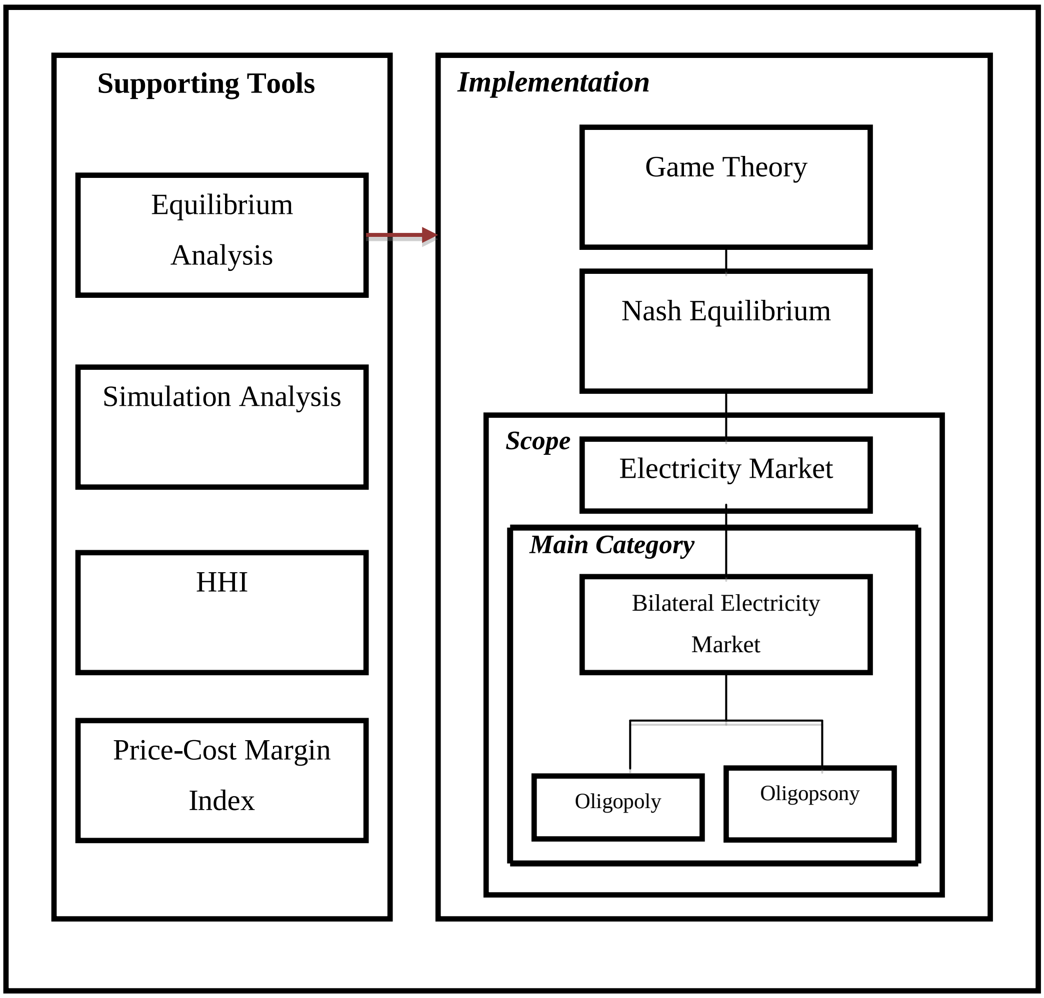


Figure 4.2:Overview of Market Power Unique Structure Measurement Tools

Several equilibrium model conditions can be identified based on strategies of market participants as follow:

- Collusion
- Bertrand Model (Game in prices)
- Cournot Model (Game in quantities)
- Stackelberg Model (Leader – follower games)
- Supply Function Equilibrium Model (SFE)
- Conjectural Variation Equilibrium Model (CVE)

The following sections compare and contrast these models and introduced the best approach for modeling both sides of bilateral electricity market in imperfect conditions.

4.3.3.4.1 Collusion

Collusion condition in imperfect bilateral electricity occurs, if GenCo i collude with other generation companies in order to sell the electricity to the SupplyCos at higher prices or they may decide to withhold their output. In both cases they will maximize their joint profits and small-scale generation companies in the market will loss. For instance, several large generation companies like coal-fired or nuclear power plants may have a combination of agreements and plans in order to make the electricity prices in wholesale market very high; these agreements and plans do not necessarily have to include any obvious communication between those companies and can take into consideration the load profile alongside their rivals reaction to their strategies. In collusion condition, the non-cooperative Game theory will be transformed to *cooperative* environment, which avoid new entrees to the bilateral contracts in the market.

4.3.3.4.2 Bertrand Model

Bertrand is the model of price competition in the electricity market [1,74]. In this model all generation companies will sell their generated electricity to the customers through the wholesale market at a price that would be in perfect competition. Therefore, under Bertrand model none of the GenCos will sell the electricity under their marginal cost (MC) in order to avoid any losses. Compared to collusion, firms in this approach are not cooperating with each other in order to maximize their joint profits.

Equation 4.7 demonstrates that the output of GenCoi, is a function of its own output and other rivals generation:

$$R_i = p_i q_i(p_i, p_{-i}) \tag{4.7}$$

Where, $'p_i'$ is the decision variable for firm i and $'p_{-i}'$ are the prices offered by its rivals.

Under the Bertrand model, all generation companies set their prices to the market and provide the amount of electricity needed by the market; therefore this model has a potential to be a perfect competition. Moreover, it is assumed that the whole demand can be satisfied through one GenCo, if it is offering the lowest price in the wholesale market; however, because of several constraint sources in the electricity market applying this approach to imperfect bilateral electricity market is not feasible.

Generally, this approach has been considered as a less efficient method for modeling imperfect double-sided electricity market in this research because of the following reasons:

- All market participants are competing in the market based on price.
- Several power system and market constraints have been ignored in this method. Considering these constraints can result in higher and fluctuated prices [77].

- Bertrand is incapable to predict the reaction of all rivals in the market, which is one of its key weaknesses.
- Generation companies' marginal costs are constant; however if this approach considered the reactions of other rivals in the market, it could react to them and GenCos' marginal costs would be dynamic.

4.3.3.4.3 Cournot Model

Cournot model is the most classic model of equilibrium methods. All the firms in the market are producing homogeneous product, as in the electricity market in which all GenCos are generating electricity in order to sell it in the wholesale market [76]. This method was widely applied in early stages of electricity market equilibrium modeling.

Basically it can be explained that the Cournot model is a game in quantity compare to Bertrand model, which was a game in prices. That means each GenCo can be selected according to its output, afterwards it accepts the market clearing price resulted by end users. Therefore, the revenue of generation companies can be calculated as follow:

$$R_i = q_i p_i(q_i, q_{-i}) \tag{4.8}$$

Where, q_{-i} is output of all GenCo i's rivals in the market sold to the supply companies and can be formulated as follow:

$$q_{-i} \equiv \sum_{j \neq i} q_j \tag{4.9}$$

In this model the equilibrium of the bilateral market can be defined when each company maximizes its profit, given the quantity produced by the other firms.

Economists believe that the outcome of Cournot model is a type, known as Nash equilibrium; thus each generation company should decide on its own output so the market clearing price will be identified according to interactions between demand and generation curves, afterwards none of the firms will have any incentive to deviate from its decisions.

Cournot model has several advantages over Bertrand model since it considers the market share of each market participant and also the demand elasticity. Furthermore Cournot can be applied in bilateral electricity market in which two parties have an agreement on the amount of electricity, which will be traded in future. However, this research has considered that Cournot model by itself cannot be an efficient and appropriate approach to model imperfect bilateral electricity market since the reactions of other rivals based on any changes in strategy of each firm has not been considered. Hereafter in this approach, generation companies do not response to any changes in the price; therefore the result will be related to the demand elasticity in the market. In contrast, the demand elasticity in the imperfect bilateral market is low, hence the prices resulted in this approach will be higher. In such a case, the Cournot model can be applied for medium-term (i.e. 1 month to 1 year) modeling rather than long-term bilateral contracts.

According to the discussion provided for both Bertrand and Cournot models, it has been realized that these two models are suffering from several weaknesses since the Bertrand model provides less market equilibrium price than the actual price. Additionally, under Cournot model the equilibrium price is much higher than the actual price; therefore these two models cannot provide an efficient electricity market equilibrium point. However it has been attempted to combine these two models in [78] to avoid these weaknesses.

4.3.3.4.4 Stackelberg Model

In this model a large GenCo is dominating the market and acts as a *leader*, tries to maximize its profit and other firms act as *followers* [79]. In this case the leader estimates the reaction of other rivals correctly and the followers do not even know that how their decisions impact the leader’s strategies. Consequently, this approach considers sort of monopolistic electricity market.

4.3.3.4.5 Supply Function Equilibrium (SFE) Model

As explained in prior section, Cournot and Bertrand models are suffering from several drawbacks, the Supply Function Equilibrium (SFE) model was introduced in order to deal with complexities of electricity market structure. One of the advantages of SFE is that GenCos can submit their quantity and price in the market rather than just price or quantity [80]. Accordingly, SFE model is appropriate for electricity Pool in which each GenCo submits its bid as a form of supply function and Market Operator (MO) calculates the market-clearing price rather than bilateral electricity market.

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 [71].

4.4 Conjectural Variation Equilibrium (CVE) Model

According to Chapter 2, economists have identified game theory as a key concept for understanding the reactions among market participants in any market environment such as the electricity market. Equilibrium methods are in line with specifications of Game theory. Two main Game theory features can be defined as follows:

1. All market participants are *rational*. This feature can help decision makers to stick with the decisions that lead them to reach to their aims and objectives.

2. They use *strategic decisions* aiming to achieve to their goals. This strategic decision includes the expectations of other rivals' actions based on each agent's decisions.

Conjectural Variation Equilibrium (CVE) is another model in the equilibrium methods family, which was introduced around 1930 by Bowley (1924) and Frisch (1933) [81]. This method has a strong relation with the two Game theory features described above. This is because; in this method each market participant chooses its desirable action considering the reactions of other rivals in the market. This approach has been employed in several economic fields in order to model non-cooperative environments.

Comparing to other models, CVE brings robustness into modeling the oligopolistic and oligopsonistic electricity markets. In addition, it helps all the decision makers in both sides of the bilateral electricity market to take into account the strategies of all competitors. Furthermore, compare to SFE model, Conjectural Variation method can be an appropriate approach for modeling bilateral electricity markets.

Game theory plays a significant role in modeling the strategic behavior of all market participants. Several research have been carried out in order to model only the generation side of the electricity market using Cournot, Stackelberg and SFE models, like [82-84]. However, these models only take a snapshot of the market and do not consider the interactions between all market participants; therefore in the bilateral electricity market in which participants can learn from other competitors' behavior, those methods cannot fulfill the requirements of modeling the system.

Additionally, considerable amounts of research have been conducted to model various market structures, e.g. Pool; however less work has been carried out to model bilateral electricity markets such as BETTA. Based on the fact that the share of bilateral contracts in BETTA is about 97.1% of the market compared to Balancing Mechanism actions, which represent about 2%, and the SO actions which are estimated to be around 0.9% [20]. Hence, the significance of bilateral electricity market modeling can be exposed, specifically for the BETTA structure with such a great portion of bilateral contracts in which SO has the responsibility to maintain the security of supply and match the generation and demand within 1 hour, and market participants try to set their strategies and their goals in order to maximize profit and understand their rivals' behaviors.

In [85], it has been suggested that the Conjectural Variation method can improve Cournot pricing in the electricity markets. It has been assumed that firms (generation companies only) make conjectures about their residual demand elasticity.

Conjectural Variation equilibrium method has been applied in some studies such as [86, 87]; however it has been attempted to model electricity spot markets in those studies. Also in [88, 89], CVE has been applied in order to model only the generation side of the electricity market and the supply side has not been taken into consideration.

Conjectural Variation method has been combined with SFE model in some research such as [71], where it is necessary to know the supply function curve; however in the algorithm presented in this research and will be introduced in Chapter 6, there is no need to identify the curve and the algorithm is interested in the equilibrium point of the bilateral market. Furthermore, CV values have been considered in a static context and cost functions should estimate the CV values [71], which can come up with unrealistic conjectures values and cause loss for all market participants in the market.

4.5 Oligopolistic Electricity Market Modeling Using CVE

As one of the novel aspects of this research, the imperfect bilateral electricity market has been divided into two sub-markets, oligopolistic and oligopsonistic markets.

This section clarifies how to model the generation side of an imperfect bilateral electricity market. Traditional perfect competition has been replaced by oligopolistic market environment and mathematical formulations have been provided to model oligopolistic electricity market in order to find out the output of generation companies in imperfect bilateral electricity market.

4.5.1 Generation Companies' Behaviors in Bilateral Electricity Market

The main goal of each generation company (GenCo) in electricity market is to maximize its profit in bilateral trading far ahead of Gate Closure, in order to reduce the exposure to price volatility risks.

Generation companies, as sellers, are a group of market participants in the market that produce the commodity, which is electricity in this case, and provide several services to the buyers or supply companies (SupplyCos). The strategies of the

GenCos are very much related to the volume of electricity they are going to generate, market price and specifically demand side, SupplyCos, behaviors.

As described in Chapter 3, in bilateral electricity markets like BETTA, the GenCos and SupplyCos will enter into bilateral negotiations in order to establish an agreement to trade electricity and fulfill the end-users requirements.

There are a few factors that determine the behavior of SupplyCos as buyers in the market, which affect the demand for electricity. Among the main factors are price and quantity. Assuming that other non-price factors are correctly defined, the demand behavior is very much dependent on the price of the generated electricity. The quantity of electricity purchased by SupplyCos normally increases with the decrease in the price and vice versa. This relationship is given by the *inverse demand function* graph as illustrated in Figure 4.3.

Figure 4.3 determines the relationship between the price of electricity and the quantity of the demand. According to inverse demand function this relationship can be seen from two aspects. The first aspect sees how the electricity price can affect the quantity of the demand. As mentioned earlier, the demand decreases as the price increases. This is the case when the SupplyCos have alternatives.

Figure 4.3:The Relationship between Price of Electricity and the Quantity of Demand

Moreover, the second aspect demonstrates that the SupplyCos are willing to pay to have a small additional amount of electricity. It also indicates how much money these consumers would want to receive as a compensation for a reduced consumption [3]. According to the second aspect, the SupplyCos are willing to pay a high price for additional electricity if they have only purchased a small amount of it. In contrast, their marginal willingness to pay for this commodity decreases when their consumption increases. The change in demand resulted from the change in price shows that the demand is 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.

4.5.2 CVE Applications and Formulations in an Oligopolistic Electricity Market

A small number of GenCos dominate the whole industry and these companies try to maximize their incomes.

For each GenCos in the market the main objective is to maximize its profit:

$$Max \quad \pi_{ig} = p_d q_{ig} - C_{ig}(q_{ig}) \qquad (i = 1, \dots, n) \tag{4.10}$$

Where:

$'n'$: Number of GenCos

$'\pi_{ig}'$: GenCo i profit

$'q_{ig}'$: Output of GenCo i

$'C_{ig}(q_{ig})'$: Cost function of GenCo i

It is noticeable that the sub-index $'g'$ in this research refers to the generation side of the bilateral electricity market.

Also, $'p_d'$ is an *initial inverse demand function* and represents the price that each generation company will sell electricity to the supply companies. In this research a novel hierarchical algorithm has been introduced and applied in order to find the equilibrium point of the bilateral market and in the proposed algorithm, which will be introduced in Chapter 6, an initial value can be identified for inverse demand function in order to perform the algorithm. More details will be provided in Chapter 6.

The purpose of introducing p_d is that it is not possible to obtain the inverse demand function based on historical data in the bilateral electricity market and use it for all GenCos, as the amount of traded electricity in bilateral trading is not disclosed. In such electricity markets, a GenCo and a SupplyCo participate in a forward contract; therefore it is not applicable to use one inverse demand function for each contract.

On the other hand in most research, e.g. [89], it is suggested to use a residual demand function (RDC), which can be computed for GenCoi:

$$RDC_i(p) = D(p) - G_{-i} \qquad (i = 1, \dots, n) \qquad (4.11)$$

Where:

$'D(p)'$: Demand curve

$'G_{-i}'$: Aggregation of generation functions of all GenCos except GenCoi.

In this case, estimating the generation function of all rivals is inevitable which is computationally costly; also it requires access to a suitable historical database. Furthermore, it would be challenging in terms of investigating the specifications of other rivals' generation functions, since based on the CVE method, rivals' reactions should be considered, whereas in bilateral markets such as BETTA the major share of trading is forward and future contracts.

However, by introducing an initial inverse demand function there is no need to estimate the rivals' supply function and calculate the RDC directly. In this case, an initial inverse demand function is assumed to be a simple linear 45 degree curve to have a feasible flat start and via an iterative method, which will be covered in Chapter 6, this curve will be updated in terms of intercept and slope to obtain an accurate and realistic shape and will result in calculating the output of each GenCo in the bilateral electricity market. It is noticeable that this initial value does not have any effect on the results [90].

To maximize the profit, the optimal solution of Equation 4.10 for n GenCos is:

$$\frac{\partial \pi_{ig}}{\partial q_{ig}} = 0 \qquad (i = 1,2,\dots,n) \qquad (4.12)$$

The optimal solution of above equation should meet the following condition:

$$MR_i(q_i) = MC_i(q_i) \qquad (i = 1,\dots,n) \qquad (4.13)$$

Where:

$'MR_i(q_i)'$: Marginal revenue of GenCo i

$'MC_i(q_i)'$: Marginal cost of GenCo i

Since p_d is a function of q_{ig} $(i = 1,2 \dots n)$, and q_{jg} $(i \neq j)$ (the output of other GenCos expect GenCoi) is an implicit function of q_{ig}, therefore the marginal revenue will be:

$$MR_i(q_i) = \frac{\partial (p_d q_{ig})}{\partial q_{ig}} = \left(\frac{\partial p_d}{\partial q_{ig}} + \frac{\partial p_d}{\partial q_{jg}}\frac{\partial q_{jg}}{\partial q_{ig}}\right) q_{ig} + p_d \qquad (i \neq j) \qquad (4.14)$$

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

$$C_{ig}(q_{ig}) = a_i + b_i q_{ig} + {}^{1}\!/_{2}\, c_i q_{ig}{}^{2} \qquad (4.15)$$

Where:

$'a_i'$: Fixed cost of GenCo i

$'b_i'$: Linear co-efficient of GenCo i cost function

$'c_i'$: Quadratic co-efficient of GenCo i cost function

Thus, the marginal cost will be:

$$MC_i(q_i) = \frac{\partial C_{ig}(q_{ig})}{\partial q_{ig}} = b_i + c_i q_{ig} \tag{4.16}$$

Thus, according to Equation 4.13:

$$\left(\frac{\partial p_d}{\partial q_{ig}} + \frac{\partial p_d}{\partial q_{jg}} \frac{\partial q_{jg}}{\partial q_{ig}}\right) q_{ig} + p_d = b_i + c_i q_{ig} \tag{4.17}$$

Based on Equation 4.17, the Conjectural Variation (CV) for generation companies in oligopolistic market can be defined as follow:

$$CV_{ijg} = \frac{\partial q_{jg}}{\partial q_{ig}} \qquad (i, j = 1,2, \ldots, n)(i \neq j) \tag{4.18}$$

Where:

$'q_{jg}'$: Output of other generation companies except GenCo i

The CV is the belief or any expectation of any market participant in the market about other rivals' reactions according to any changes in the strategy of that firm. The value of CV for GenCos in oligopoly models results from hypothesizing how

GenCos make its decision in order to maximize their profits. In order to achieve to this goal, a significant question should be answered: how does one GenCo simulate other GenCos reaction to its decisions?

CV is such an index to estimate the reactions in which the output of each GenCos is used as the decision variable. In this approach, the estimations or conjectures of generation companies in an imperfect bilateral electricity market will be changed, in terms of the possibility of competitors' future reactions and that is the reason why term q_{jg} has appeared in CV formulations (Equation 4.18).

It is notable that diverse strategies, like different CV values, can result in different oligopoly models. Further discussion will be provided in Chapter 5.

Equation 4.17 can be transformed to:

$$\left(\frac{\partial p_d}{\partial q_{ig}} + \frac{\partial p_d}{\partial q_{jg}} \mathrm{CV}_{ijg}\right) q_{ig} + p_d \;=\; MC_i(q_i) \tag{4.19}$$

Additionally, as introduced above, p_d is the initial inverse demand function in the novel algorithm, which will be discussed in Chapter 6. Since this research attempts to find a cross-over-point of both sides of the market (oligopolistic and oligopsonistic markets), and that point is the equilibrium point of the market as well, the inverse demand function can be formulated as a linear curve to simplify the calculations:

$$p_d = e_d - f_d Q \tag{4.20}$$

Where:

$'e_d'$: Intercept of inverse demand curve

$'f_d'$: Slope of inverse demand curve

Also, $'Q'$ is the total supply and should be equal to total demand, $'D'$.

$$Q = D = \sum_{i=1}^{n} q_{ig} \tag{4.21}$$

Figure 4.4 illustrates the initial *inverse* demand function. This curve represents the changes in price respect to any changes in the output.

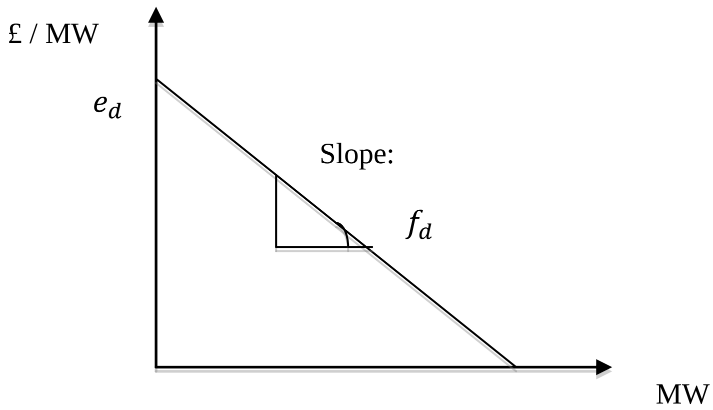


Figure 4.4: Initial Inverse Demand Curve

According to the figure above, the derivative of the inverse demand curve is to be negative.

Assuming all GenCos are playing rationally in oligopolistic electricity market, the Equation 4.10 will be transformed to:

$$Max \quad \pi_{ig} = (e_d - f_d Q)q_{ig} - (a_i + b_i q_{ig} + {}^{1}/_{2}\, c_i q_{ig}{}^{2}\,) \tag{4.22}$$

Where: $q_{ig\,min} \leq q_{ig} \leq q_{ig\,max}$

In order to optimize the profit of each GenCo the first derivative of Equation 4.22 will be:

$$\frac{\partial \pi_{ig}}{\partial q_{ig}} = e_d - f_d \frac{\partial (Q q_{ig})}{\partial q_{ig}} - b_i - c_i q_{ig} = 0 \tag{4.23}$$

According to Equation 4.21, the above equation will be:

$$\frac{\partial \pi_{ig}}{\partial q_{ig}} = e_d - f_d \frac{\partial q_{ig} \sum_{i=1}^{n} q_{ig}}{\partial q_{ig}} - b_i - c_i q_{ig} \ = 0$$

$$= e_d - 2f_d \, q_{ig} - f_d \sum_{\substack{j=1 \\ j \neq i}}^{n} q_{jg} - f_d \, q_{ig} \sum_{\substack{i=1 \\ i \neq j}}^{n} CV_{ijg} - b_i - c_i q_{ig} = 0 \quad (4.24)$$

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

$$q_{ig} = \frac{e_d - f_d \sum_{\substack{j=1 \\ j \neq i}}^{n} q_{jg} - b_i}{f_d(2 + \sum_{\substack{j=1 \\ j \neq i}}^{n} CV_{ijg}) + c_i} \quad (4.25)$$

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

$$q_{-ig} = \sum_{\substack{j=1 \\ j \neq i}}^{n} q_{jg} = Q - q_{ig} \quad (4.26)$$

According to Equation 4.25, in order to calculate the output of each generation companies the amount of generated electricity by other rivals in the market ($\sum_{\substack{j=1 \\ j \neq i}}^{n} q_{jg}$) alongside the CV_{ij}s should be known; however, it is very difficult for GenCo i to estimate those variables without knowing their individual production cost functions [86]. By aggregating all rivals into one pseudo-competitor denoted as $'q_{-ig}'$, the new variable $'CV_{ig}'$ can be defined as follow:

$$CV_{ig} = \sum_{\substack{j=1 \\ j \neq i}}^{n} CV_{ijg} \quad (4.27)$$

Therefore, by using Equations 4.26 and 4.27, Equation 4.25 can be transformed and simplified as follow:

$$q_{ig} = \frac{e_d - f_d q_{-ig} - b_i}{f_d(2 + CV_{ig}) + c_i} \qquad (4.28)$$

Consequently, the output of GenCo 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. More details will be provided in Chapters 5 and 6 in order to demonstrate how GenCos will learn about their rivals behavior and how other competitors reactions affect the output of each generation company while the hierarchical algorithm considers both sides of the market aiming to cope with oligopolistic and oligopsonistic electricity markets to find out the equilibrium point of the whole bilateral market.

4.6 Oligopolistic Electricity Market Case Study

In this section, a case study is provided, aiming to present the application of Conjectural Variation Equilibrium method in modeling only GenCos' behaviors in the oligopolistic electricity market.

In this case study, three GenCos with the following parameters have been considered:

Table 4.1: Oligopolistic Electricity Market Case Study

	a_i (£)	b_i (£/MW)	c_i (£/MW^2)	CV_{ig}
GenCo 1	0	10	0	-0.5
GenCo 2	0	20	0	-0.5
GenCo 3	0	30	0	-0.5

To simplify the calculations, the quadratic coefficient of each GenCo's cost function has been set to zero. Additionally, at this stage, the CV_{ig} for all GenCos have been considered$' - 0.5\ '$, which represents the fact that all GenCos react to their rivals' behaviors and reactions similarly.

As shown in the M-File for oligopolistic electricity market provided in Appendix A, the values of slope, f_d, and intercept, e_d, of inverse demand curve has been varied in each individual steps for the above case study, in order to illustrate the alterations in output of each generation company, q_{ig}, total output provided by all GenCos and the selling price, p_d.

4.6.1 Impact of Inverse Demand Curve Slope and Intercept on Oligopolistic Electricity Market

Table 4.2 (a-f), presents the impacts of slope and intercept of inverse demand curve on the oligopolistic electricity market. According to Table 4.2 (a-f), the intercept has been assigned values between $200\,£/MW$ to $1500\,£/MW$ and also for each intercept value, the slope varies between $0.1763\,£/MW^2$ or (10°) and $11.43\,£/MW^2$ or (85°). Table 4.2 (a-f) illustrates the impact of steepness of the inverse demand curve slope on the output of each GenCo and consequently on the market power. It can be realized that, when the slope increases the output of each generation company will decrease; therefore, the total output offered by all GenCos into the wholesale market will reduce. This will indicate that all GenCos in the electricity market are practicing market power and the oligopoly environment is affecting the electricity trading. In fact, in a real market environment a steep inverse demand curve is expected according to the low demand elasticity.

Table 4.2 (a): Impacts of Inverse Demand Curve intercept and Slope on GenCos in Oligopolistic Market (*e_d =1500)*

Intercept: e_d $(£/MW)$	Slope: f_d $(£/MW^2)$	GenCo1 Output: q_{1g} (MW)	GenCo2 Output: q_{2g} (MW)	GenCo3 Output: q_{3g} (MW)	Total Output: $Q_g(MW)$	Price: p_d $(£/MW)$
1500	**0.1763 (10°)**	2512	2398.5	2285.1	7195.5	231.4
1500	**0.3639 (20°)**	1217	1162	1107.1	3486	231.4
1500	**0.5773 (30°)**	767.1179	732.4738	697.8298	2197.4	231.4
1500	**0.839 (40°)**	527.8393	504.0014	480.1635	1512	231.4
1500	**1.1917 (50°)**	371.618	354.8352	338.0525	1064.5	231.4
1500	**1.732 (60°)**	255.6912	244.1438	232.5965	732.4315	231.4
1500	**2.7474 (70°)**	161.1914	153.9118	146.6321	461.7353	231.4286
1500	**5.6712 (80°)**	78.0888	74.5622	71.0356	223.6866	231.4286
1500	**11.43 (85°)**	38.7452	36.9954	35.2456	110.9861	231.4286

Figure 4.5 represents the impact of inverse demand curve slope on the output of GenCo 1 for intercept $e_d = 1500\ (£/MW)$. It is important to note that, further results for other GenCos have been attached in Appendix B.

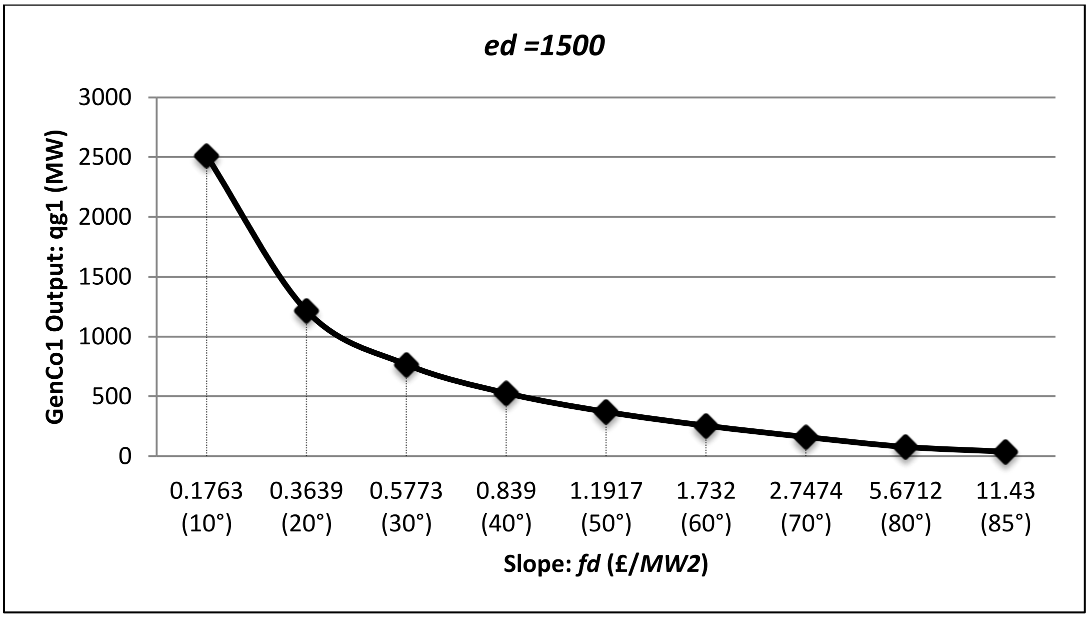


Figure 4.5: Impact of Inverse Demand Curve Slope on GenCo1 Output (e_d *=1500)*

Furthermore, the impact of inverse demand curve slope on the output of GenCo 1 for other intercepts has been represented.

Table 4.2 (b): Impacts of Inverse Demand Curve intercept and Slope on GenCos in Oligopolistic Market (e_d *=1000)*

Intercept: e_d $(£/MW)$	**Slope:** f_d $(£/MW^2)$	**GenCo1 Output:** q_{1g} (MW)	**GenCo2 Output:** q_{2g} (MW)	**GenCo3 Output:** q_{3g} (MW)	**Total Output:** $Q_g (MW)$	**Price:** p_d $(£/MW)$
1000	**0.1763 (10°)**	1701.6	1588.2	1474.8	4764.6	160
1000	**0.3639 (20°)**	824.4023	769.4422	714.482	2038.3	160
1000	**0.5773 (30°)**	519.6605	485.0165	450.3724	1455	160
1000	**0.839 (40°)**	357.5685	333.7306	309.8927	1001.2	160
1000	**1.1917 (50°)**	251.7412	234.9585	218.1757	704.8754	160
1000	**1.732 (60°)**	173.2102	161.6628	150.1155	484.9885	160
1000	**2.7474 (70°)**	**109.1941**	**101.9145**	**94.6349**	**305.7436**	**160**
1000	**5.6712 (80°)**	52.8989	49.3723	45.8457	148.1168	160
1000	**11.43 (85°)**	26.2467	24.4969	22.7472	73.4908	160

Comparing to the Table 4.2 (a) the selling price has been reduced since the intercept of inverse demand curve has been decreased.

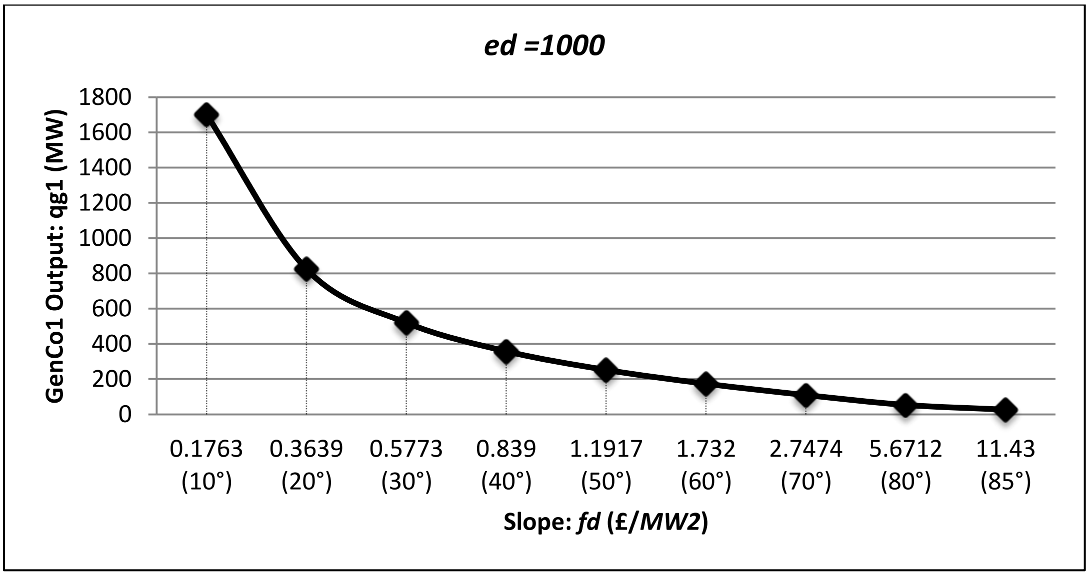


Figure 4.6: Impact of Inverse Demand Curve Slope on GenCo1 Output (e_d *=1000)*

It can be realized that once the intercept decreases, the impact of slope on the output of the GenCo 1 will be more moderate.

For $e_d = 800\ (£/MW)$ the results will be:

Table 4.2 (c): Impacts of Inverse Demand Curve intercept and Slope on GenCos in Oligopolistic Market (e_d *=800)*

Intercept: $e_d\ (£/MW)$	Slope: $f_d\ (£/MW^2)$	GenCo1 Output: $q_{1g}\ (MW)$	GenCo2 Output: $q_{2g}\ (MW)$	GenCo3 Output: $q_{3g}\ (MW)$	Total Output: $Q_g (MW)$	Price: p_d $(£/MW)$
800	**0.1763 (10°)**	1377.5	1264.1	1150.6	3792.2	131.4
800	**0.3639 (20°)**	667.3733	612.4131	557.453	1837.2	131.4
800	**0.5773 (30°)**	420.6775	386.0335	351.3895	1158.1	131.4
800	**0.839 (40°)**	289.4602	265.6223	241.7844	796.867	131.4286
800	**1.1917 (50°)**	203.7905	187.0078	170.225	561.0233	131.4286
800	**1.732 (60°)**	140.2177	128.6704	117.1231	386.0112	131.4286
800	**2.7474 (70°)**	88.3953	81.1157	73.836	243.347	131.4286
800	**5.6712 (80°)**	42.8229	39.2963	35.7697	117.8889	131.4286
800	**11.43 (85°)**	21.2473	19.4976	17.7478	58.4927	131.4286

Since the intercept of inverse demand curve represents the willingness of GenCos to sell electricity to the supply companies, it is expected that by reducing the intercept the selling price will decrease.

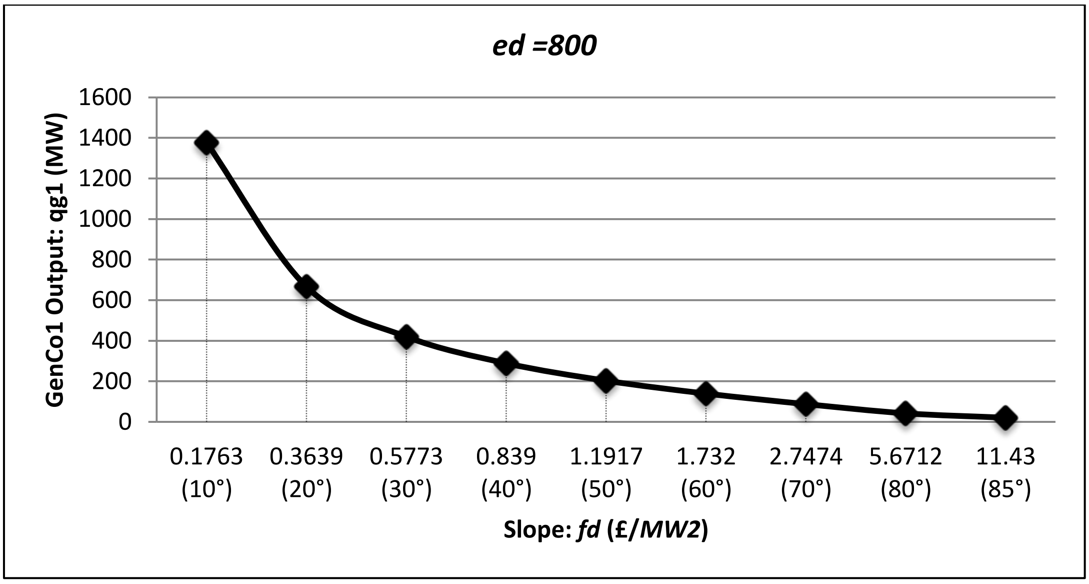


Figure 4.7: Impact of Inverse Demand Curve Slope on GenCo1 Output (e_d =800)

Furthermore, for $e_d = 600$ $(£/MW)$ the table can be updated as:

Table 4.2 (d): Impacts of Inverse Demand Curve intercept and Slope on GenCos in Oligopolistic Market (e_d =600)

Intercept: e_d $(£/MW)$	Slope: f_d $(£/MW^2)$	GenCo1 Output: q_{1g} (MW)	GenCo2 Output: q_{2g} (MW)	GenCo3 Output: q_{3g} (MW)	Total Output: $Q_g(MW)$	Price: p_d $(£/MW)$
600	**0.1763 (10°)**	1053.4	940	826.5	2819.9	102.9
600	**0.3639 (20°)**	510.3443	455.3841	400.424	1366.2	102.9
600	**0.5773 (30°)**	321.6946	287.0506	252.4065	861.1517	102.8571
600	**0.839 (40°)**	221.3519	197.514	173.6761	592.5421	102.8571
600	**1.1917 (50°)**	155.8398	139.057	122.2743	417.1711	102.8571
600	**1.732 (60°)**	107.2253	95.678	84.1306	287.034	102.8571
600	**2.7474 (70°)**	67.5964	60.3168	53.0372	180.9503	102.8571
600	**5.6712 (80°)**	32.7469	29.2203	25.6937	87.661	102.8571
600	**11.43 (85°)**	16.248	14.4982	12.7484	43.4946	102.8571

Similar to the previous table, since the willingness of selling electricity has been reduced the selling price has been dropped. Figure 4.8 illustrates the impact of inverse demand curve slope on the GenCo1 output:

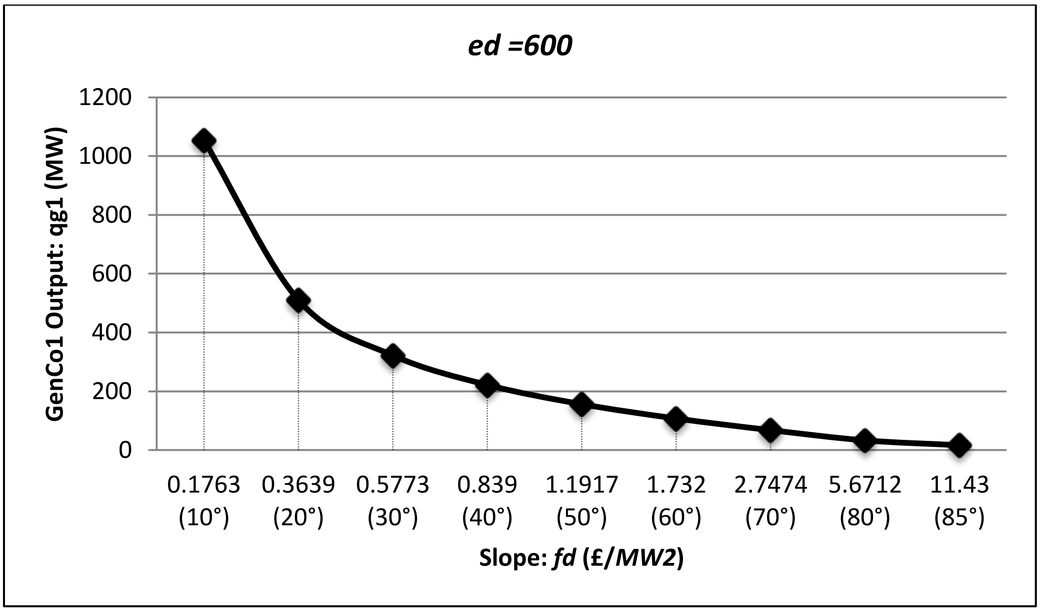


Figure 4.8: Impact of Inverse Demand Curve Slope on GenCo1 Output (e_d *=600)*

For $e_d = 400\ (£/MW)$, the Table 4.2 (e) has been provided. According to this table and Figure 4.9 there is a huge drop in the output of each GenCo and the selling price, since the intercept has been reduced and generation companies do not have any willingness to participate in the market. Furthermore, these reductions can be identified in Table 4.2 (f) and Figure 4.9 for $e_d = 200\ (£/MW)$.

Table 4.2 (e): Impacts of Inverse Demand Curve intercept and Slope on GenCos in Oligopolistic Market (e_d *=400)*

Intercept: $e_d\ (£/MW)$	Slope: $f_d\ (£/MW^2)$	GenCo1 Output: $q_{1g}\ (MW)$	GenCo2 Output: $q_{2g}\ (MW)$	GenCo3 Output: $q_{3g}\ (MW)$	Total Output: $Q_g (MW)$	Price: p_d $(£/MW)$
400	**0.1763 (10°)**	729.2764	615.8334	502.3904	1847.5	74.3
400	**0.3639 (20°)**	353.3153	298.3551	243.395	895.0654	74.2857
400	**0.5773 (30°)**	222.7116	188.0676	153.4236	564.2028	74.2857
400	**0.839 (40°)**	153.2437	129.4058	105.5679	388.2173	74.2857
400	**1.1917 (50°)**	107.8891	91.1063	74.3236	273.319	74.2857
400	**1.732 (60°)**	74.2329	62.6856	51.1382	188.0567	74.2857
400	**2.7474 (70°)**	46.7975	39.5179	32.2383	118.5536	74.2857
400	**5.6712 (80°)**	22.6709	19.1443	15.6178	57.433	74.2857
400	**11.43 (85°)**	11.2486	9.4988	7.749	28.4964	74.2857

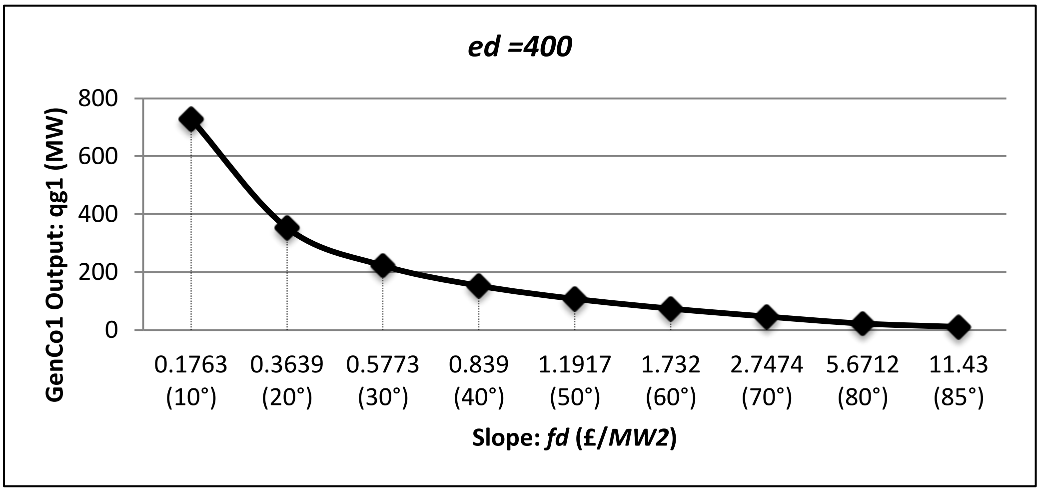


Figure 4.9: Impact of Inverse Demand Curve Slope on GenCo1 Output (e_d *=400)*

Table 4.2 (f): Impacts of Inverse Demand Curve intercept and Slope on GenCos in Oligopolistic Market *(*e_d *=200)*

Intercept: e_d $(£/MW)$	Slope: f_d $(£/MW^2)$	GenCo1 Output: q_{1g} (MW)	GenCo2 Output: q_{2g} (MW)	GenCo3 Output: q_{3g} (MW)	Total Output: $Q_g(MW)$	Price: p_d $(£/MW)$
200	**0.1763 (10°)**	405.1536	291.7106	178.2676	875.1317	45.7143
200	**0.3639 (20°)**	196.2863	141.3261	86.366	423.9783	45.7143
200	**0.5773 (30°)**	123.7287	89.0847	54.4406	267.254	45.7143
200	**0.839 (40°)**	85.1354	61.2975	37.4596	183.8924	45.7143
200	**1.1917 (50°)**	59.9384	43.1556	26.3729	129.4669	45.7143
200	**1.732 (60°)**	41.2405	29.6932	18.1458	89.0795	45.7143
200	**2.7474 (70°)**	25.9986	18.719	11.4394	56.157	45.7143
200	**5.6712 (80°)**	12.595	9.0684	5.5418	27.2051	45.7143
200	**11.43 (85°)**	6.2492	4.4994	2.7497	13.4983	45.7143

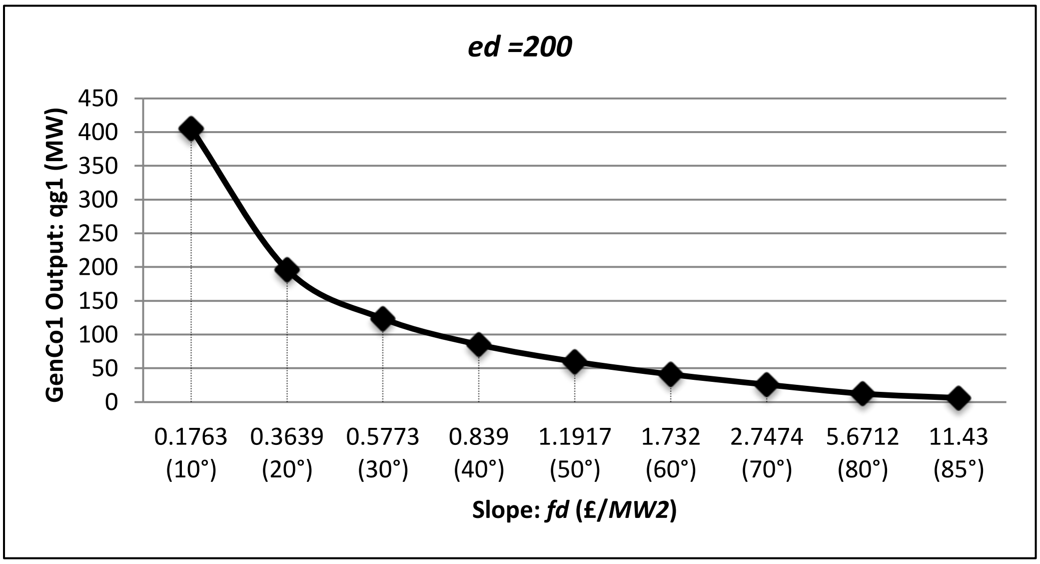


Figure 4.10: Impact of Inverse Demand Curve Slope on GenCo1 Output (e_d *=200)*

Consequently, the impact of slope on the total output of all GenCos, assuming $e_d = 1500\ (£/MW)$, has been illustrated in Figure 4.11.

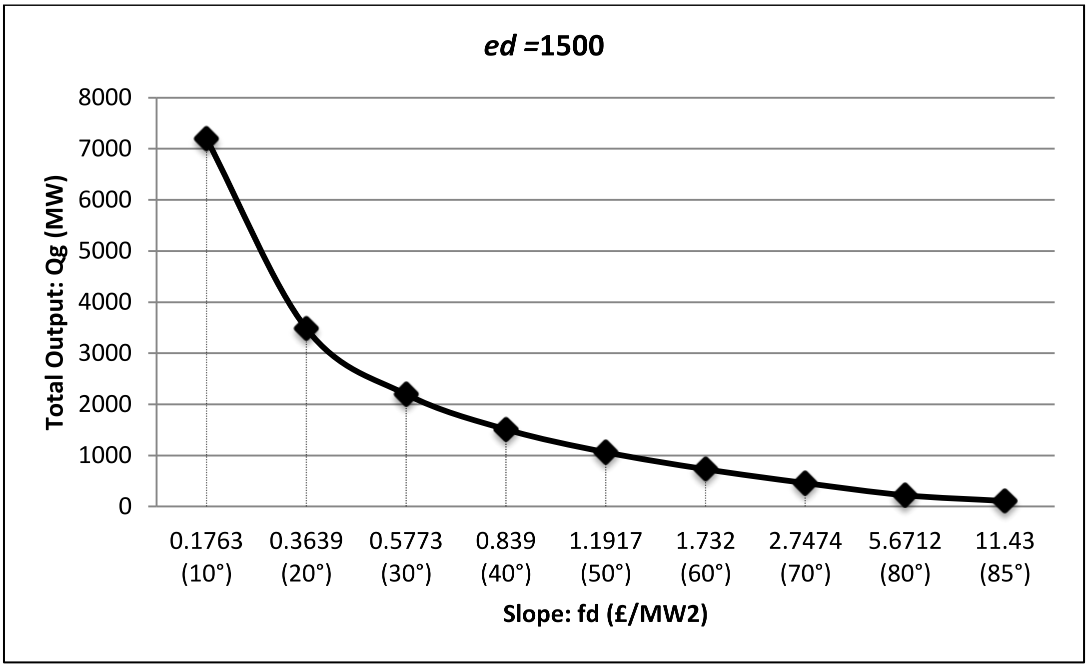


Figure 4.11: Impact of Inverse Demand Curve Slope on Total Output (e_d *=1500)*

Additionally, according to Table 4.2 the intercept, e_d, influences both the selling price and the output of each GenCo. The impact of intercept on the output of GenCo 1 has been illustrated in Figure 4.12 for slope $f_d = 2.7474\ (£/MW^2)$ (70°). Based on this figure and Equation 4.28, while the intercept decreases the output of each GenCo is expected to decrease.

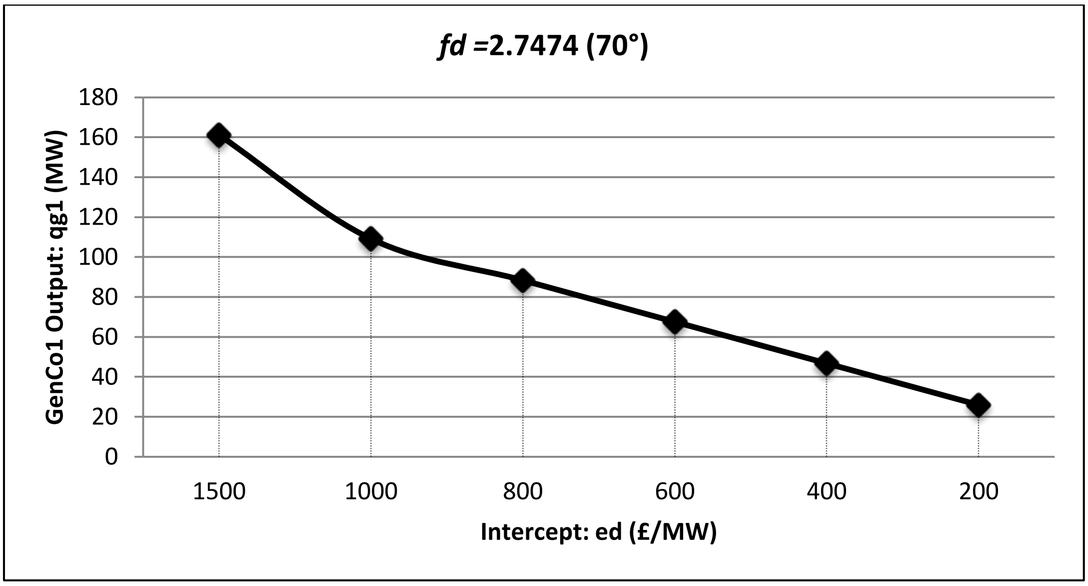


Figure 4.12: Impact of Inverse Demand Curve Intercept on GenCo1 Output (f_d=70°)

Furthermore, based on Equation 4.20, the impact of intercept on the selling price has been represented in Figure 4.13. As discussed earlier, once the intercept of inverse demand curve decreases the selling price by generation companies will drop as well as the willingness of generation companies decreases.

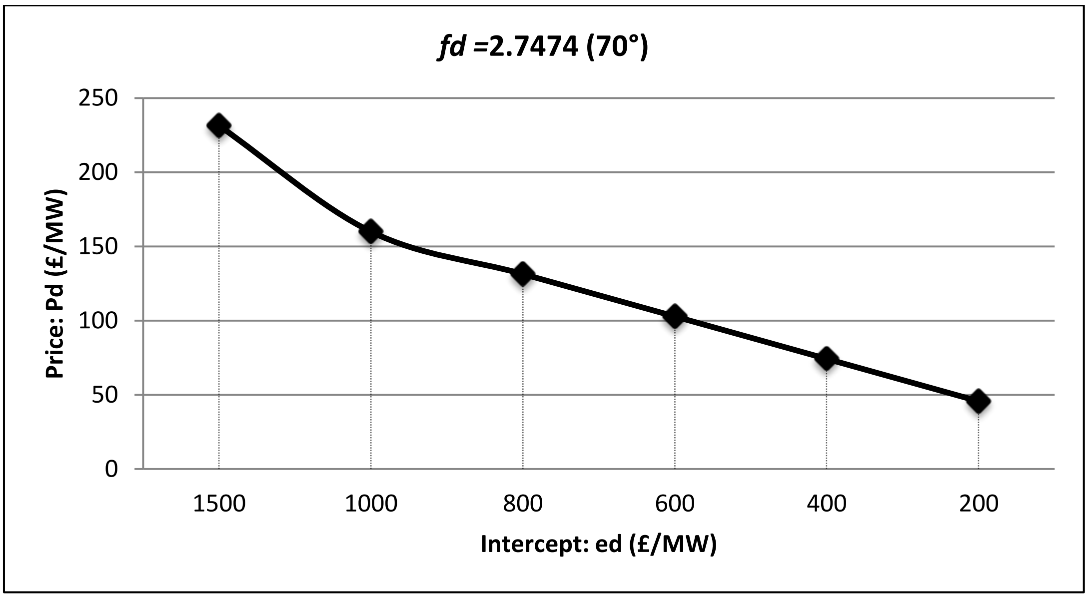


Figure 4.13: Impact of Inverse Demand Curve Intercept on Selling Price (f_d=70°)

4.7 Market Power in UK

As stated in Chapter 3, in BETTA more than 97% of energy trading is based on bilateral contracts; furthermore, there are not many market participants in the electricity market. In such an environment exercising market power is conceivable.

On the generation side, Office of gas and electricity markets (Ofgem) as the UK electricity market regulator has concerns about market power in the UK wholesale electricity sector [91]. The generation side of the market is suffering from oligopoly conditions. The '*Big Six*' electricity supply companies (more details will be provided in Chapter 5) are also the six largest owners of UK generation companies with 71.3% of total generation [92]. Moreover, within these years the number of British companies has fallen from six in 2006 to three by 2011 and their share was only about 25.9% of installed capacity by 2011 [92].

As mentioned above, the number of dominant generation companies is similar to the number of supply companies, thus in such a dominant, oligopoly environment the other market participants will have limited access to the electricity wholesale market, which causes less liquidity and an imperfect bilateral electricity market.

Figure 4.14 illustrates the share of six large generation companies: RWE npower, EDF, E.ON, Southern ElectriC (SSE), Iberdrola (ScottishPower), Centrica, in UK bilateral electricity market in 2011.

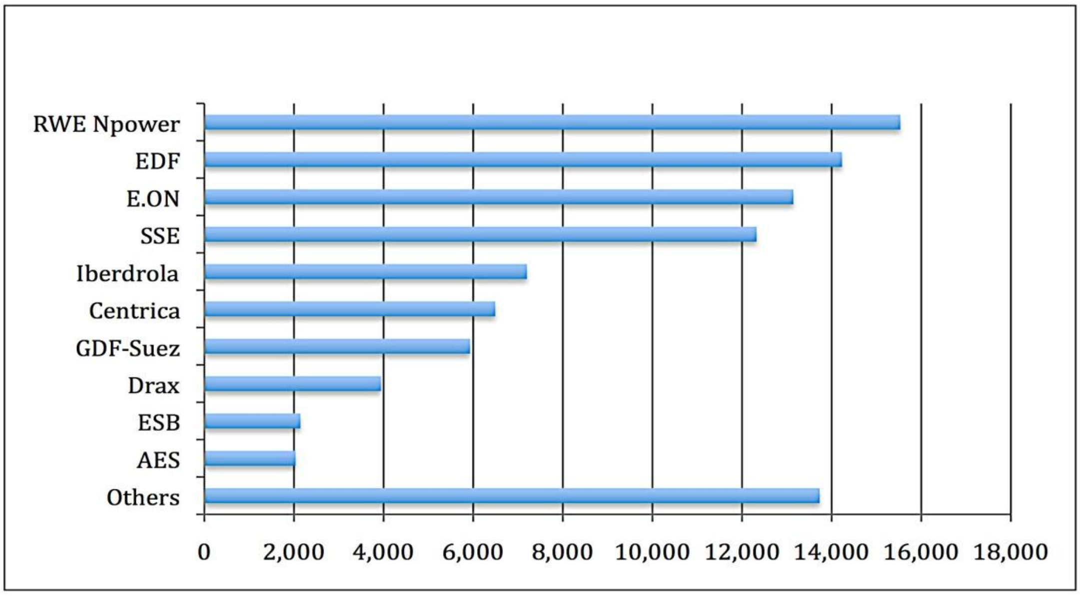
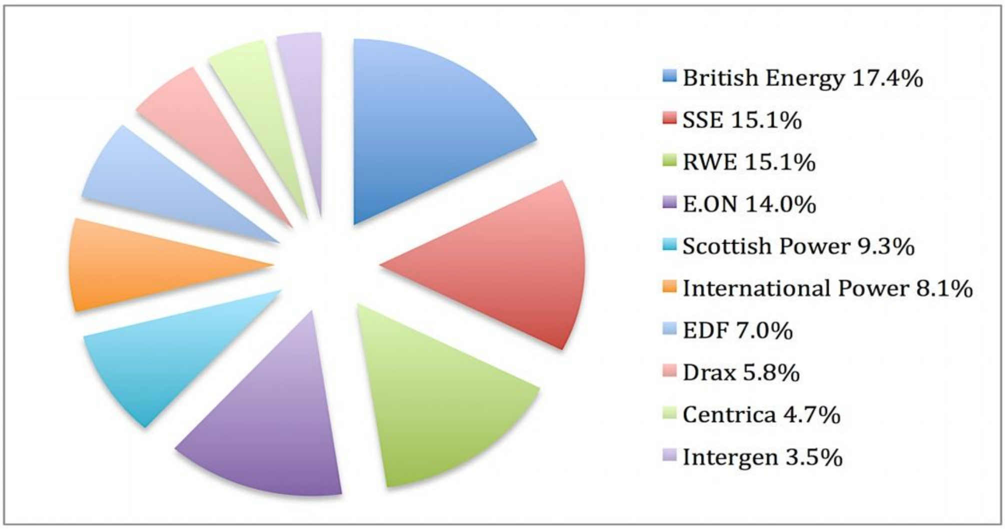


Figure 4.14: The Share of Six Large GenCos in the UK [92]

The share of market participation by the Big Six UK generation companies in oligopolistic market has remained almost constant between 2006-2011 [92], which expresses that these dominant companies are making profit and UK electricity market as a bilateral market is suffering from imperfect bilateral trading over recent years. Hence, modeling the oligopolistic electricity market is essential.

Figure 4.15 demonstrates and compares the share of dominant GenCos in UK bilateral electricity market in 2006 and 2011 and illustrates that this oligopoly environment has existed and even increased.



(a)

(b)

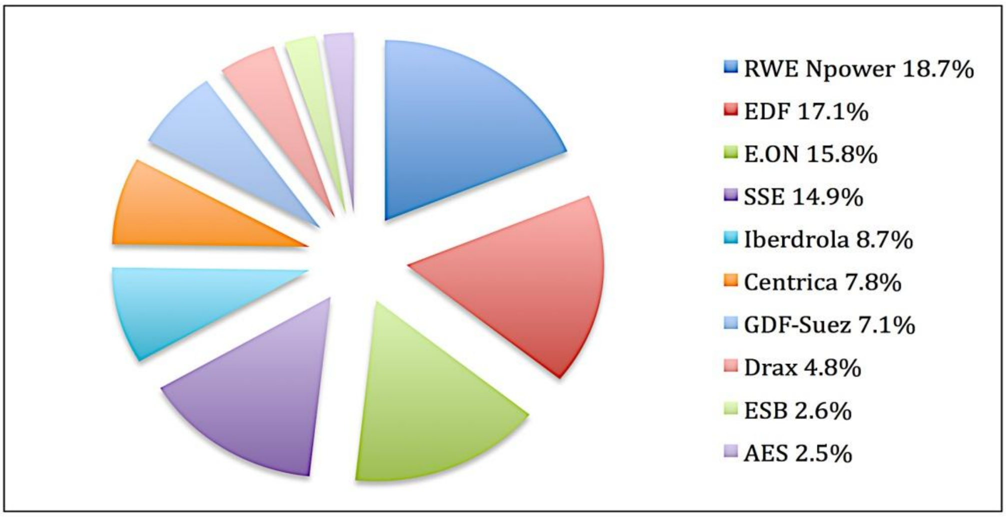


Figure 4.15: Share of Dominant GenCos in UK: (a) 2006; (b) 2011 [92]

4.8 Summary

This chapter has been divided into several sections. Firstly, it has been discussed that because of several reasons, such as market structure complexity and lack of incentivized schemes, market participants can exercise market power in bilateral electricity market. Since bilateral electricity market is a double-sided market, in this chapter the role of generation companies has been investigated. Therefore, oligopolistic electricity market has been considered and reasons behind the idea of modeling such an electricity environment discussed.

Several techniques reviewed and highlighted in this chapter in order to measure the market power; however, Equilibrium model, and particularly Conjectural Variation Equilibrium (CVE) method has been selected as a promising approach to model such imperfect environments.

At the final stage of this chapter, the oligopolistic electricity market has been formulated and behaviors of generation companies investigated. To clarify those formulations and modeling a case study provided, which demonstrates clearly the impacts of inverse demand curve parameters on generation companies behaviors.

Chapter 5: Oligopsonistic Electricity Market Modeling

5.1 Introduction

Chapter 4 discussed how to model oligopolistic electricity market using conjectural variation equilibrium method in order to assist generation companies maximize their profits while they consider their rivals' reactions in the market. Conforming to Equation 4.28, the output of each generation company can be calculated according to the inverse demand function properties (slope and intercept) and the estimation of other market competitors' behaviors.

The majority of previous research simply considers the generation side of the bilateral electricity market and models an oligopolistic electricity market. However, according to Chapter 3, in bilateral electricity markets such as BETTA, the other side of the market is likewise playing a significant role in energy trading. In this chapter the supply side of imperfect bilateral electricity market will be modeled and formulated. In addition, it will be demonstrated how supply companies in oligopsonistic electricity markets can maximize their profits while they consider other SupplyCos' behaviors in the market.

5.2 Oligopsonistic Electricity Market Modeling Using CVE

As mentioned in the previous chapter, bilateral electricity market has been divided into two sub markets: oligopolistic and oligopsonistic electricity markets. In order to discuss one of the primary novelties of the current study, this section clarifies how to model supply companies in imperfect bilateral electricity markets in a way to find the role of SupplyCos in electricity trading in imperfect bilateral electricity markets.

An oligopsonistic market is an environment in which the number of buyers, who are supply companies, is small. In this market generation companies, who act as sellers, are trading electricity to the small number of large and powerful supply companies. Consequently, the oligopsonistic market represents an imperfect market.

In an oligopsonistic market the SupplyCos can dominate the bilateral market. They can put one GenCo against another GenCo 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.

Comparing to Figure 4.1 presented in Chapter 4, the main focus of this chapter has been laid on oligopsonistic electricity market as shown in Figure 5.1.

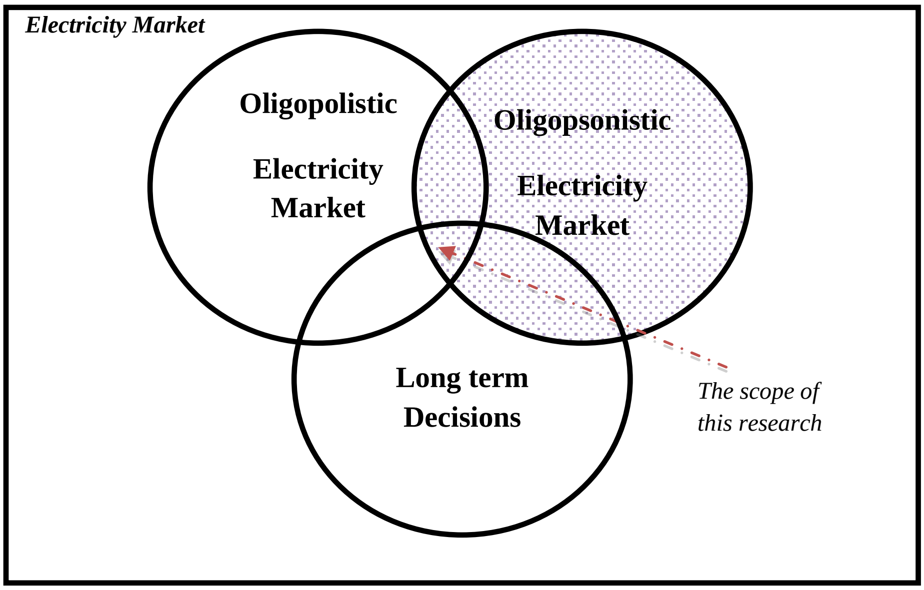


Figure 5.1: Oligopsonistic Electricity Market Boundary

5.2.1 Supply Companies’ Behaviors in a Bilateral Electricity Market

Like GenCos the main objective of each SupplyCo in electricity market is to maximize its profit in bilateral trading, in order to reduce the exposure to the price volatility risks. Unlike centralized electricity market structures, SupplyCos play active roles in the electricity market.

SupplyCos act as buyers in the wholesale market and they express their demand for electricity by entering into bilateral trading in order to provide electricity for their customers (end-users). There are some factors that define the behavior of SupplyCos in the electricity market, which affect the level of demand for electricity. Among those factors, price of generated electricity offered by GenCos, required quantity and GenCos’ behaviors and strategies play major roles.

There are several factors determining the behavior of GenCos in a bilateral electricity market. Assuming that other non-price factors are correctly defined, the generation behavior is strongly dependent on the purchased value by SupplyCos. Generation companies will increase their output with increase in the price to make more profit.

The volume of generated electricity in the market will go higher when the market price is high enough relative to the production cost. This is because the GenCos will find it profitable to increase their production when the market price is high. This definitely affects the quantity of electricity that is available to be sold to the SupplyCos in the market.

In order to determine the importance of the inverse generation curve in bilateral electricity market modeling, Figure 5.2 refers to *inverse generation function*, where generation companies have been categorized in three groups, including marginal producers, infra-marginal producers, and extra-marginal producers [1]. The marginal producers are the producers whose production costs equal to market price. Marginal producers will find that their productions are not profitable if the market price decreases. For infra- producers the cost of generating electricity is below the market price these companies set their price more than their costs to make profit. As for extra-producers, they will only find that their participation is profitable when the market price increases. Consequently, different generation companies with various cost functions are competing against each other in the bilateral market, which affect SupplyCos decisions and strategies in participating in the future trading.

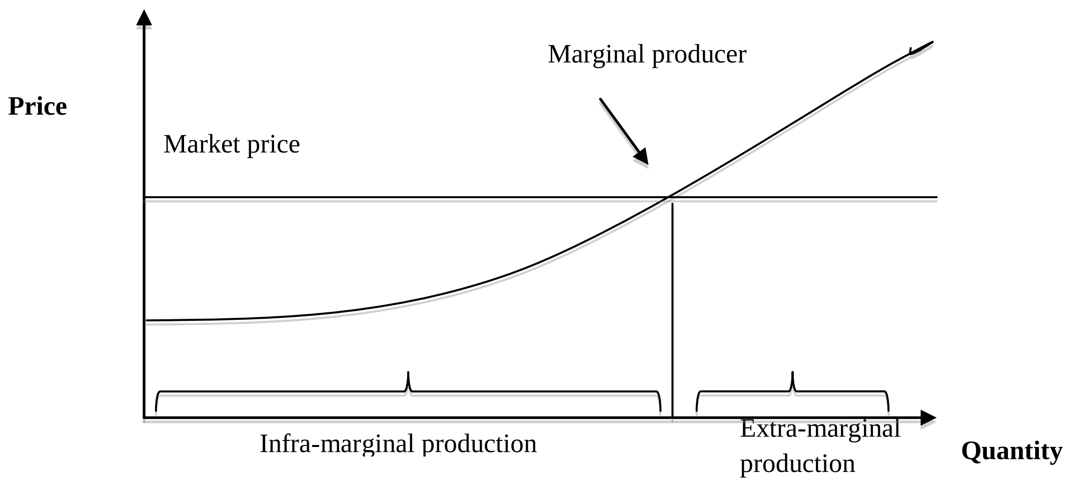


Figure 5.2: Inverse Generation Curve [1]

5.2.2 CVE Applications and Formulations in an Oligopsonistic Electricity Market

Bilateral market is a double-sided market, where both GenCos and SupplyCos have permission and willingness to participate in the market; therefore unlike a Pool structure, SupplyCos can have an active role in the market and try to maximize their profits alongside the GenCos. One of the primary novelties of this research is the modelling oligopsonistic competition in a bilateral market where a small number of SupplyCos dominate the whole market and try to maximize their profits.

Hence, for $'m'$ SupplyCos in the market the main objective is to maximize its profit:

$$Max \quad \pi_{id} = \lambda q'_{id} - p_g q_{id} - f_{ci} \qquad (i = 1, \dots, m) \tag{5.1}$$

Where:

$'m'$: Number of SupplyCos

$'\pi_{id}'$: SupplyCo i profit

$'\lambda'$: Retail market price

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

$'q_{id}'$: Purchased value by SupplyCo i

$'f_{ci}'$: Fixed cost of SupplyCo i

It is noticeable that the sub-index $'d'$ in this research refers to the supply side of bilateral electricity market.

Furthermore, $'p_g'$ is an *initial inverse generation function* and represents the price that each supply company buys electricity from generation companies.

Comparable to oligopoly structure, an initial inverse generation function, p_g, has been introduced since in a bilateral electricity market SupplyCos participate in forward contracts and it is not applicable to use one inverse generation function for each contract as the amount and price of traded electricity is not disclosed.

On the other hand using a residual generation function (RGC) can be an option that all rivals' demand functions estimations are required; however, it can be a big challenge for all supply companies since accessing to the demand function for each supply company is not possible and also requires having an access to suitable historical database as well.

Nevertheless, this initial inverse generation curve can be updated iteratively in terms of intercept and slope to get a more accurate and realistic shape to find out the share of each supply company in the bilateral electricity market using the proposed algorithm in Chapter 6. In this case, the slope of inverse generation curve has been assumed 45 degree initially, and through the hierarchical optimization algorithm the slope will be changed iteratively. As for the oligopolistic market, the reason of defining the slope as 45 degree is to have a feasible flat start and this initial value does not have any effect on the final results [90].

To carry out the modeling oligopsonistic electricity market, the following simplifying assumptions have been made:

Assumption 1:

The amount of electricity purchased by a SupplyCo from GenCos can be assumed to be equal to the amount of electricity, which has been sold to the end-users by that SupplyCo [90]:

$$q'_{id} = q_{id} \tag{5.2}$$

Therefore, no energy holding is permitted in this model, which prevents participants from abusing the market.

Assumption 2:

Since the aim of this chapter is to model SupplyCos' behaviors in wholesale electricity market and also the retail price is based on the contractual price between each SupplyCo and end-users, the electricity retail price, λ, is assumed to be a fixed value. However in Chapter 6, different retail prices will be considered for different SupplyCos.

Assumption 3:

The supply companies' 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, such as computers, software, communication assets, etc.
- Cost of renting the location
- Cost of human resources, such as salaries, etc.
- Other overhead costs.

Therefore, considering the above costs, they are not in direct relation with quantity of purchased or sold electricity.

Hence, according to Equation 5.2 and the above assumptions, Equation 5.1 can be transformed into:

$$\begin{aligned} Max \quad \pi_{id} &= \lambda q_{id} - p_g q_{id} - f_{ci} \\ &= (\lambda - p_g) q_{id} - f_{ci} \qquad (i = 1, \dots, m) \end{aligned} \tag{5.3}$$

Like p_d in oligopolistic market, the inverse generation function has been introduced as a linear function since the algorithm proposed in Chapter 6 finds the equilibrium point of the whole market looking at the cross-over point between oligopolistic and oligopsonistic markets. Thus, to simplify the calculations:

$$p_g = e_g + f_g Q \tag{5.4}$$

Where:

$'e_g'$: Intercept of inverse generation curve

$'f_g'$: Slope of inverse generation curve

Also like oligopoly condition, $'Q'$ is the total supply and should be equal to total demand, $'D'$.

Figure 5.3 illustrates the initial *inverse* generation function. This curve represents the changes in the price respect o any changes in the amount of electricity.

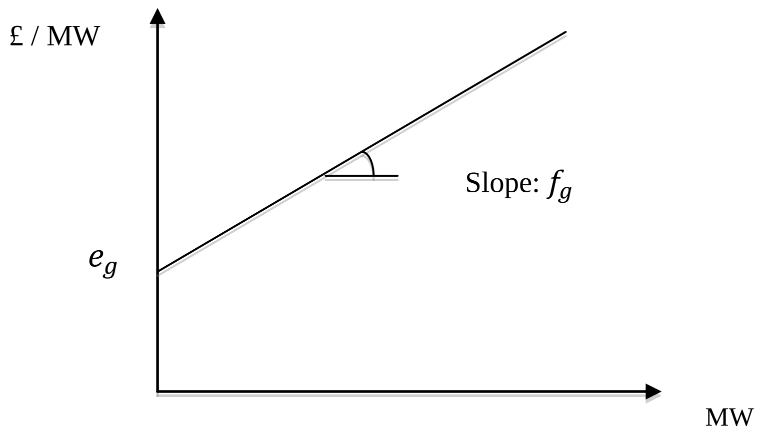


Figure 5.3: Initial Inverse Generation Curve

According to the figure above and unlike the inverse demand function in oligopolistic markets, the derivative of the inverse generation curve is to be positive.

By substituting Equation 5.4 in 5.3, the profit for SupplyCos playing rationally in the oligopsonistic market will be:

$$Max \;\; \pi_{id} = (\lambda - e_g - f_g Q\ )q_{id} - f_{ci} \tag{5.5}$$

Since after running the market simulation, one of the main constraints is that the total generation should match the total demand, hence:

$$D = Q = \sum_{i=1}^{m} q_{id} \tag{5.6}$$

In order to maximize the SupplyCo i profit

$$\frac{\partial \pi_{id}}{\partial q_{id}} = 0 \qquad (i = 1,2, \dots, m) \tag{5.7}$$

Therefore, the optimized solution will be:

$$\frac{\partial \pi_{id}}{\partial q_{id}} = \frac{\partial(\lambda q_{id})}{\partial q_{id}} - \frac{\partial\left(e_g q_{id}\right)}{\partial q_{id}} - \frac{\partial\left(f_g q_{id} \ \sum_{i=1}^{m} q_{id}\right)}{\partial q_{id}} = 0 \tag{5.8}$$

To simplify the above equation:

$$\frac{\partial \pi_{id}}{\partial q_{id}} = \lambda - e_g - f_g \left(2q_{id} + \sum_{\substack{j=1 \\ j \neq i}}^{m} q_{jd} + q_{id} \sum_{\substack{j=1 \\ j \neq i}}^{m} \frac{\partial q_{jd}}{\partial q_{id}} \right) = 0 \tag{5.9}$$

After taking the derivative and based on Equation 5.9, the Conjectural Variation (CV) for supply companies in oligopsonistic market can be identified as follow:

$$\mathrm{CV}_{ijd} = \frac{\partial q_{jd}}{\partial q_{id}} \qquad (i, j = 1,2, \dots, m)(i \neq j) \tag{5.10}$$

Where:

$'q_{jd}'$: Purchased value by other supply companies except SupplyCo i

Like CV_{ijg} in the oligopolistic market model, the CV_{ijd} is the expectation of SupplyCo i about the reactions of its rival, SupplyCoj, as a result of any changes in its strategies. In this concept, unlike other previous research, the SupplyCos have been considered to play an active role in the bilateral electricity market and the impacts of their decisions will be taken into consideration in order to find the equilibrium point of the market.

This novel conjectural variation parameter introduced in oligopsonistic electricity market reflects how much electricity other rivals will buy in case of any changes in purchased value by SupplyCo i from wholesale market.

Thus, by substituting Equation 5.10 into 5.9:

$$\frac{\partial \pi_{id}}{\partial q_{id}} = \lambda - e_g - f_g \left(2q_{id} + \sum_{\substack{j=1 \\ j\neq i}}^{m} q_{jd} + q_{id} \sum_{\substack{j=1 \\ j\neq i}}^{m} \mathrm{CV}_{ijd} \right) = 0 \qquad (5.11)$$

Hence, the above equation can be transformed into:

$$q_{id} = \frac{\lambda - e_g - f_g \sum_{\substack{j=1 \\ j\neq i}}^{m} q_{jd}}{f_g \left(2 + \sum_{\substack{j=1 \\ j\neq i}}^{m} CV_{ijd}\right)} \qquad (5.12)$$

It will be challenging for each SupplyCo to estimate the purchased value by other rivals and also have knowledge about the CV_{ijd}s. In order to simply Equation 5.12, the aggregation of other rivals' purchased value from wholesale electricity market can be represented as follows:

$$q_{-jd} = \sum_{\substack{j=1 \\ j \neq i}}^{m} q_{jd} \tag{5.13}$$

Also, variable CV_{id} can be introduced as:

$$\mathrm{CV}_{id} = \sum_{\substack{j=1 \\ j \neq i}}^{m} \mathrm{CV}_{ijd} \tag{5.14}$$

By substituting Equations 5.13 and 5.14 in Equation 5.12, the purchased value of each SupplyCo considering the reactions of other rivals can be calculated as:

$$q_{id} = \frac{\lambda - e_g - f_g q_{-id}}{f_g(2 + CV_{id})} \tag{5.15}$$

Based on the above equation, it can be considered that the purchased value by a SupplyCo in the bilateral electricity market depends on the retail price, GenCos' behaviors and the reactions of other market competitors.

In this case, the preferred purchased value by each SupplyCo, considering their rivals' behaviors, has been identified. On the other hand, the preferred selling quantity by each GenCo in wholesale market has been represented previously. Chapter 6 will focus on how to identify the equilibrium point of bilateral electricity market through applying the proposed novel hierarchical optimization algorithm.

However, it is essential to consider the specifications of CVs in both oligopolistic and oligopsonistic electricity market.

5.3 Conjectural Variations Specifications in Oligopolistic and Oligopsonistic Electricity Markets

Based on Conjectural Variation Equilibrium (CVE) concept the behavior of a GenCo or a SupplyCo in oligopolistic and oligopsonistic electricity markets, respectively, is based on its rivals' strategies and reactions, which are conjectured functions of its own strategy.

CVE method is practical for:

- Behavioral models
- Incomplete information models
- Implicit cooperation

Conjectural variations were considered as exogenous parameters [81, 89]. However, this property is in contrast to the CVE concept. In fact, according to the Equations 4.28 and 5.15 the output of each GenCo and purchased value by each SupplyCo are both functions of CVs, which demonstrates that the behaviors of market participants can be observed in the CVE method. By considering CVs as exogenous parameters the values of conjectures can be estimated from the historical data; thus, the results are valid and reflect the market participants' behaviors for short or medium term. However, for long term planning, like bilateral electricity markets, this may cause the inaccurate simulation results, since the CVs are not very sensitive to any changes in the market participants' behaviors in long term. Therefore, the CVs can be considered as endogenous parameters in the equilibrium method.

The basic idea behind the CVE method for both oligopolistic and oligopsonistic bilateral electricity markets is to the answer to this question that if one firm changes its output or purchased value, what other rivals will do in response to that change. Therefore, through this method it will be examined if one firm changes its output or purchased electricity value, how much it should expect others to increase or decrease their quantities, in other words, whether they act aggressively or passively.

5.3.1 GenCos' Conjectural Variations Boundaries

As described in Chapter 4, CV_{ig} is an index that guides GenCos to find out the reaction of their rivals in the bilateral market; however one of the significant steps in this method is to find out the boundaries and values of the CV_{ig} for each GenCo.

Compare to CV_{id}s for SupplyCos, the CV_{ig}s for GenCos are functions of several factors, such as [90]:

- Practical specifications of each generator considering the type of generator i.e. nuclear power plant, wind turbines, coal-fired power plants, etc.
- Technical characteristic like ramp rate, start up and shut down time and also whether they deliver base load or they only follow the peak load.
- Demand elasticity [93].

Different strategies can result in different values of CV_{ig}. The influence of CV_{ig} on market equilibrium point, the output of each GenCo and purchased value by each SupplyCo can be formulated. To clarify the CV_{ig} range [86], according to Equation 4.26, the Equation 4.28 can be transformed to:

$$
\begin{aligned}
CV_{ig} &= \frac{e_d - f_d q_{-ig} - b_i - 2f_d q_{ig} - c_i q_{ig}}{f_d q_{ig}} \\
&= \frac{e_d - f_d Q + f_d q_{ig} - b_i - 2f_d q_{ig} - c_i q_{ig}}{f_d q_{ig}} \\
&= \frac{e_d - f_d Q - f_d q_{ig} - (b_i + c_i q_{ig})}{f_d q_{ig}} = \frac{e_d - f_d Q - (b_i + c_i q_{ig})}{f_d q_{ig}} - 1 \\
&= \frac{p_d - MC_{ig}}{f_d q_{ig}} - 1 \qquad (5.16)
\end{aligned}
$$

According to Equation 5.16, the conjecture value for GenCo i, which is an aggregation of all CV_{ijg}s, is only dependent on the cost function of that GenCo; therefore there is no need to have knowledge about other rivals' cost functions.

As described in Chapter 4 and according to Equation 4.2, in perfect competition electricity market the wholesale price and marginal costs are equal; therefore, the value of CV_{ig} for the perfect competition will be:

$$CV_{ig} = \frac{p_d - MC_{ig}}{f_d q_{ig}} - 1 = -1 \tag{5.17}$$

In order to modify the range for CV_{ig}, it can be assumed that in electricity market normally the wholesale price should be equal or higher than the marginal cost in order to allow GenCos to make profit:

$$p_d \geq MC_{ig} \tag{5.18}$$

Hence, the value of CV_{ig} is equal or bigger than $'-1'$. Furthermore, in order to set an upper limit for the CV_{ig} the value for the monopoly, which is $'+1'$ can be considered [73, 94]. Therefore:

$$-1 \leq CV_{ig} \leq +1 \tag{5.19}$$

As long as the CV_{ig} value is close to its lower limit, the competition is close to the perfect environment, since as one GenCo or SupplyCo 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; thus, the CVs values will be negative.

On the other side, once the CV_{ig} gets positive values the market's trend will be towards monopoly competition since the difference between wholesale price and GenCo's marginal cost is higher. In this condition, if other rivals increase their quantity when GenCo i increases its output the marginal revenue will be further lower than price. Hence, it can reflect an accommodating reaction and causing *collusion* in the electricity market. As described in Chapter 4, if market participants collude, they can cause *cooperative* game theory, which is against the Conjectural Variation Equilibrium concept and causes imperfect bilateral electricity market.

In this research, in order to avoid this condition the boundaries of CV_{ig} can be modified as:

$$-1 \leq CV_{ig} \leq 0 \tag{5.20}$$

5.3.2 SupplyCos' Conjectural Variations Boundaries

According to Section 5.2, CV_{id} has been introduced in this research in order to demonstrate the reactions of all SupplyCos in the oligopsonistic electricity market. Like CV_{ig} in oligopolistic market, the boundaries and specifications of CV_{id} should be analyzed.

Compare to GenCos in oligopolistic electricity market, SupplyCos are companies that trade electricity in wholesale market and sell it to the end-users. Consequently, it can be considered that their conjectures about their rivals' actions compare to GenCos' conjectures will have less complexity and volatility.

Concerning the impact of CV_{id} on the SupplyCos' decisions and market equilibrium, the SupplyCos' conjectures in oligopsonistic market can be formulated based on Equation 5.15:

$$\begin{aligned} CV_{id} &= \frac{\lambda - e_g - f_g q_{-id} - 2 f_g q_{id}}{f_g q_{id}} \\ &= \frac{\lambda - e_g - f_g (Q - q_{id}) - 2 f_g q_{id}}{f_g q_{id}} \\ &= \frac{\lambda - e_g - f_g Q + f_g q_{id} - 2 f_g q_{id}}{f_g q_{id}} \\ &= \frac{\lambda - e_g - f_g Q - f q_{id}}{f_g q_{id}} \\ &= \frac{\lambda - p_g}{f_g q_{id}} - 1 \end{aligned} \tag{5.21}$$

According to the above equation, the CVs value for SupplyCos in oligopsonistic electricity market is a function of retail price and also their own purchased quantity from the wholesale market; thus, there is no need to have an access to confidential information like the purchased value by other SupplyCos.

Similar to the prior section, it is expected that the CV_{id} will be equal to $'-1'$ in perfect electricity market. Therefore, the lower extreme of CV_{id}s has been defined. Furthermore, by assuming the fact that, the retail price is normally higher than the wholesale market price, SupplyCos will make profit by participating in both wholesale and retail markets:

$$\lambda \geq p_g \tag{5.22}$$

Hence:

$$CV_{id} \geq -1 \tag{5.23}$$

Comparable to oligopolistic market, the upper extreme for the CV_{id} can be defined as $'+1'$. Therefore:

$$-1 \leq CV_{id} \leq +1 \tag{5.24}$$

However, in this research the positive boundary of CV_{id}s has been ignored in order to avoid collusion and cooperative game in the oligopsonistic electricity market, thus:

$$-1 \leq CV_{id} \leq 0 \tag{5.25}$$

5.4 Oligopsonistic Electricity Market Case Study

In this section, similar to Chapter 4, a case study has been examined, seeking to explain the application of the Conjectural Variation Equilibrium method in modeling specifically SupplyCos' behaviors and reactions in the oligopsonistic electricity market.

In the below case study, three SupplyCos with the following characteristics have been defined:

Table 5.1: Oligopsonistic Electricity Market Case Study

	CV_{id}	λ (£/MW)
SupplyCo 1	-0.6	250
SupplyCo 2	-0.5	250
SupplyCo 3	-0.4	250

According to prior investigation on Assumption 2, the retail price has been considered to be equal for all SupplyCos in the oligopsonistic electricity market in the current research. However, the impact of retail price on SupplyCos' behaviors in the oligopsonistic electricity market will be represented later in this chapter. Furthermore, in order to distinguish between the SupplyCos, the CV_{id} for each firm is different.

With reference to the M-File for oligopsonistic electricity market provided in Appendix C, the values of slope, f_g, and intercept, e_g, of inverse generation curve has been assumed different in all steps for the case study presented, in order to illustrate the variations in purchased value by each supply company, q_{id}, total purchased value by all SupplyCos and the buying price, p_g. Table 5.2, presents the impacts of slope and intercept of the inverse generation curve on the oligopsonistic electricity market.

5.4.1 Impact of Inverse Generation Curve Slope and Intercept on Oligopsonistic Electricity Market

According to Table 5.2 (a-f), which is comparable to Table 4.2 (a-f) in the previous chapter, the intercept has been assigned values between $5\ £/MW$ to $120\ £/MW$ and likewise for each intercept value, the slope varies between $0.1763\ £/MW^2$ or (10°) and $11.43\ £/MW^2$ or (85°). With reference to [3], the intercept for the inverse generation curve is expected to be less than the inverse demand curve's intercept.

Similar to the previous chapter, Table 5.2 (a-f) illustrates the impact of steepness of the inverse generation curve slope on the purchased value by each SupplyCo and consequently on market power. It has been observed when the slope increases the purchased value by each supply company will decrease, the total purchased electricity by all SupplyCos in the wholesale market will reduce. This will indicate that market power is being practiced by all SupplyCos in the electricity market and introduces an oligopsony environment into the electricity trading. However, comparing to the oligopoly environment, the slope of the inverse generation curve is not very steep, since in the real electricity market environment the demand side is less elastic than the generation side.

Table 5.2 (a) Impacts of Inverse Generation Curve Intercept and Slopes on SupplyCos in Oligopsonistic Market (*e_g =5)*

Intercept: e_g $(£/MW)$	Slope: f_g $(£/MW^2)$	SupplyCo 1 Purchased value: q_{1d} (MW)	SupplyCo 1 Purchased value: q_{2d} (MW)	SupplyCo 1 Purchased value: q_{3d} (MW)	Total Purchased Value: $Q_d (MW)$	Price: p_g $(£/MW)$
5	**0.1763 (10°)**	484.7709	387.8167	323.1806	1195.8	215.8
5	**0.3639 (20°)**	234.8588	187.887	156.5725	579.3184	215.814
5	**0.5773 (30°)**	148.0428	118.4343	98.6952	365.1723	215.814
5	**0.839 (40°)**	101.8655	81.4924	67.9103	251.2681	215.814
5	**1.1917 (50°)**	71.717	57.3736	47.8113	176.9019	215.814
5	**1.732 (60°)**	49.3448	39.4758	32.8965	121.7171	215.814
5	**2.7474 (70°)**	31.1076	24.8861	20.7384	76.7322	215.814
5	**5.6712 (80°)**	15.07	12.056	10.0467	37.1727	215.814
5	**11.43 (85°)**	7.4773	5.9818	4.9848	18.4439	215.814

Figure 5.4 represents the impact of inverse generation curve slope on the purchased value by SupplyCo 1 for intercept $e_g = 5\,(£/MW)$. Further results on other SupplyCos can be found in Appendix D.

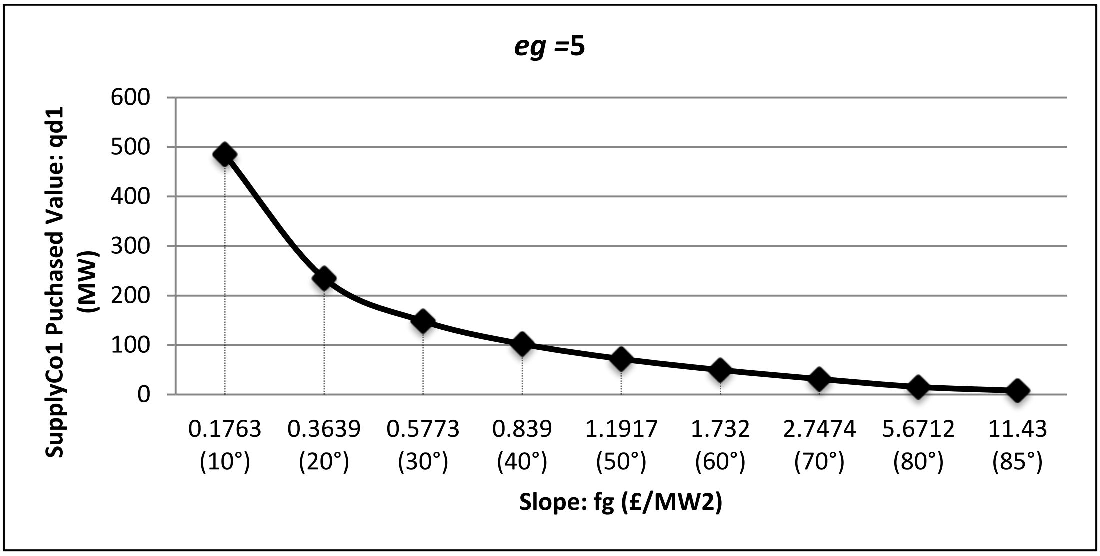


Figure 5.4: Impact of Inverse Generation Curve Slope on SupplyCo1 Purchased Value (*e_g =5)*

According to the Figure 5.4, the purchased value by each SupplyCo will decrease as the inverse generation curve becomes inelastic and gets close to the vertical line.

Furthermore, the impact of the inverse generation curve slope on the SupplyCo 1 for other intercepts has been investigated and illustrated.

Table 5.2 (b) Impacts of Inverse Generation Curve Intercept and Slopes on SupplyCos in Oligopsonistic Market (*e_g =10)*

Intercept: e_g $(£/MW)$	Slope: f_g $(£/MW^2)$	SupplyCo 1 Purchased value: q_{1d} (MW)	SupplyCo 1 Purchased value: q_{2d} (MW)	SupplyCo 1 Purchased value: q_{3d} (MW)	Total Purchased Value: $Q_d (MW)$	Price: p_g $(£/MW)$
10	**0.1763 (10°)**	474.8777	379.9021	316.5851	1171.4	216.5
10	**0.3639 (20°)**	230.0658	184.0526	153.3772	567.4955	216.5116
10	**0.5773 (30°)**	145.0215	116.0172	96.681	357.7198	216.5116
10	**0.839 (40°)**	99.7866	79.8293	66.5244	246.1402	216.5116
10	**1.1917 (50°)**	70.2534	56.2027	46.8356	173.2916	216.5116
10	**1.732 (60°)**	48.3377	38.6702	32.2251	119.233	216.5116
10	**2.7474 (70°)**	30.4728	24.3782	20.3152	75.1662	216.5116
10	**5.6712 (80°)**	14.7625	11.81	9.8416	36.4141	216.5116
10	**11.43 (85°)**	7.3247	5.8597	4.8831	18.0675	216.5116

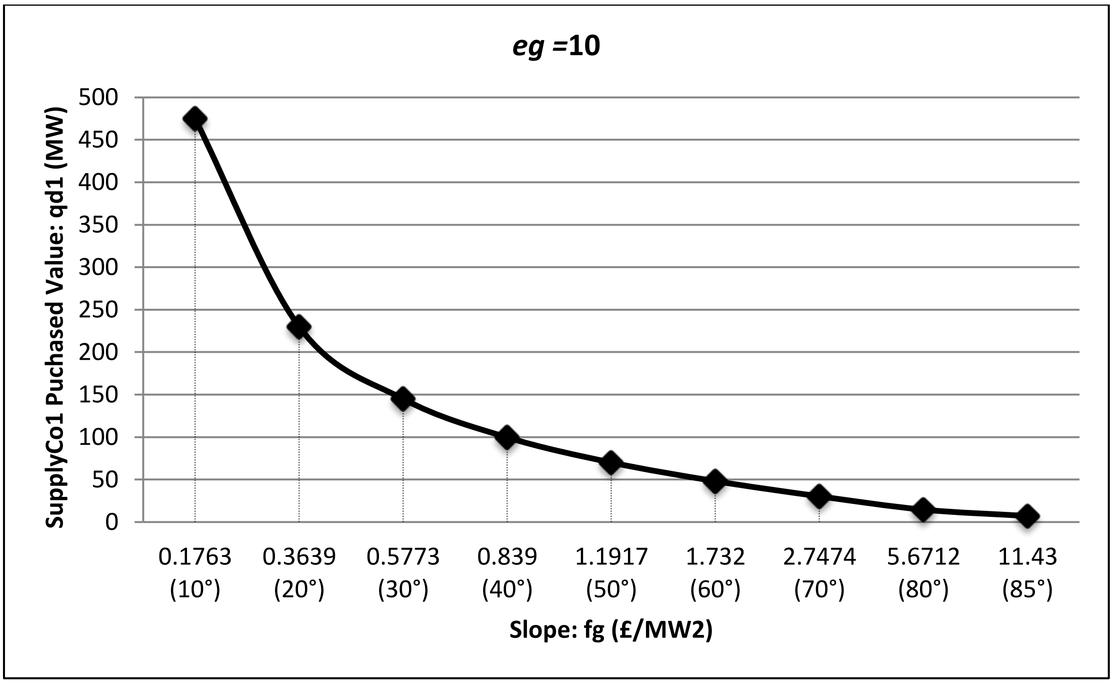


Figure 5.5: Impact of Inverse Generation Curve Slope on SupplyCo1 Purchased Value (e_g *=10)*

According to the Table 5.2 (b), once the intercept of inverse generation curve increases the maximum willingness of SupplyCo1 for purchasing electricity increases and the buying price will rise as well.

For $e_g = 50\ (£/MW)$, Table 5.2 (c) has been provided.

Table 5.2 (c) Impacts of Inverse Generation Curve Intercept and Slopes on SupplyCos in Oligopsonistic Market (e_g *=50)*

Intercept: $e_g\ (£/MW)$	Slope: $f_g\ (£/MW^2)$	SupplyCo 1 Purchased value: $q_{1d}\ (MW)$	SupplyCo 1 Purchased value: $q_{2d}\ (MW)$	SupplyCo 1 Purchased value: $q_{3d}\ (MW)$	Total Purchased Value: $Q_d (MW)$	Price: p_g $(£/MW)$
50	**0.1763 (10°)**	395.7314	316.5851	263.8209	976.1374	222.093
50	**0.3639 (20°)**	191.7215	153.3772	127.8143	472.913	222.093
50	**0.5773 (30°)**	**120.8513**	**96.681**	**80.5675**	**298.0998**	**222.093**
50	**0.839 (40°)**	83.1555	66.5244	55.437	205.1168	222.093
50	**1.1917 (50°)**	58.5445	46.8356	39.0296	144.4097	222.093
50	**1.732 (60°)**	40.2814	32.2251	26.8543	99.3609	222.093
50	**2.7474 (70°)**	25.394	20.3152	16.9293	62.6385	222.093
50	**5.6712 (80°)**	12.3021	9.8416	8.2014	30.3451	222.093
50	**11.43 (85°)**	6.1039	4.8831	4.0693	15.0563	222.093

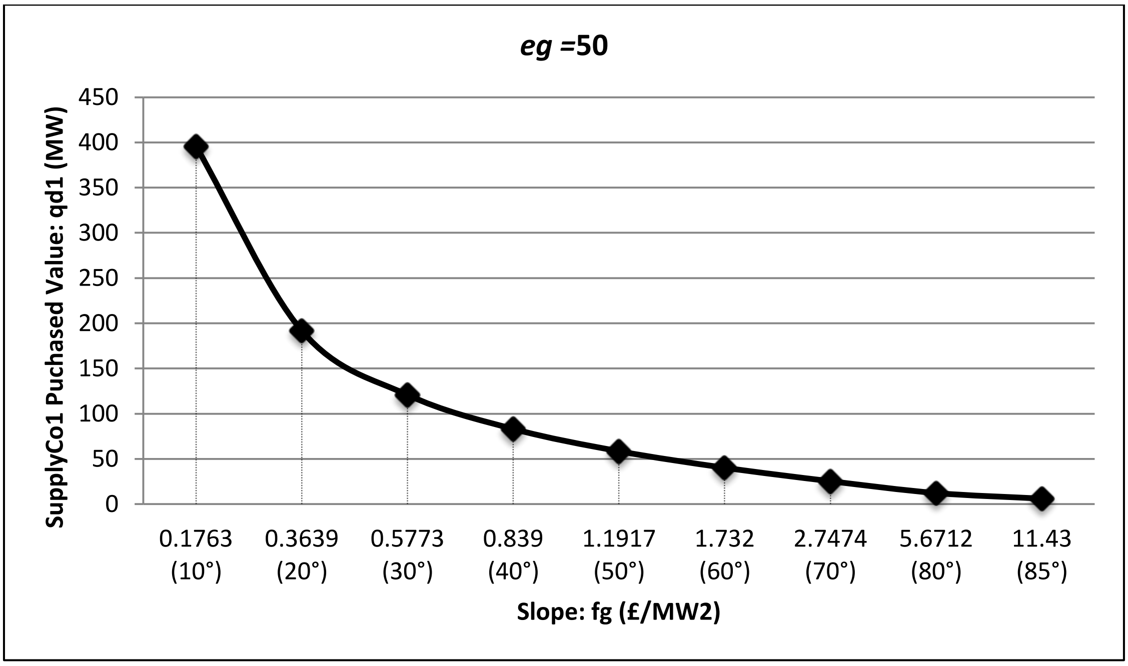


Figure 5.6: Impact of Inverse Generation Curve Slope on SupplyCo1 Purchased Value (e_g *=50)*

According to the Table 5.2 (c), the purchased value by each supply company has been reduced since the inverse generation curve becomes inelastic.

Also for $e_g = 80\ (£/MW)$, the purchasing price has increased up to $226.2791 (£/MW)$ comparing to previous intercept values.

Table 5.2 (d) Impacts of Inverse Generation Curve Intercept and Slopes on SupplyCos in Oligopsonistic Market (e_g *=80)*

Intercept: e_g $(£/MW)$	Slope: f_g $(£/MW^2)$	SupplyCo 1 Purchased value: q_{1d} (MW)	SupplyCo 1 Purchased value: q_{2d} (MW)	SupplyCo 1 Purchased value: q_{3d} (MW)	Total Purchased Value: $Q_d (MW)$	Price: p_g $(£/MW)$
80	**0.1763 (10°)**	336.3717	269.0973	224.2478	829.7168	226.2791
80	**0.3639 (20°)**	162.9632	130.3706	108.6422	401.976	226.2791
80	**0.5773 (30°)**	102.7236	82.1789	68.4824	253.3848	226.2791
80	**0.839 (40°)**	70.6822	56.5457	47.1214	174.3493	226.2791
80	**1.1917 (50°)**	49.7628	39.8102	33.1752	122.7482	226.2791
80	**1.732 (60°)**	34.2392	27.3914	22.8261	84.4567	226.2791
80	**2.7474 (70°)**	21.5849	17.2679	14.3899	53.2427	226.2791
80	**5.6712 (80°)**	10.4568	8.3654	6.9712	25.7933	226.2791
80	**11.43 (85°)**	5.1883	4.1506	3.4589	12.7978	226.2791

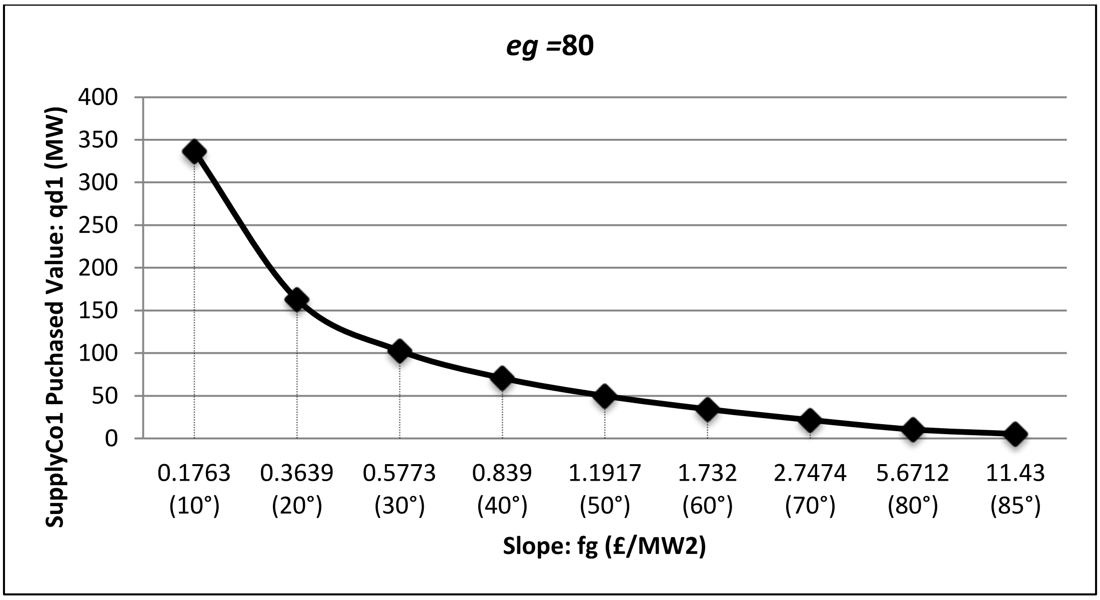


Figure 5.7: Impact of Inverse Generation Curve Slope on SupplyCo1 Purchased Value (e_g =80)

Like previous reviewed intercepts, Tables 5.2 (e) and (f) demonstrates the impact of slope and intercept variations on the purchasing value and price by each SupplyCo.

Since the intercept of inverse generation curve increases in both tables, SupplyCos prefer to buy more electricity from the bilateral trading and this can cause an increase in the price of electricity; however it is important to mention that by increasing the value of slope for each intercept, the purchasing value for each supply company decreases.

Table 5.2 (e) Impacts of Inverse Generation Curve Intercept and Slopes on SupplyCos in Oligopsonistic Market (e_g =100)

Intercept: e_g $(£/MW)$	Slope: f_g $(£/MW^2)$	SupplyCo 1 Purchased value: q_{1d} (MW)	SupplyCo 1 Purchased value: q_{2d} (MW)	SupplyCo 1 Purchased value: q_{3d} (MW)	Total Purchased Value: $Q_d(MW)$	Price: p_g $(£/MW)$
100	**0.1763 (10°)**	296.7985	237.4388	197.8657	732.103	229.0698
100	**0.3639 (20°)**	143.7911	115.0329	95.8607	354.6847	229.0698
100	**0.5773 (30°)**	90.6385	72.5108	60.4256	223.5749	229.0698
100	**0.839 (40°)**	62.3666	49.8933	41.5777	153.8376	229.0698
100	**1.1917 (50°)**	43.9084	35.1267	29.2722	108.3073	229.0698
100	**1.732 (60°)**	30.2111	24.1689	20.1407	74.5207	229.0698
100	**2.7474 (70°)**	19.0455	15.2364	12.697	46.9789	229.0698
100	**5.6712 (80°)**	9.2265	7.3812	6.151	22.7588	229.0698
100	**11.43 (85°)**	4.5779	3.6623	3.0519	11.2922	229.0698

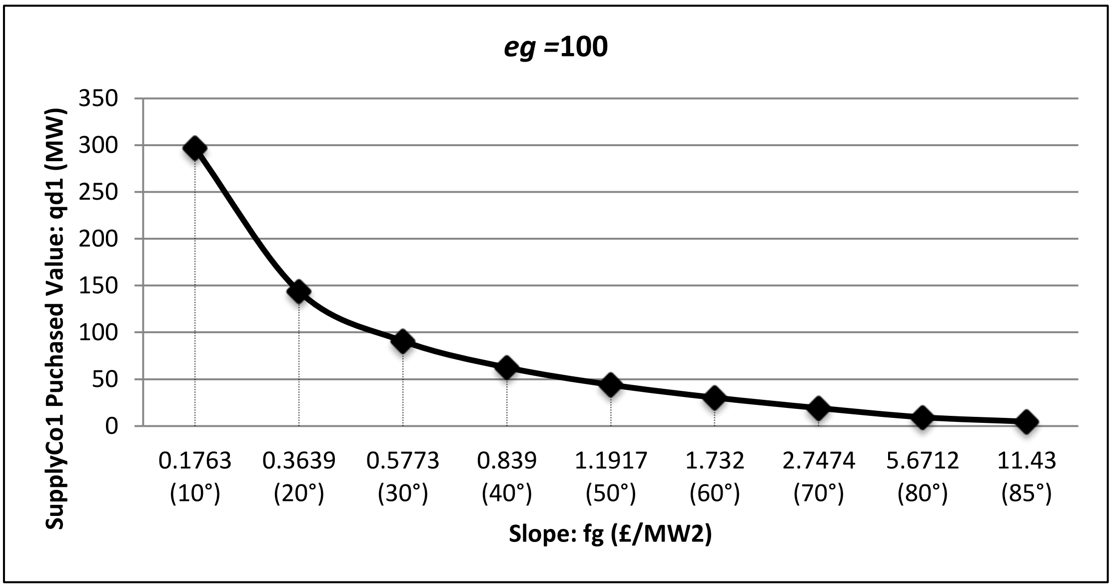


Figure 5.8: Impact of Inverse Generation Curve Slope on SupplyCo1 Purchased Value (e_g *=100)*

Based on these figures, it can be realized that when the intercepts' values increase, the variation intervals in purchased electricity by the SupplyCo will decrease.

Table 5.2 (f) Impacts of Inverse Generation Curve Intercept and Slopes on SupplyCos in Oligopsonistic Market (e_g *=120)*

Intercept: e_g $(£/MW)$	Slope: f_g $(£/MW^2)$	SupplyCo 1 Purchased value: q_{1d} (MW)	SupplyCo 1 Purchased value: q_{2d} (MW)	SupplyCo 1 Purchased value: q_{3d} (MW)	Total Purchased Value: $Q_d (MW)$	Price: p_g $(£/MW)$
120	**0.1763 (10°)**	257.2254	205.7803	171.4836	634.4893	231.8605
120	**0.3639 (20°)**	124.619	99.6952	83.0793	307.3934	231.8605
120	**0.5773 (30°)**	78.5533	62.8427	52.3689	193.7649	231.8605
120	**0.839 (40°)**	54.0511	43.2408	36.034	133.3259	231.8605
120	**1.1917 (50°)**	38.0539	30.4431	25.3693	93.8663	231.8605
120	**1.732 (60°)**	26.1829	20.9463	17.4553	64.5846	231.8605
120	**2.7474 (70°)**	16.5061	13.2049	11.0041	40.715	231.8605
120	**5.6712 (80°)**	7.9963	6.3971	5.3309	19.7243	231.8605
120	**11.43 (85°)**	3.9675	3.174	2.645	9.7866	231.8605

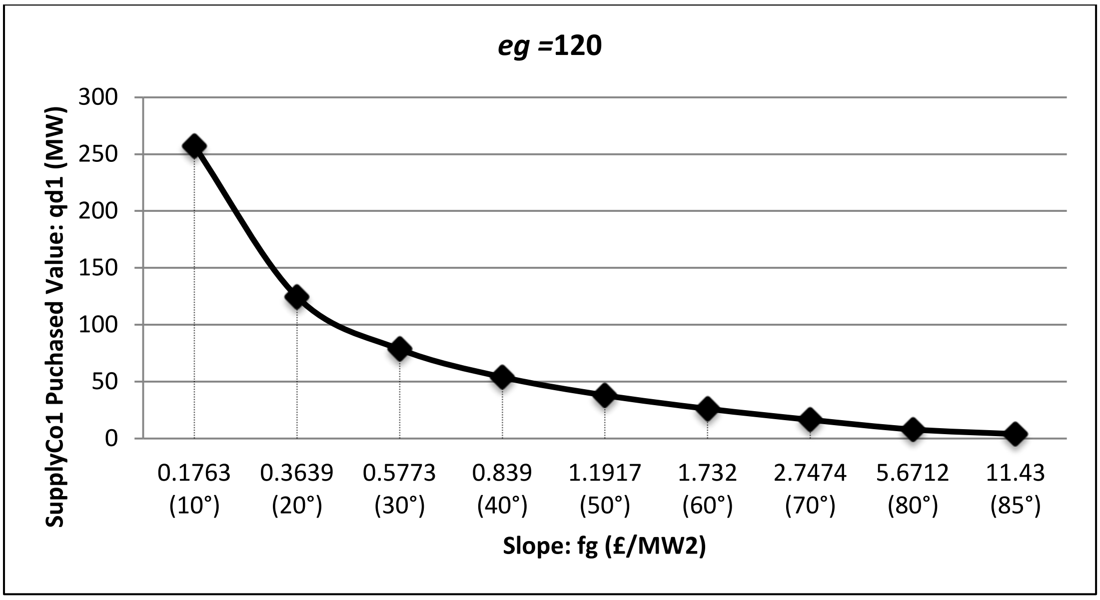


Figure 5.9: Impact of Inverse Generation Curve Slope on SupplyCo1 Purchased Value (e_g =120)

Consequently, the impact of slope on the total electricity purchased by all SupplyCos, assuming $e_g = 5$ $(£/MW)$, has been presented in Figure 5.10.

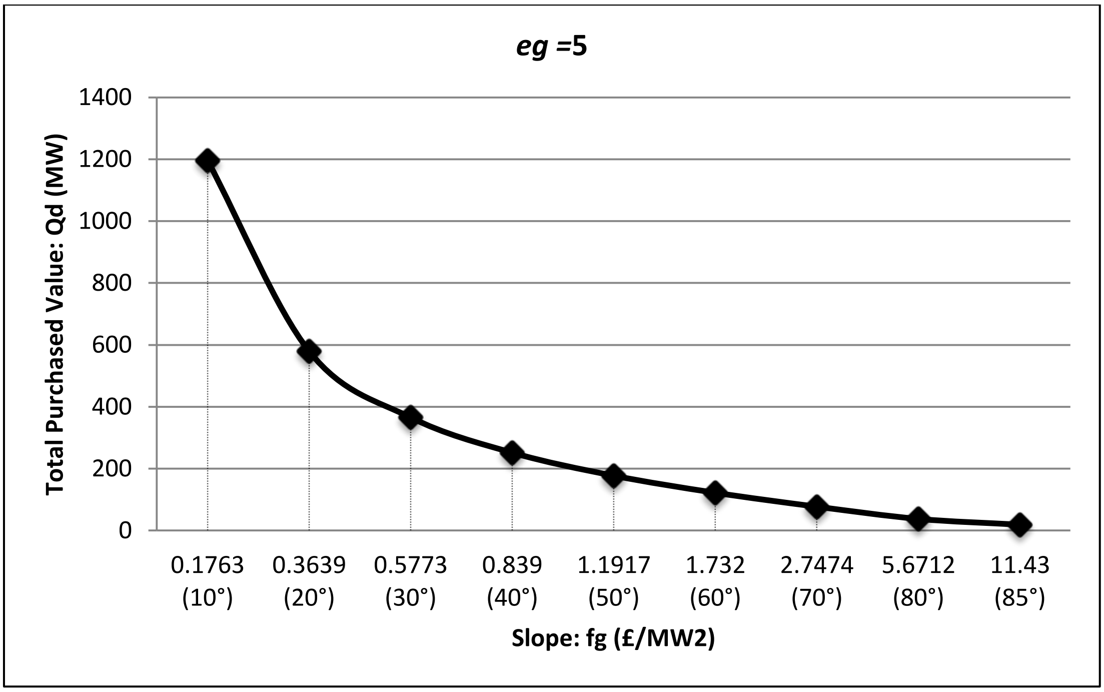


Figure 5.10: Impact of Inverse Generation Curve Slope on Total Purchased Electricity Value (e_g =5)

Additionally, according to Table 5.2 the intercept, e_g, influences both the buying price and the purchased value by each SupplyCo. The impact of intercept on SupplyCo 1 has been presented in Figure 5.11 for slope $f_g = 0.5773\,(£/MW^2)$ (30°). Based on this figure and Equation 5.15 and unlike GenCos, while the intercept increases the purchased value by each SupplyCo is expected to decrease.

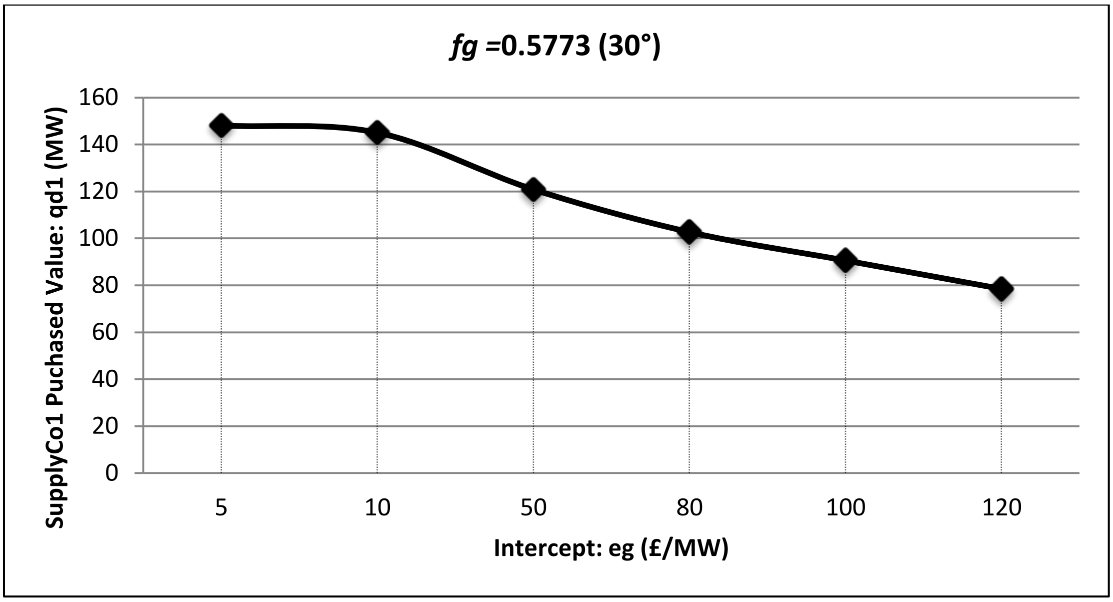


Figure 5.11: Impact of Inverse Generation Curve Intercept on SupplyCo1 (Slope=30°)

Furthermore, based on Equation 5.4, the impact of intercept on the buying price has been investigated in Figure 5.12.

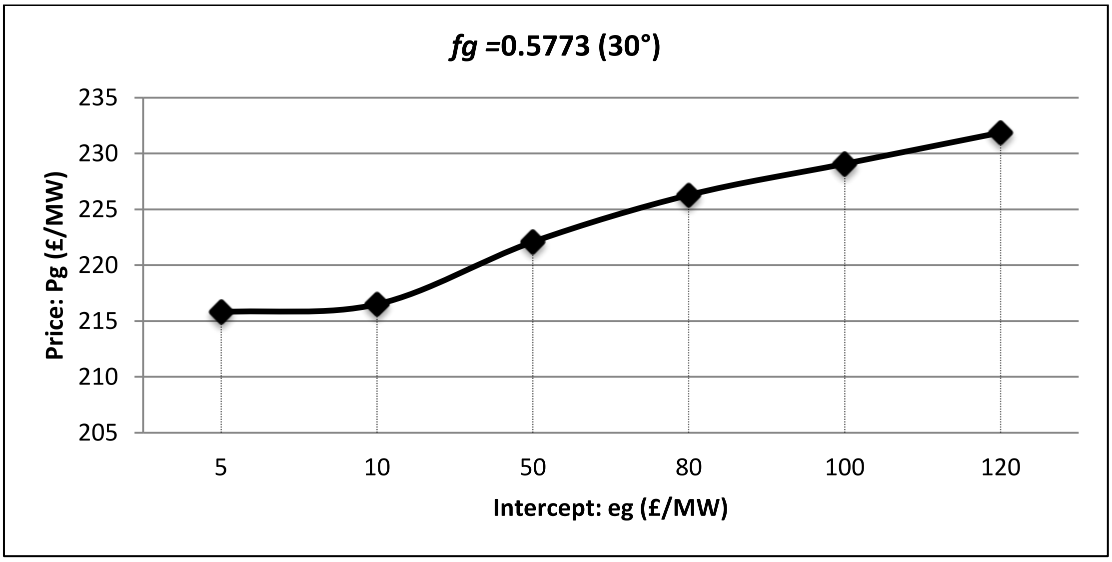


Figure 5.12: Impact of Inverse Generation Curve Intercept on Buying Price (Slope=30°)

5.4.2 Impact of Retail Price on Oligopsonistic Electricity Market

Up to now, it has been assumed that the retail prices for all SupplyCos are equal in this chapter. However, in order to demonstrate the impact of retail price on the behaviors of SupplyCos in the oligopsonistic electricity market, further investigation has been performed by changing the retail price for a specific set of slope and intercept and monitoring and comparing the behaviors of each SupplyCo.

Table 5.3: Retail Price Impacts on Oligopolistic electricity Market

Intercept e_g (£/ MW)	Slope: f_g (£/ MW^2)	Retail Price: λ (£/MW)	SupplyCo 1 Purchased value: q_{1d} (MW)	SupplyCo 1 Purchased value: q_{2d} (MW)	SupplyCo 1 Purchased value: q_{3d} (MW)	Total Purchased Value: Q_d(MW)	Price: p_g (£/ MW)
50	0.5773 (30°)	**400**	211.4897	169.1918	140.9932	521.6747	351.1628
		350	181.2769	145.0215	120.8513	447.1497	308.1395
		300	151.0641	120.8513	100.7094	372.6248	265.1163
		250	**120.8513**	**96.681**	**80.5675**	**298.0998**	**222.093**
		200	90.6385	72.5108	60.4256	223.5749	179.0698
		150	60.4256	48.3405	40.2838	149.0499	136.0465

Based on Table 5.3, when the retail price increases the SupplyCos will have more incentive to buy electricity from generation side in order to make more profit; therefore, the purchased value by SupplyCos will increase; however, they will pay more for purchasing electricity for GenCos. Figure 5.13 illustrates the impact of retail price on SupplyCo 1 whereas Figure 5.14 represents how purchasing price in the oligopsonistic electricity market can be affected by the retail price variations.

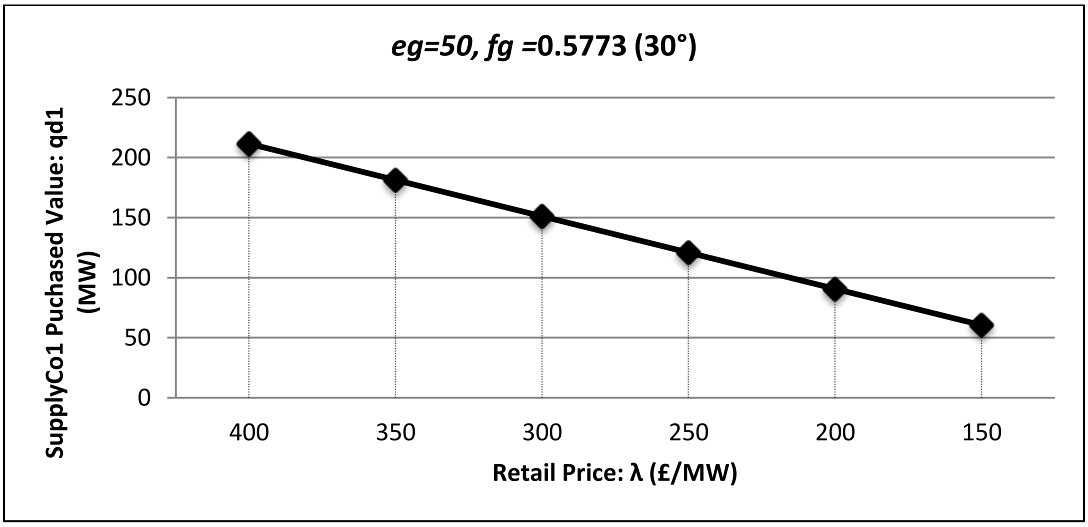


Figure 5.13: Impact of Retail Price on SupplyCo1 (Intercept=50, Slope=30°)

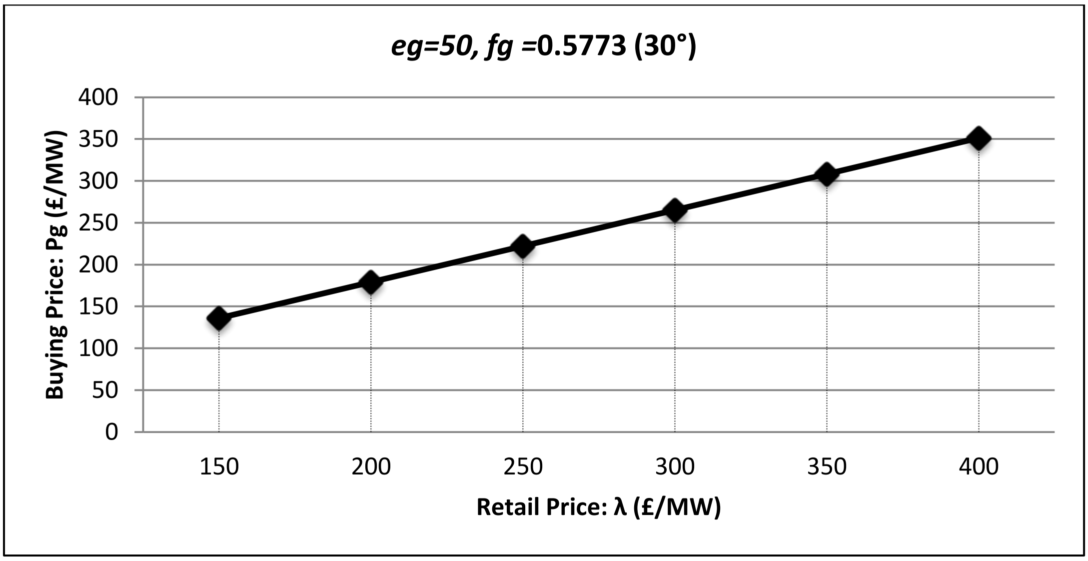


Figure 5.14: Impact of Retail Price on Buying Price (Intercept=50, Slope=30°)

It is noticeable that calculating the retail price is not within the scope of this research, since only the wholesale electricity market has been taken into consideration. However, this section illustrates the impact of retail price on the behaviors of both generation and supply companies in wholesale market.

5.5 Impact of CV_{ig} and CV_{id} on Oligopolistic and Oligopsonistic Electricity Markets

As described previously, the CV_{ig}, CV_{id} in the CVE method have significant impacts on the behaviors of each GenCo and SupplyCo in the oligopolistic and oligopsonistic electricity market models, respectively. In order to examine these impacts, the CV_{ig} for each GenCo in the prior case study in Chapter 4 and CV_{id} in the current chapter case study have been changed for a specific set of intercept and slope and the behaviors of each GenCo and SupplyCo have been monitored and investigated.

5.5.1 CV_{ig} and Oligopolistic Electricity Market

Tables 5.4, 5.5 and 5.6 represent the impacts of CV_{1g}, CV_{2g} and CV_{3g} variations on the oligopolistic electricity market, respectively.

Table 5.4: Impacts of CV_{1g} on GenCos' Strategies

Intercept: e_d (£/MW)	**Slope:** f_d (£/MW^2)	CV_{1g}	CV_{2g}	CV_{3g}	**GenCo1 Output:** q_{1g} (MW)	**GenCo2 Output:** q_{2g} (MW)	**GenCo3 Output:** q_{3g} (MW)	**Total Output:** Q_g(MW)	**Price:** p_d (£/MW)
1000	**2.7474 (70°)**	**-0.02**	-0.5	-0.5	64.7762	119.6817	112.4021	296.86	184.4068
		-0.05	-0.5	-0.5	66.466	119.0058	111.7262	297.198	183.4783
		-0.08	-0.5	-0.5	68.2463	118.2937	111.014	297.5541	182.5
		-0.1	-0.5	-0.5	69.4872	117.7973	110.5177	297.8022	181.8182
		-0.3	-0.5	-0.5	84.9288	111.6207	104.3411	300.8905	173.3333
		-0.5	-0.5	-0.5	109.1941	101.9145	94.6349	305.7436	160
		-0.8	-0.5	-0.5	191.0898	69.1563	61.8767	322.1227	115

Table 5.5: Impacts of CV_{2g} on GenCos' Strategies

Intercept: e_d (£/MW)	**Slope:** f_d (£/MW^2)	CV_{1g}	CV_{2g}	CV_{3g}	**GenCo1 Output:** q_{1g} (MW)	**GenCo2 Output:** q_{2g} (MW)	**GenCo3 Output:** q_{3g} (MW)	**Total Output:** Q_g(MW)	**Price:** p_d (£/MW)
1000	**2.7474 (70°)**	-0.5	**-0.02**	-0.5	125.7769	60.4578	111.2176	297.4523	182.7797
		-0.5	**-0.05**	-0.5	125.146	62.0349	110.5868	297.7677	181.913
		-0.5	**-0.08**	-0.5	124.4813	63.6966	109.9221	298.1	181
		-0.5	**-0.1**	-0.5	124.0181	64.8547	109.4589	298.3316	180.3636
		-0.5	**-0.3**	-0.5	118.2532	79.2669	103.694	301.2141	172.4444
		-0.5	**-0.5**	-0.5	109.1941	101.9145	94.6349	305.7436	160
		-0.5	**-0.8**	-0.5	78.6198	178.3504	64.0606	321.0308	118

Table 5.6: Impacts of CV_{3g} on GenCos' Strategies

Intercept: e_d (£/MW)	**Slope:** f_d (£/MW^2)	CV_{1g}	CV_{2g}	CV_{3g}	**GenCo1 Output:** q_{1g} (MW)	**GenCo2 Output:** q_{2g} (MW)	**GenCo3 Output:** q_{3g} (MW)	**Total Output:** Q_g(MW)	**Price:** p_d (£/MW)
1000	**2.7474 (70°)**	-0.5	-0.5	**-0.02**	124.5924	117.3128	56.1394	298.0445	181.1525
		-0.5	-0.5	**-0.05**	124.0066	116.727	57.6039	298.3374	180.3478
		-0.5	-0.5	**-0.08**	123.3894	116.1098	59.1468	298.646	179.5
		-0.5	-0.5	**-0.1**	122.9592	115.6796	60.2222	298.8611	178.9091
		-0.5	-0.5	**-0.3**	117.6061	110.3265	73.6049	301.5376	171.5556
		-0.5	-0.5	**-0.5**	109.1941	101.9145	94.6349	305.7436	160
		-0.5	-0.5	**-0.8**	80.8037	73.5241	165.6111	319.9389	121

Based on Section 5.3.1 and Equation 5.20, in this research it is expected that when the CV_{ig} has lower values, the generation companies' behaviors will shift toward perfect competition; therefore, the output of each GenCo will increase and they do not have any willingness to practice market power, consequently they provide as much electricity required to fulfill the market demand. On the other hand, since the CV_{ig}s have negative values; it will be a non-cooperative game and whenever one GenCo increases its output the other generation companies will react and decrease their output and whenever a GenCo decreases its output the others will participate more in the market to fill the gap and also make more profit. Figures 5.15, 5.16 and 5.17 investigate the reactions of GenCos 1, 2 and 3 respectively, when the CV_{1g} changes for $e_d = 1000\ (£/MW)$ and $f_g = 2.7474\ (£/MW^2)$ (70°). Further investigations on GenCo2 and 3 have been attached in Appendix E.

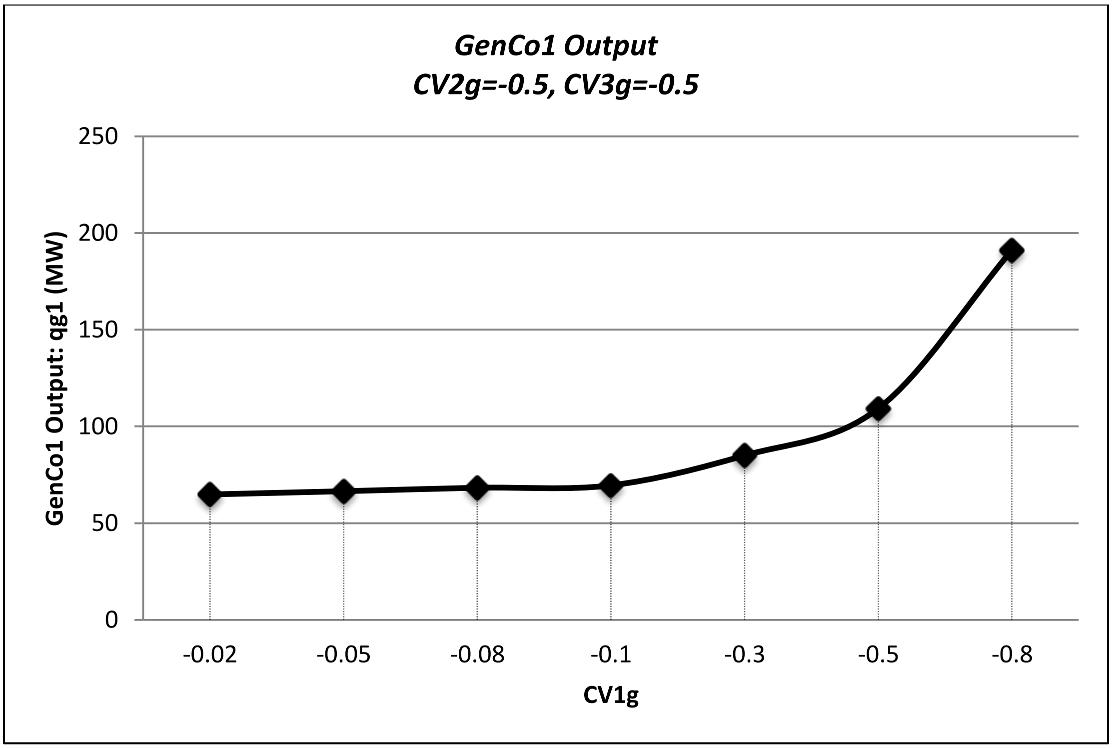


Figure 5.15: Impact of CV_{1g} on GenCo1 Output

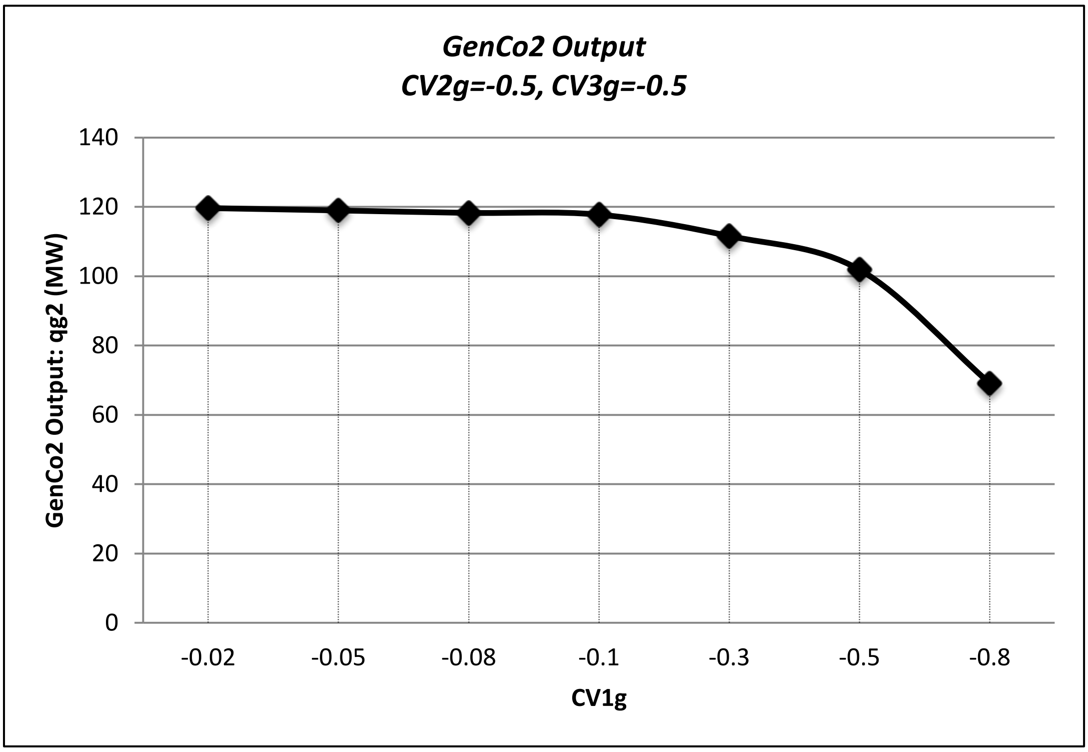


Figure 5.16: Impact of CV_{1g} on GenCo2 Output

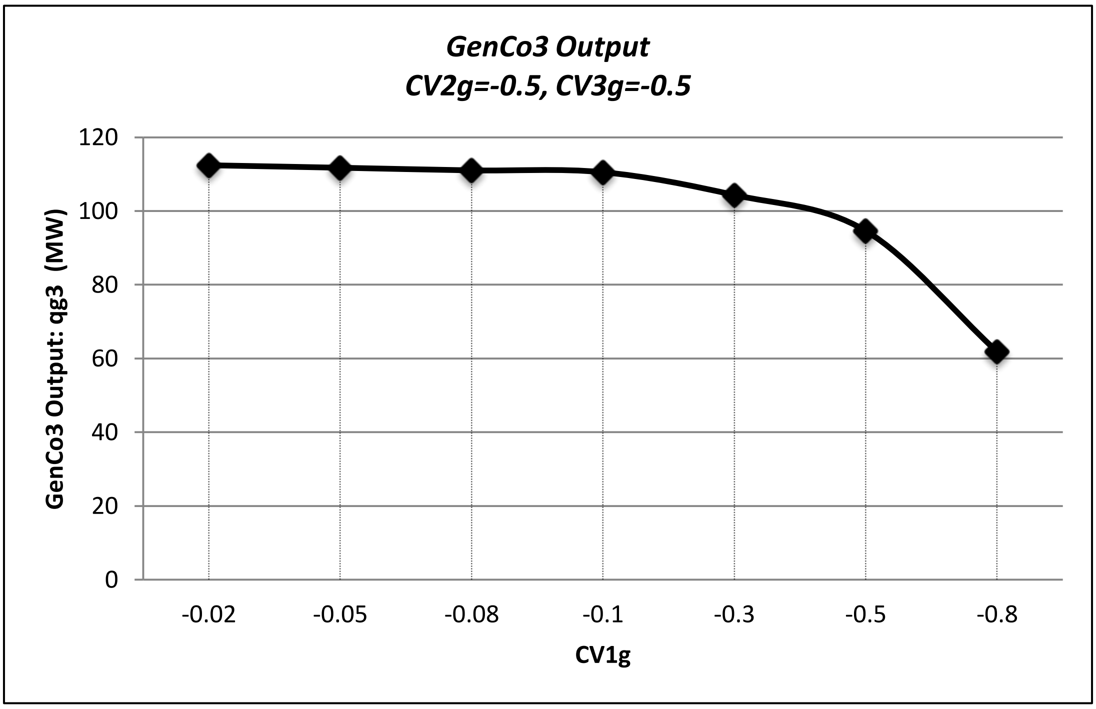


Figure 5.17: Impact of CV_{1g} on GenCo3 Output

Furthermore, it has been investigated that whenever the CV_{1g} approaches lower values, the market trend will be shifted towards perfect competition; therefore the total generated output will increase which leads to a reduction in selling price.

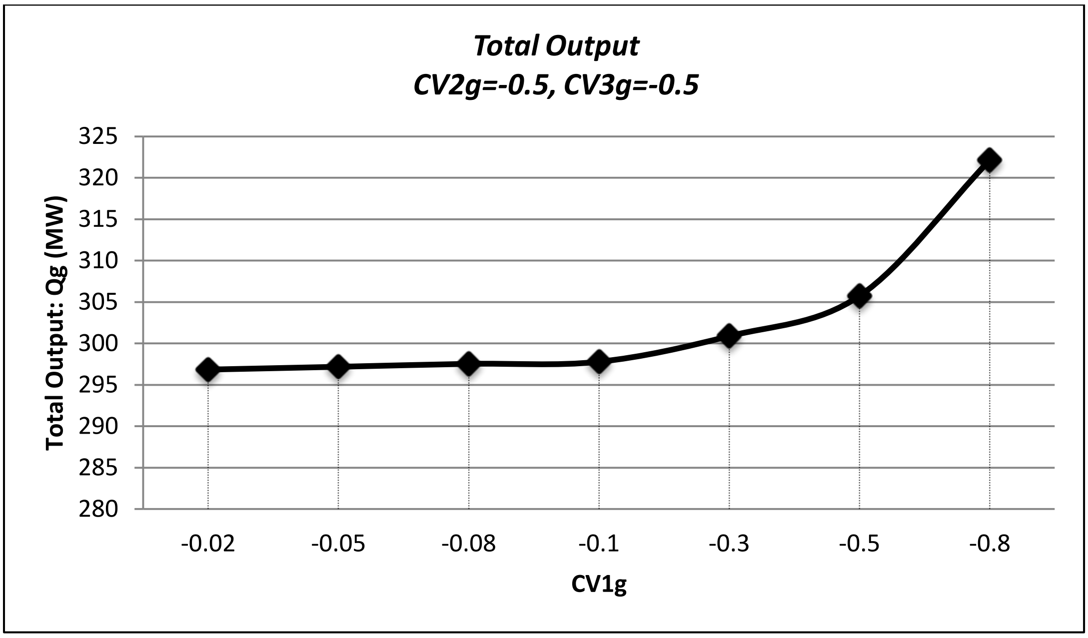


Figure 5.18: Impact of CV_{1g} on Total Output

Figure 5.19: Impact of CV_{1g} on Selling Price

5.5.2 CV_{id} and Oligopsonistic Electricity Market

Similar to the oligopolistic electricity market, Tables 5.7, 5.8 and 5.9 illustrate the impacts of CV_{1d}, CV_{2d} and CV_{3d} variations on the oligopsonistic electricity market, respectively.

As mentioned previously, in the oligopsonistic electricity market case study, different CV_{1d}s have been assigned to each SupplyCo. In this section, the impacts of CV_{id} on the behavior of supply companies in the oligopsonistic electricity market have been examined. According to Section 5.3.2 and Equation 5.25, it is expected that once the CV_{id} has lower values, the supply companies' behaviors will be shifted towards more perfect competition; therefore, the purchased value by each SupplyCo will increase and imperfect bilateral trading will be ignored, consequently they buy as much electricity as required to fulfill their demand side (end-users). Since a non-cooperative game environment has been considered in this research, the CV_{id}s have negative values; which means whenever one SupplyCo decides to purchase more electricity the other supply companies will react and decrease their purchased value and whenever a SupplyCo changes its strategy and purchases less electricity the others will participate more in the market to compensate this behavior and fill in the gap; hence, they also make more profit and manage the participation risks. Figures 5.20, 5.21 and 5.22 investigate the reactions of SupplyCos 1, 2 and 3 respectively, when the CV_{1d} changes for $e_g = 50\ (£/MW)$ and $f_g = 0.5773\ (£/MW^2)$ (30°). Further investigations on SupplyCo2 and 3 have been attached in Appendix E.

Table 5.7: Impacts of CV_{1d} on SupplyCos' Strategies

Intercept: e_g (£/MW)	Slope: f_g (£/MW^2)	CV_{1d}	CV_{2d}	CV_{3d}	SupplyCo 1 Purchased value: q_{1d} (MW)	SupplyCo 1 Purchased value: q_{2d} (MW)	SupplyCo 1 Purchased value: q_{3d} (MW)	Total Purchased Value: Q_d(MW)	Price: p_g (£/MW)
50	0.5773 (30°)	**-0.02**	-0.5	-0.4	62.1603	121.8343	101.5286	285.5232	214.8325
		-0.05	-0.5	-0.4	63.762	121.1478	100.9565	285.8664	215.0307
		-0.08	-0.5	-0.4	65.4484	120.4251	100.3543	286.2278	215.2393
		-0.1	-0.5	-0.4	66.6231	119.9217	99.9347	286.4795	215.3846
		-0.3	-0.5	-0.4	81.197	113.6757	94.7298	289.6025	217.1875
		-0.5	-0.5	-0.4	103.9321	103.9321	86.6101	294.4743	220
		-0.6	-0.5	-0.4	120.8513	96.681	80.5675	298.0998	222.093
		-0.8	-0.5	-0.4	179.1933	71.6773	59.7311	310.6017	229.3103

Table 5.8: Impacts of CV_{2d} on SupplyCos' Strategies

Intercept: e_g (£/MW)	Slope: f_g (£/MW^2)	CV_{1d}	CV_{2d}	CV_{3d}	SupplyCo 1 Purchased value: q_{1d} (MW)	SupplyCo 1 Purchased value: q_{2d} (MW)	SupplyCo 1 Purchased value: q_{3d} (MW)	Total Purchased Value: Q_d(MW)	Price: p_g (£/MW)
50	0.5773 (30°)	-0.6	**-0.02**	-0.4	139.9855	57.1369	114.3215	290.4461	217.6745
		-0.6	**-0.05**	-0.4	139.2602	58.6359	92.8401	290.7362	217.842
		-0.6	**-0.08**	-0.4	138.4958	60.2156	92.3306	291.042	218.0185
		-0.6	**-0.1**	-0.4	137.963	61.3169	91.9753	291.2551	218.1416
		-0.6	**-0.3**	-0.4	131.3221	75.0412	87.5481	293.9115	219.6751
		-0.6	**-0.5**	-0.4	120.8513	96.681	80.5675	298.0998	222.093
		-0.6	**-0.6**	-0.4	112.9697	112.9697	75.3131	301.2525	223.913
		-0.6	**-0.8**	-0.4	85.1902	170.3805	56.7935	312.3642	230.3279

Table 5.9: Impacts of CV_{3d} on SupplyCos' Strategies

Intercept: e_g $(£/MW)$	**Slope:** f_g $(£/MW^2)$	CV_{1d}	CV_{2d}	CV_{3d}	**SupplyCo 1 Purchased value:** q_{1d} (MW)	**SupplyCo 1 Purchased value:** q_{2d} (MW)	**SupplyCo 1 Purchased value:** q_{3d} (MW)	**Total Purchased Value:** $Q_d (MW)$	**Price:** p_g $(£/MW)$
50	**0.5773 (30°)**	-0.6	-0.5	**-0.02**	132.8292	106.2634	54.216	293.3086	219.3271
50	**0.5773 (30°)**	-0.6	-0.5	**-0.05**	132.176	105.7408	55.6531	293.5699	219.4779
50	**0.5773 (30°)**	-0.6	-0.5	**-0.08**	131.4873	105.1898	57.1684	293.8454	219.637
50	**0.5773 (30°)**	-0.6	-0.5	**-0.1**	131.0068	104.8055	58.2253	294.0376	219.7479
50	**0.5773 (30°)**	-0.6	-0.5	**-0.3**	125.0042	100.0034	71.431	296.4386	221.134
50	**0.5773 (30°)**	-0.6	-0.5	**-0.5**	115.4801	92.3841	92.3841	300.2483	223.3333
50	**0.5773 (30°)**	-0.6	-0.5	**-0.6**	108.2626	86.6101	108.2626	303.1353	225
50	**0.5773 (30°)**	-0.6	-0.5	**-0.8**	82.4858	65.9886	164.9716	313.446	230.9524

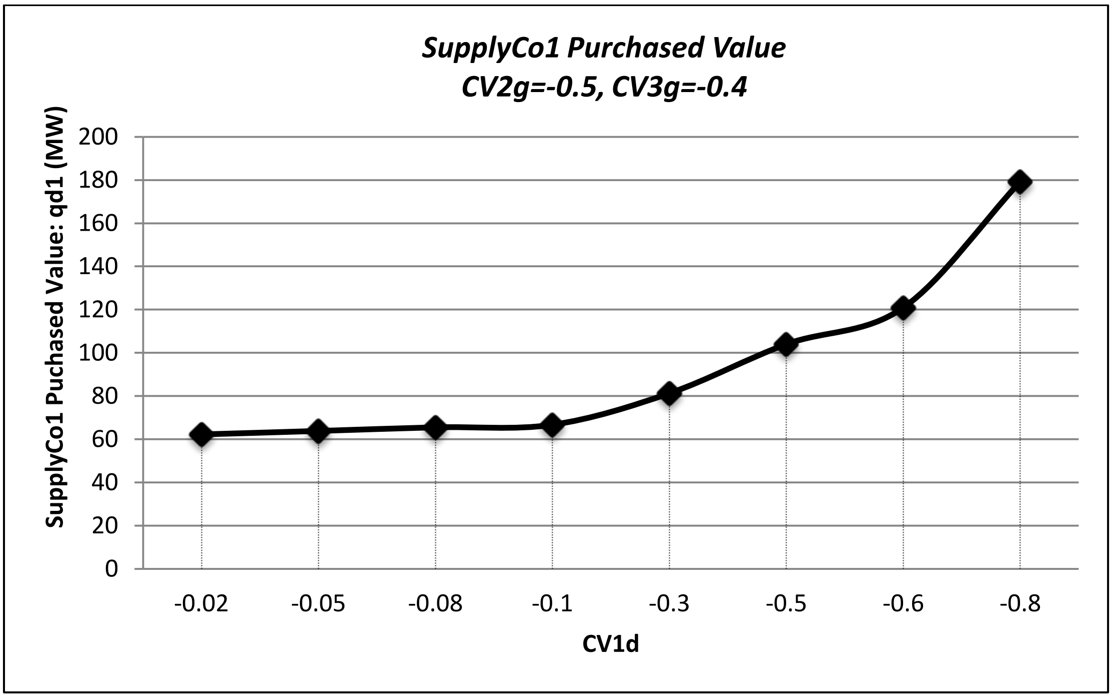


Figure 5.20: Impact of CV_{1d} on SupplyCo1

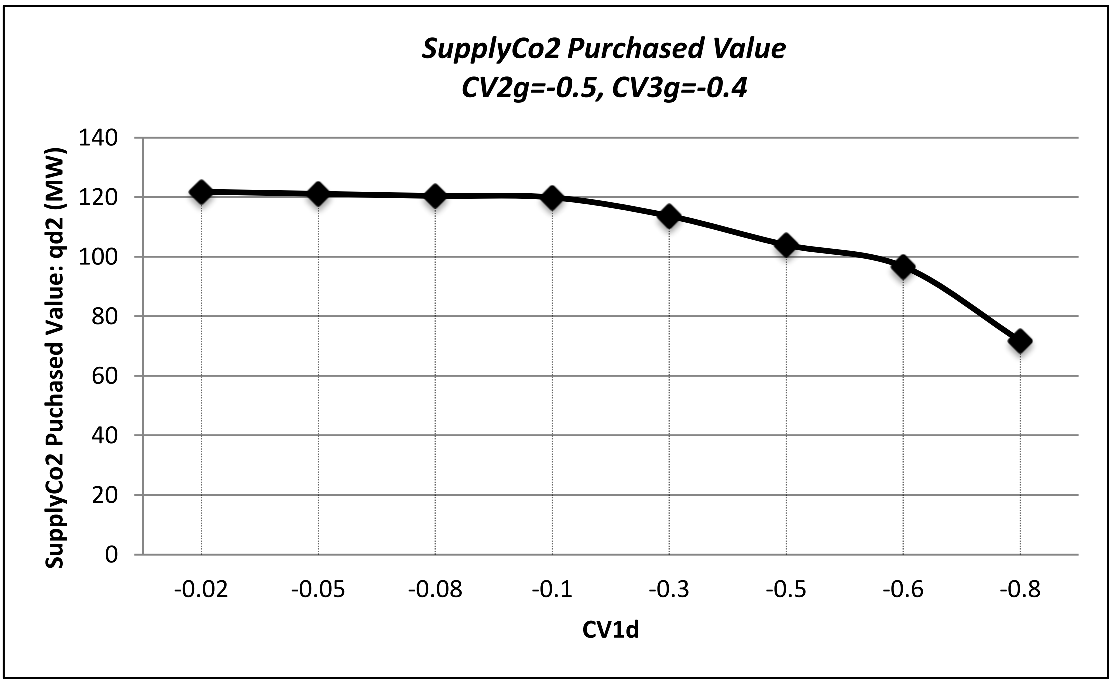


Figure 5.21: Impact of CV_{1d} on SupplyCo2

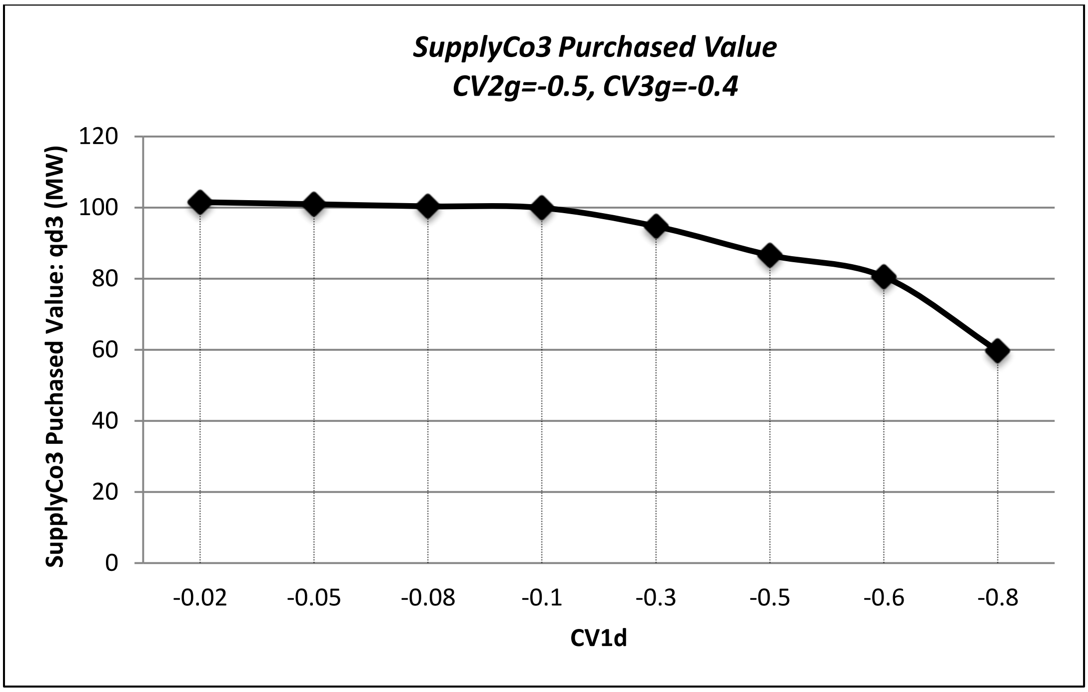


Figure 5.22: Impact of CV_{1d} on SupplyCo3

Additionally, it has been examined; whenever the CV_{1d} approaches lower values, the market trend will be shifted towards perfect competition; hence the total purchased value will increase and based on Equation 5.4 the selling price will rise.

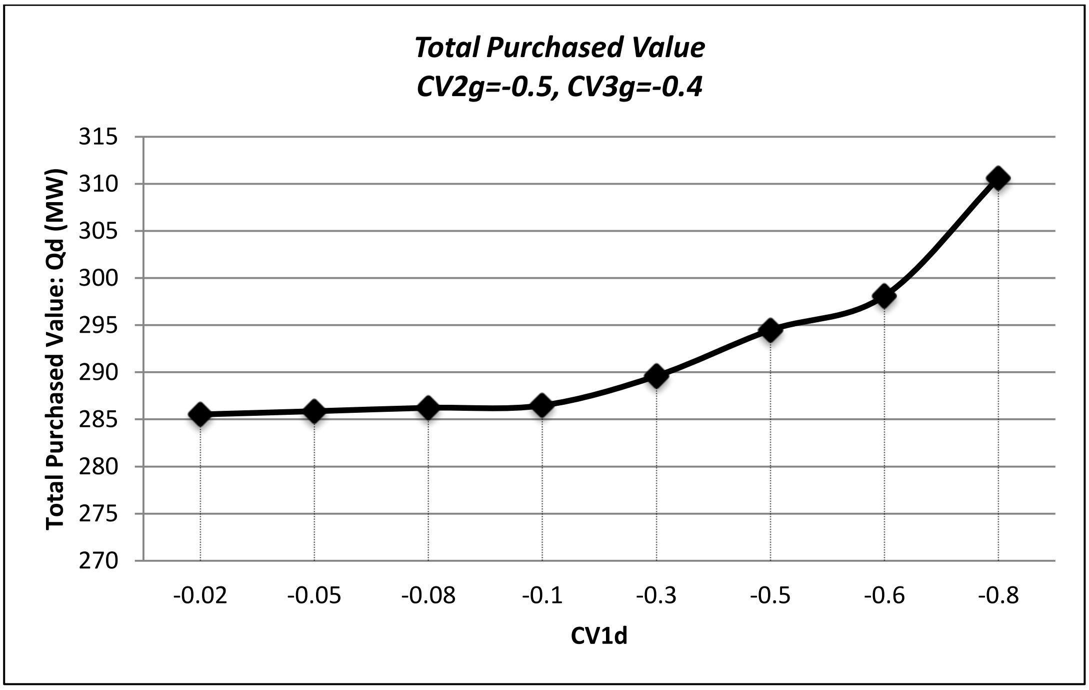


Figure 5.23: Impact of CV_{1d} on Total Purchased Value

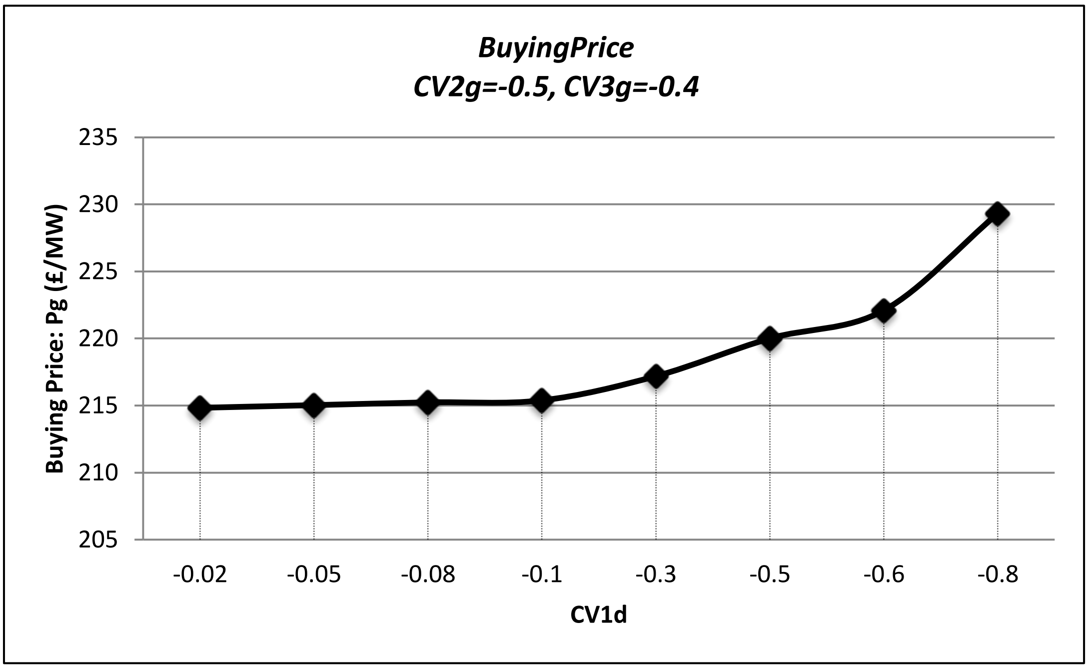


Figure 5.24: Impact of CV_{1d} on Buying Price

5.6 Oligopsony in UK Electricity Market

Ofgem as the UK electricity market regulator has a concern about market power and imperfect competition in BETTA on the supply side. According to the Ofgem annual report 2010-11 [95], the largest and dominant SupplyCos in the UK, called the *Big Six* (Scottish Power, npower, EDF Energy, Scottish and Southern Energy, E.ON and Centrica's British Gas) dominate retail supply. In such an environment the supply side of the market will be suffering from oligopsony conditions.

In an oligopsonistic market the number of SupplyCos is not high enough and these few dominant SupplyCos can cause an imperfect bilateral electricity market and limit other companies' access to the wholesale market; consequently, modeling the oligopolistic electricity market is vital.

5.7 Summary

Comparing to Chapter 4, in this chapter the other side of bilateral electricity market has been highlighted. The behaviors' of supply companies in imperfect bilateral electricity market, oligopsonistic environment, have been examined and formulated using CVE method. Therefore, several factors, which have impacts on the purchased value by SupplyCos, have been identified.

In the next step, by introducing an oligopsonistic case study, the impacts of inverse generation curve parameters on SupplyCos' behaviors have been represented. Furthermore, CVs specifications alongside their impacts on market participants on both sides of bilateral market investigated. Finally, this chapter demonstrated that the retail price could have strong influence on the supply companies' strategies as well.

Chapter 6: Hierarchical Co-ordination Algorithm

6.1 Introduction

As discussed in Chapter 4, the behavior of oligopolistic electricity markets using Conjectural Variation Equilibrium method has been investigated in detail. Furthermore, Chapter 5 looked at the other side of the market by exploring the impacts of applying CVE method on supply companies' behaviors.

According to evidences from results on Chapter 4 and 5, it can be stated that the slopes and intercepts of both inverse demand and generation curves have significant influences on the behaviors of market participants in the imperfect bilateral electricity market. Likewise, CV_{ig} and CV_{id} play significant roles in determining market power in both markets.

Since a bilateral electricity market, is a double-sided market; the behaviors of both sides of the market should be analyzed simultaneously. The aim of this chapter is to provide a novel algorithm in order to find the equilibrium point of the whole bilateral market, whilst market participants in both sides of the market are making profit.

6.2 Market Equilibrium

In an oligopolistic electricity market, GenCos are dominating the market by their behaviors and decisions; on the contrary, SupplyCos play significant roles in the oligopsonistic electricity market. In order to find the stable state of the bilateral market, it is essential to investigate the equilibrium point of the market, in which the aim of all market participants, which is profit maximization, can be satisfied.

Whenever, the GenCos and SupplyCos do not have any influence on volume and price of traded electricity by their decisions, the electricity market will have a perfectly competitive environment. In realistic competitive electricity market, the equilibrium point of the market can be defined, when the quantity that GenCos provide into the market is equal to the volume of electricity SupplyCos are willing to purchase. Therefore, the market will be in an equilibrium state, where the resulted quantity and price will define a market equilibrium point.

Figure 6.1 illustrates the market equilibrium point.

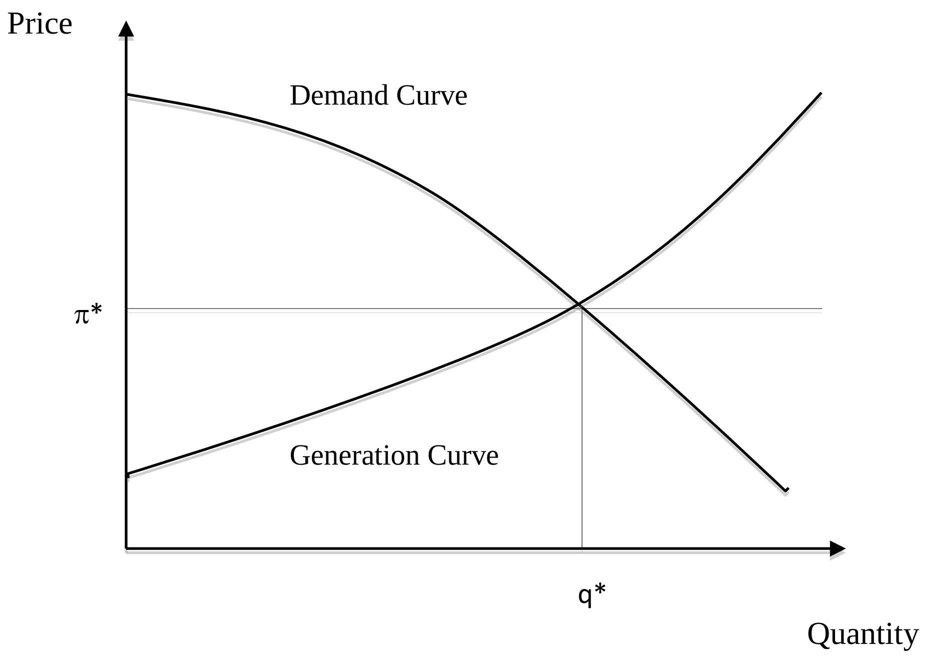


Figure 6.1: Market Equilibrium

According to the above figure, the equilibrium point of the electricity market is based on inverse demand and generation curves, which their impacts on the market participants' strategies in both oligopolistic and oligopsonistic electricity markets were discussed in Chapters 4 and 5.

According to Figure 6.1, the market equilibrium point is a crossover point of those curves in which both GenCos and SupplyCos are making profit; however, according to Figure 6.2, whenever the price is higher than the equilibrium price, participating in the market has no economical justification for SupplyCos as electricity buyers; therefore they will not participate in the electricity trading. In this case, the generation companies will reduce their generation, in order to sell electricity equal to the amount that SupplyCos are willing to purchase [1].

On the other hand, if the market price is less than equilibrium price, the number of GenCos who are participating in the market will be reduced, since they will not make profit by involving in electricity trading, which causes shortage in generated electricity and some amount of demand will not be met and imperfect competition will be introduced in the market. Hence, finding market equilibrium point is essential for all the firms. According to Section 5.5, the CVE method can assist electricity market to be settled at the equilibrium point.

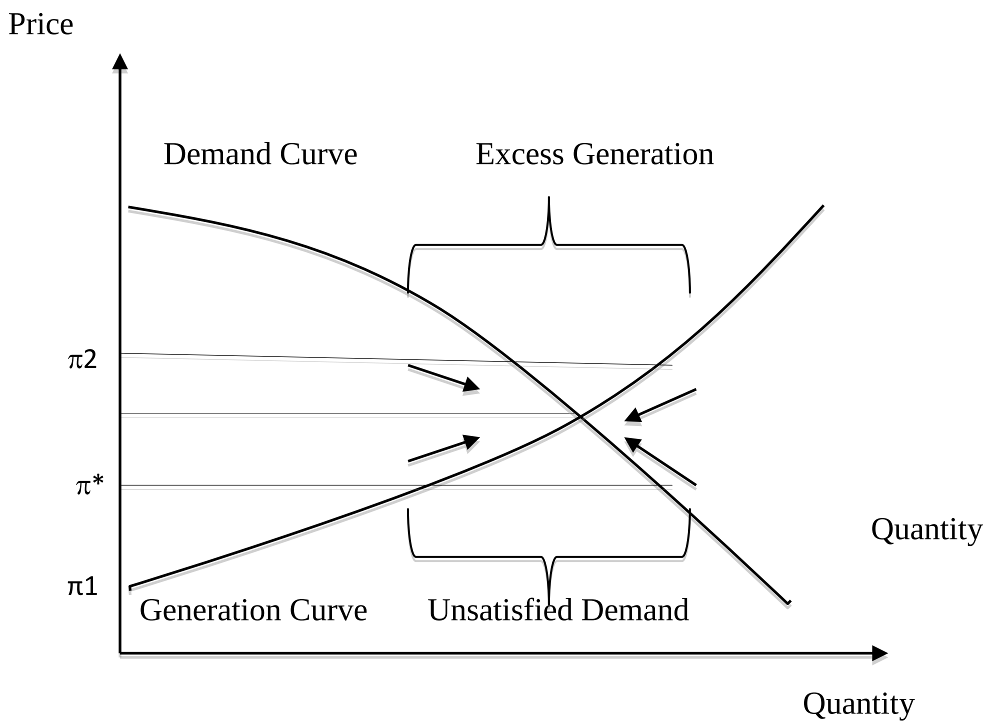


Figure 6.2: Stability of the Market Equilibrium [1]

6.3 Co-ordination between Oligopolistic and Oligopsonistic Electricity Markets

In order to find the equilibrium point of a bilateral electricity market, considering both sides of the market is essential. With reference to Chapter 4, the behavior of GenCos in an imperfect bilateral electricity market can be modeled using the CVE method. Furthermore, the behaviors of SupplyCos in an oligopsonistic electricity market have been investigated.

An additional novelty of this research is that an algorithm has been introduced in order to calculate the equilibrium point of the bilateral electricity market, in which all market participants are making profit and have willingness to participate in electricity trading.

Modeling oligopolistic and oligopsonistic bilateral markets simultaneously provides an opportunity to introduce an algorithm which works as a *broker* that tries to match the generation and demand [90]. Based on Chapter 4 and [86], in the CVE method the equilibrium point is a Nash equilibrium, since each firm participates in the market rationally. Therefore in long-term trading, such as bilateral electricity markets, the market participants on both sides of the market will make decisions according to Equations 4.28 and 5.15, which are the outcome of CVE modeling and define firms' behaviors in the electricity market. In this case, the results from Equations 4.28 and 5.15 will be settled and the market will reach to the equilibrium points on both sides of the market. The role of co-ordinations algorithm is to provide a framework in which the final equilibrium point of the bilateral market represents the strategies of all market participants on both sides of the market.

6.3.1 Role of Oligopolistic Electricity Market in Co-ordination Algorithm

In order to define a framework, which provides a platform for both sides of the bilateral electricity market, it is essential to consider the role of GenCos in this coordinated framework.

In order to demonstrate the impact of GenCos behaviors and decisions on this framework, Equation 4.28 can be transformed into [86]:

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

$$2q_{ig}f_d + q_{ig}f_dCV_{ig} + c_iq_{ig} + f_dq_{-ig} = e_d - b_i \qquad (i = 1, \dots, n) \qquad (6.1)$$

Since Equation 6.1 is for a set of GenCos, it can be formed into a matrix format, which gives a better perspective to the hierarchical optimization algorithm that will be proposed in the next section:

$$\underbrace{\begin{bmatrix} f_d(2+CV_{1g})+C_1 & f_d & f_d & \cdots & f_d \\ f_d & f_d(2+CV_{2g})+C_2 & f_d & \cdots & f_d \\ f_d & f_d & f_d(2+CV_{3g})+C_3 & \cdots & f_d \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ f_d & f_d & f_d & \cdots & f_d(2+CV_{ng})+C_n \end{bmatrix}}_{[A_G]}$$

$$\times \underbrace{\begin{bmatrix} q_{1g} \\ q_{2g} \\ q_{3g} \\ \vdots \\ q_{ng} \end{bmatrix}}_{[B_G]} = \underbrace{\begin{bmatrix} e_d - b_1 \\ e_d - b_2 \\ e_d - b_3 \\ \vdots \\ e_d - b_n \end{bmatrix}}_{[C_G]} \qquad (6.2)$$

Equation 6.2 provides a better overview regarding the dependency of final GenCos' strategies, matrix $[B_G]$, to the slope and intercept of the inverse demand curve.

6.3.2 Role of Oligopsonistic Electricity Market in Co-ordination Algorithm

In order to investigate how an oligopsonistic electricity market can co-operate with the other side of market, the purchased value by SupplyCos can be transformed into a matrix format.

Based on 5.15, the impact of SupplyCos' behaviors and strategies on this coordinative framework can be transformed into:

$$q_{id} \times f_g(2+CV_{id}) = \lambda - e_g - f_g q_{-id} \quad \rightarrow$$

$$2q_{id}f_g + q_{id}f_gCV_{id} + f_d q_{-id} = \lambda - e_g \qquad (i = 1, \ldots, m) \qquad (6.3)$$

Similar to the generation side, Equation 6.3 is for a set of SupplyCos, and it can be transformed into a matrix format, which gives a better overview to the hierarchical optimization algorithm that will be proposed later:

$$\underbrace{\begin{bmatrix} f_g(2+CV_{1d}) & f_g & f_g & \cdots & f_g \\ f_g & f_g(2+CV_{2d}) & 1 & \cdots & f_g \\ f_g & f_g & f_g(2+CV_{3d}) & \cdots & f_g \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ f_g & f_g & f_g & \cdots & f_g(2+CV_{md}) \end{bmatrix}}_{[A_D]} \times$$

$$\underbrace{\begin{bmatrix} q_{1d} \\ q_{2d} \\ q_{3d} \\ \vdots \\ q_{md} \end{bmatrix}}_{[B_D]} = \underbrace{\begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \vdots \\ \lambda_m \end{bmatrix}}_{[C_D]} - e_g \tag{6.4}$$

According to Equations 6.2 and 6.4 output of each GenCo and purchased value by each SupplyCo can be calculated through this co-ordination algorithm which provides a *virtual Pool* structure [90] to the market and can be formed by introducing two matrices for these two sides of the market.

The above matrices are linked together, Figure 6.3, through an original hierarchical optimization algorithm proposed in the next section. The algorithm works as a virtual broker and tries to match the total quantity and price in both oligopoly and oligopsony matrices in such a way that GenCos and SupplyCos would maximize their profits. This will be applied by changing the slopes and intercepts, which are variables in both left and right hand sides of these matrices.

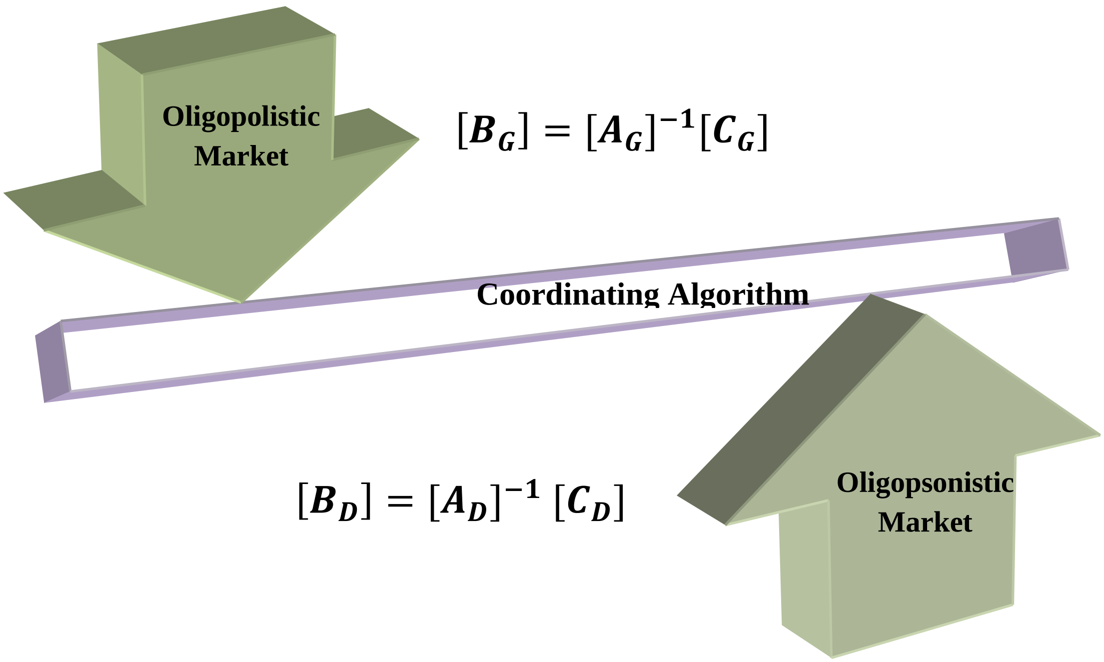


Figure 6.3: Co-ordination between Oligopolistic and Oligopsonistic Markets

Based on Equations 6.2 and 6.4, several principles can be realized:

- The retail price, λ, plays a significant role in this co-ordination algorithm since the right hand side of Equation 6.4 is strongly dependent on this price.
- The intercept value of inverse demand function, e_d, should be bigger than the maximum linear coefficient of generators' cost function, b_i.
- The intercept value of inverse generation function, e_g, should be sufficiently less that the retail price, λ.
- The intercept value of inverse generation curve, e_g, is less that the intercept of inverse demand curve, e_d.
- Because of the demand inelasticity, the slope of inverse demand curve, f_d, should be high; therefore the equilibrium quantity is assumed to be the actual value for end-users [90].

6.4 Hierarchical Optimization Algorithm

In this research in order to investigate the equilibrium point of a bilateral electricity market, a hierarchical optimization algorithm has been suggested. To perform this algorithm accurately further assumptions and modifications are required to obtain the equilibrium point of the whole market. The slopes and intercepts of initial conditions for the inverse demand and generation functions, $\{{e_d}^{(0)}, {f_d}^{(0)}, {e_g}^{(0)}, {f_g}^{(0)}\}$, can be set to any values, which satisfy the four principles, covered in the last section. Since the intercept of the inverse demand function represents market power it should be set to a higher value, also the inverse generation function is estimated to be a more moderate curve, thus the ${f_g}^{(0)}$ should be lower than ${f_d}^{(0)}$. These guesses would help to set the initial values within the scope of both oligopolistic and oligopsonistic markets and have a feasible starting point for iteration.

After the initial guess, the variables of inverse demand function and inverse generation function, $\{e_d, f_d, e_g, f_g\}$, can be varied to obtain new q_{ig} and q_{id}. Therefore, an iterative hierarchical optimization method can be proposed. This method is called hierarchical because it coordinates both the oligopolistic and oligopsonistic markets and operates in such a way to seek an overall match between the two CVE models in order to find the equilibrium of the market.

There are some assumptions for this hierarchical algorithm:

- Bilateral electricity market can be modeled as a virtual *Pool* with a virtual broker, which tends to find the market equilibrium based on the conjectural variations of both GenCos and SupplyCos.
- CV_{ig} and CV_{id} for both GenCos and SupplyCos are constant. (The calculation of CVs is outside of the scope of this research and will be discussed as a possibility for future work).
- No holding is permitted for each supply company, to avoid practicing market power.

Consequently, the hierarchical optimization algorithm contains the following steps:

Hierarchical Optimization Algorithm

Step 1) Initialize inverse demand and generation functions: $\{{e_d}^{(0)}, {f_d}^{(0)}, {e_g}^{(0)}, {f_g}^{(0)}\}$

Step 2) Define the generators' cost function variables: a_i, b_i, c_i for oligopolistic market and retail price, λ, for oligopsonistic market.

Step 3) Define the CV_{ig} and CV_{id} based on historical data and technical characteristics of each GenCo and SupplyCo respectively.

Step 4) Computing the output of each GenCo, q_{ig}, and the purchased amount of electricity by each SupplyCo, q_{id}, using Equations 6.2 and 6.4

Step 5) Calculating the $\sum_{i=1}^{n} q_{ig}$ and $\sum_{i=1}^{m} q_{id}$.

Step 6) Computing the price values for oligopolistic and oligopsonistic markets, P_d and P_g respectively, using Equations 4.20, 5.4, P_g and P_d, based on inverse demand and inverse generation functions respectively.

Step 7) Using Hierarchical Optimization method, to obtain:

$$\boldsymbol{Min}\ \left(\sum_{i=1}^{n} \boldsymbol{q_{ig}}^{(k)} - \sum_{i=1}^{m} \boldsymbol{q_{id}}^{(k)}\right)^2 + \left(\boldsymbol{p_g}^{(k)} - \boldsymbol{p_d}^{(k)}\right)^2 \qquad (6.5)$$

Step 8) If the objective function is minimized, the equilibrium point $(\sum_{i=1}^{n} q_{eq}{}^{*}, p_{eq}{}^{*})$ can be calculated, if not, the optimizer keeps increasing the number of iterations, $k = k + 1$, and replaces the slopes and intercepts parameters with updated values, $\{{e_d}^{(k+1)}, {e_g}^{(k+1)}, {f_d}^{(k+1)}, {f_g}^{(k+1)}\}$, then goes to *step (4)*.

Figure 6.4: Hierarchical Optimization Algorithm

Figure 6.5 illustrates the hierarchical optimization algorithm applied in this chapter.

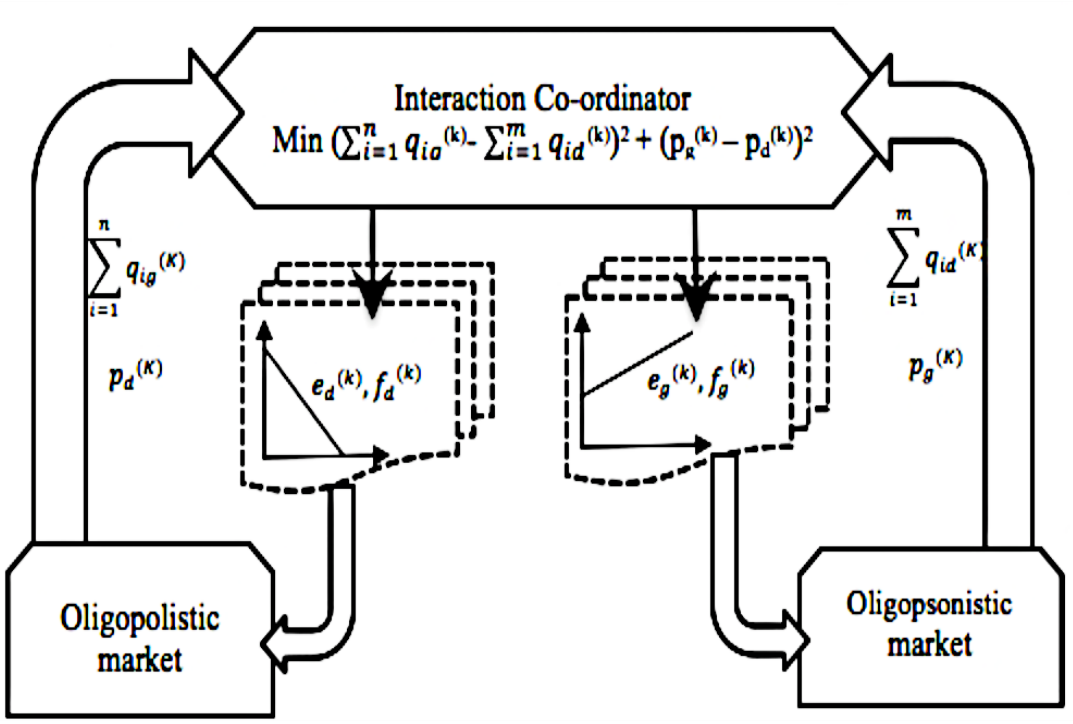


Figure 6.5: Hierarchical Optimization Structure

It should be mentioned that, in step 7, all $\sum_{i=1}^{n} q_{ig}{}^{(k)}$, $\sum_{i=1}^{m} q_{id}{}^{(k)}$, $p_g{}^{(k)}$ and $p_d{}^{(k)}$ are functions of $\{e_d, f_d, e_g, f_g\}$ and $'k'$ is the number of iterations.

6.4.1 Hierarchical Algorithm Optimizer

Matlab has been selected in order to perform all the mentioned steps including the least squares optimization problem, Equation 6.5, in *Step 7* (Appendix F). In order to boost the calculation's processing time and reduce computational analysis, a derivative-free optimization method can be employed to optimize the objective function.

Two toolboxes for optimization have been provided in Matlab:

- *Optimization Toolbox*
- *Global Optimization Toolbox*.

Most of the functions in the first toolbox are gradient-based; however there are some derivative-free solvers in the Global Optimization Toolbox such as *Patternsearch*.

Patternsearch, which is also known as Direct Search, has a proven convergence and also has a user-supplied start point approach unlike Genetic Algorithm (GA) [96]. Furthermore, this method has less function evaluations compare to other approaches such as Simulated Annealing and Genetic Algorithm (GA), which makes it faster compare to other methods [96]. While most of the traditional optimization methods have been founded on exact or approximate data about the gradient, Patternsearch is a kind of metaheuristic optimization method, which doesn't use gradient or Hessian matrix and the objective function can be continuous and non-differentiable and be able to be computed by a black box simulation. Therefore, it can be applied to cases in which the analytic derivatives are unknown or difficult to calculate [97] such as Equation 6.5.

This approach starts at an initial guess in *step 1* provided by the user with an initial pattern matrix, P_0, and a scalar parameter solution, Δ_0. In order to define a natural stopping criterion for the search, Δk has been introduced. The Generalized Patternsearch has been characterized by Exploratory Moves according to [97], and the algorithm finds the next step by applying exploratory moves: s_k: (Δ_k, P_k). Whenever, $f\ (x_k + s_k) < f\ (x_k)$, then $x_{k+1} = x_k + s_k$ and the (Δ_k, P_k) will be updated, otherwise it will stick to the current point.

In Figure 6.5, firstly the Patternsearch algorithm tries the step $s_k{}^1$. However, $(x_k{}^1)$ $> f\ (x_k)$; therefore this method tries the next step, $s_k{}^2$ and the objective function can be evaluated at $x_k{}^2 = x_k + s_k{}^2$. Since $f\ (x_k{}^2) < f\ (x_k)$, the $s_k{}^2$ move can be accepted.

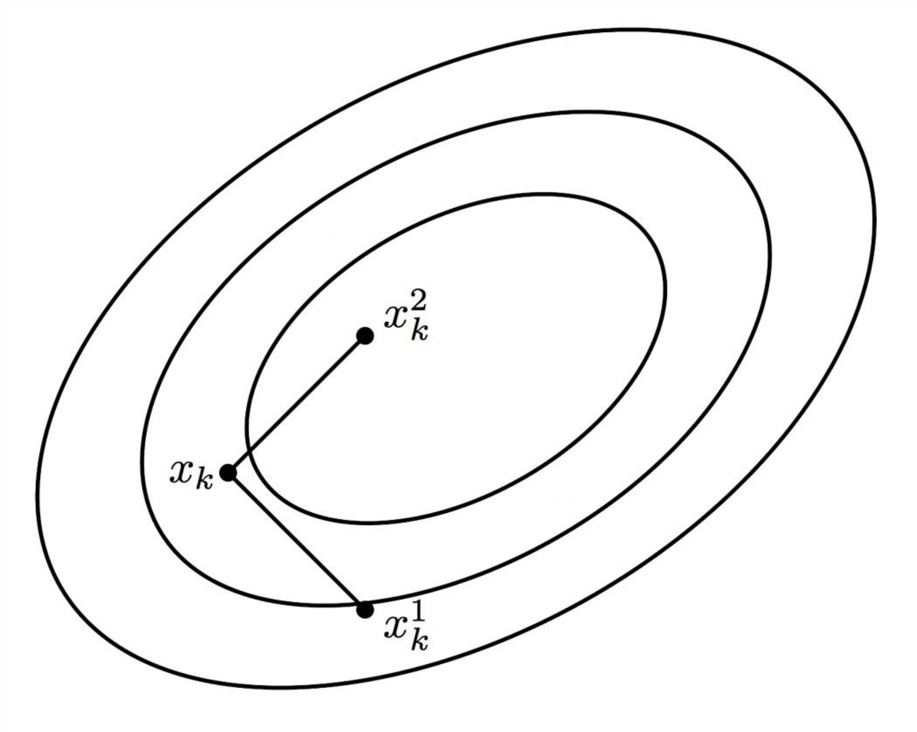


Figure 6.6: Patternsearch Exploratory Moves

Patternsearch tries to minimize the objective function using the feasible start points from *step (1)* and comes up with new suggested values of $\{e_d, f_d, e_g, f_g\}$ to reduce Equation 6.5.

6.5 Hierarchical Optimization Algorithm Case Study

In order to demonstrate the validity of the above algorithm, the CVE method has been applied into oligopolistic and oligopsonistic electricity markets simultaneously.

An oligopolistic market including 3 GenCos and an oligopsonistic market with 4 SupplyCos have been taken into consideration. The specifications of market participants in both market environments can be found in Tables 6.1. and 6.2.

According to the tables, the fixed coefficients of generators' cost functions have been assumed to be zero to simplify the calculations and the SupplyCos fixed costs has also been set to zero. Unlike Chapter 5, the retail price for each SupplyCo is different, which will influence the strategies and behaviours of each SupplyCo in participating in bilateral electricity market.

Table 6.1: Oligopolistic Market Participants' Parameters

	a_i (£)	b_i (£/MW)	c_i (£/MW^2)	CV_{ig}
GenCo 1	0	10	0.005	-0.01
GenCo 2	0	12	0.007	-0.02
GenCo 3	0	15	0.008	-0.03

Table 6.2: Oligopsonistic Market Participants' Parameters

	CV_{id}	f_{ci} (£)	λ (£/MW)
SupplyCo 1	-0.09	0	280
SupplyCo 2	-0.1	0	290
SupplyCo 3	-0.2	0	300
SupplyCo 3	-0.3	0	310

In Chapter 5, the impacts of CV values on the market participants' strategies on both sides of the market were investigated. Now the aim of this chapter is to find the equilibrium point of the whole bilateral market; therefore, CV values are assumed to be within the range described Chapter 5. In this case the CV_{ig} values for GenCos are less than those for SupplyCos, which demonstrates that GenCos have more market power; furthermore the number of SupplyCos, is greater comparing to number of GenCos participating in the market.

This section represents how the hierarchical Direct Search algorithm can find the equilibrium point of bilateral oligopolistic and oligopsonistic electricity markets alongside profit maximization for both GenCos and SupplyCos by applying the Patternsearch optimizer. By applying the hierarchical optimization algorithm for the above system the final values for $\{e_d, f_d, e_g, f_g\}$ can be identified in Table 6.3:

Table 6.3: Intercepts and Slopes Values for Both Sides of the Market

Slopes & Intercepts	Values
e_d	1001.501
e_g	60.125
f_d	7.21
f_g	1.8

Based on Table 6.3, the intercept of inverse demand curve, e_d, is much higher, comparing to the inverse generation curve, e_g, which was predictable earlier because of demand inelasticity and market power. Additionally, the slope of the inverse generation curve, f_g, is moderate, about 60.94°, compare to 82.2° of the inverse demand curve slope. It is remarkable that because of the steepness of inverse demand curve and inelasticity of it, this curve represents the demand value [90]. Also, Figure 6.7 illustrates the Matlab results for intercepts and slopes values:

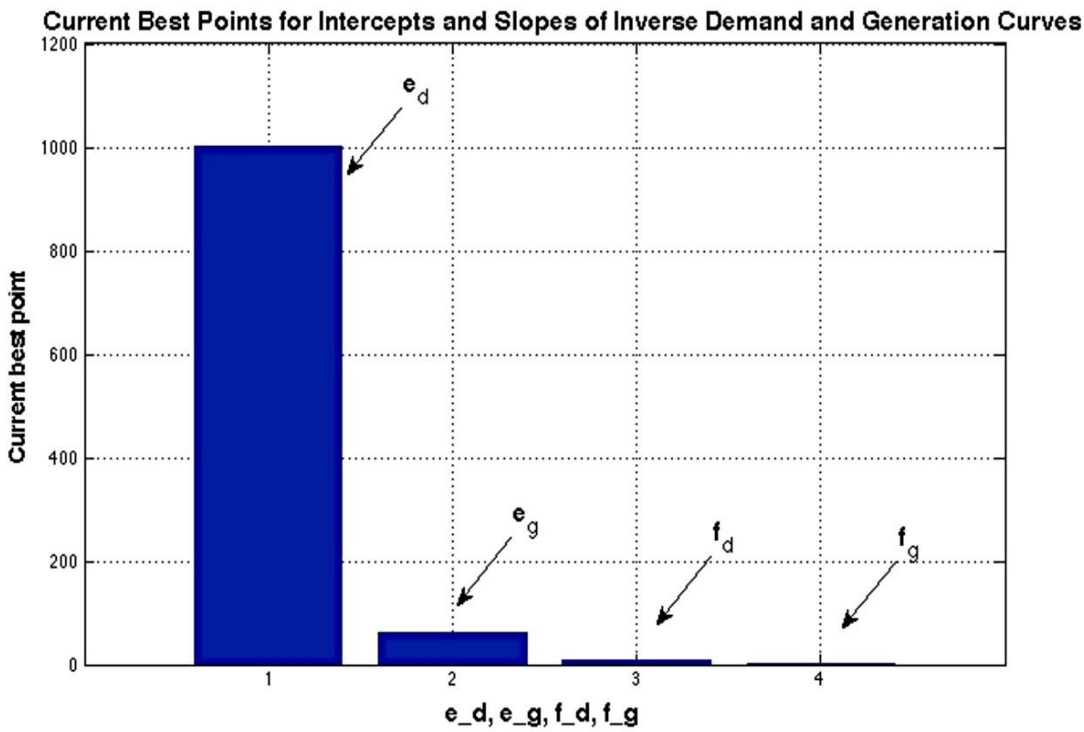


Figure 6.7: Best Points for Intercepts and Slopes of Inverse Demand and Generation Curves

Figure 6.8 shows the objective function, Equation 6.5, after performing the hierarchical optimization, which has obtained a very small value. Based on this figure, this function has been converged more gradually at the early iterations, afterwards its value drops steeply.

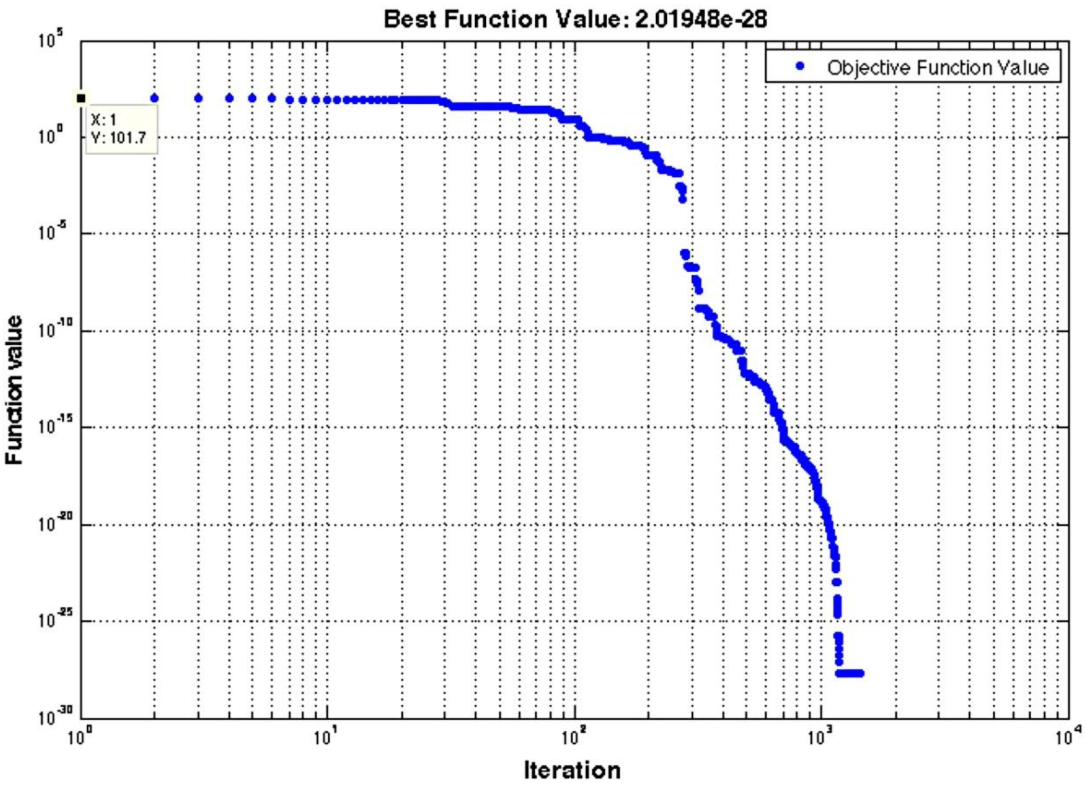


Figure 6.8: Objective Function Value

In Generalized Patternsearch (GPS) a pattern is a set of vectors that the Patternsearch algorithm uses to determine which points to search. At each step, Patternsearch searches a set of points, called a *mesh*, for a point that improves the objective function. After each iteration the optimizer multiply each pattern vector by a small scalar which is called *mesh size* to add it to a current point to reach to the solutions. Fig 6.9. demonstrates the mesh size of this algorithm after each iteration. As it is illustrated after several fluctuations in the value of mesh size in early iterations, its value would get a decreasing trend iteration by iteration, which means the hierarchical optimization algorithm is reaching the equilibrium point of the market.

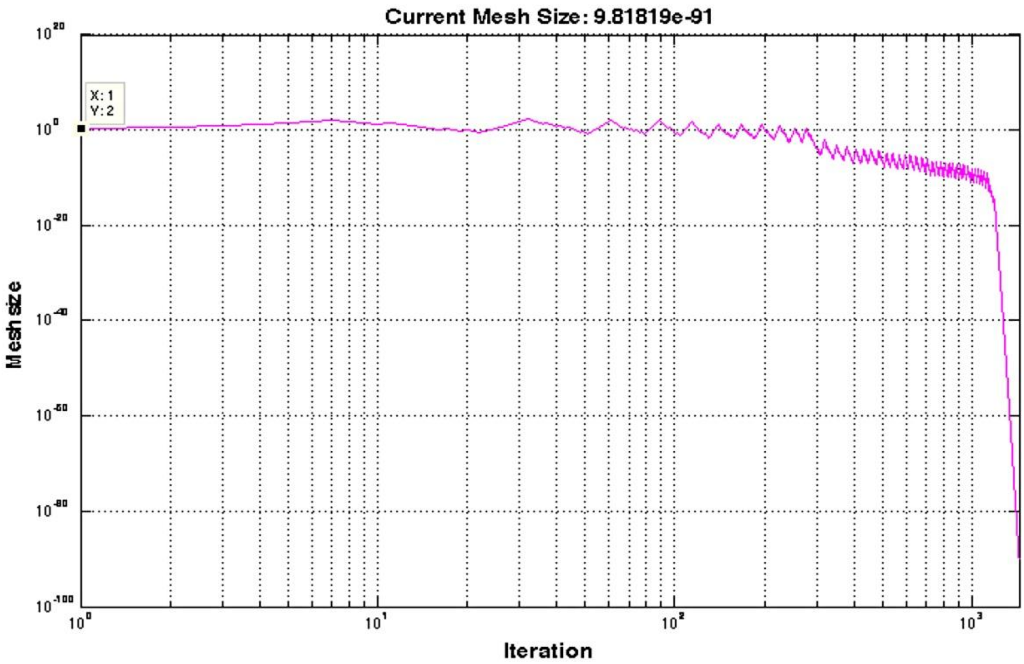


Figure 6.9: Patternseach Mesh Size Value

According to the figure above, at the early stage, the added scalar value to reach to the solution is higher comparing to the later iterations; which illustrates how hierarchical optimization algorithm reaches the equilibrium point of the electricity market.

Finally, the optimum inverse demand function and inverse generation function,

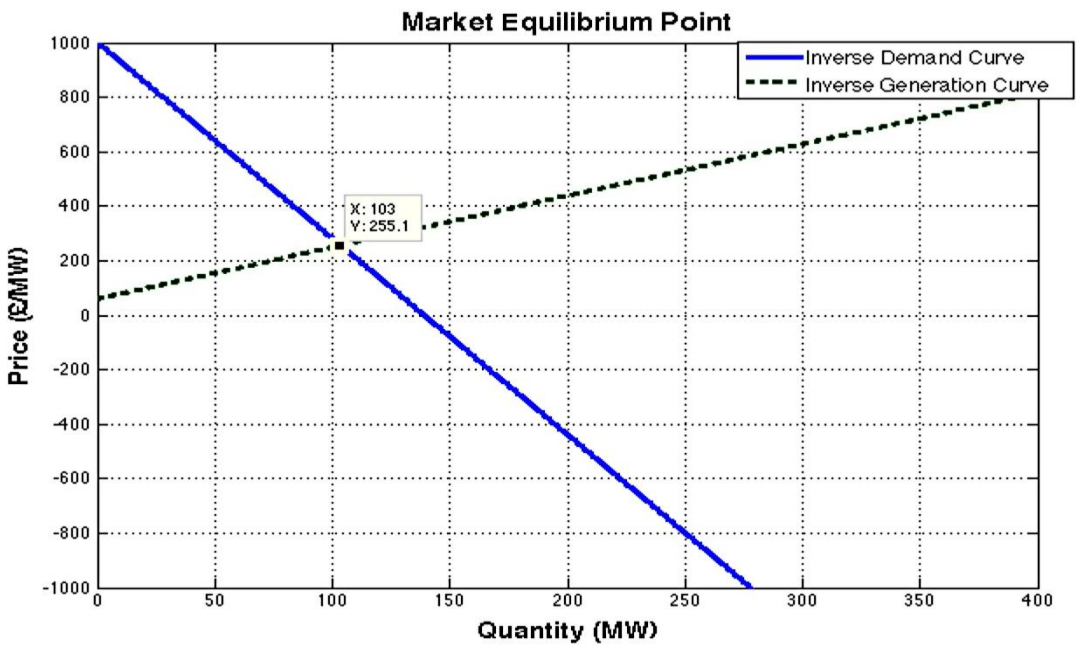


Figure 6.10: Market Equilibrium Point

alongside the combined market equilibrium point have been calculated and represented in Figure 6.10. Where the equilibrium point of the market $(p_{eq}{}^{*}, q_{eq}{}^{*})$ is:

Table 6.4:Market Equilibrium Point

Equilibrium	Values
$p_{eq}{}^{*}$	256.0712
$q_{eq}{}^{*}$	103.5320

Furthemore, it is possible to investigate the output of each GenCo and purchased value by each SupplyCo individually:

Table 6.5: GenCos' Market Share

Output of GenCos	Values
q_{1g}	34.4976
q_{2g}	34.5563
q_{3g}	34.4781

Table 6.6: SupplyCos' Market Share

Purchased Value by SupplyCos	Values
q_{1d}	13.8937
q_{2d}	19.9188
q_{3d}	29.0133
q_{4d}	40.7062

It was expected that the output of GenCo1 will be higher comparing to others based on their cost functions. However, accoridng to Table 6.1, the CV_{1g} is higher than other generation companies; therefore based on Chpater 5 investigations, it causes reduction in GenCo1's market share. Also because the CV_{1d} value of SupplyCo1 is higher than others, its share in the market is very low comparing to SupplyCo4, which its share is almost three times bigger. It is important to notice that, the retail price has a strong influence on the strategies of SupplyCos as well. Accoridng to Table 6.2 the SupplyCo 1 has been offered less retail price to sell elelctricity to the end-users; hence, it does not have strong incentives comparing other supply companies to participate in the wholesale market. Equation 5.15 can validate this fact.

Additionaly, it is possible to use the above market equilibrium point, resulting slopes and intercepts, to perform optimization in both oligopolistic and oligopsonistic models seperately, to find out whether both GenCos and SupplyCos are making profit under this condition or not. Tables 6.7 and 6.8. demonstrate the profits for firms on both sides of the market:

Table 6.7: GenCos' Profits

GenCos Profit	Values
$\boldsymbol{\pi_{1g}}$	8488.865829
$\boldsymbol{\pi_{2g}}$	8157.747209
$\boldsymbol{\pi_{3g}}$	7794.505441

Table 6.8: SupplyCos' Profits

SupplyCos Profit	Values
$\boldsymbol{\pi_{1d}}$	332.4595686
$\boldsymbol{\pi_{2d}}$	675.8209814
$\boldsymbol{\pi_{3d}}$	1274.519453
$\boldsymbol{\pi_{4d}}$	2195.236519

Consequently, based on the tables above, all market participants are making profit corresponding to the equilibrium point of this specific case study. However, because of the demand inelasiticty, higher number of SupplyCos and also assumed retail prices, GenCos are making more profits.

6.6 Summary

This chapter focuses on calculating equilibrium point of whole bilateal elelctricity market consodering both oligpolistic and oligopsonistic electricity markets. In order to achieve this goal, it is essential to consider both sides of the market, simutanesly. It has been investigated that how these two models can co-ordinate with each other in order to find the stable point of the market. According to this coordinative idea, a hierarchical optimization algorithm introduced, which assists to calculate equilibrium point alongside the share of each firms in the elelctricity market. The objective function in this hierarchical algorithm has been optimized using derivative-free optimizer.

Chapter 7: Conclusions and Future Works

7.1 Introduction

In Chapter 6, the novel hierarchical optimization algorithm was introduced and by applying this algorithm on both sides of the bilateral electricity market, the equilibrium point of electricity trading was calculated and according to the proposed case study all market participants made profit using this coordinative algorithm. This chapter attempts to summarize all the achievements made through this research and highlight the contributions and novelties of this study, alongside suggested directions for future works.

7.2 Achievements and Contributions

The electricity sector all over the world has undergone considerable changes during the past decade. Main developments are the liberalization of electricity markets and the promotion of renewable electricity generation; therefore market players and policy makers must deal with new aspects like market power and appearance of fluctuating energy sources. A promising approach for the scientific analysis of these new developments is Conjectural Variation Equilibrium (CVE) method. Nowadays, electricity markets are an evolving system of complex interactions between physical structures, market rules and market participants; hence, their goals, objectives, beliefs and decision processes vary markedly. Such a diversity of inputs can lead to a rich diversity of market outcomes. From structural viewpoint the equilibrium method represents the overall market behaviors and particularly CVE method attempts to estimate market participants’ behaviors in an electricity market.

The design of the BETTA, as a bilateral electricity market example, and its rules incentivize players to maximize their opportunities to trade in a free market and control their own generation or consumption. Therefore generation and supply companies are self-dispatched. Because of the absence of centralized decision-making authority, both GenCos and SupplyCos face uncertainties in making their decisions and strategies; therefore, that need to rely on their own judgments about the market environment and decide how to participate in energy trading. The existence of single decision maker agents in market can cause some risks; especially the exposure to the imbalance prices arises. This problem is very serious for intermittent generations like wind energy, which is hard to predict the output.

From SupplyCos' perspective, managing risks of price variations is very important. They purchase electricity in the wholesale market and sell it to the end-users at different retail prices. They can make benefit in an oligopsonistic electricity market and dominate the market by purchasing less electricity in order to force GenCos to sell their generated electricity at the lower price. Furthermore, since the elasticity of demand for electricity is relatively small, because of the nature of electricity as a commodity, they can make profit in the retail market as well. It is essential to mention that considering retail market is not within the scope of this research; however, since there is a strong linkage between wholesale trading and retail market, the impacts of retail prices on SupplyCos' decisions have been investigated in both Chapters 5 and 6. In some circumstances, the electricity suppliers may pay more for buying electricity from the wholesale market than the price they charged to their end-users.

On the other hand generation companies should mange the risks of participating in long-term bilateral electricity trading and must provide the amount of electricity they have agreed to avoid any imbalance settlement charges according to the structure of bilateral electricity markets such as BETTA as investigated in chapter 3. However, the cost of generation companies comprises the fuel costs, the cost of start-up and shut down and fuel transportation charges; therefore they may face imbalance conditions in the long-term. In this case they are required to buy electricity in the spot market or adjust their positions by participating in the balancing mechanism; which means they are exposed to the risk of price volatility. For instance, as a result of an unexpected and sudden power outage, GenCos can face very high spot and balancing mechanism prices especially at the peak times; therefore, they need to have a good knowledge about their rivals' decisions and reactions and also be able to consider the other side of the market in other to prepare themselves for any possible market power exercises. It is worth to mention that, one of the incentives for investments on the generation side and intermittent energy infrastructures is the high electricity selling price for generation companies; therefore, it is expected that generation companies make more profit comparing to supply companies in the electricity market; as the results of case study in Chapter 6 illustrates this fact.

Bilateral electricity market characteristics guide us to use CVE to model the behaviors of parties in this market. CVE method can provide insights into pricing and strategic behaviors in complex new markets like bilateral electricity market and manage the firms' strategies in such a way that all of them can make profit while the market is at the stable point according to Nash Equilibrium and they do not have any willingness to deviate from their strategies.

The followings are some of the findings of this research:

1) The bilateral market structure can improve the industry efficiency of market participants, since all of them are responsible for their own decisions.
2) SupplyCos' exposures to the risk in bilateral electricity market are greater than GenCos' exposures.
3) GenCos' have an inherent ability to make more profit comparing SupplyCos' because of the nature of demand inelasticity.
4) The flexible power plants will be valuable in this market structure since they can merge their risks and make their conjectures adaptable based on their learning about other rivals' behaviors using historical data.
5) By implementation of this model the percentage of trading in BM will be reduced, and in an imperfect bilateral electricity market all the firms on both sides can maximize their profits.
6) The retail price can have strong impacts on SupplyCos' strategies in the wholesale bilateral trading, since they can have more willingness to buy more electricity in order to make further profit.
7) The slope and intercept of inverse demand function clarify the strategies of GenCos in the bilateral electricity market, as the slope and intercept of inverse generation curve have strong influence on the SupplyCos strategies.
8) The CVs values can indicate the level of imperfectness of the market on both sides.
9) In the CVE method not only the cost functions parameters have influence on the generation companies; but their conjectures about their rivals can have strong influence on their decisions. This fact applies to SupplyCos as well.
10) According to the Matrix 6.4, once the inverse generation curve becomes elastic and gets the form of horizontal line, the price that SupplyCos are going to buy at, is equal to the inverse generation curve intercept, which

would be the retail price.

11) According to the hierarchical algorithm, whenever high values of inverse demand curve intercept are selected by the optimizer, the slope of this curve will get high values as well by the optimizer, in order to reduce the mismatch between the prices of both markets.

The main contributions and novelties of this research lies on tackling the potentially interesting topic of imperfect bilateral electricity market modeling based on CVE approach:

1) Considering a bilateral electricity market, with large amount of electricity traded in long-term contracts years ahead of gate closure, such as BETTA structure, while as mentioned in Chapter 2, most of the studies and market modeling are dedicated to electricity Pool structure.
2) Considering both sides of bilateral electricity market and splitting it into two sub-markets.
3) Considering imperfect environment on generation side of the market by taking into consideration oligopolistic electricity market. However, in other studies the oligopoly environment has been considered in the Pool structure and oligopolistic market have been traditionally represented in electricity markets equilibriums, as mentioned in Chapters 2 and 4.
4) Considering the supply side of the bilateral electricity market simultaneously, by investigating oligopsonistic electricity market.
5) In most studies the monopoly competes with a monopsony in a single market, however, bilateral oligopoly in which oligopoly competes with oligopsony has not been explored in the literature.
6) Apply Conjectural Variation Equilibrium method on both markets and particularly formulate the behaviors of SupplyCos through this equilibrium method, while the role of retail price has been investigated in this research as well.
7) Dependency of residual demand curve and residual generation curve by applying the novel-coordinating algorithm.
8) Introducing a novel hierarchical algorithm in order to find out the equilibrium point of the whole bilateral market by considering both types of the market, simultaneously. A new overall model of a bilateral market has been

presented. This combines a Conjectural Variations Equilibrium model of an oligopolistic set of GenCos with a corresponding oligopsonistic equilibrium model of a set of supply companies. These models each include an assumed demand (or generation) curve for the *other side* of the bilateral market. The assumed curves are iteratively adjusted with the objective of obtaining a ‘match’, in both quantity and price, between the two equilibrium models. This match can be found by a hierarchical optimization approach in which a coordination level optimization adjusts the slopes and intercepts of the supply and demand curves until a minimum imbalance between the two equilibrium models is found. The coordinated solution (which can be viewed as representing a virtual broker between the oligopoly and the oligopsony) determines the output levels of all GenCos and the purchase levels by all SupplyCos as it was proven by a numerical case.

Also, it should be mentioned that in [86] the application of Conjectural Variation Equilibrium model for generation side (oligopolistic electricity market) has been compared with other equilibrium methods and improved results have been achieved. This can be an appropriate validation for this research. Furthermore, by working with one or more generation or supply companies the theory of oligopsonistic electricity modeling and hierarchical optimization algorithm could be evaluated under practical conditions.

7.3 Directions for Future Works

Although the CVs’ impacts on GenCos’ and SupplyCos’ market behaviors have been investigated in Chapter 5, since these parameters’ values for both generation and supply companies during the hierarchical optimization algorithm have been treated static; therefore, this research then leaves open the question of how the CVs values can be modified based historical data. Based on a long-term analysis of market outcome data it could be possible to estimate the values of CVs, which would ‘explain’ the dynamic behaviors of the market.

The analysis presented in the thesis is a static equilibrium model, by allowing for dynamic responses of market participants; time-varying set of CVs could be considered.

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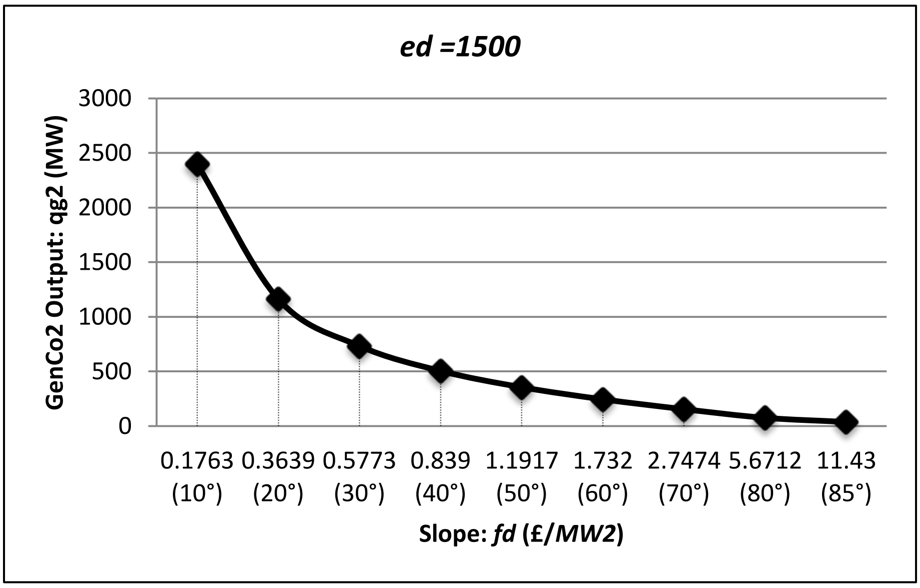
Appendix A

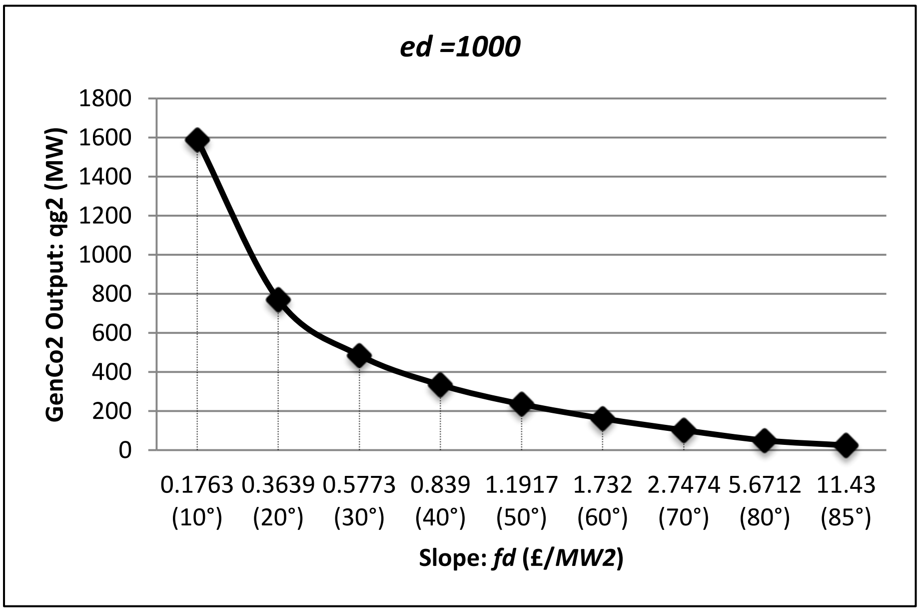
```
%%%%%%%% Oligopolistic Electricity Market %%%%%%%%%
%%%% Generation Companies' Behaviors Analysis %%%%%

clc

clear all

% Asking Users to Provide Intercepts and Slopes of Inverse
Demand Curve:
% x (1,1) is the Inverse Demand Curve Intercept.
% x (3,1) is the Inverse Demand Curve Slope.

x (1,1) = input(' Please Enter the Initial Intercept of
Inverse Demand Curve\n e1 = ');

x (3,1) = input(' Please Enter the Initial Slope of Inverse
Demand Curve\n f1 = ');

% Defining the number of GenCos and SupplyCos:

ngc = 3;

nsc = 3;

% Defining the Retail Market Price:

Pr = 250;

% Defining the GenCos' Cost Functions:

cost_function = [0 0 0;10 20 30;0 0 0];

% Defining the CVs Values for GenCos:

conjecture_variation_G = [-0.5,-0.5,-0.5];

% Applying CVE Method on Oligopolistic Electricity Market

for k = 1 : ngc

    v (1,k) = x(3,1) * (2 + conjecture_variation_G (1,k)) +
cost_function (3,k) - x(3,1);

end

for kk = 1 : ngc

    b (kk,1) = x (1,1) - cost_function (2,kk);

end
```

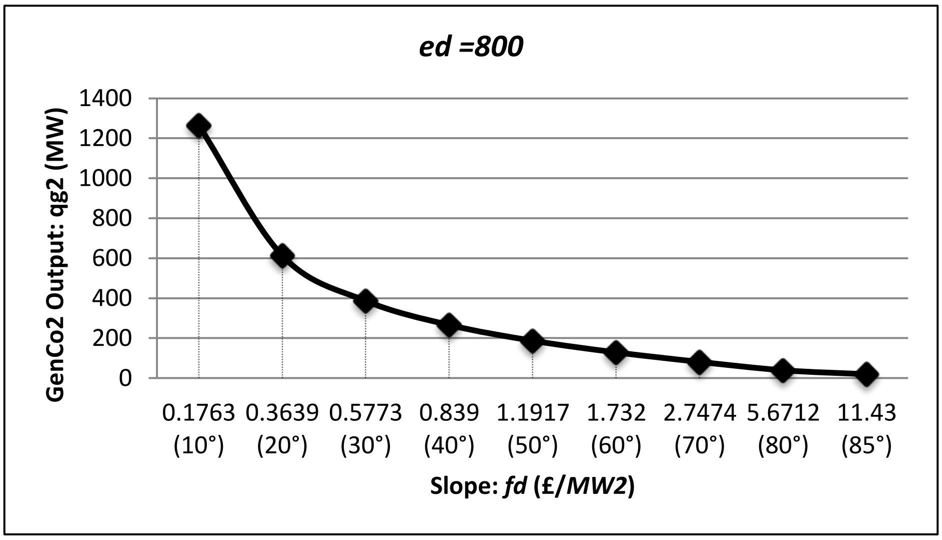
```
% Calculating the Output of each GenCo

y = diag (v) + diag (x (3,1));

qg = y \ b

% Calculating the Total Output of All GenCos

t = 0;

for i = 1 : ngc

    t = qg (i,1) + t;

end

Qg = t;

z (1,1) = Qg

% Computing the Price for Inverse Demand Curve

Pd = x(1,1) - x(3,1) * Qg;

z( 2,1) = Pd
```

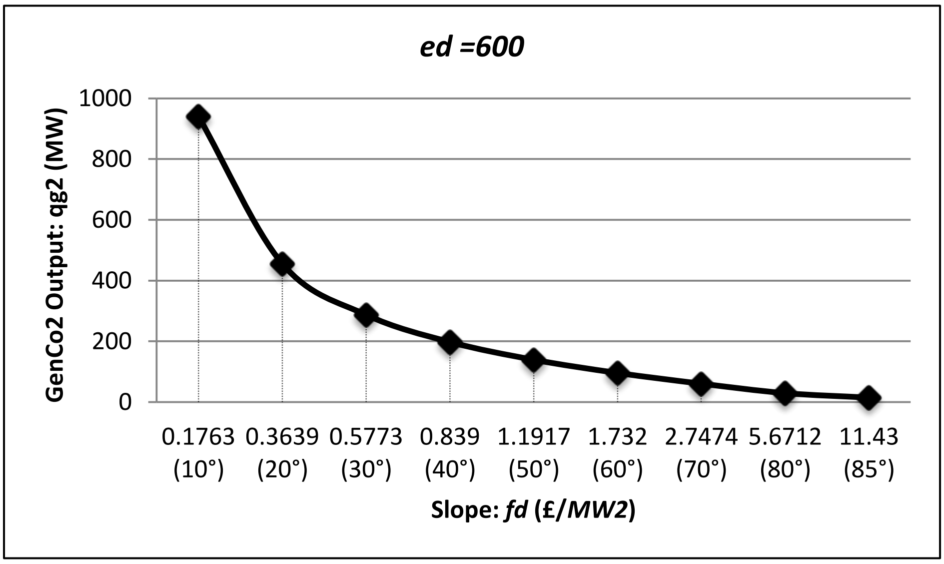
Appendix B

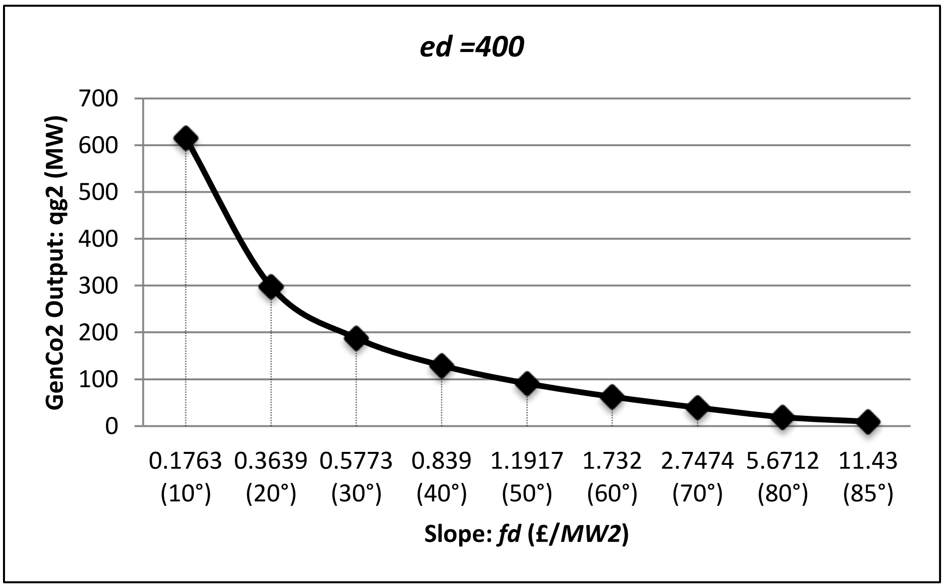
In Chapter 4, the impacts of inverse demand curve's slope on the GenCo1 have been investigated based on CVE formulation for oligopolistic electricity market. In this section the impacts of inverse demand curve's slope on GenCos 2 and 3 have been highlighted. It can be concluded that the output variations for GenCo3 is less than GenCo2 and GenCo1.

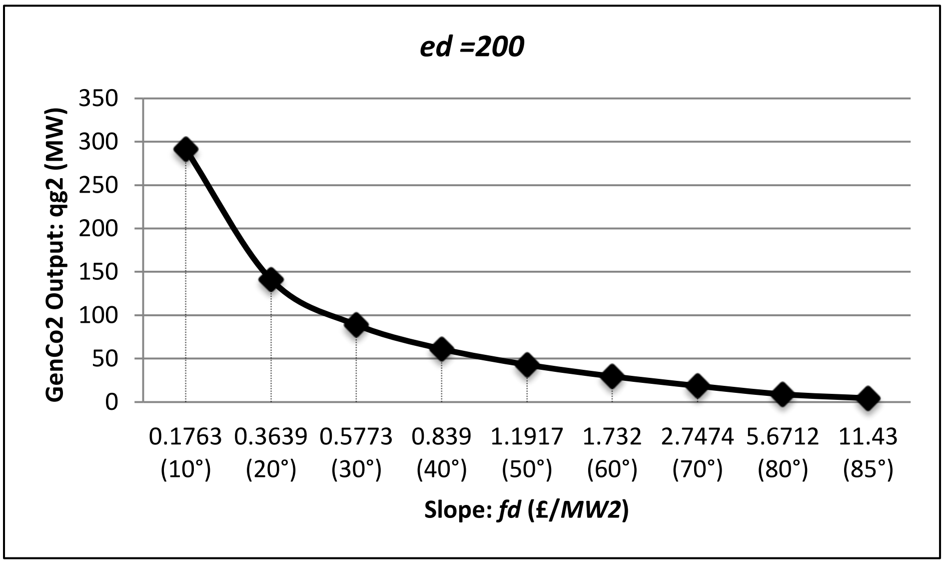


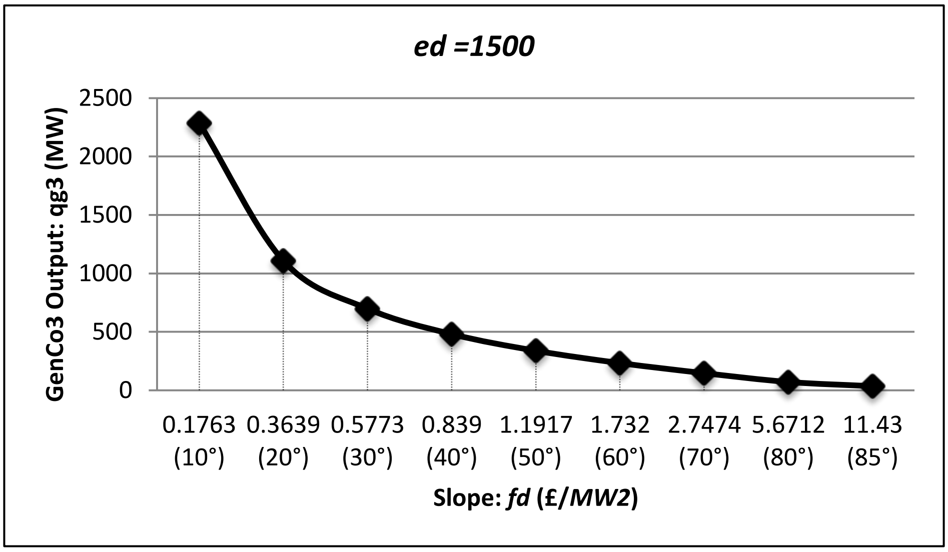


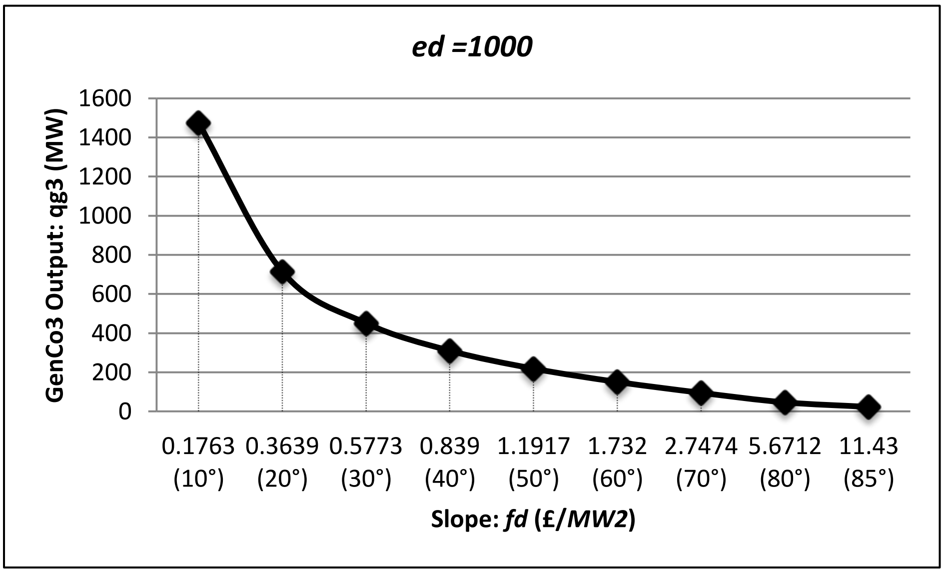

ed =800
1400
1200
1000
800
600
400
200
0
GenCo2 Output: qg2 (MW)
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fd (£/MW2)

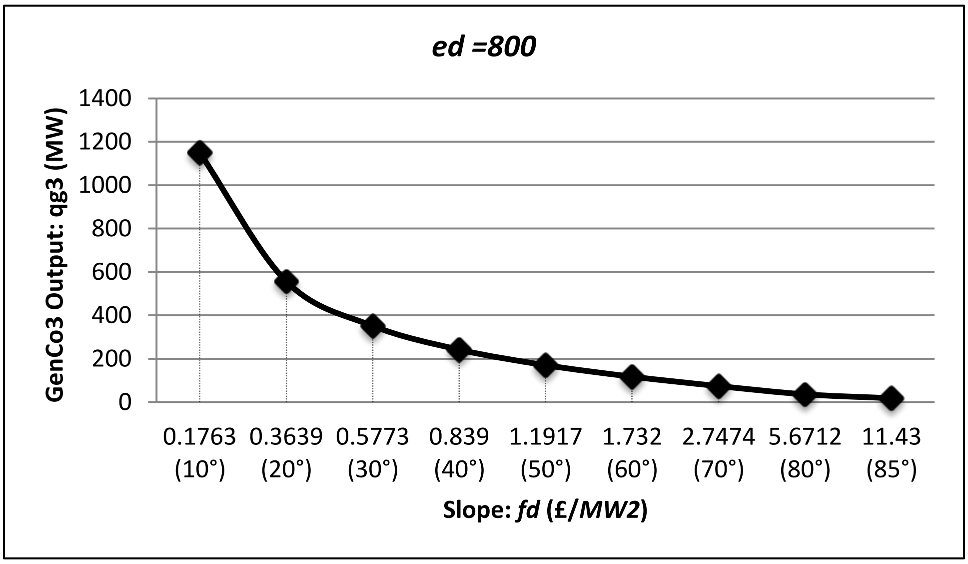

ed =600
1000
800
600
400
200
0
GenCo2 Output: qg2 (MW)
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fd (£/MW2)

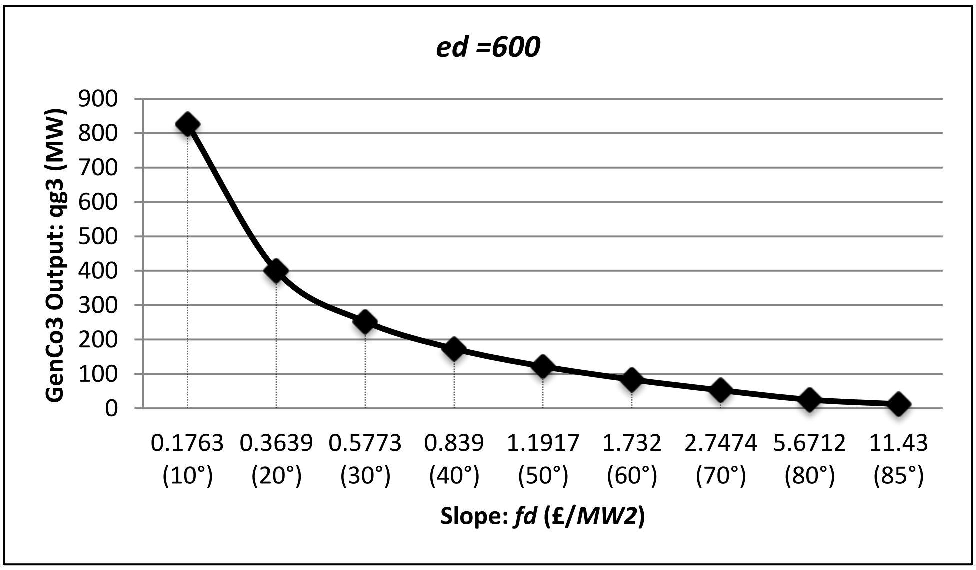

ed =400
700
600
500
400
300
200
100
0
GenCo2 Output: qg2 (MW)
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fd (£/MW2)

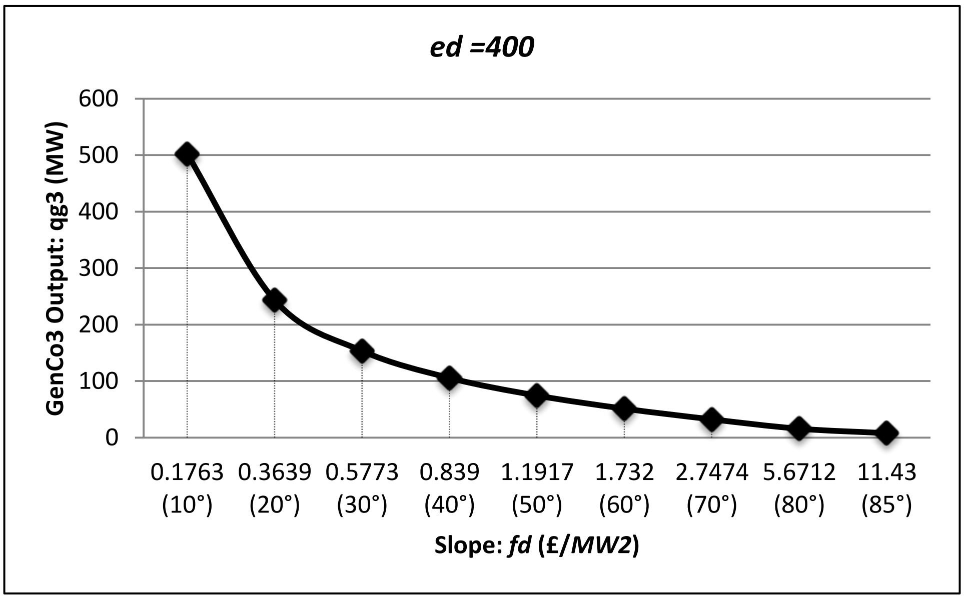

ed =200
GenCo2 Output: qg2 (MW)
350
300
250
200
150
100
50
0
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fd (£/MW2)

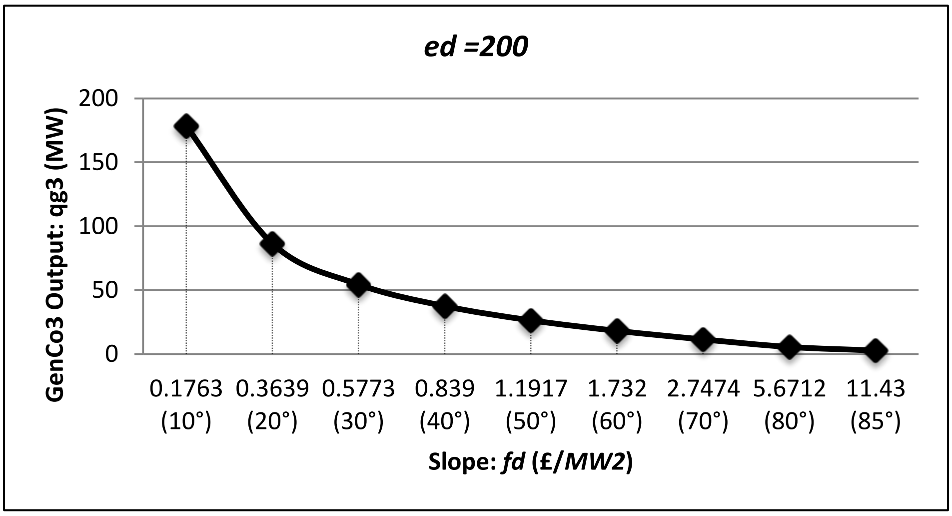

ed =1500
GenCo3 Output: qg3 (MW)
2500
2000
1500
1000
500
0
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fd (£/MW2)


ed =1000
GenCo3 Output: qg3 (MW)
1600
1400
1200
1000
800
600
400
200
0
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fd (£/MW2)

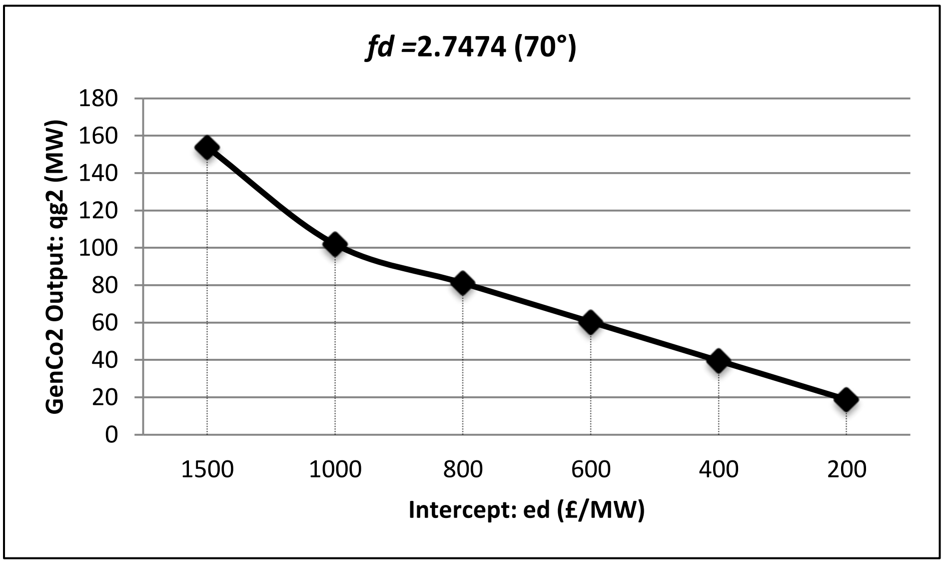

ed =800
1400
1200
1000
800
600
400
200
0
GenCo3 Output: qg3 (MW)
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fd (£/MW2)

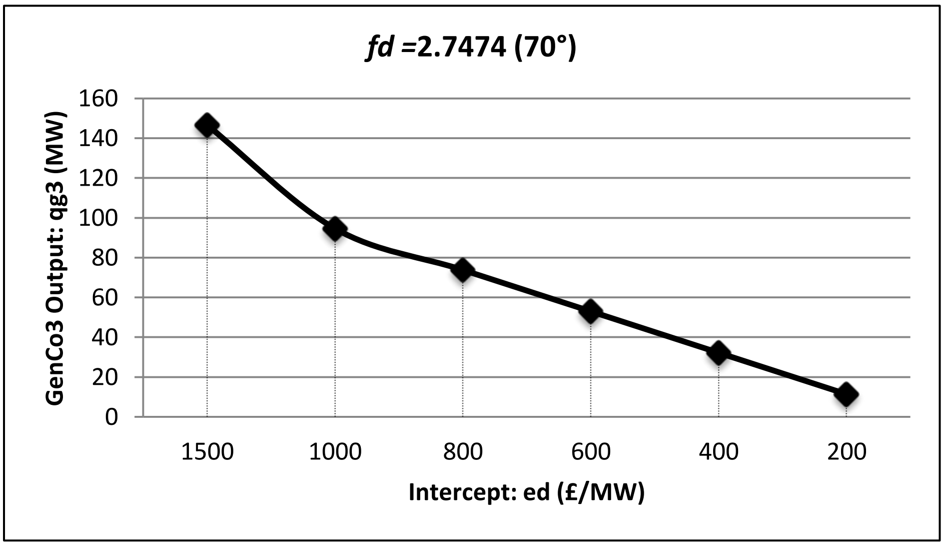

ed =600
900
800
700
600
500
400
300
200
100
0
GenCo3 Output: qg3 (MW)
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fd (£/MW2)


ed =400
600
500
400
300
200
100
0
GenCo3 Output: qg3 (MW)
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fd (£/MW2)



Furthermore, like GenCo1, it is possible to investigate the impacts of intercept on the output of other GenCos for a specific slope according to CVE formulations for oligopolistic electricity market.





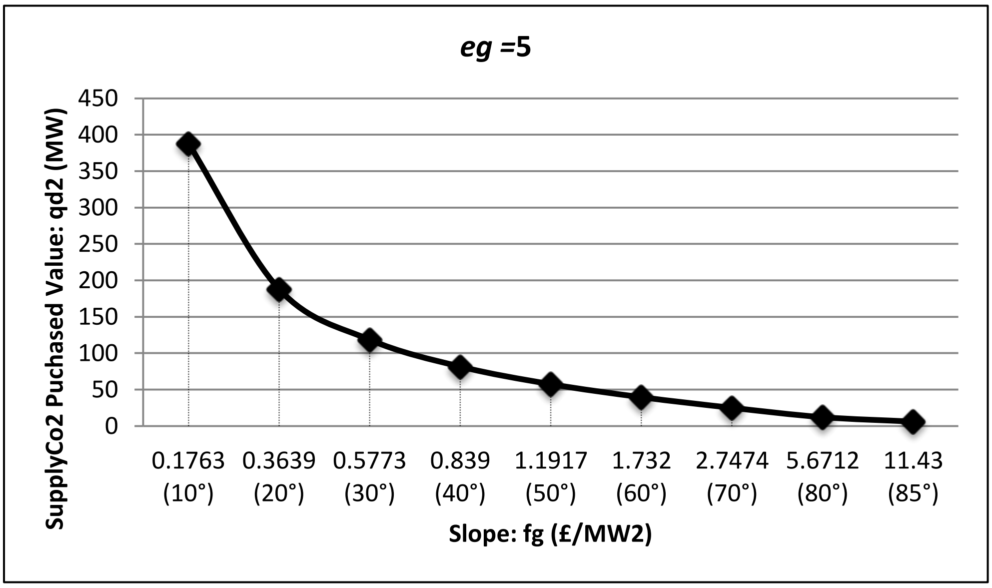
Appendix C

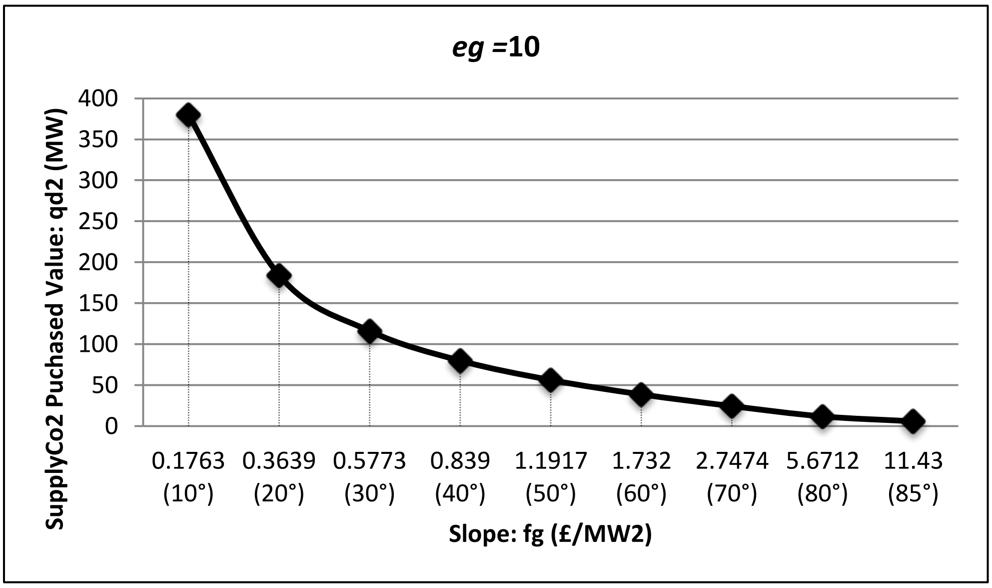
```
%%%%%%%% Oligopsonistic Electricity Market %%%%%%%%
%%%%%%% Supply Companies' Behaviors Analysis %%%%%%%

clc

clear all

% Asking Users to Provide Intercepts and Slopes of Inverse
Generation Curve:
% x (2,1) is the Inverse Generation Curve Intercept.
% x (4,1) is the Inverse Generation Curve Slope.

x (2,1) = input(' Please Enter the Initial Intercept of
Inverse Generation Curve\n e2 = ');

x (4,1) = input(' Please Enter the Initial Slope of Inverse
Generation Curve\n f2 = ');

% Defining the number of GenCos and SupplyCos:

ngc = 3;

nsc = 3;

% Defining the Retail Market Price:

Pr=150;


% Defining the CVs Values for SupplyCos:

conjecture_variation_D = [-0.6,-.5,-.4];

% Applying CVE Method on Oligopsonistic Electricity Market

for k = 1 : nsc

    vv (1,k) = x(4,1) * (2+conjecture_variation_D (1,k)) -
x(4,1);

end

for kk = 1 : nsc

    bb (kk,1) = Pr - x(2,1);

end

% Calculating the Purchased Value by each SupplyCo

yy = diag (vv) + diag (x(4,1));
```

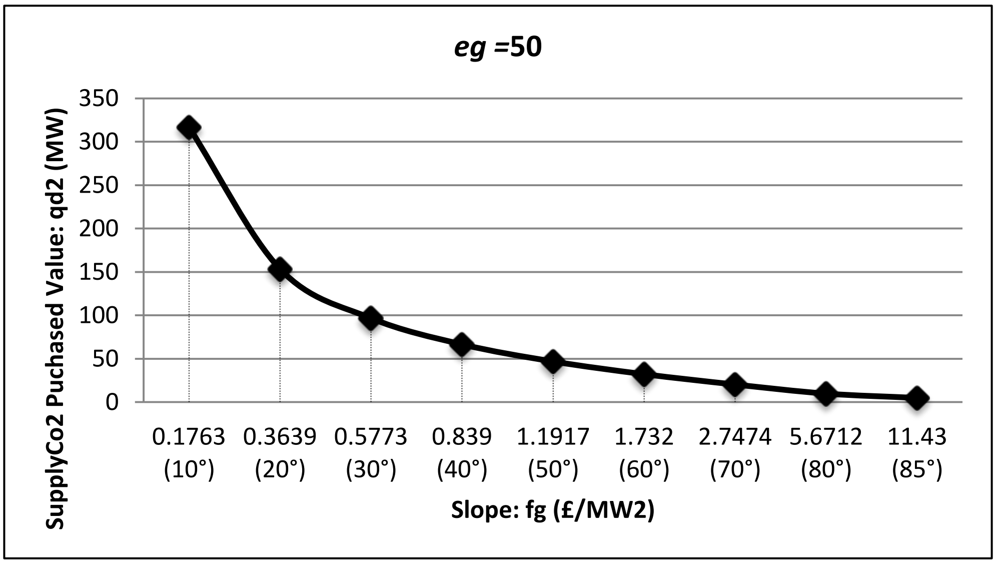
```
qd = yy \ bb

% Calculating the Total Purchased Value by All SupplyCos

t = 0;

for i = 1 : nsc

    t = qd (i,1) + t;

end

Qd = t;

z (3,1) = Qd

% Computing the Price for Inverse Generation Curve

Pg = x(2,1) + x(4,1) * Qd;

z (4,1) = Pg
```

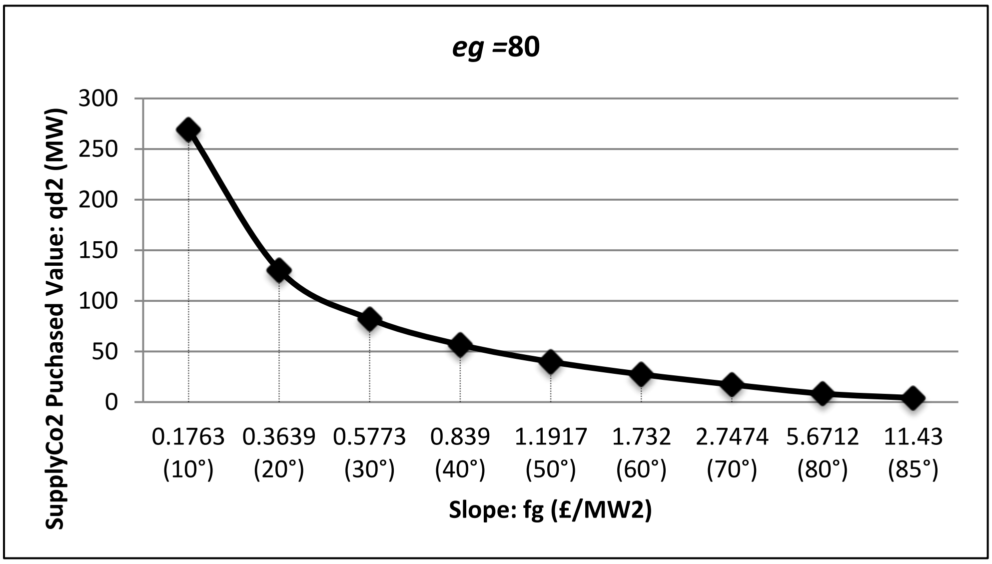
Appendix D

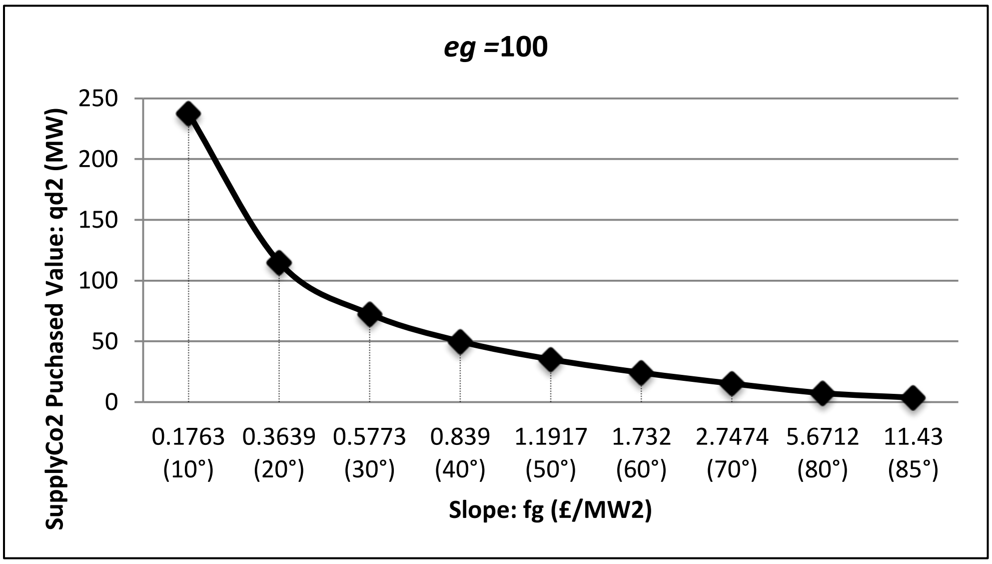
In Chapter 5, the impacts of inverse generation curve's slope on the SupplyCo1 have been investigated based on CVE formulation for oligopsonistic electricity market. In this section the impacts of inverse generation curve's slope on SupplyCos 2 and 3 have been highlighted. It can be concluded that the variations in purchased value by SupplyCo3 is less than SupplyCo2 and SupplyCo1.

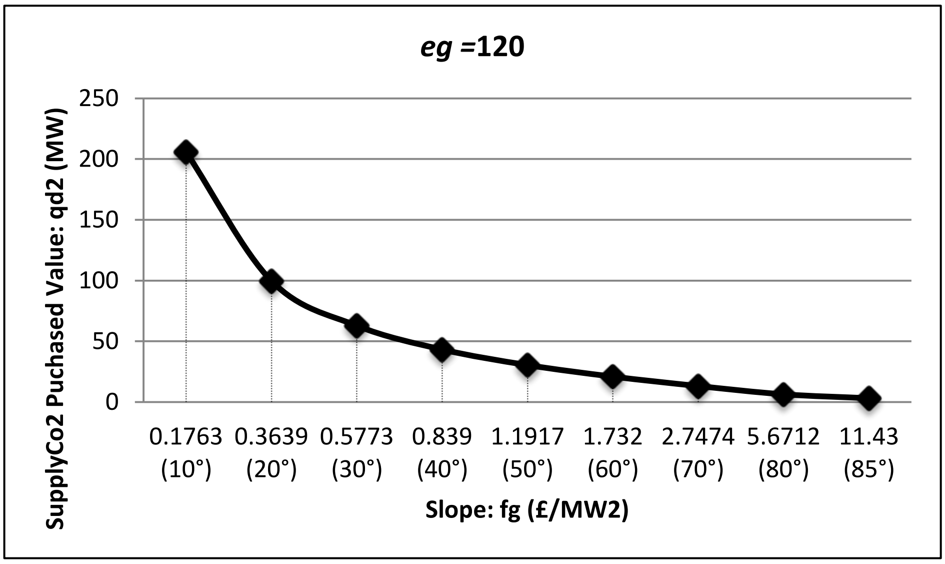


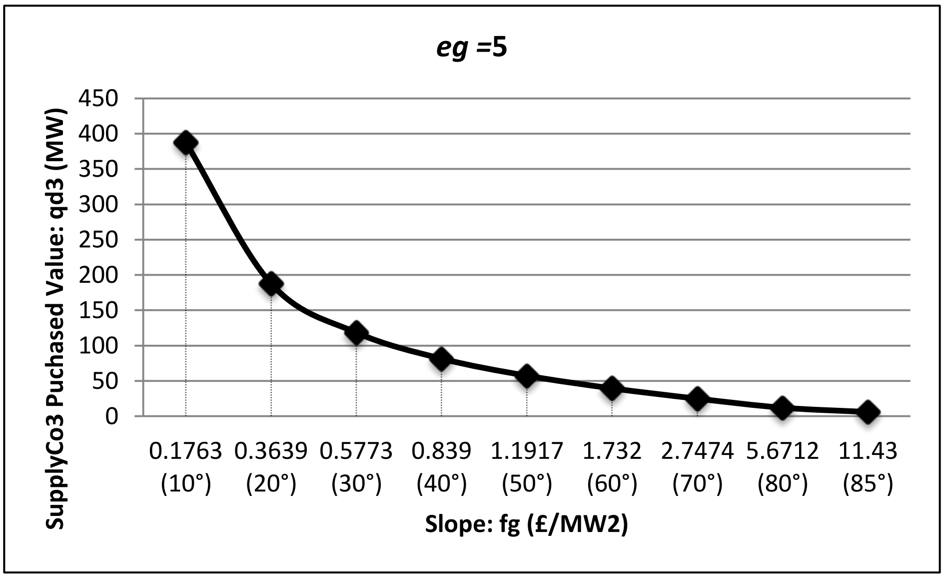


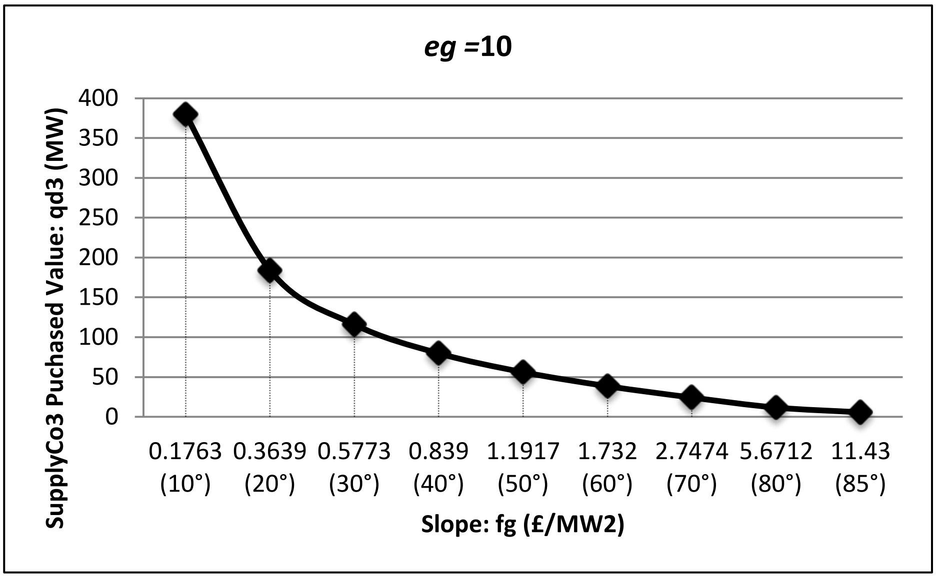

eg =50
SupplyCo2 Puchased Value: qd2 (MW)
350
300
250
200
150
100
50
0
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fg (£/MW2)

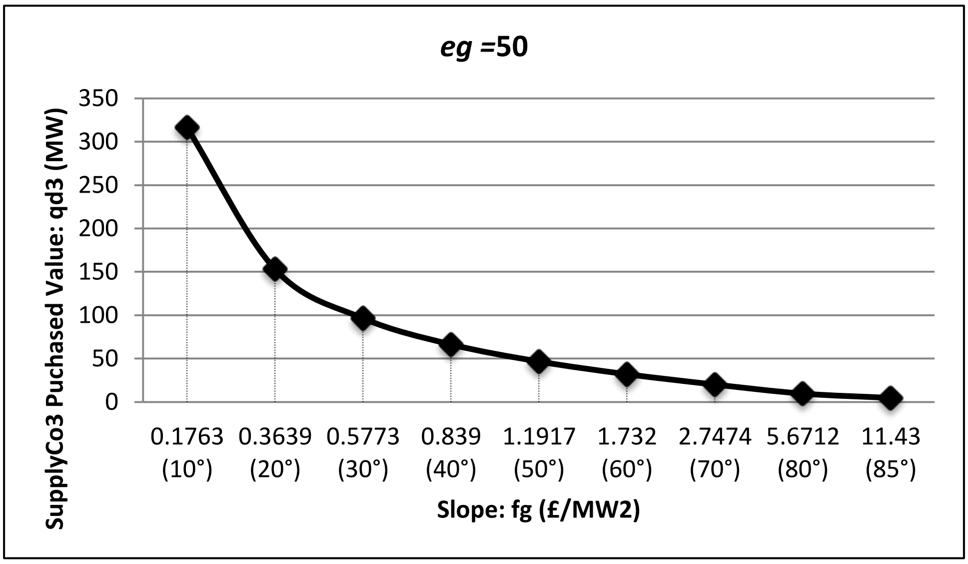

eg =80
SupplyCo2 Puchased Value: qd2 (MW)
300
250
200
150
100
50
0
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fg (£/MW2)


eg =100
SupplyCo2 Puchased Value: qd2 (MW)
250
200
150
100
50
0
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fg (£/MW2)

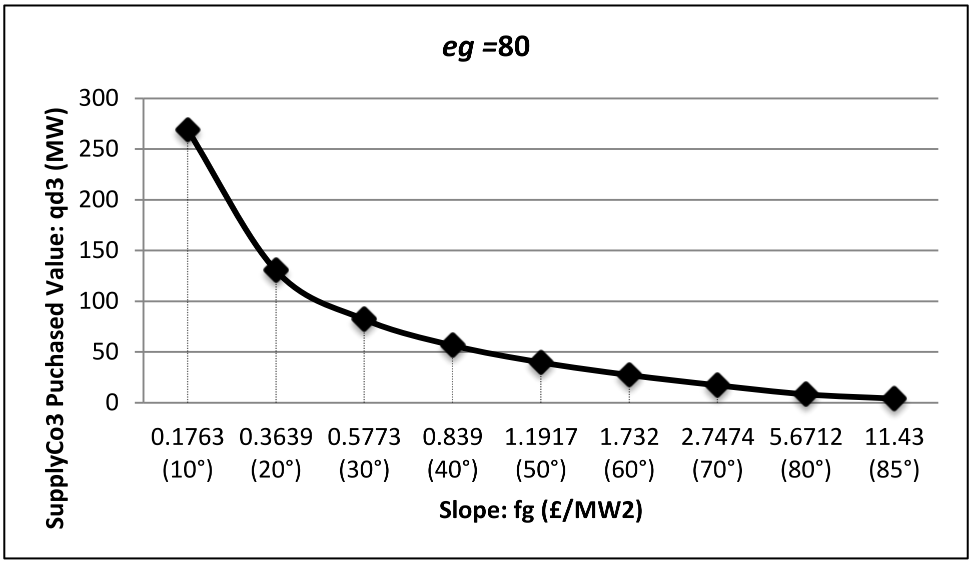

eg =120
SupplyCo2 Puchased Value: qd2 (MW)
250
200
150
100
50
0
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fg (£/MW2)


eg =5
SupplyCo3 Puchased Value: qd3 (MW)
450
400
350
300
250
200
150
100
50
0
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fg (£/MW2)

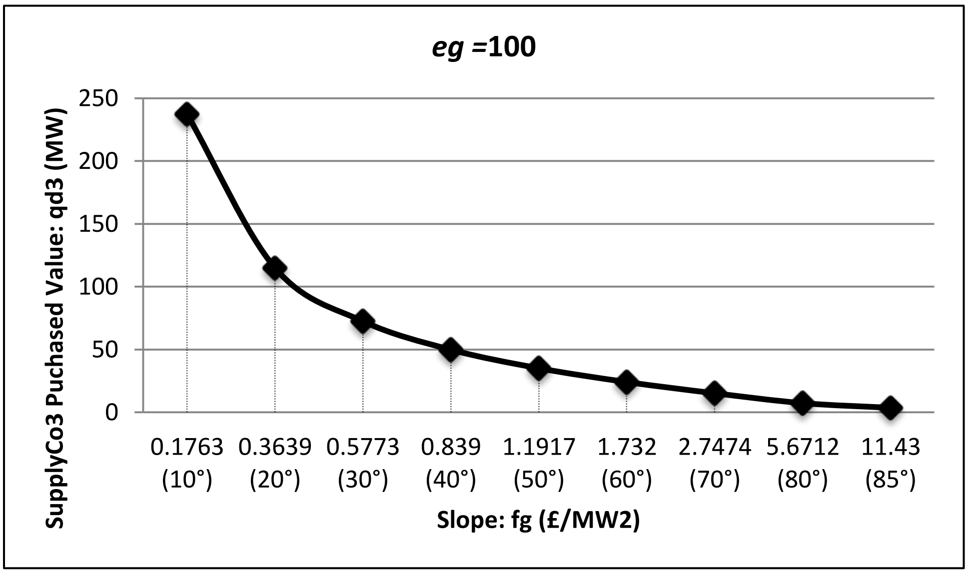

eg =10
SupplyCo3 Puchased Value: qd3 (MW)
400
350
300
250
200
150
100
50
0
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fg (£/MW2)



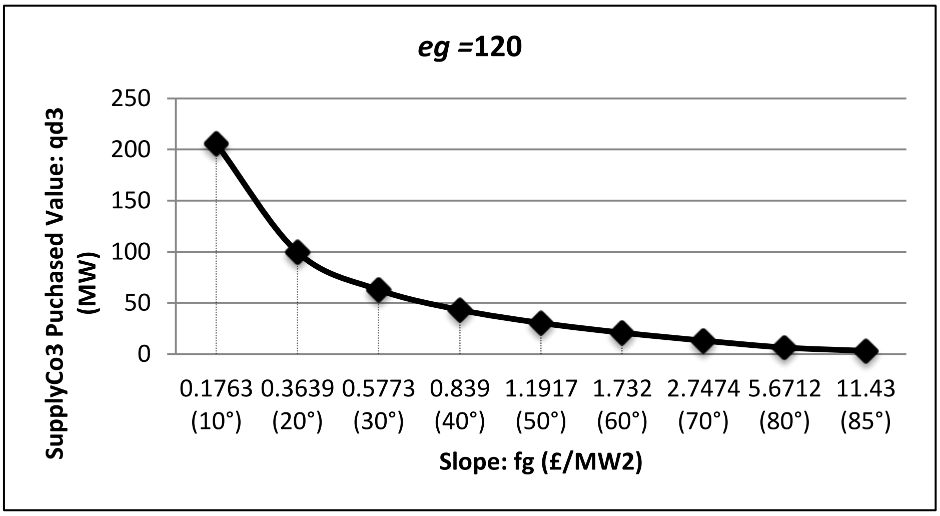
eg =50
350
300
250
200
150
100
50
0
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fg (£/MW2)
SupplyCo3 Puchased Value: qd3 (MW)



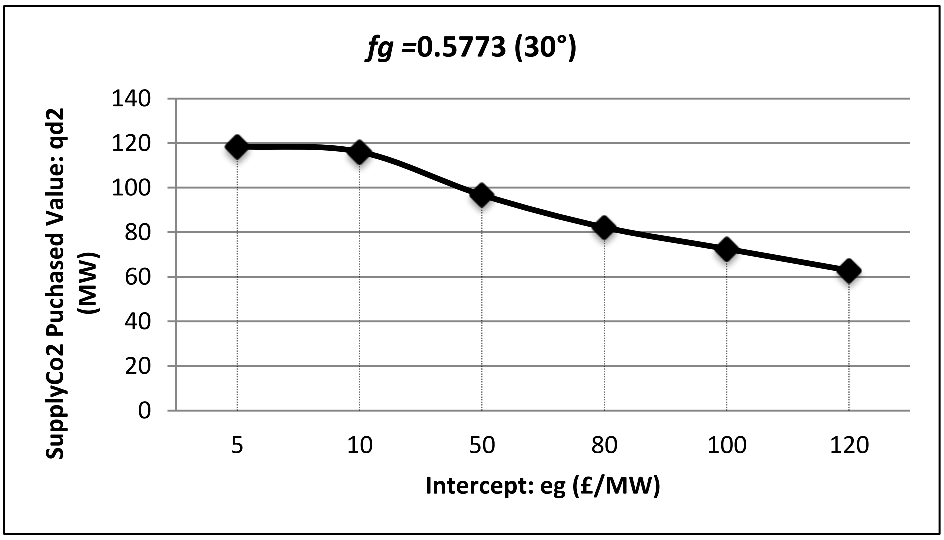
eg =80
300
250
200
150
100
50
0
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fg (£/MW2)
SupplyCo3 Puchased Value: qd3 (MW)

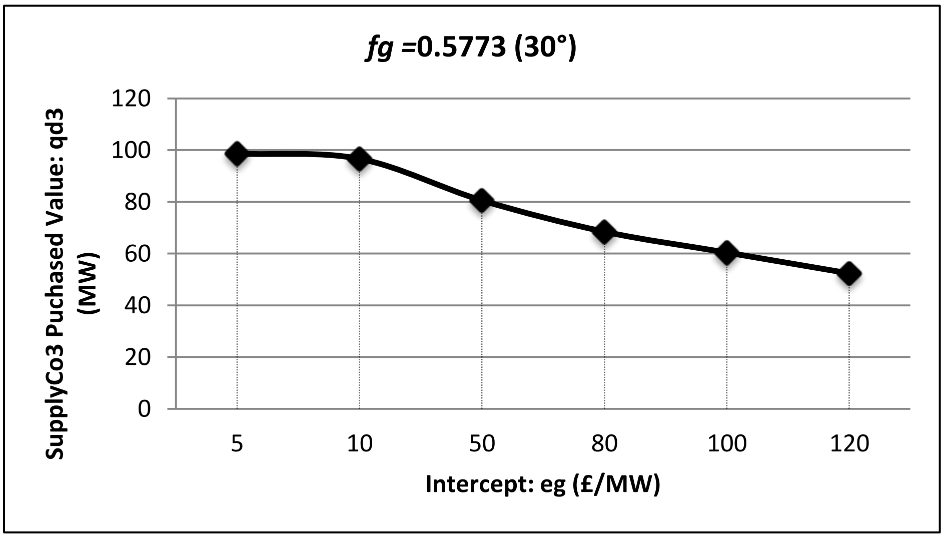


eg =100
250
200
150
100
50
0
0.1763 (10°)
0.3639 (20°)
0.5773 (30°)
0.839 (40°)
1.1917 (50°)
1.732 (60°)
2.7474 (70°)
5.6712 (80°)
11.43 (85°)
Slope: fg (£/MW2)
SupplyCo3 Puchased Value: qd3 (MW)

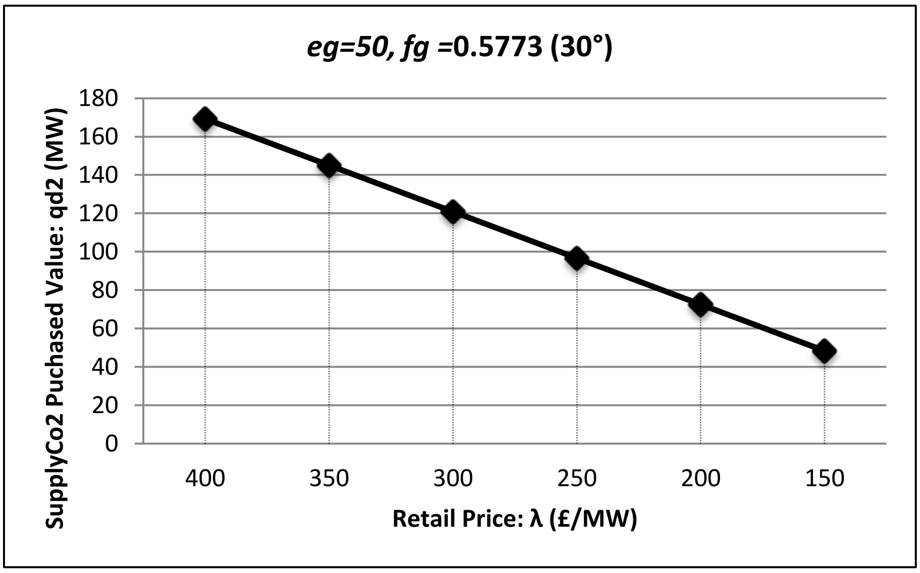


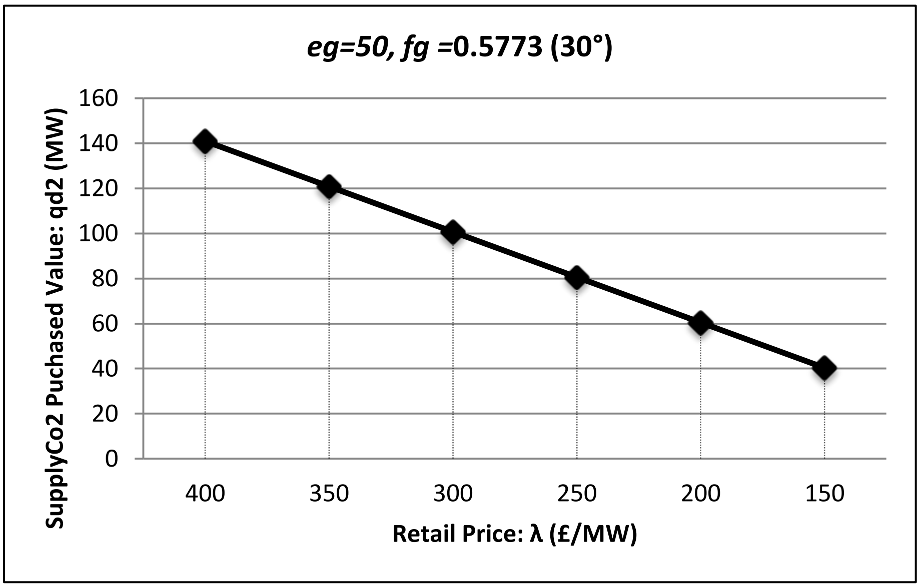
Additionally, the impacts of intercept on the purchased value by other SupplyCos have been investigated for a specific slope according to CVE formulations for oligopsonistic electricity market.





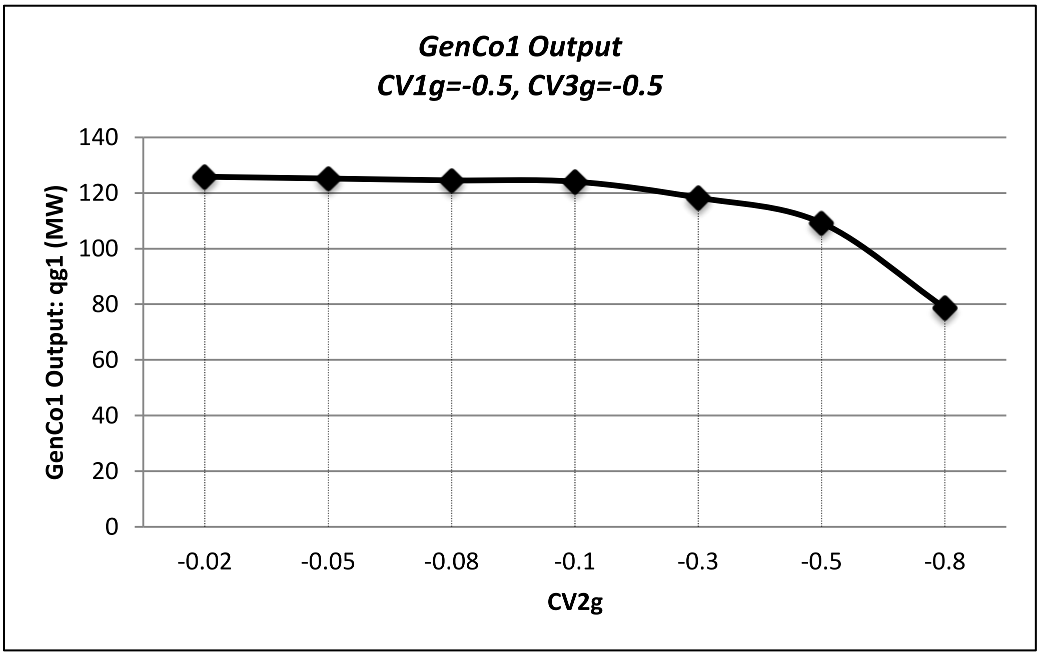
Furthermore, the impacts of retail price on SupplyCos 2 and 3 have been highlighted:

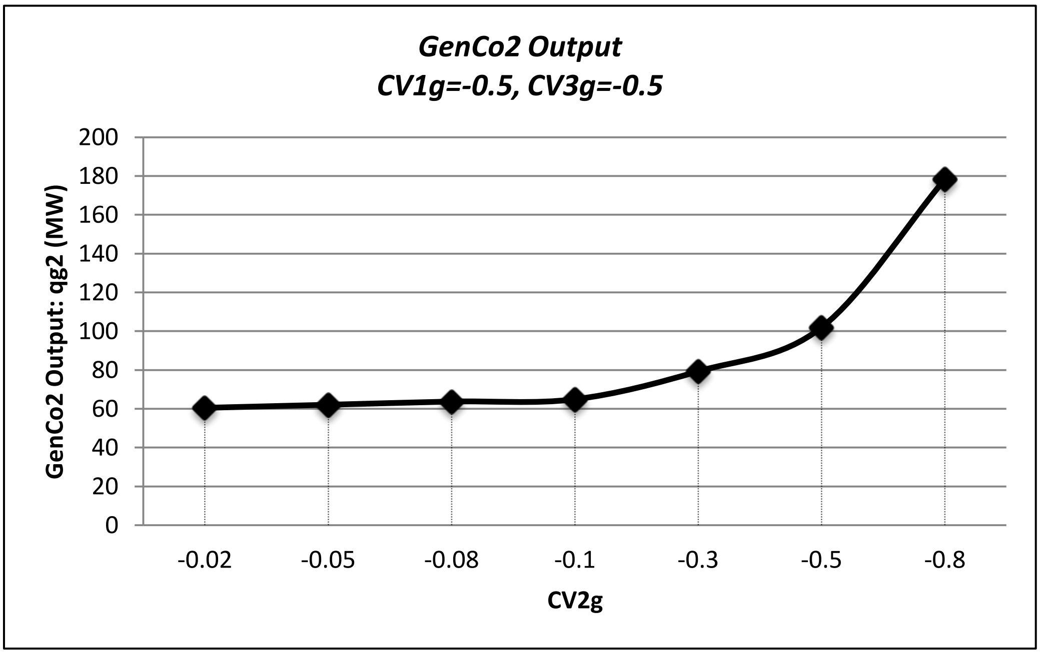


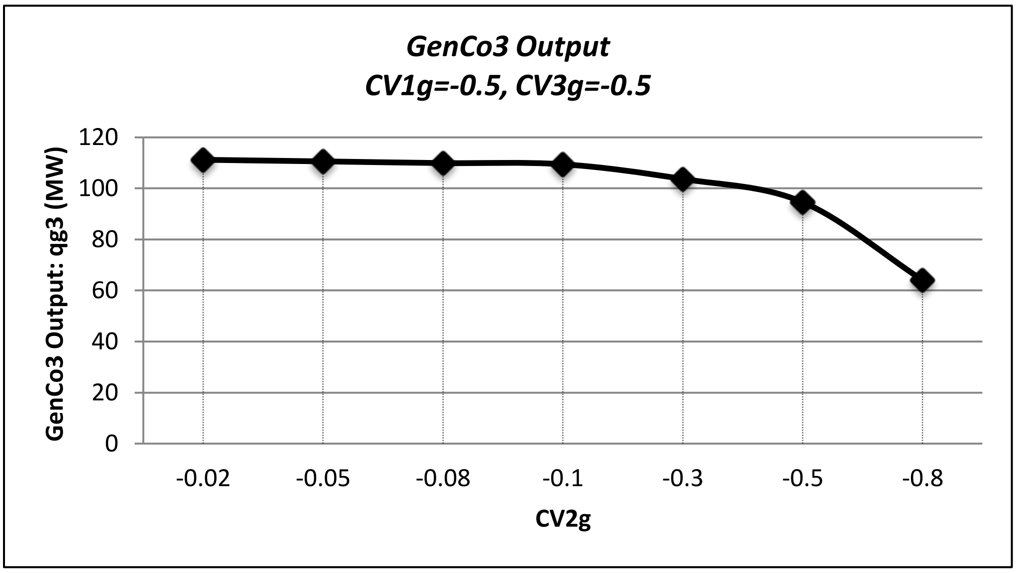


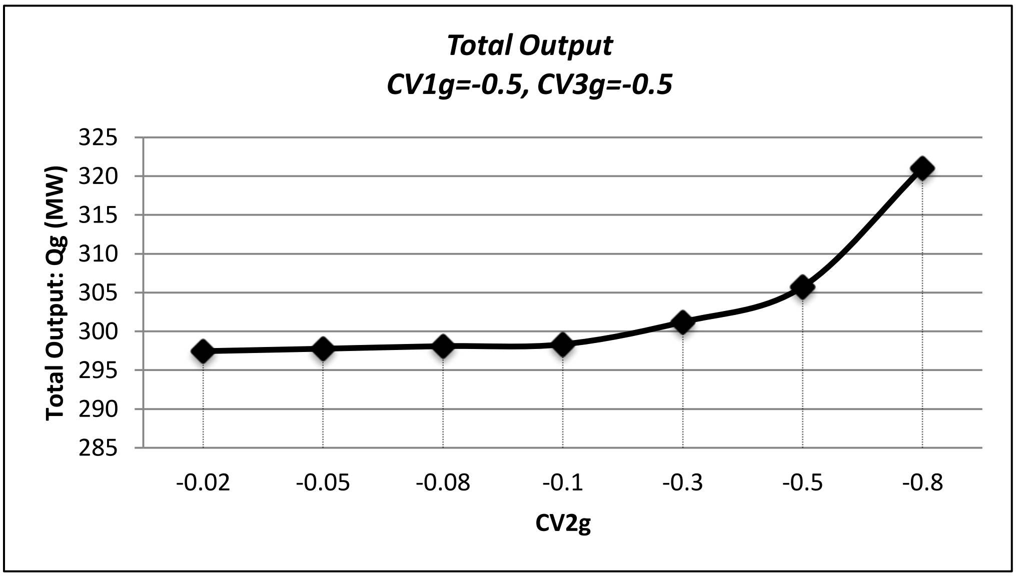
Appendix E

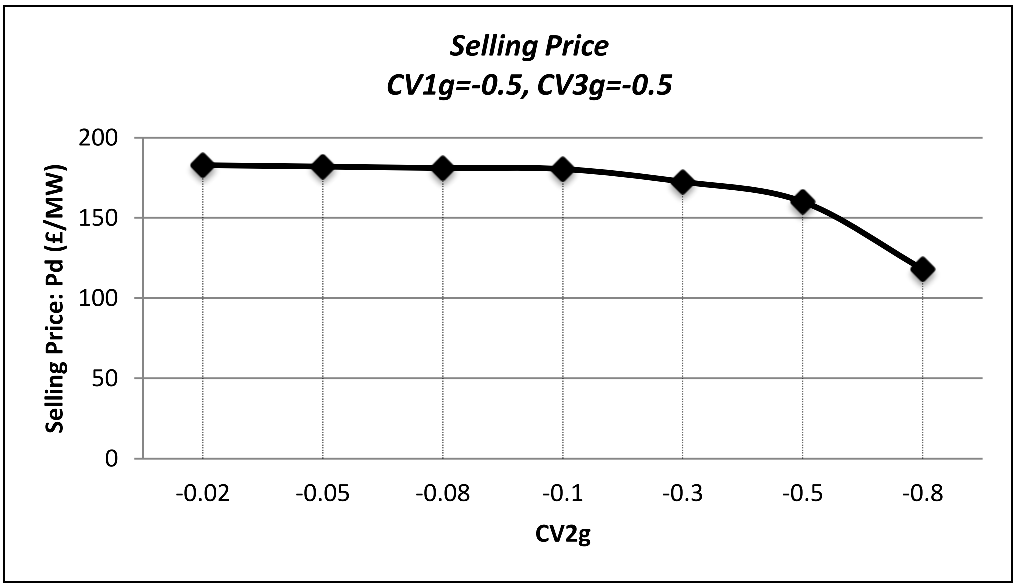
In this section, the impacts of CV_{2g} and CV_{3g} variations on the output of GenCos 1, 2, 3, total output and selling price have been investigated.

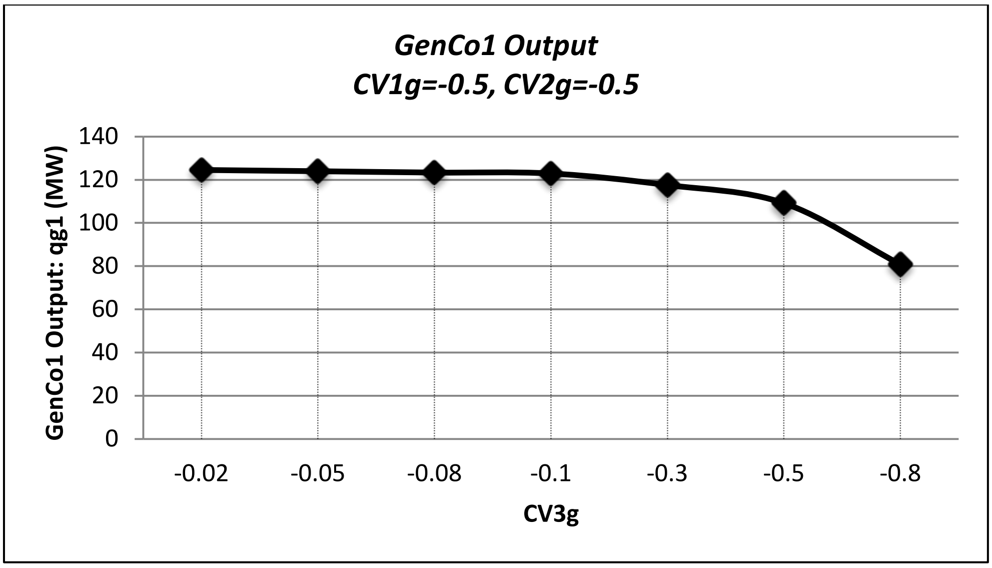


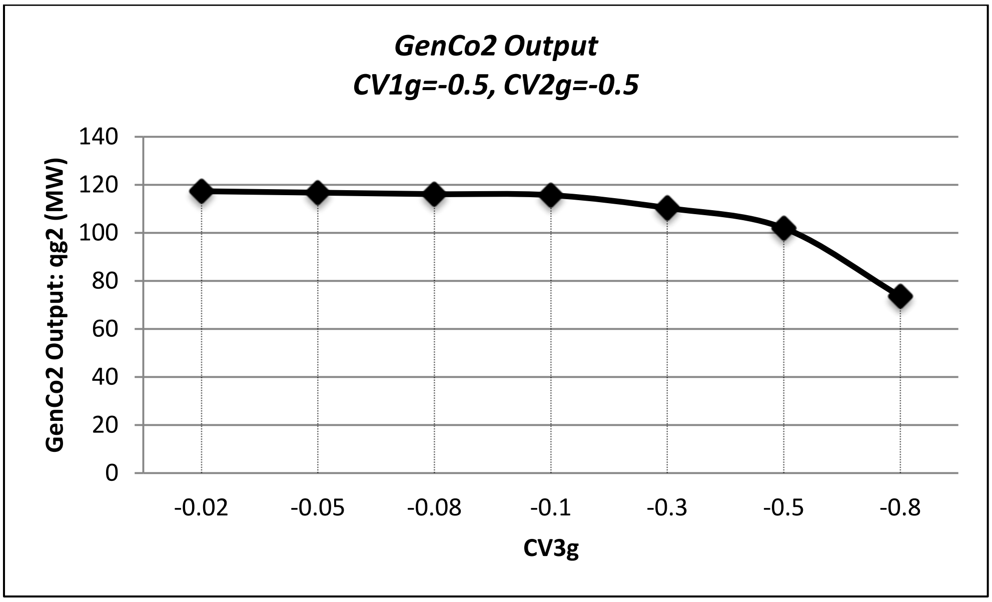


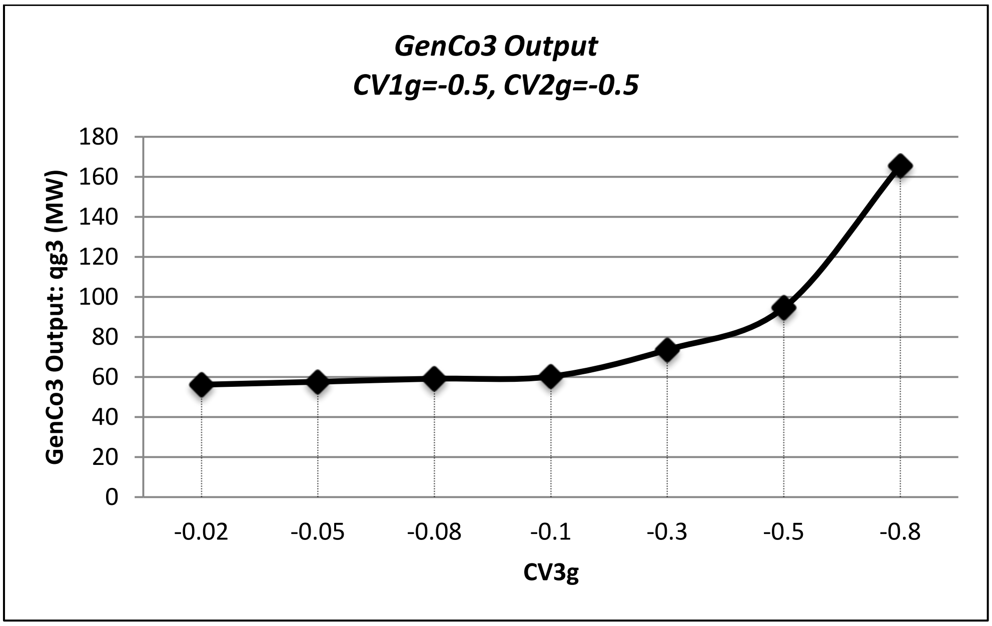

GenCo3 Output
CV1g=-0.5, CV3g=-0.5
GenCo3 Output: qg3 (MW)
0
20
40
60
80
100
120
-0.02
-0.05
-0.08
-0.1
-0.3
-0.5
-0.8
CV2g

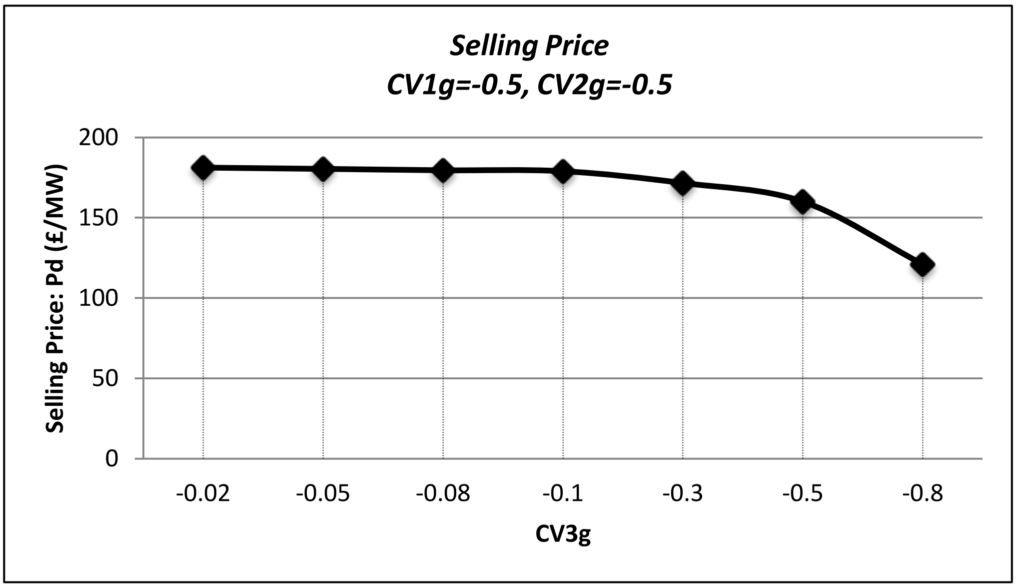

Total Output
CV1g=-0.5, CV3g=-0.5
Total Output: Qg (MW)
285
290
295
300
305
310
315
320
325
-0.02
-0.05
-0.08
-0.1
-0.3
-0.5
-0.8
CV2g

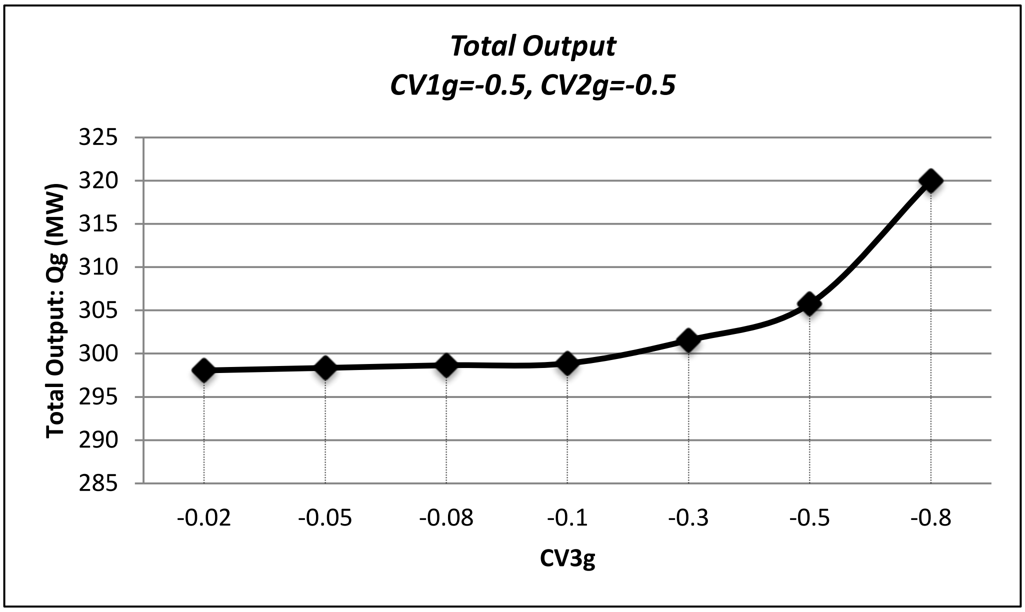

Selling Price
CV1g=-0.5, CV3g=-0.5
Selling Price: Pd (£/MW)
0
50
100
150
200
-0.02
-0.05
-0.08
-0.1
-0.3
-0.5
-0.8
CV2g


GenCo1 Output
CV1g=-0.5, CV2g=-0.5
GenCo1 Output: qg1 (MW)
140
120
100
80
60
40
20
0
-0.02
-0.05
-0.08
-0.1
-0.3
-0.5
-0.8
CV3g

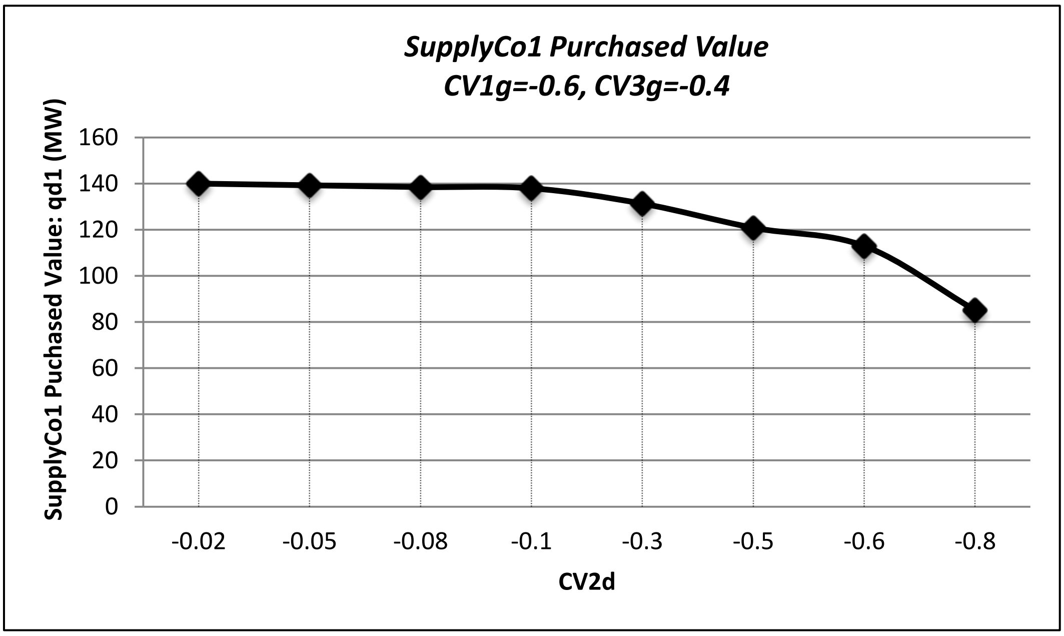

GenCo2 Output
CV1g=-0.5, CV2g=-0.5
GenCo2 Output: qg2 (MW)
140
120
100
80
60
40
20
0
-0.02
-0.05
-0.08
-0.1
-0.3
-0.5
-0.8
CV3g

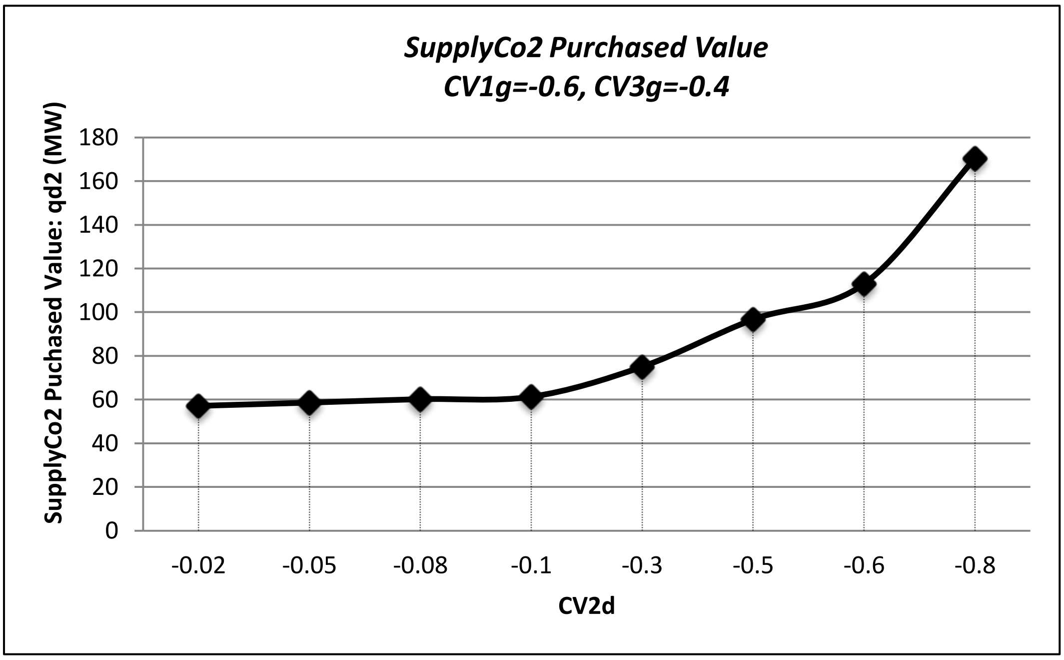

GenCo3 Output
CV1g=-0.5, CV2g=-0.5
GenCo3 Output: qg3 (MW)
180
160
140
120
100
80
60
40
20
0
-0.02
-0.05
-0.08
-0.1
-0.3
-0.5
-0.8
CV3g

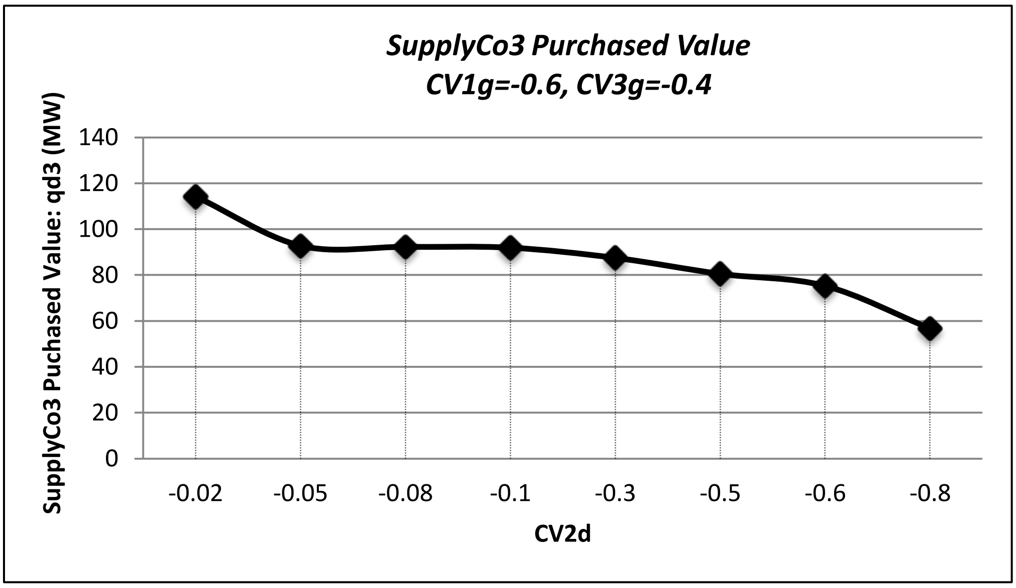

Selling Price
CV1g=-0.5, CV2g=-0.5
Selling Price: Pd (£/MW)
200
150
100
50
0
-0.02
-0.05
-0.08
-0.1
-0.3
-0.5
-0.8
CV3g

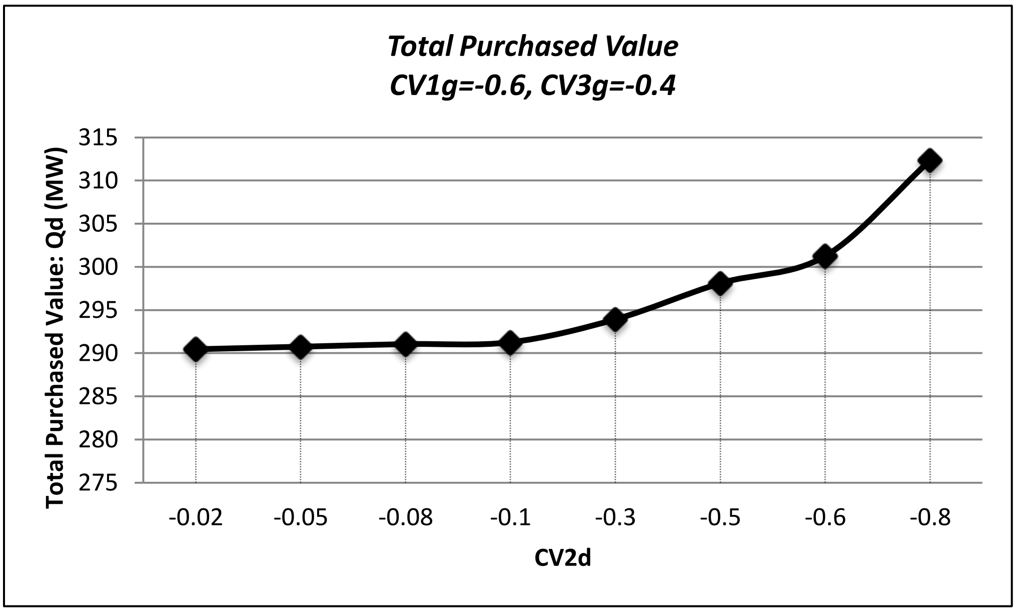

Total Output
CV1g=-0.5, CV2g=-0.5
Total Output: Qg (MW)
325
320
315
310
305
300
295
290
285
-0.02
-0.05
-0.08
-0.1
-0.3
-0.5
-0.8
CV3g

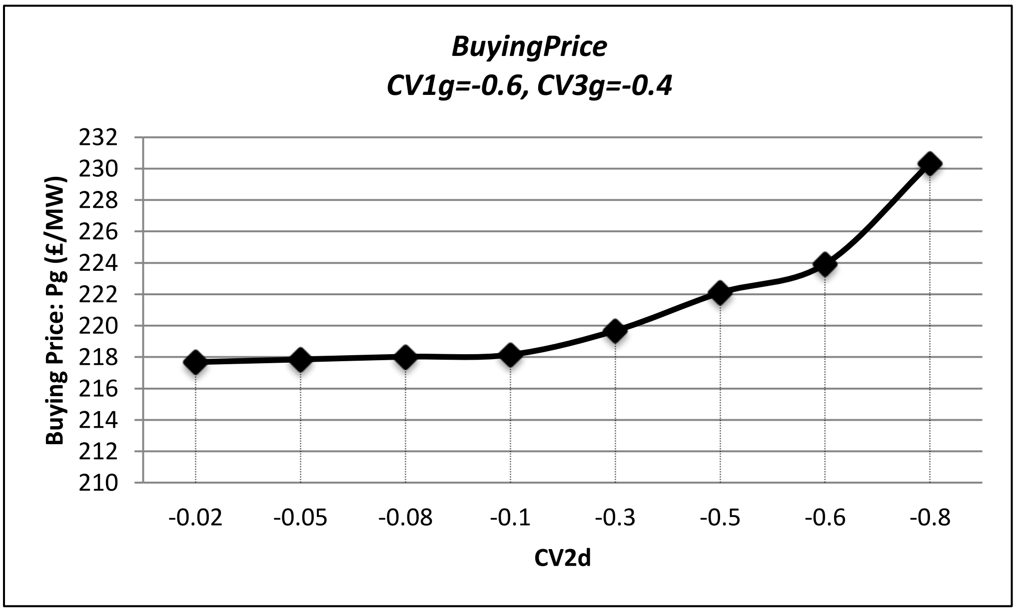
Additionally the impacts of CV_{2d} and CV_{3d} variations on the purchased value of SupplyCo 1, 2, 3, total purchased value and buying price have been investigated.

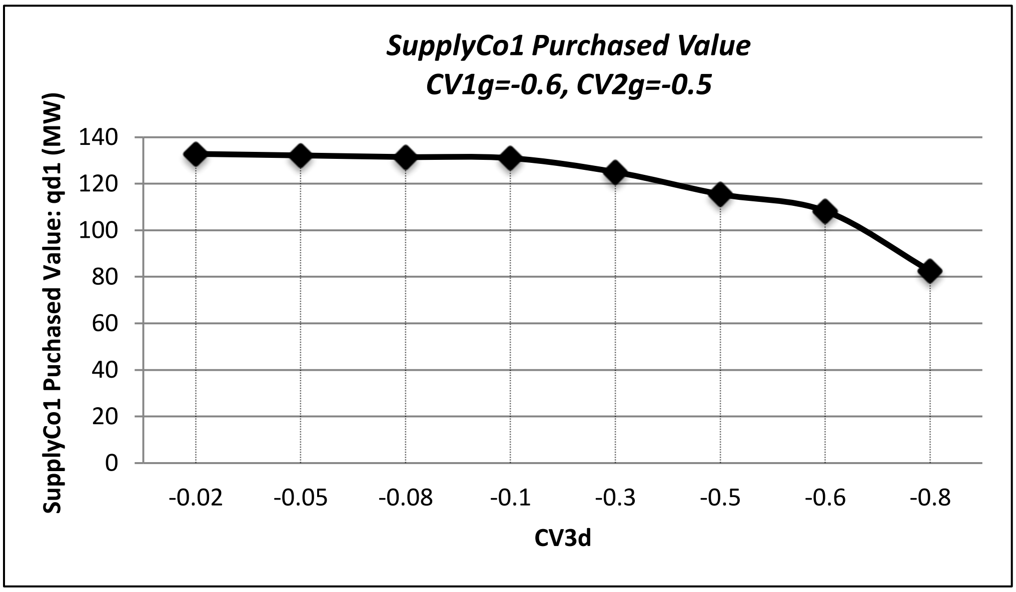


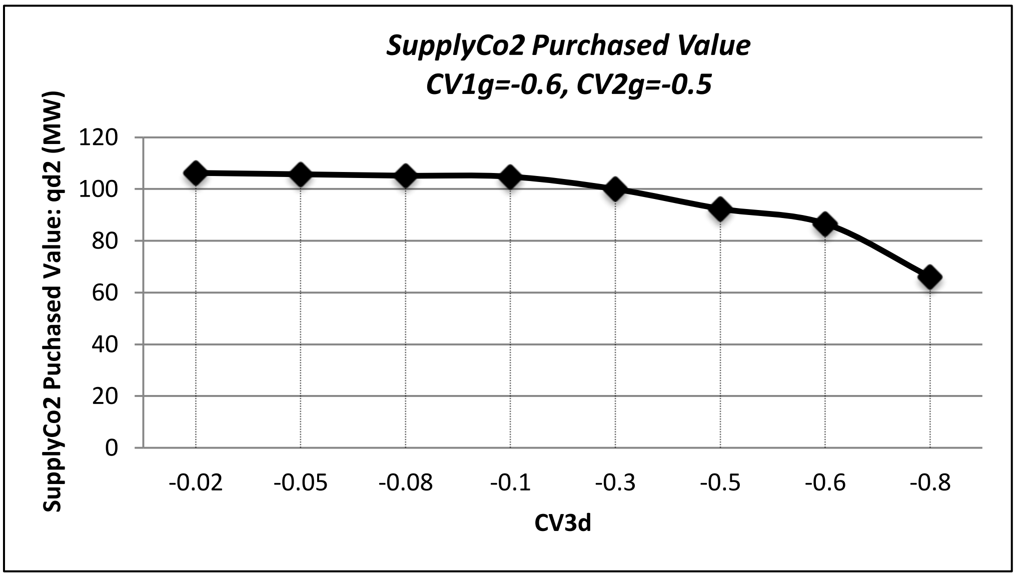


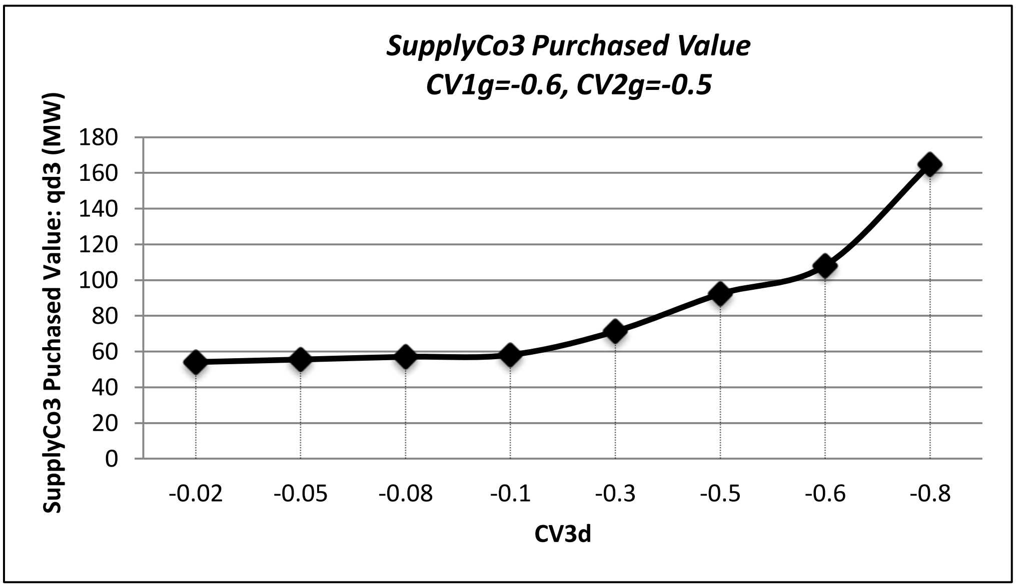

SupplyCo3 Purchased Value
CV1g=-0.6, CV3g=-0.4
SupplyCo3 Puchased Value: qd3 (MW)
140
120
100
80
60
40
20
0
-0.02
-0.05
-0.08
-0.1
-0.3
-0.5
-0.6
-0.8
CV2d

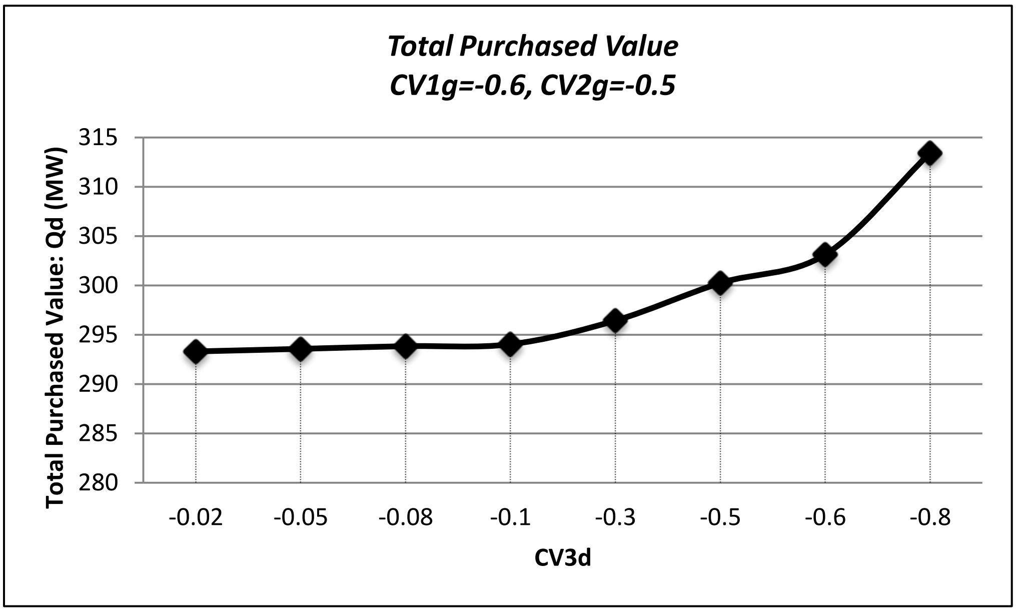

Total Purchased Value
CV1g=-0.6, CV3g=-0.4
Total Purchased Value: Qd (MW)
315
310
305
300
295
290
285
280
275
-0.02
-0.05
-0.08
-0.1
-0.3
-0.5
-0.6
-0.8
CV2d

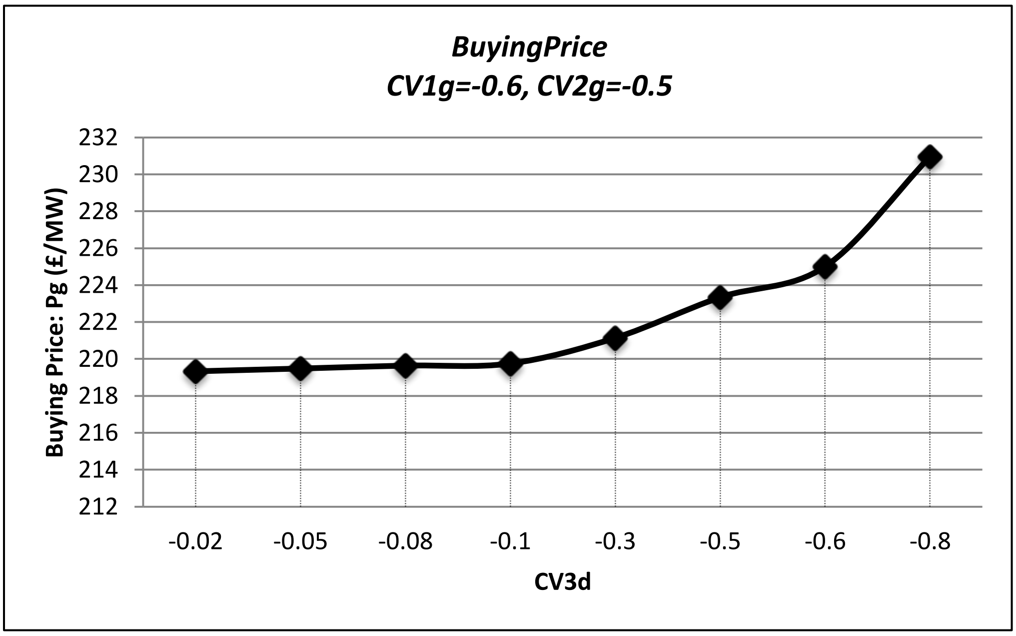

BuyingPrice
CV1g=-0.6, CV3g=-0.4
Buying Price: Pg (£/MW)
232
230
228
226
224
222
220
218
216
214
212
210
-0.02
-0.05
-0.08
-0.1
-0.3
-0.5
-0.6
-0.8
CV2d


SupplyCo1 Purchased Value
CV1g=-0.6, CV2g=-0.5
SupplyCo1 Puchased Value: qd1 (MW)
140
120
100
80
60
40
20
0
-0.02
-0.05
-0.08
-0.1
-0.3
-0.5
-0.6
-0.8
CV3d


SupplyCo2 Purchased Value
CV1g=-0.6, CV2g=-0.5
SupplyCo2 Puchased Value: qd2 (MW)
120
100
80
60
40
20
0
-0.02
-0.05
-0.08
-0.1
-0.3
-0.5
-0.6
-0.8
CV3d


SupplyCo3 Purchased Value
CV1g=-0.6, CV2g=-0.5
SupplyCo3 Puchased Value: qd3 (MW)
180
160
140
120
100
80
60
40
20
0
-0.02
-0.05
-0.08
-0.1
-0.3
-0.5
-0.6
-0.8
CV3d


Total Purchased Value
CV1g=-0.6, CV2g=-0.5
Total Purchased Value: Qd (MW)
315
310
305
300
295
290
285
280
-0.02
-0.05
-0.08
-0.1
-0.3
-0.5
-0.6
-0.8
CV3d


BuyingPrice
CV1g=-0.6, CV2g=-0.5
Buying Price: Pg (£/MW)
232
230
228
226
224
222
220
218
216
214
212
-0.02
-0.05
-0.08
-0.1
-0.3
-0.5
-0.6
-0.8
CV3d

Appendix F

```
%%%%%% Main Mfile for Electricity Market Equilibrium
Calculations %%%%%%%

clc

clear all

close all

global www

% Modifying the flat start

www=0;

% Asking User to Provide the Flat Start Points for Slopes and
Intercepts of Inverse Demand and Generation Curves:
% x (1,1) is the Inverse Demand Curve Intercept.
% x (2,1) is the Inverse Generation Curve Intercept.
% x (3,1) is the Inverse Demand Curve Slope.
% x (4,1) is the Inverse Generation Curve Slope.

x (1,1) = input(' Please Enter the Initial Intercept of
Inverse Demand Curve\n e1 = ');

x (2,1) = input(' Please Enter the Initial Intercept of
Inverse Generation Curve\n e2 = ');

x (3,1) = input(' Please Enter the Initial Slope of Inverse
Demand Curve\n f1 = ');

x (4,1) = input(' Please Enter the Initial Slope of Inverse
Generation Curve\n f2 = ');

% Executing PatterSearch Optimizer and Defining the Inequality
Constraints for the Optimizer

lb = [100 10 1.1917 0.0000001];

ub = [1100 250 11.43 2.7474];

Aineq = [-1 1 0 0];

bineq = [0];

options = psoptimset
('MaxIter',10000*12,'MaxFunEvals',10000*12,'TolMesh',1.0000e-
0090,'TolX',1.0000e-0090,'TolFun',1.0000e-
0090,'PlotFcns',{@psplotbestf,@psplotbestx,@psplotmeshsize,@ps
plotfuncount},'Display','iter');

% Calling Pattern1 Mfile
```

```
[x f] = patternsearch
(@pattern1,x,Aineq,bineq,[],[],lb,ub,[],options)

% Plotting the Final Inverse Demand and Generation Curves
According to the Co-ordination Algorithm and Output of
PatterSearch Optimizer and Illustrating the Equilibrium Point
of the Market

m=0:1000;

y1=x(1,1)-x(3,1)*m;

y2=x(2,1)+x(4,1)*m;

figure;

xlabel('Q')

ylabel('P')

plot(m,y1,'-',m,y2,'-.')

legend('Inverse Demand Curve','Inverse Generation Curve')

grid on;

%%%%% Pattern1 Mfile for Modifing Market Participants'
Specifications and Applying Oligopolistic and Oligopsonistic
Market Formulations by Calling Hierarchical Optimization
Algorithm Mfile%%%%%%


function f = pattern1 (x);

global www

global  conjecture_variation_G

global conjecture_variation_D


% Set Constant Variables such as: Number of GenCos and
SupplyCos, Retail Prices for Each SupplyCo and CVs Values for
Both GenCos and SupplyCos (Can be asked from users as well)

ngc = 3;

nsc = 4;

Pr = [280,290,300,310];

cost_function = [0 0 0 ;10 12 15 ;0.005 0.007 0.008];

    conjecture_variation_G = [-.01,-.02,-.03];

    conjecture_variation_D = [-.09,-.1,-.2,-.3];
```

```
% Calling the Hierarchical Optimization Mfile

[z] = Hierarchicalopt
(ngc,nsc,Pr,conjecture_variation_G,conjecture_variation_D,cost
_function,x);

% Objective Function

f = (z (1,1) - z (3,1)) ^ 2 + (z (4,1) - z (2,1)) ^ 2;

%%%%% Hierarchical optimization Algorithm for Both
Oligopolistic and Oligopsonistic Electricity Markets %%%%%


function [z] = Hierarchicalopt
(ngc,nsc,Pr,conjecture_variation_G,conjecture_variation_D,cost
_function,x);

global www

% Calculating the Output of Each GenCo

for k = 1 : ngc

    v (1,k) = x(3,1) * (2 + conjecture_variation_G (1,k)) +
cost_function (3,k) - x(3,1);

end

for kk = 1 : ngc

    b (kk,1) = x (1,1) - cost_function (2,kk);

end

y = diag (v) + diag (x (3,1) );

qg = y \ b

% Calculating the Total Output of All GenCos

t = 0;

for i = 1 : ngc

    t = qg (i,1) + t;

end

Qg = t;

z (1,1) = Qg

% Computung the Price ofr Inverse Demand Curve
```

```
Pd = x(1,1) - x(3,1) * Qg;

z(2,1) = Pd

% Calculating the Purchased Value by Each SupplyCo

for g = 1 : nsc

    vv (1,g) = x(4,1) * (2+conjecture_variation_D (1,g)) -
x(4,1);

end

for gg = 1 : nsc

    bb (gg,1) = Pr(1,gg) - x(2,1);

end

yy = diag (vv) + diag (x(4,1));

qd = yy \ bb

% Calculating the Total Purchased Value by All SupplyCos

ttt = 0;

for ii = 1 : nsc

    ttt = qd (ii,1) + ttt;

end

Qd = ttt;

z (3,1) = Qd

% Computing the Price for Inverse Genration Curve

Pg = x(2,1) + x(4,1) * Qd;

z (4,1) = Pg
```