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ON THE BATTLEGROUND OF ENVIRONMENTAL AND COMPETITION POLICY: THE RENEWABLE ELECTRICITY MARKET

by

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ON THE BATTLEGROUND OF ENVIRONMENTAL AND COMPETITION POLICY: THE RENEWABLE ELECTRICITY MARKET

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Renewable energy sources have become increasingly important in the efforts to provide energy security and to fight global warming. In the last decade environmental policy has increased the support for renewable electricity. At the same time the electricity sector was often subject of antitrust investigation because of relevant market concentration, and market power. This dissertation looks at the renewable electricity market to analyze the effect of environmental policy on competition.

The first chapter provides a short introduction into the regulatory schemes of electricity markets. The second chapter analyzes the demand side of the electricity market. The estimations show that there was no significant change in the income and price elasticity in the electricity consumption of the US households between 1993 an 2001, although there was several policy initiatives to increase energy efficiency and decrease consumption.

The third chapter derives a theoretical model where the feed-in tariff and the tradable green certificate system can be analyzed under oligopolistic market structure. The results of the model suggest that the introduction of the environmentally friendly regulatory schemes can decrease the electricity prices compared to the case when there is no support for renewable energy. The other findings of this model is that the price of electricity rises when the requirement for renewable energy increases.

In the fourth chapter a simulation model of the UK electricity market is used to test the effect of mergers and acquisitions under the environmental support scheme. The results emphasize the importance of the capacity limit, because it can constrain the strategic action

of the electricity producers. The results of the simulation also suggest that the increasing concentration can increase the production and lower the price of electricity and renewable energy certificates in the British Renewable Obligation system.

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I dedicate this dissertation to my family, it would not have been possible without their constant love, support and encouragement. Köszönök mindent, dziękuję za wszystko.

Mészáros Mátyás Tamás

TABLE OF CONTENTS

CHAPTER

Table of Contents – Continued

CHAPTER

APPENDICES

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

Renewable Energy Markets

1.1 Introduction

As the scientific evidence builds, global warming is emerging as one of the biggest threats to humanity. One of the main causes of global warming is the increasing emission of greenhouse gases (UNEP Intergovernmental Panel on Climate Change, 2007), and the energy sector plays one of the biggest roles in this process. For example, in the United States the biggest part, 34% of the total CO_2 emission, comes from electricity generation (EPA, 2008). Several policies exist that help reduce the amount of the greenhouse gas emissions in this sector. The main two methods to achieve this goal without direct "command and control" intervention in the market are the emission rights trading schemes, and the system of tradable green certificates. The first one limits the total maximum emission and leaves the optimal allocation of emission rights to the market. The disadvantage of this method is that it limits the maximum electricity production and consumption compared to the case when there is no regulation. The second policy is more flexible in this field; the tradable green certificate is a support scheme for green and renewable energy to substitute other fossil-fuel sources. This method can decrease the greenhouse gas emission without any constraint in the overall energy production.[1]

This first chapter gives a short description of the electricity markets and provides an introduction as to how the environmental regulation changed this sector by creating the markets of tradable green certificates.

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[1] Although the higher cost of the renewable electricity can decrease the total consumption.

1.2 The regulation of the electricity sector

Electricity is a special good because it cannot be stored[2] so the supply must always be equal to the demand. The sector can be divided into three parts: generation, which is the electricity production of the power plants; transmission, which is the transportation of electricity on the grid; and distribution, which is made by the utilities converting, delivering, and metering the electricity. The generation and the transmission of electricity are capital intensive industries, which can create an entry barrier and natural monopoly. The creation of the monopoly power is helped by the fact that electricity has no substitutes in many cases. In addition, the electricity sector is a particularly strategic branch of the economy because, without electricity the whole economy can be stopped. These are the main reasons why this sector is widely regulated in all developed countries based on careful considerations, like energy security and reliability.

At the onset of the first regulation of the electricity sector, the market players were treated as a controlled monopolist, using price cap regulation. This method provided a maximum price for the utilities and power plants, allowing them a reasonable profit rate on their investments. This view of regulation changed in the 1990s, when the regulatory authority realized that the transmission is the only bottleneck monopoly in this sector, and there can be competition in the generation and the distribution side of the market if there is free access to the transmission grid. This change in the economic concepts resulted in a restructuring and liberalization of the electricity markets. The regulatory authorities started to separate the transmission from the generation and distribution by trying to grant access to the transmission grid for everyone, hoping that this would introduce competition in the sector, improving the efficiency, and therefore abolishing the need for price regulation.

The first change in the regulation of the electricity sector in the European Union (EU) is the 96/92/EC Directive on the liberalization of the electricity market. This was extended

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[2] As a last resort there are some special possibilities, like pumped hydropower, but it is very costly and inefficient.

by the 2003/54/EC Directive about the common electricity market. These two directives aim for the free entry into the electricity market in any country of the EU without any administrative obstacles. The example of the free and open electricity market is the power exchange, which works like a stock exchange. In the power exchange, most of the trade takes place in the forward market for the following day, and the products are the standardized amount (1 MWh) of electricity delivered into the transmission grid for a given hour of the next day. Usually the price for the peak hours (8-20) is higher than for the off-peak hours. In addition, there is a spot market which does the balancing of the system, equalizing the demand and the supply in real time. The extra available capacities are sold to providers who did not buy enough electricity on the previous day.

These directives on market liberalization aim to separate the production and distribution from the transmission in the energy sector as well. These legislations are directives and not regulations; they just describe the principles and goals for the governments and each member state can decide what type of law or regulation to use to reach the target described in the directive during the given period of time.

The market opening created one new problem: the possibility of increased market power. In the electricity sector, there are large vertically and horizontally integrated concerns owning large production and distribution capacities. With the removal of the price control, there is a possibility for abuse of market power in the market of electricity generation because it is very capital-intensive with a huge sunk cost which creates an entry barrier. In addition, the huge and long administrative procedure to set up a new power plant makes impossible a "hit and run" entry, which could force down the prices like in contestable markets.

The market power is a serious concern in the EU. Matthes et al. (2007) showed that there is significant market concentration in Europe in the field of electricity generation. The latest report of the European Commission mentions as well that the market concentration is relevant and there are possibilities to exercise market power (European Commission, DG Competition, 2007). In addition, this report emphasizes the importance to review the mergers and acquisitions in this sector. In the last years, the energy sector was very active in the field of merger and acquisitions. The number of transactions grew from 154 in 2003 to 768 in 2007, and the value of the transactions grew from 43 billion USD to 372.5 billion USD (Pricewater Waterhouse Coopers, 2008). The biggest part of the transactions took place in Europe and more than half of the deals were domestic. There is no clear trend; there is vertical integration such as the French power company Suez merging with the domestic gas supplier Gaz de France to ensure cheaper gas supply for production, or there is horizontal intergration like when the Italian Enel bought the Spanish Endesa to gain relevant size on the European market (Verde, 2008). There are horizontal mergers and acquisitions on domestic markets as well: one of the latest acquisitions of the Scottish and Southern Energy, the second largest British gas and electricity supplier, is Airtricity, a renewable energy company operating wind farms in the UK.

1.3 Environment friendly regulation in the energy sector

The first regulatory measures in relation to environmental protection came in the '80s. The so-called "carbon taxes" were direct state interventions in the sector. In the '90s, with liberalization of the sector, a new system was introduced for CO_2 emission reduction with the name of "tradable emission rights". Later, at the end of the '90s, parallel to the technological development in the field of renewable energy production, two new regulation schemes emerged to support the diffusion of green electricity: the feed-in tariff and the market based tradable green certificates system. In the following sections, the operation of these regulations in the renewable energy sector is described based on Pál (2002), Mészáros (2003) and Bertoldi, Rezessy, Langniss, and Voogt (2005).

The concept of the green certificate and the feed-in tariff is connected to renewable resources and it tries to promote the usage of environmental friendly energy sources. The reason for the insufficient usage of renewable resources is the fact that electricity production by these methods is much more costly than production in a normal fossil fuel power plant. Table 1.1 summarizes the total levelized production cost of 1 MWh electricity from different renewable and non-renewable resources.

Table 1.1 Electricity Production Costs in USD/MWh for Different Energy Sources

Energy source	Minimum	Maximum
Non-Renewables		
Coal	25	60
Gas	37	63
Nuclear	21	50
Renewables		
Wind	35	140
Small Hydro	40	100
Photovoltaic/Solar	150	300

Source: OECD Nuclear Energy Agency and International Energy Agency (2005)

The data shows that the renewable energy sources have higher cost range than the non-renewable energy sources. This is the reason why renewable electricity producers can not survive without subsidies in the liberalized electricity market where they have to compete with the cheaper fossil-fuel power plants. The goal of the environmental regulation is that it can generate extra revenues for the renewable electricity producers with low negative externalities and environmental pollution. In the case of the feed-in tariff, the state provides direct financial subsidies to the renewable electricity producers by purchasing their product at a higher price than the market price. This artificially high income insures the survival of these power plants. The tradable green certificate system was originally designed to replace the feed-in tariff regulation by substituting the direct financial state intervention in the energy sector with market-conform methods.

The new system works in the following way: The renewable producer does not have a direct state subsidy, but receives a universal certificate confirming that the energy it sells is environmentally friendly. The government does not buy renewable electricity at a higher price, thus all producers have to sell their electricity on the power exchange. On the free electricity market, however, the "green" energy is unable to compete in prices with "black" energy.[3] At the market clearing price the producers of renewable electricity certainly would suffer losses. The government helps these companies to convert the certificates into money not only to recover the losses but also to earn profit and be sustainable in the market. The renewable energy production provides the supply side of the green certificates market, but there is no demand for certificates without any governmental intervention. The environmental regulation requires each electricity provider and distributor to use renewable energy to a certain proportion of the total distributed electricity. [4] If the electricity providers do not fulfill this minimum requirement, they have to pay a fine for the missing quantity or face other types of penalties like revoked licenses. The only way they can avoid the penalty without using green energy is to buy the sufficient amount of green certificates from the renewable producers.

It is important to make a clear distinction between the two markets involved in this process: the electricity market and the market of green certificates. This clear division ensures that the electricity providers do not have to buy the certificates and electricity from the same producer. This way the providers can buy no green electricity but only green certificates.

The separation of certificates and electricity increases efficiency because the market will support the most efficient technologies. The lowest cost technologies will supply most of the certificates at the lowest market price, and the more expensive technologies will have smaller market share because they are less efficient.

1.4 Regulation of renewable energy in the European Union

The renewable electricity market is regulated by the 2001/77/EC Directive which gives the base for the support of the renewable energy in the European Union. The directive aims to double the level of electricity from renewable energy sources (RES-E) by 2010. Table 1.2 shows the target level for each EU country. The target level is determined on the

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[3] The "green" is used for the renewable resources and the "black" for the fossil fuel sources.

[4] This is the reason why the United States calls this system the Renewable Portfolio Standard.

potential of renewable resources of each country. The countries with higher quotas (e.g. Austria, Sweden) are typically countries abundant with hills and fast rivers, where there is a huge potential for hydro power plants, and where it is already the main energy source of that country.

Table 1.2 National Indicative RES-E Targets by 2010 for EU Member States

	RES-E % in 1997	RES-E % in 2010
Austria	70	78
Belgium	1.1	6
Denmark	8.7	29
Finland	24.7	31.5
France	15	21
Germany	4.5	12.5
Greece	8.6	20.1
Ireland	3.6	13.2
Italy	16	25
Luxembourg	2.1	5.7
Netherlands	3.5	9
Portugal	38.5	39
Spain	19.9	29.4
Sweden	49.1	60
UK	1.7	10
Cyprus	0.05	6.0
Czech Republic	3.8	8.0
Estonia	0.2	5.1
Hungary	0.7	3.6
Latvia	42.4	49.3
Lithuania	3.3	7.0
Malta	0.0	5.0
Poland	1.6	7.5
Slovakia	17.9	31.0
Slovenia	29.9	33.6
EU 25	12.9	21.0

Source: Commission of the European Communities (2004)

Since the 2001/77/EC is a directive, each country can define their own pace and tools to reach the yearly increasing rate of renewable energy to finally fulfill the long run goal given in this law. The increasing requirement rate is revised based on the market outcome of the past years and the technical limits of the transmission network.[5]

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[5] Since much renewable electricity production depends on weather conditions, the size of the balanc-

The two main types of tools to support renewable resources are the feed-in laws and the tradable renewable energy certificates. The feed-in laws are more common among the member states, but they are not supported by the EU because they are based on direct state intervention in the market.

1.4.1 Renewable Feed-in Tariff (REFIT)

Under the feed-in regulation, each renewable producer can join to the transmission grid and feed-in their production. Each electricity provider should pay a higher price for the required level of renewable electricity which is is often called "feed-in tariff". This tariff is usually higher than the market clearing price of electricity on the power exchange, which is mainly determined by the big fossil-fuel power plants.

This higher price is a fixed amount given by the regulatory authority for each type of renewable resource, or in many cases it is a fixed proportion of the price of the electricity on the free market. The extra cost of the renewable energy, which is above the electricity price of the power exchange, is reimbursed by the government to the providers.

The base of this reimbursement is the Guarantee of Origin (GoO) system, which works in the following way: The governmental regulatory authority runs an office which certifies for each renewable energy producer the amount of energy produced, from what sources, and by what technologies. There are slight differences in the regulation of which power plants can take part in this program. In some countries, the big producers are excluded, since they can reach the economies of scale. In other countries, the power plants can receive these certificates for only a limited time, usually for 8-10 years starting from the investment. The reason for the time limit is that the government wants to help the introduction of the renewable energy and then leave the market alone. In addition, the government expects that with technological development and with the changing attitude of the people towards renewable resources the production of renewble electricity will become profitable.

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ing capcity in the system can constrain the maximum level of the production of electricity from renewable sources.

Under the feed-in laws, when the renewable producer sells its energy to a provider, the producer has to give the GoO to the provider. The provider then submits these certificates to the regulatory authority for reimbursement of the higher feed-in tariff. This clearing happens usually one time in a year and the certificates are then removed from circulation.

1.4.2 Tradable Renewable Energy Certificate (TREC)

The other type of regulation, which is preferred by the EU, is the tradable renewable energy certificate[6] system. In this case ,the flow of electricity and the GoO certificates flow are separated. The renewable producers have to sell their electricity on the power exchange.

Under the green certificate system, the renewable producers will sell their electricity on the power exchange competing with other non-renewable electricity producers. They then submit their GoO certificates and register them in the TREC system[7]. These registered GoO certificates are transformed to green certificates in the TREC system. The ownership does not change during the registration; the renewable power producers will be the owner of the green certificates. The GoO is transformed to green certificates at different exchange rates, depending how environmentally friendly the production technology. The rate of conversion is determined by the regulatory authority. The green certificates have a common denomination, usually 10-100 MWh, and are valid only for a given period of time. This registration system provides the supply side of the green certificates market.

The demand under the TREC system is generated by the minimum requirement, often called "mandatory quota obligations". In most of the countries, the minimum requirement regulation requires each provider to surrender to the regulatory authority a minimum number of green certificates in a given month of each year. This amount is a fixed proportion of the total electricity supplied by the provider. The cost of the certificates is paid by the utilities and, by surrendering the minimum level of green certificates, the providers can

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[6] This certificate is often called "the green certificate".

[7] Usually this registration system is operated by private companies.

avoid facing any penalty.

In the TREC system, the certificates are traded like in an exchange. In some countries, they are traded together with the emission rights on the power exchange, and in some other countries there is a separate market for them. The green power producers can trade their GoO without registration as well, but since it is not registered in the TREC system, it cannot be used to fulfill the quota obligation.

The current EU regulation allows each provider to produce some proportion of their supplied electricity in their own power plants. Among these electricity generation stations there can be renewable plants as well. The providers make their own decision about how they deal with the extra cost of the certificates. It can be that they offer a special "renewable energy mix" to customers at higher prices, or since the demand for such products is very small, usually the distributors spread this extra cost over all customers.

After the date of surrender of the green certificates, all the used and unused certificates in the GoO and in the TREC system are erased, and a new year starts. There is no option to bank and take over the extra unused certificates for the next year, although there is an option to trade them with other member states before they expire. The yearly clearing of the certificates ties the production of renewable energy to the amount of certificates. If it is possible to use the certificates at a later time, the renewable plants can then hold back the renewable energy certificates to increase the prices in the present and sell the unused green certificates in the future to deter new entrants attracted by the higher prices in the present.

1.5 The first experiences of the TREC

By 2006 only five of the 27 EU members introduced some type of tradable renewable energy certificates system. The results are mixed, but in some countries the changes in the price of the certificates and production show a clear trend. Tables 1.3 to 1.7 summarize the market outcomes of the electricity and renewable electricity market in these countries.

Table 1.3 The Electricity Market in Belgium (Flanders)

Year	Quota[a]	Punishment[a] Euro/MWh	Price of certificate[a] Euro/MWh	Consumer price of electricity[b] Euro/MWh
2002	0.80%	75	73.85	173.30
2003	1.20%	75	91.18	169.20
2004	2.00%	100	109.01	174.20
2005	2.25%	125	110.30	181.40
2006	2.50%	125	110.00	181.70

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[a] *Source: Vlaamse Reguleringsinstantie voor de Elektriciteits- en Gasmarkt*
[b] *Source: EUROSTAT*

There are two special features of the TREC system in Belgium. First, there is a minimum level of the certificate price which is determined by the regulatory authority (Vlaamse Reguleringsinstantie voor de Elektriciteits- en Gasmarkt). Second, from 2004 on, the GoO certificates are valid longer and can be registered within 5 years from the issue. Table 1.3 shows that the price of the certificates and electricity was mostly rising in the last couple of years.

Table 1.4 The Electricity Market in Italy

Year	Quota[a]	Price of certificate[a] Euro/MWh	Consumer price of electricity[b] Euro/MWh
2002	2.00%	84.18	94.70
2003	2.00%	82.40	101.10
2004	2.35%	97.39	96.30
2005	2.70%	108.92	102.00
2006	3.05%	125.28	111.70

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[a] *Source: Gestore dei Servizi Elettrici*
[b] *Source: EUROSTAT*

In Italy there are two special rules in the TREC system: first, the minimum requirement has to be fulfilled by the power producers and the electricity importers; second, there is no fixed penalty for not fulfilling the obligation. If a company does not comply with the minimum requirement, then the system operator can limit the power plant access to the grid or impose a fine for the mandatory quota equal to one and a half times the maximum price of the green certificates in the market. The first experiences of Italy are similar to Belgium, because the price of the certificates was rising along the electricity price.

Table 1.5 The Electricity Market in Poland

Year	Quota[a]	Punishment[a] PLN/MWh	Price of certificate[b] PLN/MWh	Consumer price of electricity[c] PLN/MWh
2005	2.5%	240.00	175.00	391.00
2006	3.0%	240.00	219.00	410.10

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[a] *Source: Ministry for Economic Affairs*
[b] *Source: Towarowa Giełda Energii*
[c] *Source: EUROSTAT*

In Poland the TREC system was introduced only at the end of 2005. The first outcomes of the market show the same trend, as in previous cases, that the price of the certificates and electricity are rising together with the minimum requirement.

Table 1.6 The Electricity Market in Sweden

Year	Quota[a]	Punishment[a] SEK/MWh	Price of certificate[a] SEK/MWh	Consumer price of electricity[b] SEK/MWh
2003	7.4%	175	201	1238
2004	8.1%	240	231	1316
2005	10.4%	306	216	1264
2006	12.6%	278	191	1336

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[a] *Source: Swedish Energy Agency*
[b] *Source: EUROSTAT*

In Sweden before 2003, the requirement had to be fulfilled by the consumers. In 2003 there was an amendment to the regulation because of high administrative costs of the system. Since 2003 the electricity provider has had to fulfill the minimum requirement on behalf of the consumer. In addition, the large hydro power plants are excluded from the system because the economies of scale make them profitable at the current level of electricity prices. Table 1.6 shows that the prices of the certificates are decreasing over time and the reason for this can be that Sweden is one of the few regions of the EU where the market concentration is not significant (Matthes et al., 2007).

In the United Kingdom the large hydro power plants are also excluded from the TREC system. The penalty, which is also called "buy-out price" in the UK, was fixed in 2002 in 30 GBP and adjusted yearly by the price index. Another interesting feature of the British

Table 1.7 The Electricity Market in UK

Year	Quota[a]	Punishment[a] GBP/MWh	Price of certificate[a] GBP/MWh	Consumer price of electricity[b] GBP/MWh
2003	4.3%	30.51	45.94	70.90
2004	4.9%	31.39	53.43	75.20
2005	5.5%	32.33	45.05	82.00
2006	6.7%	33.24	42.54	101.20

[a] *Source: Office of Gas and Electricity Markets*
[b] *Source: EUROSTAT*

system is that the total amount of the fine, "the buy-out fund", is redistributed among the firms who bought certificates. This is the reason why the price of the certificate is above the buy-out price in all the years.

We can see, that in all countries, except the case of the United Kingdom and Sweden, the price of the certificates is rising together with the price of electricity. These results can support the assumption that the electricity producers use their market power in the renewable energy market. In perfect competition, the price of the certificates would reflect the cost difference between the green and black electricity production. The advancement of technology decreases the production cost of renewable electricity over time (Bird et al., 2008). Meanwhile, the cost of fossil fuel production has increased from a range of 24-52 USD/MWh to that of 35-63 USD/MWh between 1998 and 2005 (OECD Nuclear Energy Agency and International Energy Agency, 1998, 2005). In perfectly competitive electricity markets the price of the green certificates should be decreasing, reflecting a smaller marginal cost difference. However, the price of the certificates for many countries presented in Tables 1.3 - 1.5 has moved in the opposite direction suggesting that market power can be prevalent in these markets.

1.6 Summary

This chapter provided a short introduction of the regulation of the renewable electricity market in the European Union. The chapter emphasizes the problem of significant concentration and market power in the electricity sector which can limit the competition and increase the electricity prices. The prices of the green certificates for subsequent years after the introduction of the environmentally friendly regulation still indicate the sign of non-competitive markets. This is the reason why it is important to analyze the effect of the environmental policy (renewable energy support schemes) on the degree of competition in the electricity market.

Chapter 2 looks at the effect of environmental policy on the demand side of the electricity market. The chapter uses quantile regression analysis to determine how the environmental regulation has changed consumer's behavior over time, i.e. to compare how the price and income elasticity changed between 1993 and 1997 with moderate regulation[8], and between 1997 and 2001 when more aggressive measures were introduced[9].

Chapters 3 and 4 analyze the effect of environmental policy on the supply side of the market. The environmental regulation is beneficial for the society as long as it introduces renewable electricity without decreasing competition. Chapter 3 derives cost conditions and market structure conditions (i.e. number of firms) under which the environmental regulation can decrease the price of electricity and increase competition. Chapter 4 extends these results with the possibilities of mergers and shows that in the electricity market with environmental regulation even mergers and acquisitions can increase competition and lower prices with certain limitations.

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[8] The moderate policy is the introduction of the Energy Star labeling for educational purposes to improve energy efficiency.

[9] The more aggressive policy is the introduction of tax credit for improving home insulation and rebates for energy efficient appliances

CHAPTER 2

Electricity Demand of US Households

2.1 Introduction

As shown in Table 2.1, there has been an increasing energy use in the United States. Under the current environmental regulation, which requires more and more renewable electricity, this increasing demand requires more and more renewable energy which is not easy to obtain. If the attitude of consumers toward environmental issues would change and the electricity consumption would decrease over time, then there would be not so much need for governmental intervention and support for introduction of renewable energy in the electricity market.

Table 2.1 Electricity Prices and Consumption in the US

Year	Electricity price USD/MWh	Electricity consumption MWh/capita
1990	79	10.59
2002	85	12.24

Source: International Energy Agency (2006)

In the last decade the US government introduced several policies to increase energy efficiency and decrease demand, but Table 2.1 shows that the *per capita* electricity consumption was rising along with the electricity prices. On one hand, it is expected that when electricity becomes a more expensive good, it would be substituted with other, cheaper energy sources, and the quantity demanded would decrease over time. On the other hand, there are very limited options to substitute electricity directly with other energy sources. In addition, electricity is a normal good; as the income rises, the demand for it increases as well. Thus, an increase in price may not be able to reduce the demand substantially.

These factors imply that the consumption may increase over time with increases in income and prices as well. However, over time, the newer and more energy efficient appliances are becoming available thereby putting a downward pressure on the electricity demand. The question that arises is to what extent such changes (such as the arrival of more energy efficient resources or government policies designed to reduce the electricity demand) have achieved their goals, in terms of decreasing electricity demand over time? Since we cannot test directly the impact of the environmental regulation on the electricity demand, we follow an indirect route. We check to what extent the price and income elasticity of the consumers (i.e. the overall behavior) have changed over time. The income and price elasticity provide information how the price of electricity and the consumer's income influence the demand decision. Furthermore, the analysis looks at how other factors, like the number of appliances or government assistance, affect electricity demand over the years.

It is also worth noting that the new, more energy efficient electric appliances are expected to be more expensive which implies that only relatively higher income groups, although less sensitive to any increase in electricity prices compared to relatively lower income groups would be able to afford them. Similarly, people will have incentive to buy these expensive energy efficient products only if they use it to a substantial amount (higher user group) and it is a relevant share of their budget. Thus, it is also interesting to examine how the price and income elasticities have changed across different *user groups* of electricity consumption over the years. This calls for a quantile regression analysis which enables us to estimate the elasticities across various quantiles of the dependent variable, in our case, the demand for electricity.

2.2 The theoretical model

There is a broad literature on the demand for energy, especially gas and electricity.[1] The theoretical model is based on the mixture of the models of Fisher and Kaysen (1962), Garbacz (1986), and Wilder and Willenborg (1975).

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[1] For broad literature review look at Griffin (1993), Madlener (1996) and Ferrer-i-Carbonell et al. (2002)

The demand for electricity of the households in the short run is a derived demand, because we cannot consume electricity directly; we can only utilize it through different devices. The quantity demanded is determined by the stock of the appliances using electricity and by the utilization of these appliances. Let us denote the stock of the appliances $S(\cdot)$, and the level of utilization by $U(\cdot)$, then the demand equation is the following:

$$Q_e = U(\bar{P_e}, Y, HC_i, HHC_j) * S(VAP, FAP_k) \tag{2.1}$$

where Q_e is the demanded electricity in a given period of time; $\bar{P_e}$ is the average price of the electricity during the time period; Y is the income during the same time period; HC_j captures different characteristics of the house, such as the size and the type of insulation of the home and whether the unit is rented or not[2]; and HHC_i captures different characteristics of the household, such as age distribution or employment status.

In contrast with the existing literature we assume that the total stock of appliances has two types. One is the set of household appliances which can be assumed to be fixed and exogenously given during the time period, which we denoted as FAP_k. These are typically large, expensive items like a stove, washer, dryer, refrigerator, etc. The other type is the set of variable stock of appliances which is assumed to be endogenous, i.e. determined during the same time period with the demand for electricity and we denoted this as VAP.[3] Since the decisions of the electricity consumption and size of the variable appliance stock are simultaneous, they are not independent from each other and this causes the problem of endogeneity. To deal with this problem, we assume that the total number of these smaller, cheaper appliances like ceiling fans, dehumidifiers, microwave ovens, computers, lighting

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[2] The inclusion of the rental information should take care of the possible principle agent problem, which arises from the facts that the landlord is buying the equipment but the leasee is paying the electricity bill.

[3] This differentiation is supported by the descriptive statistics in Table A.2. The average number of the fixed appliance stock remained the same from 1993 to 2001, meanwhile the variable appliance stock is doubled.

fixtures, etc., is determined by the equation:

$$VAP = f(Y, HC_l, HHC_m) \tag{2.2}$$

where Y is the household income, and HC_l and HHC_m are the house and the household characteristics not necessarily the same ones included in equation (2.1). The independent variables identifying equation (2.2) are different from the set of HC_i and HHC_j, and assumed to be independent from the demand for electricity. The race and sex of the household head, and the number of vehicles in the households are included only in the appliance equation and not in equation (2.1) which uniquely identifies equation (2.2). Alternatively the dummies of the fixed appliance stock are included only in equation (2.1) and identify the demand equation.

Finally, we assume that the demand for electricity is based on the average price of the electricity ($\bar{P_e}$) and not by the variable block prices[4] as in Barnes et al. (1981). The reason for this is that when the typical consumer decides about electricity consumption and looks at the monthly bill, then he or she evaluates the average price of the electricity and not the price of the last unit he or she consumed. Wilder and Willenborg (1975) proved that from the point of econometric estimation, it does not change anything if we use the average price instead of the marginal price of electricity in the demand equation. The difference between the two models shows up only in the constant term. Based on data availability we use average price.

Dubin and McFadden (1984) and Halvorsen and Larsen (2001) argue that the electricity price is exogenous because there is no price variability and the consumption rarely shifts between the different blocks of pricing. We follow that route and treat the price of electricity exogenously. Similarly to existing literature we expect that in this system of equation the price elasticity coefficient will be negative, the income elasticity coefficient will be

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[4] The block pricing is the decreasing or increasing price of electricity for the higher consumption ranges. This can be viewed as the marginal price of electricity.

positive and the appliance variables have positive impact on electricity consumption.

2.3 The dataset

The data come from the Residential Energy Consumption Surveys, which was conducted by the Energy Information Administration of the U.S. Department of Energy in 1993, 1997, and 2001. The three samples were selected randomly from the US population and conducted through personal interviews. The size of the samples is 7,108 in 1993, 5,896 in 1997 and 4,750 in 2001. Since we only have data on three years and the surveys have many attrition issues, we must consider them as three separate cross section samples.

The questionnaires are generally the same over the years, but there are some differences. For example, there was a subset of questions on the energy efficiency of the household appliances in 1997, which was not included in the surveys conducted in 1993 and 2001.In general the following areas are included in the surveys. The first part of the questionnaire concerns the housing unit, e.g.: the size and the age of the house, the type of heating and insulation. The second part is on the household appliances and includes questions on the number, the type, and the age of the different appliances. In addition, there is a set of questions on the intensity of usage of these appliances as well. For example, how many times does the household cook at home or what temperature is set in the heating unit? Then there are some basic demographic questions on the household characteristics, such as: the size of the household, age structure, income range and whether the subjects own or rent the housing unit. The final part of the survey includes the detailed consumption data on different fuel sources. In the cases of gas and electricity, the consumption data come directly from the supplier to avoid the bias coming from people inaccurately recalling past information. Finally, the datasets also contain information on the number of cooling and heating days and the deviation from the average temperature. The basic descriptive statistics of the main variables are in Table A.2 in the Appendices.

2.4 Estimation

With three years of cross sectional data that are not a panel data set, it is not appropriate to use time series methods like Bentzen and Engsted (1993) and Silk and Joutz (1997) or a panel model like Maddala et al. (1997) and Berkhout et al. (2004). Instead, the estimation follows the approach of Branch (1993) and Dubin and McFadden (1984). The short-run income and price elasticity are estimated for each year separately and then the yearly results are compared.

Many authors like Dubin and McFadden (1984), Hsiao and Mountain (1985) and Halvorsen and Larsen (2001) estimate a model with two equations where the second equation is on the determination of the appliance stock. They argue that the price equation can be left out from the model because there is not much price variability with respect to the demand for electricity by a typical consumer or that the effect of block pricing is not significant, so the price of electricity is not treated as endogenous variable.

Two measures are used for the variable appliance stock. First, the endogenous appliance stock, i.e the number of appliances (a non-negative integer), is transformed into a continuous variable using the data from Long Island Power Authority (2005). In this case, the variable appliance stock is measured as the total electric power usage of these small appliances in Watts[5] instead of as the total number of the appliances. Second, to check the robustness of the results (to be discussed later), the number of appliances is used as the measure of the endogenous appliance stock. The estimated specification is as follows:

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[5] This is the maximum hourly total power consumption of these appliances in Watts

$$ln(Q_e) = \alpha_0 + \alpha_1 ln(\bar{P_e}) + \alpha_2 ln(Y) + \alpha_3 w + \sum_{i=1}^{K} \beta_i FAP_i + \sum_{i=1}^{I} \gamma_i HC_i + \sum_{i=1}^{J} \delta_i HHC_i + \varepsilon_1 \tag{2.3a}$$

$$w = \eta_0 + \eta_1 ln(Y) + \sum_{i=1}^{L} \kappa_i HC_i + \sum_{i=1}^{M} \lambda_i HHC_i + \varepsilon_2 \tag{2.3b}$$

where w is the total power of the variable appliance stock, and the other covariates are the same as defined previously. The detailed definitions of the variables are provided in Table A.1 in the Appendices.

This system of equations is estimated by three methods to examine price and income elasticity in a comprehensive manner. The first method is the standard two-stage least-squares regression, which is commonly used in the literature. This method gives a base value for comparison with the other methods. The second is a parametric endogenous quantile regression proposed by Arias et al. (2001), and the third is a series based (semi-parametric) quantile regression developed by Lee (2007). The use of these new techniques is one of the contributions of this study to the literature because the last two estimators have not been applied before in the estimation of the household electricity demand. Note that the first two estimations are parametric while the last one is semiparametric. Moreover, the second and the third are quantile based regressions which allow us to analyze the price and income elasticity at different levels of consumption whereas the first one is a more conventional parametric mean regression.

2.4.1 Correction for grouping in the income variable

The information of household income is categorized into income ranges in the dataset. To avoid possible bias coming from the grouping of observations, we follow the technique of Hsiao and Mountain (1985) and the categorical variable is replaced by the unconditional mean of each income group. It is assumed that the income has log-normal distribution, and the maximization of the following likelihood function provides the mean and standard deviation of the distribution:

$$\max_{\mu,\sigma} \prod_{i=1}^{8} \left(\Phi\left(\frac{w_i - \mu}{\sigma}\right) - \Phi\left(\frac{w_{i-1} - \mu}{\sigma}\right) \right)^{n_i} \tag{2.4}$$

where w_i and w_{i-1} are the upper and lower boundary, n_i is the number of observations in the income range i, and $\Phi(\cdot)$ is the standard normal cumulative distribution function. The theoretical frequency is predicted and compared with observed values. χ^2 test is applied to test if the assumption of log-normal distribution is correct or not.

Table 2.2 Estimation of Income Distribution for 2001

Income range	Logarithm of income range	Actual	Unimodal[a]	Bimodal[b]
0-10000	$-\infty$ - 9.2103	470	349	469
10000-20000	9.2103 - 9.9035	752	906	757
20000-30000	9.9035 - 10.3090	634	835	629
30000-40000	10.3090 - 10.5966	618	641	615
40000-50000	10.5966 - 10.8198	589	474	598
50000-75000	10.8198 - 11.2252	977	711	968
75000-100000	11.2252 - 11.5129	353	351	357
100000-	11.5129 - ∞	357	482	357
χ^2 statistics			277.179	0.333
p-value			0.000	0.999

---

[a] $\mu = 10.4634, \sigma = 0.8457$

[b] $\mu_1 = 10.8649, \sigma_1 = 0.3285, \mu_2 = 10.2583, \sigma_2 = 0.9544, p = 0.27$

In the year 2001, $\mu = 10.4364$ and $\sigma = 0.8457$ maximize the likelihood function. The predicted values are very far from actual values, especially in the range of 50,000-75,000 USD. It suggests that the distribution is not unimodal, so we assume that the income distribution is bimodal. In this case, the likelihood function will be the following:

$$\begin{aligned} \max_{\mu,\sigma} \prod_{i=1}^{8} & \left(\Phi\left(\frac{w_i - \mu_1}{\sigma_1}\right) - \Phi\left(\frac{w_{i-1} - \mu_1}{\sigma_1}\right) \right)^{pn_i} \\ & \left(\Phi\left(\frac{w_i - \mu_2}{\sigma_2}\right) - \Phi\left(\frac{w_{i-1} - \mu_2}{\sigma_2}\right) \right)^{(1-p)n_i} \end{aligned} \tag{2.5}$$

Table 2.3 Estimation of Income Distribution for 1997

Income range	Logarithm of income range	Actual	Unimodal[a]	Bimodal[b]
0-10000	$-\infty$ - 9.2103	885	789	881
10000-20000	9.2103 - 9.9035	1263	1424	1281
20000-30000	9.9035 - 10.3090	965	1075	941
30000-40000	10.3090 - 10.5966	740	733	746
40000-50000	10.5966 - 10.8198	578	499	593
50000-75000	10.8198 - 11.2252	872	686	851
75000-100000	11.2252 - 11.5129	309	310	319
100000-	11.5129 - ∞	284	380	283
χ^2 statistics			127.959	2.136
p-value			0.000	0.952

---

[a] $\mu = 10.1818, \sigma = 0.8763$

[b] $\mu_1 = 10.8213, \sigma_1 = 0.3696, \mu_2 = 10.0382, \sigma_2 = 0.9053, p = 0.17$

Table 2.4 Estimation of Income Distribution for 1993

Income Range	Log of income range	Actual	Unimodal[a]	Bimodal[b]	Trimodal[c]
0-10000	$-\infty$ - 9.2103	1085	926	1089	1085
10000-20000	9.2103 - 9.9035	1493	1742	1485	1493
20000-30000	9.9035 - 10.3090	1072	1323	1076	1071
30000-40000	10.3090 - 10.5966	915	898	951	899
40000-50000	10.5966 - 10.8198	889	607	819	884
50000-75000	10.8198 - 11.2252	1017	824	1081	1039
75000-100000	11.2252 - 11.5129	359	364	324	359
100000-	11.5129 - ∞	278	425	285	278
χ^2 statistics			337.482	15.112	0.808
p-value			0.000	0.045	0.998

---

[a] $\mu = 10.1762, \sigma = 0.8586$

[b] $\mu_1 = 10.7704, \sigma_1 = 0.3101, \mu_2 = 9.9991, \sigma_2 = 0.9131, p = 0.21$

[c] $\mu_1 = 10.7315, \sigma_1 = 0.1539, \mu_2 = 9.5048, \sigma_2 = 0.6912, \mu_3 = 10.6976, \sigma_3 = 0.5814, p_1 = 0.08, p_2 = 0.45$

where with probability p the observation comes from the $N(\mu_1, \sigma_1)$ distribution and with probability $1-p$ the observation is from the $N(\mu_2, \sigma_2)$ distribution. Table 2.2 shows that the prediction of the bimodal distribution follows the actual ones closely and the null hypothesis, that the logarithm of income follows bimodal distribution, cannot be rejected with a p-value near 1.

The procedure is repeated for 1997. In the first case, the standard log-normal distribution with $\mu = 10.1818$ and $\sigma = 0.8763$ is rejected because the χ^2 statistics is 127.959 in Table 2.3, but again the bimodal specification of the distribution is accepted with p-value 0.952. In 1993, even the bimodal distribution can be rejected at 5% significance level. In this year a trimodal model is applied, which is supported by the low 0.808 χ^2 statistics in Table 2.4.

The parameters of the correct distribution are used for calculating the unconditional group means of the income distribution with the following formula:

$$m_i = \sum_{j=1}^{Z} p_j \left(\mu_j - \sigma_j \frac{\varphi\left(\frac{w_i - \mu_j}{\sigma_j}\right) - \varphi\left(\frac{w_{i-1} - \mu_j}{\sigma_j}\right)}{\Phi\left(\frac{w_i - \mu_j}{\sigma_j}\right) - \Phi\left(\frac{w_{i-1} - \mu_j}{\sigma_j}\right)} \right) \tag{2.6}$$

where Z=1,2,3 depending how many modus the distribution has. $\varphi(\cdot)$ denotes the density function of the standard normal distribution, and m_i is the predicted mean for income group i and is used as the observed value of the income in that given group.

2.4.2 Results from the estimations

The result of the conventional parametric 2SLS estimator is reported in Table 2.5. It shows that the price and income elasticity coefficients are not statistically significantly different for 1993, 1997, and 2001.[6] The income elasticity is around 0.05 over the years which means a 1% increase in the income would increase the electricity consumption by 0.05%

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[6] The finding that elasticities are not significantly different across samples is based on simple textbook *t-test* across samples.

over the years. Similarly, the price elasticity is around -0.9 between 1993 and 2001, which can be translated that 1% increase in the electricity price would induce *ceteris paribus* 0.9% decrease in the electricity consumption during this time period. The price elasticity is inelastic because it is less than one. This tells us that the consumers are facing regulated prices, because an unregulated monopolist would operate at the elastic part of the demand.

The reason for the similar income and price elasticities over the years can be because electricity is necessity. The cost of electricity is only a small fraction of the household budgets and it is hard to substitute with other goods.

The income and the availability of energy efficient appliances were rising over the years. As a result, one would expect that energy consumption would decrease by the replacement of the old inefficient devices, but the results did not confirm these expectations. The estimated parameter of the variable appliance stock is a semi-elasticity and shows the changes in the efficiency of the devices and in the behavior of the consumers. If there is an improvement in the efficiency of these appliances and *ceteris paribus* the intensity of usage remains the same, then the estimated coefficient should decrease over time because a more efficient device would increase the consumption only by a smaller amount. However, our results do not indicate a statistically significant difference in this coefficient estimate for the three different years, suggesting that there has been no improvement in the utilization of the household devices or a change in the behavior of the consumers.

As the table reflects, the households in mobile homes have higher electricity consumption compared to the other type of homes. The electricity demand is higher for mobile homes, because usually the electricity is the main source of energy in these households. The availability of natural gas, the substitute product, decreases the demand for electricity, which confirms the expectations. The electricity consumption is increasing with the size of the home, and poor insulation increases the use of this energy source. The results also show that as the size of the household increases, the demand for electricity increases, as expected. The effect of the age composition is negative: the higher the number of children under 12 years old, or retired people in a given household, the use of electricity is the lower. Finally, we find that the government assistance (given to relatively poorer households) did not have any effect on consumption in 1993 (coefficient is statistically insignificant) although it has become effective (with a positive and statistically significant coefficient) in the more recent years (1997, 2001).

Table 2.5 Result of the 2SLS Estimation

	2001		1997		1993	
lQ_e	Coef.	Std. Err.	Coef.	Std. Err.	Coef.	Std. Err.
w	0.0002*	3.32e-05	0.0002*	3.54e-05	0.0001*	2.69e-05
lP_e	-0.9123*	0.0690	-0.8238*	0.0321	-0.8637*	0.0228
lY_{ps}	0.0420*	0.0138	0.0587*	0.0119	0.0396*	0.0062
FAP_1	0.0806†	0.0340	0.0456	0.0432	0.1570*	0.0396
FAP_2	0.0778†	0.0318	0.1129*	0.0433	0.0830†	0.0397
FAP_3	0.0653*	0.0181	0.0655*	0.0162	0.0965*	0.0153
FAP_4	0.0987*	0.0144	0.0878*	0.0121	0.0879*	0.0100
HC_1	0.0002*	1.12e-05	0.0001*	9.23e-06	0.0002*	1.01e-05
HC_2	1.81e-06	5.41e-06	2.01e-05*	4.34e-06	1.30e-06	4.06e-06
HC_{32}	-0.1390*	0.0289	-0.1548*	0.0252	-0.1495*	0.0232
HC_{33}	-0.2031*	0.0400	-0.1782*	0.0305	-0.1195*	0.0291
HC_{34}	-0.1848*	0.0384	-0.2135*	0.0350	-0.2718*	0.0305
HC_{35}	-0.3249*	0.0387	-0.3643*	0.0294	-0.3739*	0.0286
HC_7	-0.2362*	0.0160	-0.3493*	0.0137	-0.2457*	0.0122
HC_{11}	-0.0359*	0.0089	-0.0188†	0.0081	-0.0236*	0.0074
HC_{12}	4.23e-05*	7.46e-06	0.0001*	1.07e-05	0.0001*	6.52e-06
HHC_1	0.1053*	0.0078	0.0880*	0.0076	0.1194*	0.0063
HHC_2	-0.0344*	0.0104	-0.0355*	0.0101	-0.0388*	0.0088
HHC_3	-0.0522*	0.0127	-0.0087	0.0107	-0.0583*	0.0104
HHC_4	0.0423*	0.0147	0.0368*	0.0126	0.0214‡	0.0116
HHC_{13}	0.0395‡	0.0236	0.0459†	0.0202	-0.2420	0.1710
constant	5.4177*	0.2047	5.7207*	0.1433	5.6972*	0.0857

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*Significant at 1% level.
†Significant at 5% level.
‡Significant at 10% level.

We employ two additional econometric techniques, namely (i) parametric quantile regression and (ii) semiparametric quantile regression. The results for the control covariates are found to be qualitatively similar for all the regression (sign and significance wise). Note that, our main variables of interest are the income and the price elasticity, therefore, the new estimation techniques applied focus on the effects of these two on electricity demand in a more comprehensive way.

The results of different estimations are summarized in Figure 2.1. The left panels represent the estimated price elasticities whereas the right panels show the estimated income elasticities. On the horizontal axis are the different quantiles of electricity consumption. In each graph the dashed straight line shows the estimated coefficient from the 2SLS regression, the dotted line with crosses represents the estimates of the semiparametric quantile regression and the light gray area is the 95% confidence interval around it. The solid line shows the results of the parametric quantile regression and the dark grey area is the 95% confidence interval.

The estimated elasticities from the quantile regressions are significant for most values of demand (electricity usage). While comparing parametric versus semiparametric quantile estimates of income elasticity, we find that the lower (higher) quantiles have smaller (larger) estimates under semiparametric specification than its parametric counterpart. We also see that the semiparametric quantile estimates have larger variability than the parametric quantile estimates. However, parametric and semiparametric quantile regressions give qualitatively similar results. We find that the price elasticity is decreasing (i.e., becoming less sensitive) for the higher quantiles, which can be attributed to the fact that the richer households presumably have higher levels of consumption[7] and their budget is not affected so much by price increase like the poorer households. The other explanation for this is that the high user groups cannot avoid the electricity use thereby making them price insensitive. The price elasticity of the biggest consumers is around -0.75 for all three years.

Similarly, the common pattern in the income elasticity is that it is insignificant for the 10th percentile in all the years, suggesting that an increase in the income of the lowest consumption groups will not influence their electricity consumption. The income elasticity then becomes significant beyond the 10th percentile and increases with the usage. Finally,

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[7] The statistical tests detailed in Table A.4-A.6 in the Appendices show that there is a direct association between the higher income and higher levels of consumption.

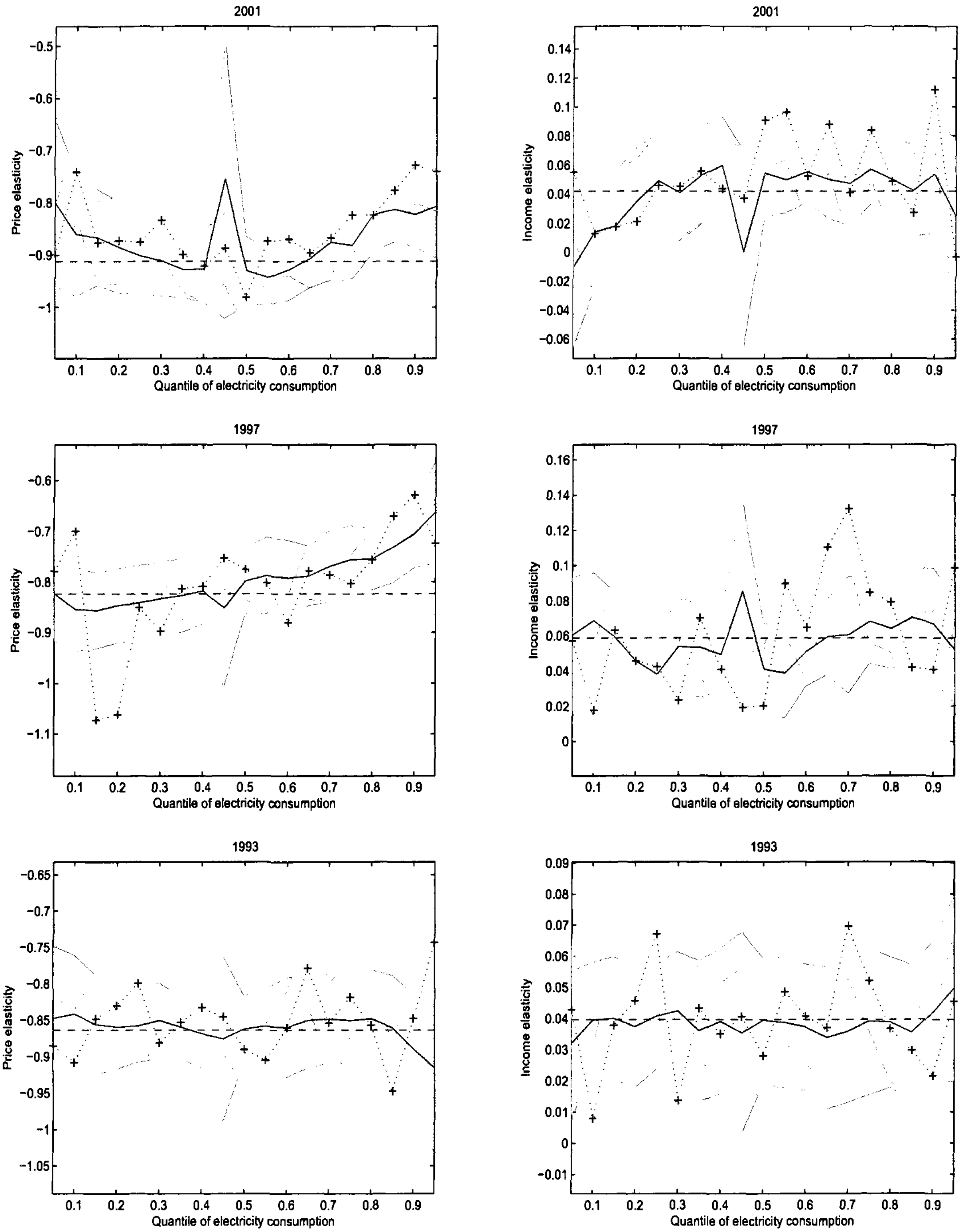

Figure 2.1 Price and Income Elasticities in Different Estimations

in the higher quantiles of demand, the income elasticity decreases. This pattern shows that as the income increases, the electricity consumption does not change for the low level users because they are likely to spend their additional money on more basic needs. As the level of consumption reaches a certain level, the households start to spend more on appliances and electricity. The income elasticity is the highest for the 70th percentile with figures around 0.1, which is twice as much as the results of the parametric estimation. Finally, the biggest consumers of the society can afford to invest in energy efficient appliances, which may also reduce the income elasticity. Also their demand becomes more income-insensitive because they may have already reached a level of satiation as far as electricity consumption is concerned.

Table 2.6 summarizes the goodness of fit statistics for the various models that are used. It shows that the semiparametric quantile estimator (SPQ) on average always performs better than the parametric quantile (Q) or the mean regression (2SLS).

Table 2.6 The Goodness of Fit Statistics of the Different Specifications

R^2	2001	1997	1993
Q	0.3777	0.4072	0.3762
2SLS	0.5634	0.6317	0.6089
SPQ	0.6088	0.6514	0.6119

2.4.3 Alternative specification

To test the robustness of the results of the original model, an alternative specification is estimated. Following Garbacz (1986) we include a price equation in the model. In this alternative specification the decreasing block prices make the average electricity prices endogenous with respect to demand, which is determined by the equation:

$$\bar{P_e} = g(Q_e, G_n) \tag{2.7}$$

where Q_e is the consumed electricity and G_n are geographical factors of the household, describing the differences in block prices of the electricity utilities in the different geographical areas and regions. The exact loglinear form of the alternative specification of equations (2.1),(2.2) and (2.7) to be estimated are as follows:

$$\begin{aligned} ln(Q_e) =& \alpha_0 + \alpha_1 ln(\bar{P_e}) + \alpha_2 ln(Y) + \alpha_3 VAP + \sum_{k=1}^{K} \beta_k FAP_k \\ &+ \sum_{i=1}^{I} \gamma_i HC_i + \sum_{i=j}^{J} + \delta_j HHC_j + \varepsilon_1 \end{aligned} \tag{2.8a}$$

$$ln(\bar{P_e}) = \phi_0 + \phi_1 ln(Q_e) + \sum_{n=1}^{N} \rho_n G_n + \varepsilon_2 \tag{2.8b}$$

$$VAP = \eta_0 + \eta_1 ln(Y) + \sum_{i=1}^{l} \kappa_l HC_l + \sum_{m=1}^{M} \lambda_m HHC_m + \varepsilon_3 \tag{2.8c}$$

where I, J, K, L, M, and N are the number of independent variables in the different equations.

The other notable change in the alternative model is that the variable appliance stock in the data set is estimated with a count-data model to check if the imputation of power data from different sources creates bias and significant change in the parameter. There is no significant change in the estimated coefficients if we estimate the model with equations (2.3a), (2.3b) and (2.8b), and we use w instead of VAP in the above specification.

Equation (2.8c) is estimated first by the Poisson model and then the overdispersion test of Cameroon and Trivedi (1986) is executed. In all years the null hypothesis of the test is rejected at 1 % significance level, and therefore, the negative-binomial model is estimated finally for the variable appliance stock equation. This estimated equation provides us the predicted stock of the household appliances, which is endogenous in equation (2.8a).This is because the decision on the number of small household devices is made at the same time as the demand for electricity. For the estimation of electricity demand we use the predicted value to replace the endogenous appliance stock. In line with Garbacz (1986) equation (2.8a) and (2.8b) are simultaneous equations and estimated with 2SLS in the parametric framework to deal with the problem of endogeneity, that the price and quantity are correlated with the error terms.

The detailed results of the appliance stock equation are in Table A.3 in the Appendices. The p-value of the overdispersion test of Cameroon and Trivedi (1986) equals to zero in all years. This means that in all the three years the hypothesis of Poisson distribution is rejected, and the alternative hypothesis, that the appliance stock has negative binomial distribution, is accepted. The predicted values of the appliance stock from the negative binomial model are used in the estimation of electricity demand equation. Most of the estimated parameters in the appliance equation are significant and the sign of the parameters have the same expected sign over the years. These results are in line with Garbacz (1983): the income and the size of the household have a positive effect on the size of the appliance stock, and the non-white households have less electronic devices compared to the white ones. In addition, our estimation suggests that if the households own their homes, then they have a bigger stock of appliances; and if they own more vehicles, they tend to have more devices as well. The same statement is true for households with a home business. Moreover, the appliance holding in rural areas is smaller than in cities. If a household is poor and eligible for government assistance, they tend to have fewer electronic devices.

The result of the price equation is as expected. The increasing consumption lowers the average price because of the block pricing, but the effect is decreasing over the years. The location variables again confirm the results of Garbacz (1983) that the highest prices are in the Northeast part of the United States.

Table 2.7 Parametric Estimation of the Alternative Specification

	2001		1997		1993	
	Coef.	Std. Err.	Coef.	Std. Err.	Coef.	Std. Err.
lQ_e						
lP_e	-0.9326*	0.0387	-0.8133*	0.0301	-0.7896*	0.0311
lY_{ps}	0.0653*	0.0113	0.0704*	0.0106	0.0385*	0.0053
$V\hat{A}P$	0.0241*	0.0050	0.0211*	0.0050	0.0363*	0.0059
FAP_1	0.0884*	0.0312	0.0558	0.0468	0.1584*	0.0379
FAP_2	0.0722†	0.0306	0.1184†	0.0467	0.1061*	0.0377
FAP_3	0.1087*	0.0166	0.0925*	0.0162	0.1181*	0.0149
FAP_4	0.1296*	0.0129	0.1153*	0.0117	0.1087*	0.0103
HC_1	0.0002*	9.79e-06	0.0001*	9.32e-06	0.0002*	9.29e-06
HC_2	8.29e-06‡	4.89e-06	1.59e-05*	4.16e-06	1.18e-06	3.79e-06
HC_{32}	-0.1253*	0.0278	-0.1427*	0.0249	-0.1460*	0.0236
HC_{33}	-0.2094*	0.0344	-0.1834*	0.0299	-0.1095*	0.0295
HC_{34}	-0.1976*	0.0346	-0.2475*	0.0333	-0.2808*	0.0298
HC_{35}	-0.3533*	0.0324	-0.4033*	0.0279	-0.3932*	0.0268
HC_7	-0.2151*	0.0152	-0.3381*	0.0133	-0.2491*	0.0124
HC_{111}	0.2287*	0.0663	0.2223*	0.0702	0.2771*	0.0463
HC_{112}	0.2340*	0.0661	0.2122*	0.0701	0.2776*	0.0462
HC_{113}	0.1743*	0.0670	0.2154*	0.0707	0.2667*	0.0467
HC_{12}	4.45e-05*	7.28e-06	0.0001*	1.23e-05	0.0001*	6.55e-06
HHC_1	0.0968*	0.0084	0.0874*	0.0072	0.1061*	0.0066
HHC_2	-0.0371*	0.0106	-0.0332*	0.0093	-0.0333*	0.0087
HHC_3	-0.0487*	0.0121	-0.0168	0.0105	-0.0508*	0.0101
HHC_4	0.0513*	0.0141	0.0338*	0.0125	0.0189	0.0116
HHC_{13}	0.0628*	0.0230	0.0331‡	0.0195	-0.2479‡	0.1506
constant	5.0548*	0.1610	5.5346*	0.1501	5.6245*	0.1049
lP_e						
lQ_e	-0.1254*	0.0080	-0.1728*	0.0063	-0.1579*	0.0059
G_{22}	-0.0312†	0.0151	-0.0006	0.0131	0.0297†	0.0120
G_{23}	-0.3164*	0.0153	-0.2931*	0.0133	-0.2628*	0.0121
G_{24}	-0.3709*	0.0178	-0.3862*	0.0152	-0.3291*	0.0137
G_{25}	-0.3027*	0.0164	-0.3111*	0.0136	-0.2432*	0.0121
G_{26}	-0.5123*	0.0181	-0.5231*	0.0153	-0.4663*	0.0143
G_{27}	-0.2940*	0.0174	-0.3513*	0.0147	-0.2356*	0.0134
G_{28}	-0.3805*	0.0171	-0.4212*	0.0150	-0.4002*	0.0137
G_{29}	-0.2326*	0.0148	-0.2850*	0.0130	-0.2467*	0.0119
constant	-0.9873*	0.0701	-0.5742*	0.0553	-0.7833*	0.0519

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*Significant at 1% level.
†Significant at 5% level.
‡Significant at 10% level.

The results of the two-stage least-squares estimation of the simultaneous equation system are summarized in Table 2.7. The results do not change much compared to the previous model. Most of the parameter estimates including price and income elasticity estimates are significant and have the same sign and magnitude as in the first case. It shows that the results are robust in the parametric framework. We cannot check the robustness under the other estimation techniques because the inclusion of the price equation in the alternative specification does not allow us to estimate quantile or semiparametric regression of the existing types that we are using.

2.5 Summary

The results of this chapter show that the households with higher level of electricity consumption are less price and income sensitive than the households with lower level consumption, *but over the years these measures of sensitivity have not changed.* This means that there is no relevant change in the behavior of US households over the years toward electricity use which questions the effectiveness of the different support programs for improvement in energy efficiency and energy use.

The results also suggest that an increase in the tax on electricity alone is not likely to decrease the *per capita* consumption. The reasons are two-fold: prices were rising over the years but the reaction to price changes remained the same; meanwhile, the increasing income outweighed the effect of the increasing prices of electricity. In summary, the results of this study suggest that the market forces and the existing government policies are not able to solve the problem of increasing electricity consumption, which calls for more vigorous policy to increase energy efficiency. The results also suggest that the new policy measures should target the median families, because these are the households who show the largest reaction to changes in income and prices.

CHAPTER 3

Market Power and Environmental Regulation

3.1 Introduction

The previous chapter looked at how the environmental policy has affected the demand side of the electricity market. This chapter analyzes the affect of the environmental policy on the supply side. While in the demand side the anticompetitive market behavior is not an important issue because of the large number of buyers, in the supply side the problem of market power can be important because of the small number of power producers and the large stranded cost, which can limit the possibility of new entry. The oligopolistic situation in the electricity supply is often analyzed in the economics literature all around the world, for example Hilke (2008) for the United States, Weigt and von Hirschhausen (2008) for Germany, Ahn and Niemeyer (2007) for Korea and Salies (2008) for the United Kingdom.

In the end of the first chapter, the early experiences are described for several countries after the introduction of environmental regulation (i.e. some kind of tradable green certificate system) in the energy sector. The increasing electricity and certificate prices suggest that the problem of market power can be significant in the renewable electricity markets. The environmental regulation can increase the price of electricity because of the higher cost of renewable energy, but the support for green energy can increase the number of new entrants in the market which can increase competition and lower prices. One of the goals of this chapter is to analyze how the different environmental regulation schemes can influence the prices in the electricity market with oligopolistic market structure.

The minimum requirements are a very important policy variable in the different environmentally friendly regulatory regimes, and they can have a large influence on the prices and quantities in the electricity market. This chapter provides an analysis on how an increase of the minimum requirements can affect theoretically the prices and production of electricity under different market structures and environmental regulations.

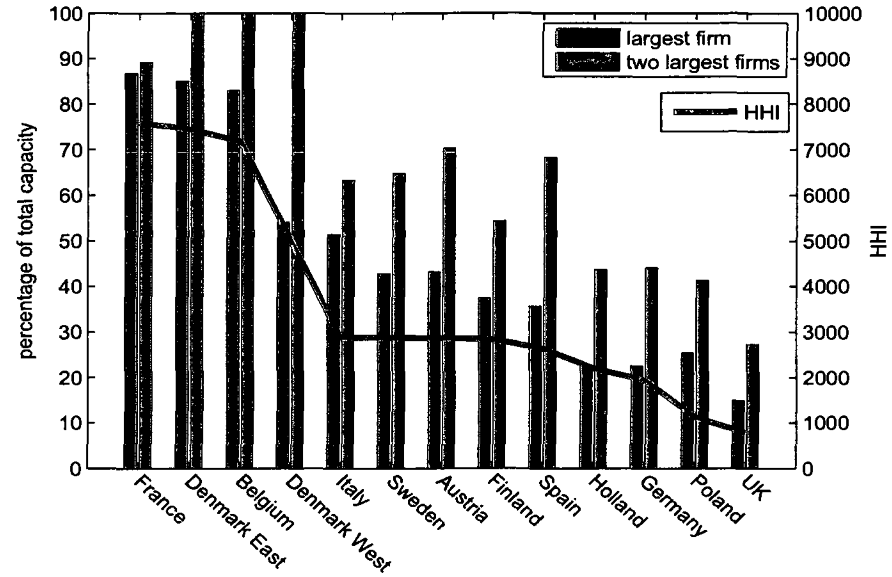
The results of this theoretical model can help the decision making of the policymakers by determining the important market conditions (i.e. marginal cost difference between the renewable and fossil-fuel plants or the number of firms), under which the market power of the power plants can cause significant price increase with increasing renewable electricity requirements. In addition, the results of this theoretical model can be used as a base of the structural form in a simulation model to analyze mergers and acquisitions.

In the first part of the chapter, some theoretical models of the literature are described connected to the electricity markets and especially to the tradable green certificates. The models will be introduced briefly; only the main results are mentioned which are relevant to the modeling. After this, a model is derived, which is used to analyze how an increase in the minimum requirements will affect the price and quantities in different market structures and regulations.

3.2 Electricity market models

The typical national power producer market is an oligopolistic market. There are only a few actors selling a homogeneous product and there is a huge entrance cost which limits the potential number of new entries. There is no possibility for "hit and run entry" because there is high sunk cost and long licensing procedure. Therefore, the threat of a new possible entry in the market is small and cannot force the prices down.

The oligopolistic market structure can also be supported by indicators of market concentration. Figure 3.1 shows the Hirschmann-Herfindhal Index and the market share of the two largest firms for several EU countries. In most cases, the two largest power producers control more than 50 percent of the total production capacity of electricity. In addition, the ten biggest Western European electricity producers control more than 60 percent of the energy supply in the EU, and they engaged in an aggressive expansion in the newly joined



Source: Commission of the European Communities (2007)

Figure 3.1 Market Concentrations in the EU

Eastern European countries (Greenpeace International, 2005).

Given this market structure, it is clear that the models based on perfect competition cannot be used in this study. These models do not allow the strategic behavior of firms and assume that actors are price-takers. Instead, an oligopolistic model is applied, which is possibly the best one in reflecting the structure of the energy market.

The renewable energy market is a newly regulated market. It needs several years until the whole sector can work on a competitive market basis. During this period there is a high level of uncertainty about which rules and laws will apply in the final stage. Under such ambiguous circumstances it can be assumed that the strategies of the firms on the market will be determined primarily by short-term goals and interests. This reasoning suggests to use a static model to analyze this particular market.

Most of the static energy market models use either the Cournot-Nash equilibrium (Borenstein and Bushnell, 1999; Kennedy, 1994), or the so-called "supply-function" equilibrium as a solution algorithm (Green, 1999; Newbery, 1998). The supply-function equilibrium differs from the Cournot model in one assumption: it assumes that the producers face a stochastic demand. In this case it is more profitable for the producers not to compete with fixed quantities, but rather with production plans dependent on prices. These production plans are called supply functions based on the model of Klemperer and Mayer (1989). The supply function models have more competitive outcomes compared to the Cournot model, because the positive slope of the supply functions makes the residual demand curves more elastic.

The disadvantage of the supply-function equilibrium is that it can have infinite equilibrium solutions, and is computationally very complex. The main reason against this model in a static framework is that, in the short-run, the demand for electricity is fixed. The hourly demand for electricity can be projected with high precision; there are very few uncertainties associated with this type of modeling. Although the Cournot-model provides systematically more pessimistic results with regards to welfare than other models do,[1] it is still worth examining such a model, because it can answer several important regulatory questions. One important argument for the Cournot-equilibrium is that the computation is quite simple.

We have not seen any studies modeling the electricity market as a price or spatial competition. It looks like there are not enough strong reasons supporting the use of these types of models. The main reasons against these models are that electricity is a homogeneous good and in many cases there exist only mixed equilibrium price strategies[2]. It would be a misleading assumption to base the short-term strategic interactions only on quantity competition due to the very high sunk costs, but industries with monopolistic competition and very high fixed costs of the establishment of production can be best characterized by Cournot-competition (Tirole, 1988).

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[1] The Cournot model predicts for the same firms higher prices and lower production in comparison to Bertrand price competition or to the Stackelberg leader-follower model.

[2] In the equilibrium they use different prices with different probabilities depending on the cost structure of the competitors

The studies on the system of green certificates include mainly qualitative and descriptive analyses like how the system was implemented (Dinica and Arentsen, 2003), and what are the early experiences (Fristrup, 2003). The main analytical models are similar to the early emission rights models. These papers look at the system from macroeconomic and international perspectives (Morthorst, 2003a,b), and of course their analysis is ultimately long-run.

One of the few microeconomic models which deals with renewable energy under oligopolistic competition is Jensen and Skytte (2003). In this theoretical paper there is an algebraic derivation of the effects of the minimum requirement on green certificate prices. In their static equilibrium model they showed that there is a linear relationship between the energy price and the certificate price, and the parameter describing this linear relationship depends on the minimum purchase requirements. The authors, based on the Danish market, assumed monopolistic competition on the electricity market and perfect competition on the certificates market. In the model of this chapter we will not use this assumption, since in most of the countries the renewable energy sector is still underdeveloped with only a few producers possessing large market shares, or the new investment in this sector is made by the companies already in the market extending their market shares.

Amundsen and Mortensen (2001) built a static model for the Danish market with green certificate trading and emission permits at the same time. They assumed that perfect competition is in all markets. They showed that the increase of the minimum requirements increases the price of the electricity and decreases the total amount of electricity in the market. Amundsen and Bergman (2004) derive the condition for optimal production of the individual power plants with the green certificate system. There are two concerns with this study. First, it is assumed that there is perfect competition on the certificates market. In this case, in the optimum the marginal revenue of the electricity is equal to the linear combination of the marginal costs of the black and green producers. Second, they assumed that the renewable producers have market power and they can hold back certificates, but can not hold back production. This condition can be applied only for markets where the certificates are valid for more than one period, so it can be that the renewable producers sell more electricity than certificates. In addition, it is assumed that the renewable plants must have enough revenues from a smaller amount of certificates to finance the high cost of operation. In this case, the condition says that at the optimal production the marginal revenue from the electricity and green certificates has to be equal to the linear combination of the marginal costs.

This study aims to extend the last model by allowing the renewable producers to cut back electricity production and not just the number of certificates. The model analyzes how the different regulatory schemes, like the feed-in tariff and the tradable green certificates market affect the electricity prices and production under the assumption of imperfect competition in all markets. In addition, the models are used to predict the effect of the increasing minimum requirements on the prices and production.

3.3 The base model: Market demand and cost structure

It is assumed, based on previous studies like Newbery (1998), that the final demand for electricity of the consumers is known and it is described by a linear function:

$$p_e = a - bQ \tag{3.1}$$

Where p_e is the price paid by the final consumers and Q is the total amount of energy bought in the market, and it includes green and black energy as well.

The electricity providers face the demand of final consumers. If they do not receive state subsidies for the required renewable energy purchases, they will spread the extra cost of the certificates over all the customers. They transform the demand of the consumers into a new demand function in the wholesale market of electricity and in the market of renewable certificates. It is assumed that in the providers market there is perfect competition, because the entry and exit in this part of the energy sector is not costly. This assumption means that the profit of electricity providers is zero, and their total revenue is equal to their total costs. This condition in formulas as follows:

$$p_e Q = p_w Q + p_c \alpha Q \tag{3.2}$$

Where p_w is the wholesale price of the electricity paid to the power plants, p_c is the price of the green certificates and α is the minimum requirement ratio. The left hand side of equation (3.2) is the total revenue and the right hand side is the total cost. We can simplify this equation and express the wholesale price that the electricity producers are facing.

$$p_w = p_e(Q) - \alpha p_c = a - bQ - \alpha p_c \tag{3.3}$$

In addition, we assume there are m symmetric fossil fuel power plants on the market that produce energy with the cost function:[3]

$$C_b = c_b q_b + f_b \tag{3.4}$$

Where q_b is the produced electricity by each black firm, c_b is the constant marginal cost and f_b is the fixed cost. [4]

Similarly, we assume there are n symmetric renewable energy producers on the market that produce energy with the cost function:[5]

$$C_g = c_g q_g + f_g \tag{3.5}$$

where q_g is the produced electricity by each renewable producer, $a > c_g > c_b$ is the constant

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[3] The $_b$ index symbolize the "black" energy producers.

[4] The constant marginal cost assumption is used in several other studies in this field, like Kennedy (1994) and Newbery (1998).

[5] The $_g$ index symbolize the "green" energy producers.

marginal cost and f_g is the fixed cost.

If there is no environmental regulation in the sector then each firm would maximize profit. This problem can be written for the representative firms as follows:

$$\max_{q_b} \Pi_b = p_e(Q)q_b - C_b \tag{3.6a}$$

$$\max_{q_g} \Pi_g = p_e(Q)q_g - C_g \tag{3.6b}$$

In the equilibrium the same type of plants produce the same quantity, so if q_b and q_g are substituted back in the first order condition, it provides the equilibrium production for the green and black firms.[6]

$$q_b = \frac{a - c_b + n(c_g - c_b)}{b(m+n+1)} \tag{3.7a}$$

$$q_g = \frac{a - c_g - m(c_g - c_b)}{b(m+n+1)} \tag{3.7b}$$

$$Q = \frac{m(a - c_b) + n(a - c_g)}{b(m+n+1)} \tag{3.7c}$$

$$p_e = \frac{a + mc_b + nc_g}{m+n+1} \tag{3.7d}$$

This will be the equilibrium if

$$c_g < c_b + \frac{a - c_b}{m+1} \Rightarrow \frac{m}{m+1} < \frac{a - c_g}{a - c_b} \tag{3.8}$$

Equation (3.8) is the condition for the renewable producers to have a positive quantity in the optimum. If the marginal cost of the renewable energy is higher than the value in con-

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[6] The detailed derivation of the first order conditions and market equilibrium is in Appendix B

dition 3.8 then the renewable production is zero and in the equilibrium the production is as follows:

$$q_b = \frac{a - c_b}{b(m+1)} \tag{3.9a}$$

$$q_g = 0 \tag{3.9b}$$

$$Q = \frac{m(a - c_b)}{b(m+1)} \tag{3.9c}$$

$$p_e = \frac{a + mc_b}{m+1} \tag{3.9d}$$

The price of electricity will be lower in the case when condition 3.8 is true and there is renewable electricity production in the market without any government support. These results are the base values when there is no support scheme in the market, and these values are used later to compare the effect of the different regulatory schemes.

3.3.1 Case 1: Feed-in-law based on market prices

In the first type of the environmental regulations, which is a special case of the feed-in tariff, both the black and green producers are competing in the electricity market with quantities. In this regulatory scheme, the electricity providers receive a state subsidy after the purchased renewable electricity. The minimum requirement and the provided quantities determine the price of the tariff, and the government pays the subsidy. The maximization problem is the following for the representative power plants:

$$\max_{q_b} \Pi_b = p_e(Q)q_b - C_b \tag{3.10a}$$

$$\max_{q_g} \Pi_g = (p_e(Q)+t)q_g - C_g \tag{3.10b}$$

The equilibrium must fulfill the minimum requirement condition:

$$\sum_{i=1}^{n} q_g^i \geq \alpha Q \tag{3.11}$$

If (3.8) is fulfilled, then condition (3.11) is not binding only if

$$\alpha \leq \frac{n(m+1)(a-c_g) - nm(a-c_b)}{m(a-c_b)+n(a-c_g)} \tag{3.12}$$

This means that the environmental policy will not affect the market outcome if the minimum requirement is so small that it fulfills condition (3.12). In this case the government has no payment obligation.

The equilibrium

The feed-in tariff t, from the solution of the first order conditions when condition (3.11) is binding is as follows:

$$t = \frac{m(n+\alpha)(a-c_b)}{n(m+1-\alpha)} - (a-c_g) \tag{3.13}$$

The transfer is positive if

$$\frac{m}{m+1} > \frac{a-c_g}{a-c_b} \tag{3.14}$$

This condition is just the opposite of (3.8). It means that the government must provide financial support in the feed-in tariff system for the renewable energy only if there is no renewable electricity in the market without the environmental support scheme. Substituting back the value of the feed-in tariff into the optimal production plan of the two types of power plants gives:

$$q_b = \frac{(1-\alpha)(a-c_b)}{b(m+1-\alpha)} \tag{3.15a}$$

$$q_g = \frac{m\alpha(a-c_b)}{bn(m+1-\alpha)} = \frac{m\alpha}{n(1-\alpha)} q_b \tag{3.15b}$$

$$Q = \frac{(a-c_b)}{b(m+1-\alpha)} \tag{3.15c}$$

The production cost of the renewable energy producers does not influence the production of the fossil fuel plants. The amount of electricity produced from renewable resources is determined by the minimum requirement, by the number of firms and by the amount of black production. The cost of green electricity has no influence on the produced quantities; it only determines the size of the feed-in tariff and it compensates proportionally for the cost difference. The reason for this is that the government takes care of this extra cost, and the cost of the renewable energy does not influence the price of the electricity. The feed-in regulation increases the total production and decreases the price of electricity compared to the case when there is no environmental regulation.

Comparative statics

The partial derivatives of the equilibrium values are calculated to analyze the effect of the minimum requirement on the equilibrium values:

$$\partial_\alpha t = \frac{m(1+m+n)(a-c_b)}{n(1+m-\alpha)^2} > 0 \tag{3.16}$$

$$\partial_\alpha p_e = \frac{m(-a+c_b)}{(1+m-\alpha)^2} < 0 \tag{3.17}$$

$$\partial_\alpha q_b = \frac{m(-a+c_b)}{b(1+m-\alpha)^2} < 0 \tag{3.18}$$

$$\partial_\alpha q_g = \frac{m(1+m)(a-c_b)}{bn(1+m-\alpha)^2} > 0 \tag{3.19}$$

$$\partial_\alpha Q = \frac{m(a-c_b)}{b(1+m-\alpha)^2} > 0 \tag{3.20}$$

The increasing minimum requirement increases the value of the tariff. The reason for this is that the increasing requirement raises the demand for green electricity and the renewable companies can use out the increased demand and require higher prices. The increase in the tariff does not decrease the demand for electricity, because the government pays for the higher cost of renewable energy.

The government finances the decrease in the electricity prices and the higher quota results in higher feed-in tariff. This higher subsidy makes the renewable producers more competitive and they increase the renewable energy production which replaces partially the black resources. The increase of the renewable electricity production is bigger than the decrease in the production of the fossil-fuel power plants. The total production will increase and this results in an overall decrease in the price of the electricity in the market.

The feed-in tariff with increasing minimum requirements can create a big burden for the budget if the production costs remain the same over time because the size of the tariff increases together with the produced quantity. If the difference in the marginal costs decreases then the size of the tariff decreases, but the quantity of renewable electricity still increases. This environmental policy can affect the government budgets in the long-run, so let us consider another case which is neutral to the budget balance because the providers have no subsidy and they have to take care of the extra cost of the green certificates.

3.3.2 Case 2: Quota obligation with green certificates

The second regulatory scheme is a tradable green certificates system, where all the renewable companies are selling the electricity and the certificates separately to the electricity providers, who are obliged to fulfill the minimum requirement rule. Both the black and green producers are competing in the electricity market with quantities. The utilities have no state subsidy for the renewable energy, so the power plants face the demand functions of the wholesale market described by equation (3.3), which is derived from the demand of the consumers defined by equation (3.1). The price of the certificates is determined by the supplied quantities and by the demand generated through the minimum requirement ratio. The maximization problem is the following for the representative power plants:

$$\max_{q_b} \Pi_b = p_w(Q)q_b - C_b \tag{3.21a}$$

$$\max_{q_g} \Pi_g = (p_w(Q) + p_c)q_g - C_g \tag{3.21b}$$

The equilibrium must fulfill the minimum requirement condition:

$$\sum_{i=1}^{n} q_g^i \geq \alpha Q \tag{3.22}$$

The equilibrium

In the equilibrium q_b, q_g are the same for all firms, because of the symmetry. The solution for the first order conditions are as follows:

$$q_b = \frac{n(1-\alpha)(a-(\alpha c_g + (1-\alpha)c_b)}{b(n(m+(\alpha-1)^2 + m\alpha^2)} \tag{3.23a}$$

$$q_g = \frac{m\alpha(a-(\alpha c_g + (1-\alpha)c_b)}{b(n(m+(\alpha-1)^2 + m\alpha^2)} = \frac{m\alpha}{n(1-\alpha)} q_b \tag{3.23b}$$

$$Q = \frac{mn(1+2\alpha)(\alpha(a-c_g) + (1-\alpha)(ac_b))}{b(n(m+(\alpha-1)^2 + m\alpha^2)} \tag{3.23c}$$

The market clearing price of the green certificates are as follows:

$$p_c = \frac{m(n+\alpha)(a-c_b) - n(m+1-\alpha)(a-c_g)}{n(m+(\alpha-1)^2)+m\alpha^2} \tag{3.24}$$

The price of the certificates will be positive if:

$$\frac{m}{m+1} > \frac{a-c_g}{a-c_b} \tag{3.25}$$

which is true if there was no green electricity in the market before the environmental regulation.

In this case, the production of the power plants is influenced by the marginal cost of renewable electricity as well. It is different from the previous case where only the marginal cost of the fossil-fuel plants determines the production. The black firms weight the marginal cost of the different production techniques by the minimum requirements to determine the optimal production. The derived demand function can explain this effect. The production of the renewable power plants is determined in the same way as in the previous case. The green production is a fixed proportion of the black production because equation (3.22), the minimum requirement constraint, is binding. Similarly to the feed-in tariff system, the total electricity production increases under the green certificate system compared to the case when there is no support for renewable electricity.

Comparative statics

The sign of the partial derivatives is analyzed again to evaluate the comparative statics. In many cases it is not possible to determine a unique sign of the partial derivatives. In order to analyze the effect of the minimum requirements more clearly, values from the UK electricity market are used to present graphically the partial derivatives. In the British electricity market the number of main fossil-fuel power plants is around 40 (m=40), and the number of larger renewable firms is around 15 (n=15). A sufficient condition is calculated for the derivatives under which the sign of the derivatives can be unambiguously evaluated.

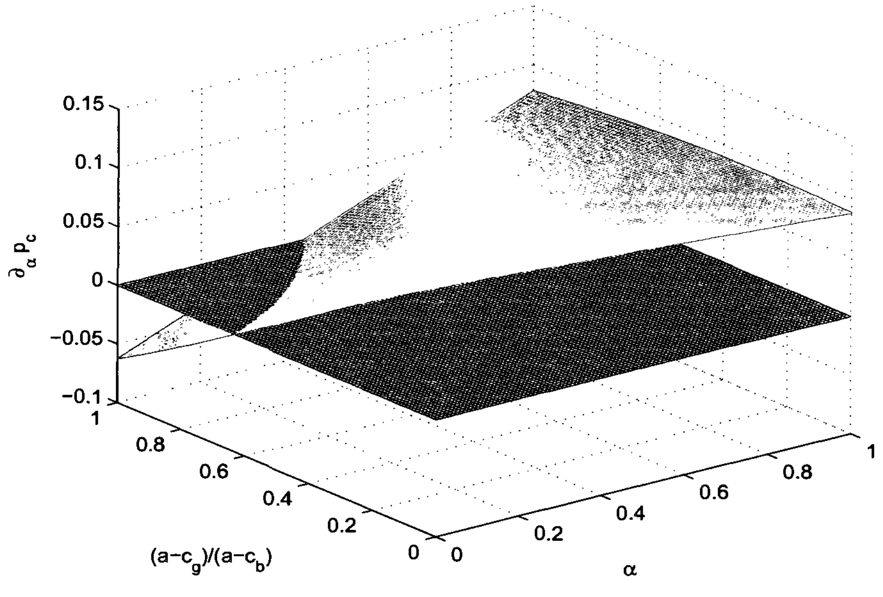

Figure 3.2 The Partial Derivative of p_c if m=40 and n=15

$$\begin{aligned}\partial_\alpha p_c =& \frac{m(n(1+m+2n)-2n(m+n)\alpha-(m+n)\alpha^2)(a-c_b)}{(n(m+(-1+\alpha)^2)+m\alpha^2)^2}\\ &+\frac{n(-(1+m)n+2(1+m)(m+n)\alpha-(m+n)\alpha^2)(a-c_g)}{(n(m+(-1+\alpha)^2)+m\alpha^2)^2}\end{aligned} \tag{3.26}$$

As shown in Figure 3.2, the price of the certificates is increasing with alpha for many cases. The increase in the minimum requirement increases the price of the certificates only when the quota is small and the cost difference of the green and black production is small. The sufficient condition for the $\partial_\alpha p_c > 0$ is if

$$\frac{n}{m+n} < \alpha \tag{3.27}$$

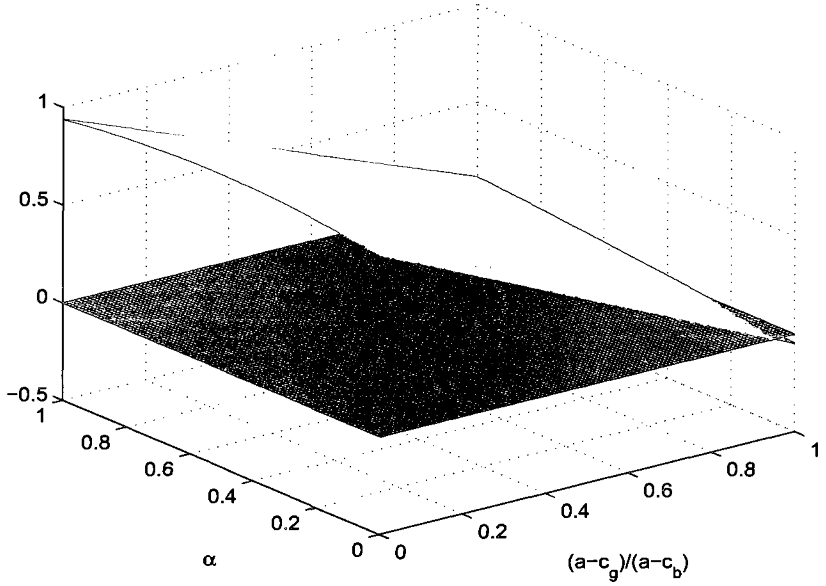

Figure 3.3 The Partial Derivative of p_e if m=40 and n=15

$$
\begin{aligned}
\partial_\alpha p_e = & \frac{-mn(n(-1+\alpha)^2 - mn + m(-2+\alpha)\alpha)(a-c_b)}{(n(m+(-1+\alpha)^2)+m\alpha^2)^2} \\
& + \frac{mn(-n-mn+(m+n)\alpha^2)(a-c_g)}{(n(m+(-1+\alpha)^2)+m\alpha^2)^2}
\end{aligned} \tag{3.28}
$$

Figure 3.3 shows the price of electricity is increasing almost always as the renewable obligation increases. The price of electricity decreases only when the minimum requirement is very small and the marginal cost of the renewable electricity is almost the same as the marginal cost of the black energy. The sufficient condition for $\partial_\alpha p_e > 0$ is if $\alpha > \frac{n}{m+n}$.

$$
\begin{aligned}
\partial_\alpha q_b = & \frac{2mn(-1+\alpha)(n+\alpha)(a-c_b)}{(b(n(m+(-1+\alpha)^2)+m\alpha^2)^2)} \\
& + \frac{n(-m\alpha^2+n(m+(-1+\alpha)^2-2m\alpha))(a-c_g)}{(b(n(m+(-1+\alpha)^2)+m\alpha^2)^2)} < 0
\end{aligned} \tag{3.29}
$$

The amount of black energy is always decreasing as the minimum requirements increase, and this result is independent of the number of firms or the cost difference of the two production technologies.

$$\begin{aligned}\partial_\alpha q_g = & \frac{m((m+1)n(1-2\alpha)-\alpha^2(m-n))(a-c_b)}{b(n(m+(-1+\alpha)^2)+m\alpha^2)^2} \\ & + \frac{2mn(1+m-\alpha)\alpha(a-c_g)}{b(n(m+(-1+\alpha)^2)+m\alpha^2)^2}\end{aligned} \tag{3.30}$$

Figure 3.4 shows that in the tradable green certificate system the amount of green electricity is increasing with the minimum renewable requirement for many cases. The green energy decreases in this environmental regulation when the minimum requirement and the marginal cost difference of the different technologies are small. The sufficient conditions

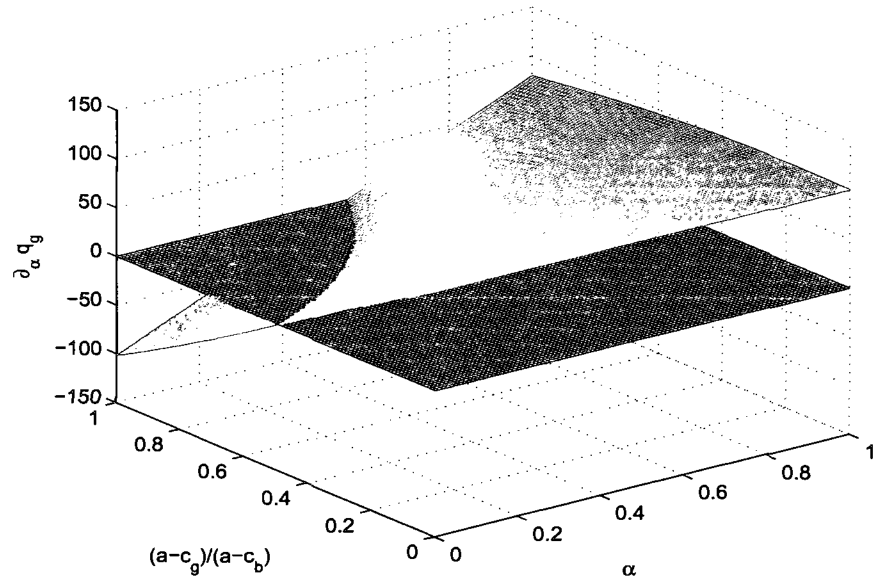

Figure 3.4 The Partial Derivative of q_g if m=40 and n=15

for $\partial_\alpha q_g > 0$ are if $\frac{n}{m+n} < \alpha$ and $m > n$.

$$\partial_\alpha Q = \frac{mn((m+n)((\alpha-1)^2-1)-(m-1)n)(a-c_b)}{b(n(m+(-1+\alpha)^2)+m\alpha^2)^2} + \frac{mn((1+m)n-(m+n)\alpha^2)(a-c_g)}{b(n(m+(-1+\alpha)^2)+m\alpha^2)^2} \tag{3.31}$$

Figure 3.5 shows the total production of electricity decreases almost always as the quota

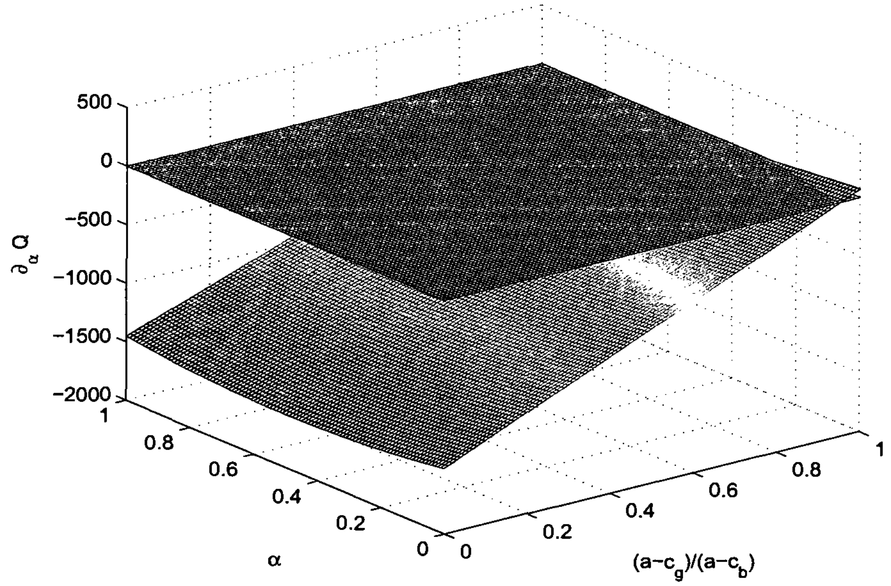

Figure 3.5 The Partial Derivative of Q if m=40 and n=15

increases. It increases only when the cost of green energy and the minimum requirement are very low. The $\partial_\alpha Q < 0$ if $\alpha > \frac{n}{m+n}$.

To check the sensitivity of the comparative statics, the partial derivatives are calculated for different number of green and black producers. The results are presented in Figure 3.6 to 3.9. The graphs show that the price of the certificate is always increasing independently from the number of black and green firms, although the increase in the certificate price is larger when there is few fossil-fuel power plants. The renewable production always increases as the minimum requirement increases and it is independent from the number of fossil-fuel and renewable power plants.

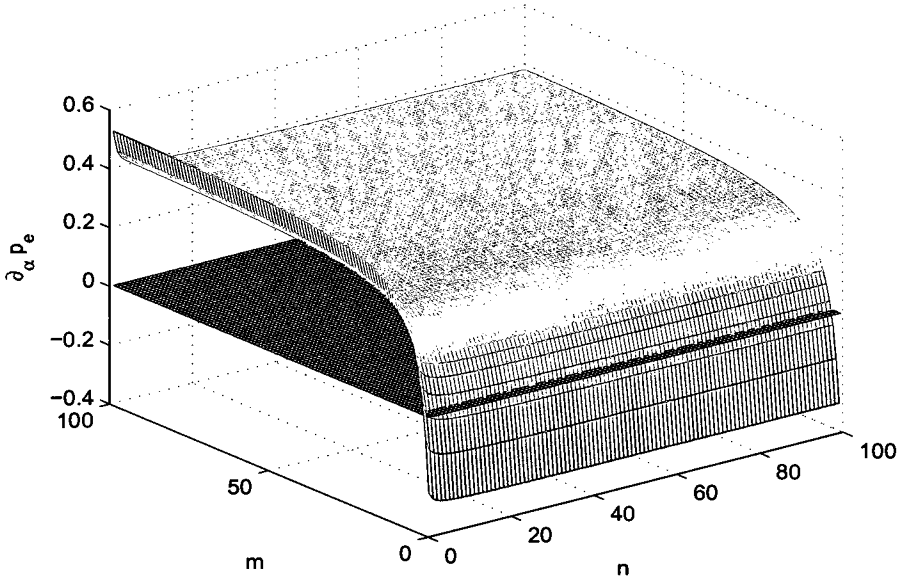

Figure 3.6 The Partial Derivative of p_e if $\alpha = 7.9\%$

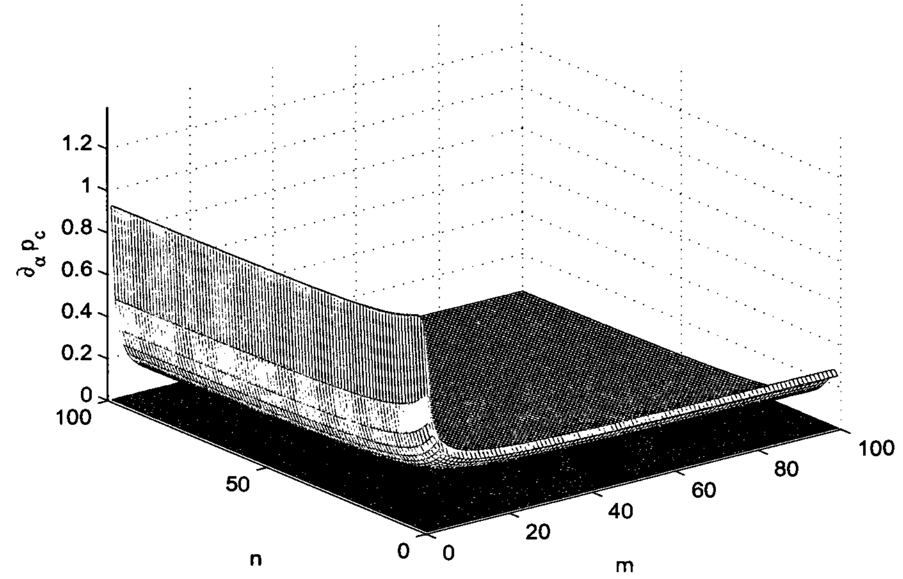

Figure 3.7 The Partial Derivative of p_c if $\alpha = 7.9\%$

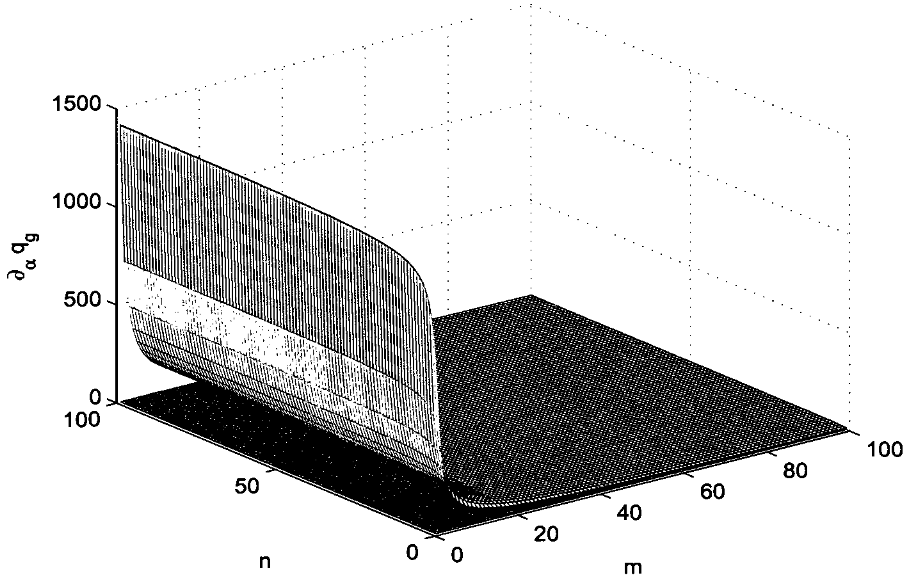

Figure 3.8 The Partial Derivative of q_g if $\alpha = 7.9\%$

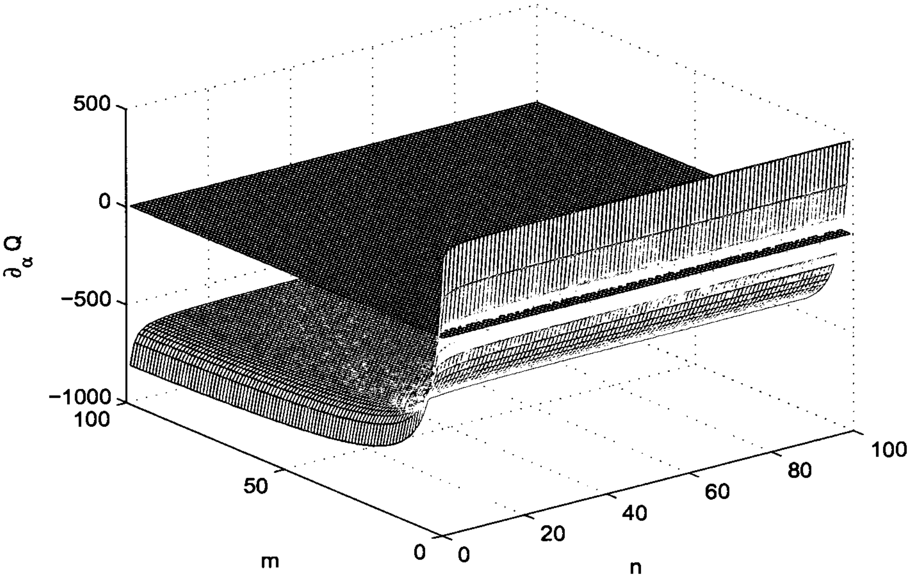

Figure 3.9 The Partial Derivative of Q if $\alpha = 7.9\%$

The price of electricity is decreasing when the quota is increasing only when the number of fossil-fuel firms is small. Finally, the opposite is true for the total electricity production: as the quota increases the total production increases only if the number of fossil fuel plants is less than 4. The number of renewable power plants does not influence significantly the partial derivative of the electricity price and production.

Under the tradable green certificate regulation, the price of the certificates will increase with the increase of the minimum requirements if the minimum requirements are smaller than the proportion of the renewable firms. The left hand side of condition (3.27) can be translated as a measure of the relative market concentration, because the firms are symmetric and the higher the number of firms the smaller the market shares for each of them. This condition can be restated that if the number of firms compared to the size of the market is smaller for the certificate market than for the electricity market then the increase of the minimum requirements results in higher certificate prices. The intuition supports this result as well because the smaller the number of firms, the more incompetitive the market.

The production of the fossil-fuel power plants will decrease because the higher reserve requirement ratio decreases the demand and some of the black production is replaced by green energy. The total production depends on which change is bigger: the increase in the green or the decrease in the black production. As the quota increases, the decrease in the demand for electricity is stronger in most of the cases than the increase in the demand for renewable energy.

3.4 Comparison of the different cases

The comparison of the different cases is presented graphically using values from the UK electricity market. Based on the Digest of the UK Energy Statistics (DUKES) the average production is around 62000 MW, and the price of electricity without taxes is around 40 GBP/MWh. The price elasticity is assumed to be 1, and it is checked that the results are not sensitive for other values of elasticities. From the electricity price and production, the value of a and b can be calculated.[7] The average production cost of fossil-fuel electricity is around 30 GBP/MWh, and the cost of renewable energy is 50 GBP/MWh (The Royal Academy of Engineering, 2004). In the British market there are around 40 black producers and 15 renewable firms; these values are substituted for m and n. Figure 3.10 represents the prices of electricity and certificates under the different scenarios. Figure 3.11 shows the production of the representative firms as a function of the minimum requirement under the different regulatory schemes. In the graphs the number in the subscripts refers to the number of the scenario.

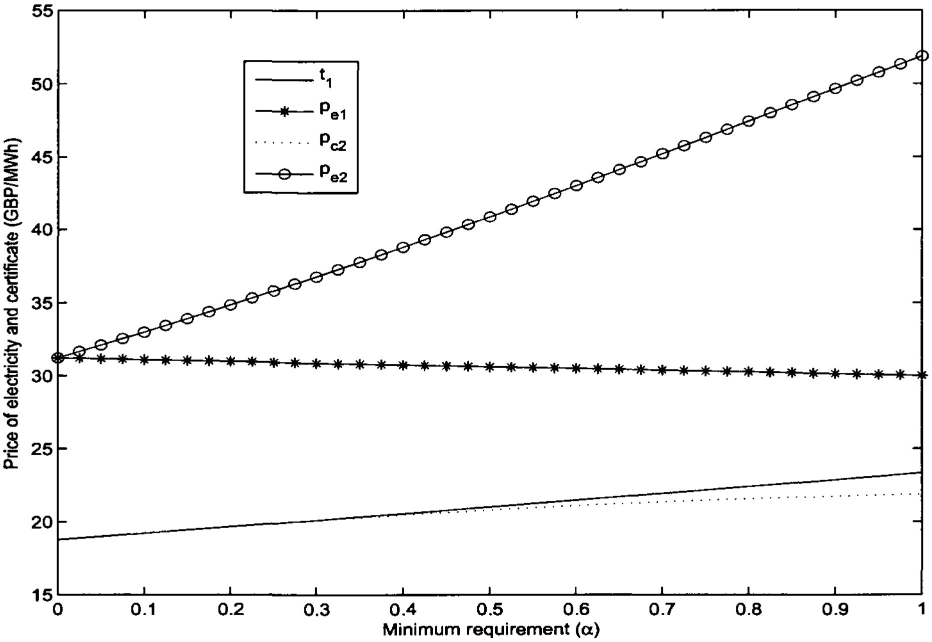

Figure 3.10 The Price of Electricity and Certificates if m=40 and n=15

The graphs show that the price of electricity will decrease with increasing renewable requirements only in the first scenario, when the government pays for the extra cost of renewable energy. In the other case, the higher the α is, the higher the price of the electricity. In both cases the price of the certificate is increasing. When the number of renewable firms is large, the first and the second scenarios give almost the same result. When the

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[7] Under these assumptions $a = 80$ and $b = 0.0007$.

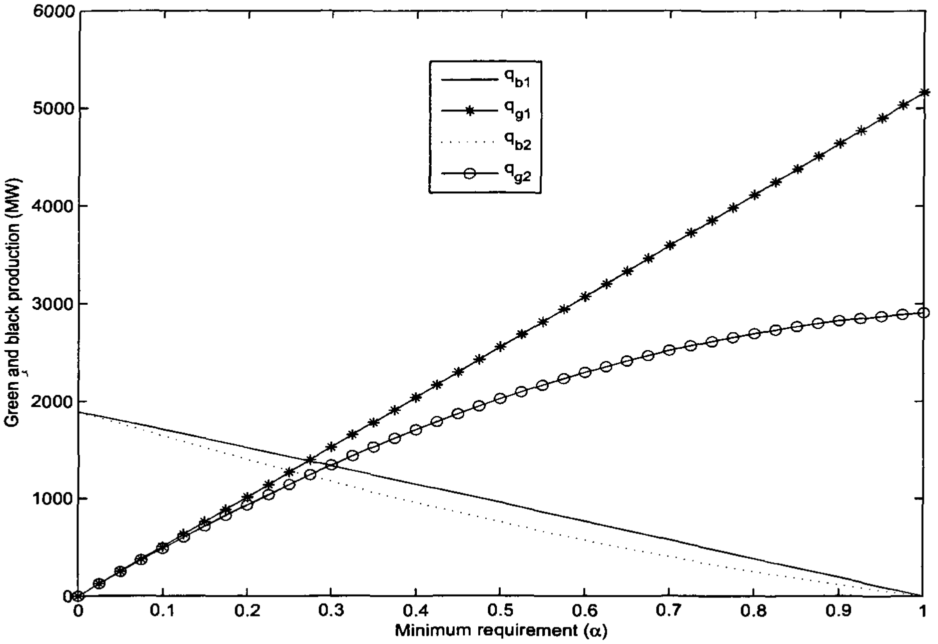

Figure 3.11 The Electricity Production if m=40 and n=15

number of green producers is small then the certificate price in the second case is smaller than in the first case. The reason for this difference is that, in the first case, the demand is not influenced by the certificate price, while in the second case, the higher certificate price decreases the demand.

The production of the fossil fuel plants is always decreasing as the quota increases. This is independent from the scenario or from the number of power plants. The renewable production is increasing with the increasing α. The change in the production depends on the number of firms. If the number of green power plants is bigger than the number of fossil fuel producers, then the production of black energy is decreasing at a higher rate than the renewable production increases. The opposite is true when the number of black producer is bigger than the number of green plants. These results will not change qualitatively when the number of firms is different, only the volume of production decreases as the number of firms increases.

As an aggregate indicator, the total production is calculated to compare the different scenarios. In the following formulas again the index number shows the number of the case. It is possible to rank Q_1 and Q_2 under the following condition:

$$\alpha > \frac{n}{m+n} \Longrightarrow Q_1 > Q_2 \tag{3.32}$$

Table 3.1 summarizes the results of comparative statics for the different cases with separated power producers. These results show that the fossil-fuel production is always decreasing and, under some conditions, the amount of renewable energy is always increasing as the minimum requirement ratio gets higher. In the case of the feed-in tariff, the increasing minimum requirements increases the total production and lowers the price of electricity, whereas in the case of the green certificates system the effect is the opposite. The price of energy increases and the production decreases as the quota is raised.

Table 3.1 Summary of the Comparative Statics

Model	$\partial_\alpha q_g$	$\partial_\alpha q_b$	$\partial_\alpha Q$	$\partial_\alpha p_e$	$\partial_\alpha p_c / \partial_\alpha t$
Case 1.	+	-	+	-	+
Case 2.	+[a]	-	-[a]	+[a]	+[a]

[a] if $\frac{n}{m+n} < \alpha$

3.5 Summary

The two different scenarios of this chapter show that under the assumption of linear demand, constant marginal cost, and symmetric firm size, the introduction of the environmentally friendly regulation increases the competition and lowers the prices in the electricity market if there is no renewable electricity production without the support schemes.

The effect of the minimum requirement is significantly different under the two different regulatory schemes. The only common pattern is that the amount of renewable electricity increases in both cases. In the feed-in tariff system, the increasing quota increases the size of the tariff, lowers the electricity prices and the total production increases. For the tradable green certificate system, the increasing minimum requirements in most of the cases increase the price of the certificates and the price of electricity as well, which decreases the demand and production.

In summary, the results of these models show that the introduction of an environmental policy can increase the market competition in the electricity market, but the stronger and stronger intervention (higher renewable requirements) can increase the price of electricity in the green certificates system.

CHAPTER 4

Simulation Model of the Renewable Electricity Market

4.1 Introduction

All the models, which theoretically analyze the effect of possible oligopoly collusion under the green certificates system, are using several assumptions like linear demand, symmetric firm size and cost structure, or no capacity limit. If we release these assumptions under oligopolistic competition then the model becomes so complicated that it cannot be solved analytically. This is the reason why the researchers often use simulation models in this field to analyze different outcomes in the electricity market (Contaldi et al., 2007; Mészáros, 2003).

The two biggest energy simulation models are the Market Allocation (MARKAL) model of the Energy Technology Systems Analysis Programme and the National Energy Modeling System (NEMS) of the Energy Information Administration of the US Department of Energy. Both systems are extensive, general equilibrium models based on different structural assumptions of the whole economy. Neither of these models deal with possibilities of imperfect competition in the market and it is not possible to analyze changes in ownership structure of the energy companies. In this chapter, a simulation model is built which can be used to analyze different market outcomes taking into consideration the possibility of abuse of market power and to analyze the effects of possible mergers and acquisitions between the renewable and fossil fuel power plants. Finally, the simulation can check if the increasing minimum requirements increase the price of electricity and certificates as they do in the theoretical model of the previous chapter.

The simulation is based on the UK electricity market, which is a fine example of the liberalized electricity market where the market power is a relevant problem (Newbery, 1998). In addition, from 2002 a tradable green certificate system is in force under the name of Renewable Obligation. Another important argument for using the British market is that there is a lot of information on the electricity market that is publicly available. The simulation of this chapter can be adapted as well to other renewable certificate systems and markets, such as the different Renewable Portfolio Standard schemes in the United States. The main requirement of the simulation is the detailed data of the power plants.

4.2 The electricity market in the UK

The British electricity market is one of the first examples of liberalized markets. The privatization and separation of the power companies started in the late 80s. For many other countries this model is a base for the deregulation of the energy sector. The liberalization introduced competition in the market, although the problem of market power still remained relevant and the latest tendency of vertical reintegration increases these concerns (Salies, 2008).

The support of the renewable energy started with the Non-Fossil Fuel Obligation (NFFO) program in 1990. This was similar to the feed-in tariff scheme, where the regulatory authority required the purchase of renewable energy. To support the investment into the renewable technologies, the orders required each public electricity supplier to contract and buy from renewable production capacities for several years. The centralized Non-Fossil Purchase Agency (NFPA) purchased this electricity through competitive bidding. The renewable power plants had to bid and provide a price at which they could provide the given amount of electricity and the NFPA awarded the contracts to the lowest bidders. The contracted price was always higher than the price of electricity in the power exchange and the higher cost of the green energy was reimbursed to the suppliers. The reimbursement was financed through the Fossil-Fuel Levy (FFL), which was built into the price of the electricity to consumers and it was adjusted yearly to cover the cost of the obligation in the previous year (Connor, 2003; Mitchell, 2000).

This regulation was changed in 2002 to the market based Renewable Obligation (RO) system, which works like a tradable green certificate system. Under the NFFO the electricity suppliers were buying renewable energy directly at higher prices, and the FFL was set by the regulatory authority. Under the new system, the suppliers do not have to buy renewable energy. It can be that they buy only the Renewable Obligation Certificate (ROC) from the green power plants, or they can partially substitute the mandated quota with payment to the "buy-out" fund.[1] Every year this fund is redistributed proportionally among the suppliers who bought ROC. The regulatory authority sets in this system the level of renewable energy and the price of the buy-out payment. The price of the ROC is determined on the market of certificates, which is separated from the flow of the renewable electricity.

In the economics literature, since the beginning of the market liberalization, there was relevant concern regarding the possible market power problems (Newbery, 1998). Wolfram (1999) showed that there is relevant market power in the UK electricity market but not as much as the theoretical models would predict. Macatangay (2001) emphasized that there is a relevant problem with market definition in the regulation of the liberalized electricity market, which can be exploited by the dominant firms in the market. In addition, there is a systematic pattern in the price of the electricity which can be attributed to the market power of the dominant power plants (Mount, 2001). Salies and Price (2004) showed that after the liberalization of the residential electricity market, the prices were significantly higher than the production and transmission costs, which raises the concern of relevant market power in the oligopoly market structure. Finally, this situation did not change after the latest wave of mergers and acquisition in the sector (Salies, 2008).

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[1] The buy-out payment is like the punishment for not fulfilling the minimum requirement in the tradable green certificate system.

4.3 Simulation considerations

The simulation based on a partial equilibrium model, only looks at the electricity market. This approach needs less data than the general equilibrium models, because it uses information only on the supply and demand side of the electricity market.

The firms know the demand function for electricity. It can take two forms: it can be linear or constant elasticity of demand (CED). The first one is often used in the theoretical models in the economic literature. The second is commonly used in the empirical estimations, and derived from the Cobb-Douglas utility function.

Based on the Digest of the UK Energy Statistics (DUKES), the average used production capacity in the UK is around 62000 MW, the price of electricity is about 40 GBP/MWh and the price of the Renewable Obligation is around 40 GBP/MWh. There are several possible demand curves passing through this point. This situation is presented in Figure 4.1.

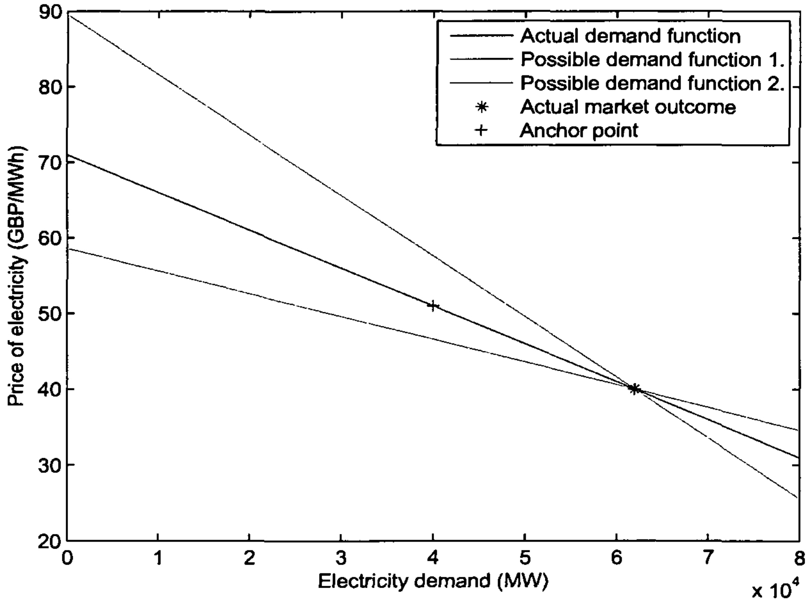

Figure 4.1 Example of the Calibration

To determine the exact demand function, an additional point is needed. This is the so-called anchor point, a price-quantity pair which is on the demand function, representing another possible price and consumption. This point determines the exact demand function from all the possible demand curves. The demand curve and the anchor point are chosen such that the market outcomes in the simulation would give similar results to the one that can be observes in the actual market under the current market structure. This search procedure is the calibration of the model, where the anchor point is chosen from a wide range of price quantity pairs in such a fashion that the price and quantity from the simulation determined by the anchor point would be similar to the actual ones.

The following functional form describes the CED demand:

$$P_e = a * Q^{-\frac{1}{\varepsilon}} \tag{4.1}$$

where ε is the constant elasticity. In the case of the linear demand, the following equation describes the demand:

$$P_e = a - b * Q \tag{4.2}$$

where a and b are calculated so that, at the anchor quantity and price ratio, the elasticity will be equal to ε. In the case of the CED function, the value of a is calculated by the following formula:

$$a = P_0 * Q_0^{\frac{1}{\varepsilon}} \tag{4.3}$$

where P_0 and Q_0 are the price and quantity at the anchor point. In the case of the linear demand, the parameters are determined by the following equations:

$$a = P_0 \frac{1+\varepsilon}{\varepsilon}; \quad b = \frac{1}{\varepsilon} \frac{P_0}{Q_0} \tag{4.4}$$

The values of the elasticities are taken from previous estimations of different studies like Narayan et al. (2007) and Garbacz (1986). The range of the estimated price elasticities in the existing studies is very wide, usually between 0.1 and 1.1. The simulation uses the demand for a representative hour of the year. The hourly demand is very inelastic, because it is very hard to cut back consumption and substitute electricity substantially with other resources from one minute to the next one. Based on this reasoning, the estimated elasticities of the second chapter will not be used because those are yearly elasticities and are based only on the demand of the households excluding the industrial consumers. The simulation uses 0.1 and 0.5 to check if the results are sensitive to changes in the elasticity.

The supply of green and black electricity, the minimum requirement and the buy-out price determines the price of the certificates. It is assumed that in the demand side there is perfect competition among the electricity providers who are obliged to buy the Renewable Obligations. The maximum price that an electricity provider would pay for a certificate is P_c, which is equal to the buy-out price, P_b, plus P_r, the refund for each supplied unit from the buy-out fund.

$$P_c = P_b + P_r \tag{4.5}$$

P_r can be calculated from the budget balance condition of the buy-out fund. The revenue side of the fund is the difference between the supplied and the required electricities multiplied by the buy-out price. The expense side is the value of refund per unit times the produced green energy. This can be represented in the following equation form:

$$P_r Q_g = P_b(\alpha(Q_b + Q_g) - Q_g) \tag{4.6}$$

P_r can be expressed from (4.6), and substituted back to (4.5). This results in the price determination of the ROC.

$$P_c = \alpha P_b \frac{Q_b + Q_g}{Q_g} \tag{4.7}$$

The power plants face the demand of the wholesale market as presented in equation (3.3) in the previous chapter. The wholesale demand is a transformed demand of the consumers, because the price of the certificates is built into the price of the electricity and the electricity providers spread the cost of the renewable energy on all customers.

On the supply (production) side it is assumed that each firm is maximizing profit in a

Cournot-competition by determining the level of production of green and black energy, and it is allowed that one firm can own more than one power plant. Furthermore, it is assumed that the power plants have constant marginal cost. Since there is no exact information on the production cost of each plant, the estimated levelized cost[2] of production for different technologies is used, which is usually described by a range of values. The cost ranges used in the simulation are in Table C.3 in the Appendices. The simulation takes four cost scenarios: the first uses the average value of the range as the production cost. The second scenario takes a random value from the cost range. The third case uses the maximum cost difference, i.e. the minimum cost for the black firms and the maximum cost for the green firms. The last scenario is the minimum cost difference, where the maximum cost is applied for the fossil-fuel plants and the minimum cost for the renewable producers.

The objective function of a representative firm is as follows:

$$\max_{q_{bi},q_{gi}} \sum_{q_{bi}\in N_b} (p_w - c_{bi})q_{bi} + \sum_{q_{gi}\in N_g} (p_w + p_c - c_{gi})q_{gi} \tag{4.8}$$

where N_b and N_g is the set of black and green power plants of the N^{th} firm, p_w and p_c is the wholesale price of electricity and the price of renewable obligation, and q_{bi}, c_{bi}, q_{gi} and c_{gi} are the production and cost of each power plant.

It is assumed that the producer will start to produce at the lowest cost plant and as it reaches the capacity limit the second lowest cost plant will start producing and this process continues until the maximal capacity of the firm is reached. This way, it is the cost, capacity and ownership information of the power plants that determine the supply. It is assumed that only the firms with more than 1 MW installed capacity are playing the oligopoly game in a Cournot-fashion, both in the electricity and in the Renewable Obligation markets. The rest of the smaller firms are behaving like a competitive edge. These small firms are producing at maximum capacity if the prices are higher than the production costs, otherwise

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[2] The levelized cost can be interpreted as the average cost to produce 1 MWh electricity. It contains the cost of input(s), the cost of capital, and the cost of operation and management.

their production is zero. This creates breaks and jumps in the residual demand function, which is used in the optimization problem of the oligopolistic firms.

The equilibrium is searched in a loop with the following algorithm. At one time, a firm is taken out from the market and maximizes its profit assuming that the production of the other plants is fixed. Then the next firm maximizes its profit, assuming the other plants' production is fixed, and so on. The other firms' production is always updated with the new value of the given company. After each firm's optimization, the price of the certificates is updated as well. This update process runs until any of the firms change its production plan. If all the firms reached their common production optimum, the simulation process would stop.

In the original market structure there are 48 oligopolistic firms in the market. Six of them are integrated, and have green and black production capacity as well. This original situation is compared with two other possibilities. One of them is where the renewable plants are separated from the others. In this case the number of firms is 54. The second scenario is where more than one-third of the fossil fuel firms merge with a renewable one. In this case the number of companies in the market is 36. The results are compared under different settings, like different demand elasticities and functional forms, or different cost assumptions. Finally, the effects of the increasing minimum requirement and buy-out price are tested in the different cases.

4.4 Data

The data used in the simulation has different sources. The information on the ownership structure, installed capacity, and production technology of the power plants is from the Digest of the UK Energy Statistics (DUKES), which is available from the Department of Business Enterprise and Regulatory Reform (BERR). The data on eligibility for Renewable Obligation Certificate is from the Office of the Gas and Electricity Markets (OFGEM). The levelized cost of production for different technologies is coming from two different sources: the studies of the OECD Nuclear Energy Agency and International Energy Agency (2005) and The Royal Academy of Engineering (2004). The detailed data and cost information are in Table C.1-C.3 in the Appendices.

4.5 Results

The results of the calibration are in Table 4.1. The table contains the anchor quantities and prices where the demand curve passes through, the applied parameters, and the price of electricity and production in the simulation model. These price and quantity pairs are the closest to the ones that can be observed in the real market. In the later scenarios these anchor values are used for the demand of electricity.

Table 4.1 Summary of the Calibration

Anchor point		Applied parameters					Simulation results		
q_0 MW	p_0 £/MWh	ε	α	P_b £/MWh	Demand	Cost	P_e £/MWh	P_c £/MWh	Q MW
52000	34	0.1	7.9%	34.3	CED	avg.	37.46	34.93	62346
38000	43	0.5	7.9%	34.3	CED	avg.	37.77	34.90	62289
52000	34	0.1	7.9%	34.3	CED	random	37.42	33.96	60605
46000	39	0.5	7.9%	34.3	CED	random	37.61	34.94	62367
52000	34	0.1	7.9%	34.3	CED	max.diff.	37.46	34.90	62296
44000	40	0.5	7.9%	34.3	CED	max.diff.	37.69	34.85	62205
52000	34	0.1	7.9%	34.3	CED	min.diff.	37.46	34.95	62374
44000	40	0.5	7.9%	34.3	CED	min.diff.	37.72	34.74	62007
32000	37	0.1	7.9%	34.3	linear	avg.	37.47	34.75	62019
46000	41	0.5	7.9%	34.3	linear	avg.	37.83	34.78	62082
36000	36	0.1	7.9%	34.3	linear	random	38.81	40.72	72683
46000	41	0.5	7.9%	34.3	linear	random	37.82	34.94	62367
54000	34	0.1	7.9%	34.3	linear	max.diff.	37.47	34.78	62077
46000	41	0.5	7.9%	34.3	linear	max.diff.	37.79	34.85	62202
36000	36	0.1	7.9%	34.3	linear	min.diff.	37.46	34.80	62115
42000	45	0.5	7.9%	34.3	linear	min.diff.	37.81	34.81	62136

The first case is when the buy-out price is increased to 37 GBP and then to 40 GBP. The results in Table 4.2 show that an increase in the buy-out price increases mainly the price of the certificates, while its influence on the price of electricity is very slight. The electricity production decreases in all cases, and the change is greater when the elasticity of the demand is smaller. The 2.7 GBP increase in the buy-out price increases the price of obligation by 1.94 GBP and the price of electricity by only 24 pennies on average. The 5.7 GBP change increases the certificate prices by 3.98 GBP and the price of electricity by 0.47 GBP on average. The increase in the certificate price is smaller when the demand is more inelastic. The electricity production decreases on average by 1366 MW when the buy-out price is 37 GBP and by 2850 MW when the buy-out price is 40 GBP. There is no significant difference between the linear and CED scenarios. These results show that when the demand is more elastic, the increase in the buy-out price is reflected more in the price of the electricity and certificates.

Table 4.2 The Case of Increasing Buy-out Price

Applied parameters					Simulation results		
ε	α	P_b £/MWh	Demand	Cost	P_e £/MWh	P_c £/MWh	Q MW
0.1	7.9%	37	CED	avg.	37.57	36.57	60506
0.5	7.9%	37	CED	avg.	38.07	37.06	61318
0.1	7.9%	37	CED	random	37.55	35.42	58604
0.5	7.9%	37	CED	random	38.15	36.63	60612
0.1	7.9%	37	CED	max.diff.	37.58	36.51	60407
0.5	7.9%	37	CED	max.diff.	37.94	37.10	61390
0.1	7.9%	37	CED	min.diff.	37.62	36.06	59667
0.5	7.9%	37	CED	min.diff.	37.96	37.00	61223
0.1	7.9%	37	linear	avg.	37.64	36.54	60450
0.5	7.9%	37	linear	avg.	38.16	36.96	61148
0.1	7.9%	37	linear	random	38.86	43.48	71945
0.5	7.9%	37	linear	random	38.27	36.98	61192
0.1	7.9%	37	linear	max.diff.	37.62	36.62	60594
0.5	7.9%	37	linear	max.diff.	38.04	37.16	61487
0.1	7.9%	37	linear	min.diff.	37.60	36.74	60789
0.5	7.9%	37	linear	min.diff.	38.22	36.86	60983
0.1	7.9%	40	CED	avg.	37.74	37.81	57870

Table 4.2 – continued

		Applied parameters			Simulation results		
ε	α	P_b £/MWh	Demand	Cost	P_e £/MWh	P_c £/MWh	Q MW
0.5	7.9%	40	CED	avg.	38.46	39.26	60082
0.1	7.9%	40	CED	random	37.66	37.16	56868
0.5	7.9%	40	CED	random	38.36	39.15	59924
0.1	7.9%	40	CED	max.diff.	37.74	37.80	57848
0.5	7.9%	40	CED	max.diff.	38.39	39.17	59947
0.1	7.9%	40	CED	min.diff.	37.74	37.78	57821
0.5	7.9%	40	CED	min.diff.	38.39	39.12	59873
0.1	7.9%	40	linear	avg.	37.84	38.26	58561
0.5	7.9%	40	linear	avg.	38.45	39.42	60330
0.1	7.9%	40	linear	random	39.00	45.75	70011
0.5	7.9%	40	linear	random	38.13	40.23	61565
0.1	7.9%	40	linear	max.diff.	37.83	38.32	58644
0.5	7.9%	40	linear	max.diff.	38.45	39.43	60343
0.1	7.9%	40	linear	min.diff.	37.82	38.38	58743
0.5	7.9%	40	linear	min.diff.	38.52	39.29	60137

In the second scenario, the minimum requirement is increased to 10 percent and then to 15 percent, when the original quota almost doubled. In this setup again, generally the price of the renewable obligation increased, but in this case the change is more drastic. The 2.1% increase in the minimum requirement increases the ROC price by 3.73 GBP on average. When the minimum requirement is almost doubled, the price of the certificate increases by 14.49 GBP on average, which is equivalent to a 41% increase in the prices. Again, the more elastic the demand, the higher is the price increase. The production decreases by 7926 MW and 16086 MW on average. Meanwhile the price of the electricity rises by 1.26 GBP/MWh and 3.31 GBP/MWh on average.

Table 4.3 The Case of Increasing Minimum Requirement

		Applied parameters			Simulation results		
ε	α	P_b £/MWh	Demand	Cost	P_e £/MWh	P_c £/MWh	Q MW

Table 4.3 – continued

Applied parameters					Simulation results		
ε	α	P_b	Demand	Cost	P_e	P_c	Q
		£/MWh			£/MWh	£/MWh	MW
0.1	10.0%	34.3	CED	avg.	38.31	35.31	49783
0.5	10.0%	34.3	CED	avg.	39.43	40.53	57151
0.1	10.0%	34.3	CED	random	38.14	35.58	50168
0.5	10.0%	34.3	CED	random	39.31	40.49	57085
0.1	10.0%	34.3	CED	max.diff.	38.25	35.87	50577
0.5	10.0%	34.3	CED	max.diff.	39.30	40.57	57197
0.1	10.0%	34.3	CED	min.diff.	38.27	35.67	50299
0.5	10.0%	34.3	CED	min.diff.	39.40	40.31	56837
0.1	10.0%	34.3	linear	avg.	38.49	37.12	52344
0.5	10.0%	34.3	linear	avg.	39.40	40.92	57691
0.1	10.0%	34.3	linear	random	39.68	42.85	60413
0.5	10.0%	34.3	linear	random	39.49	41.13	57988
0.1	10.0%	34.3	linear	max.diff.	38.52	36.91	52037
0.5	10.0%	34.3	linear	max.diff.	39.31	41.08	57919
0.1	10.0%	34.3	linear	min.diff.	38.51	37.02	52196
0.5	10.0%	34.3	linear	min.diff.	39.40	40.90	57671
0.1	15.0%	34.3	CED	avg.	38.78	46.89	44073
0.5	15.0%	34.3	CED	avg.	43.16	50.76	47710
0.1	15.0%	34.3	CED	random	38.54	48.06	45177
0.5	15.0%	34.3	CED	random	43.10	50.51	47478
0.1	15.0%	34.3	CED	max.diff.	38.41	51.58	48480
0.5	15.0%	34.3	CED	max.diff.	42.26	52.62	49465
0.1	15.0%	34.3	CED	min.diff.	38.90	45.45	42720
0.5	15.0%	34.3	CED	min.diff.	43.20	50.29	47276
0.1	15.0%	34.3	linear	avg.	39.36	46.93	44113
0.5	15.0%	34.3	linear	avg.	42.96	50.76	47710
0.1	15.0%	34.3	linear	random	40.79	47.88	45010
0.5	15.0%	34.3	linear	random	42.64	52.85	49673
0.1	15.0%	34.3	linear	max.diff.	38.90	51.58	48480
0.5	15.0%	34.3	linear	max.diff.	42.33	52.62	49465
0.1	15.0%	34.3	linear	min.diff.	39.50	45.45	42720
0.5	15.0%	34.3	linear	min.diff.	43.12	50.27	47251

4.5.1 Results with separated producers

In the next scenario, all the renewable plants are separated from the fossil fuel plants to check if the integration has an effect on the prices. In this setup we use the same anchor points as in the previous ones, since the demand structure remains the same and only the supply side of the market is changed.

Table 4.4 The Base Result with Separated Firms

Applied parameters					Simulation results		
ε	α	P_b £/MWh	Demand	Cost	P_e £/MWh	P_c £/MWh	Q MW
0.1	7.9%	34.3	CED	avg.	37.51	34.46	61505
0.5	7.9%	34.3	CED	avg.	37.77	34.90	62289
0.1	7.9%	34.3	CED	random	37.39	34.28	61174
0.5	7.9%	34.3	CED	random	37.68	34.81	62119
0.1	7.9%	34.3	CED	max.diff.	37.44	35.11	62665
0.5	7.9%	34.3	CED	max.diff.	37.71	34.81	62119
0.1	7.9%	34.3	CED	min.diff.	37.46	34.95	62374
0.5	7.9%	34.3	CED	min.diff.	37.72	34.74	62011
0.1	7.9%	34.3	linear	avg.	37.47	34.75	62019
0.5	7.9%	34.3	linear	avg.	37.84	34.77	62058
0.1	7.9%	34.3	linear	random	38.87	40.26	71859
0.5	7.9%	34.3	linear	random	38.03	34.65	61836
0.1	7.9%	34.3	linear	max.diff.	37.49	34.67	61871
0.5	7.9%	34.3	linear	max.diff.	37.79	34.84	62187
0.1	7.9%	34.3	linear	min.diff.	37.46	34.80	62115
0.5	7.9%	34.3	linear	min.diff.	38.01	34.49	61562

The results in Table 4.4 show that with separated power producers the production is decreasing by 150 MW on average compared to the starting scenario. The price of electricity increased by 4 pennies/MWh, the price of the certificate decreased by 8 pennies/MWh compared to the original case in Table 4.1.

The increase of the buy-out price is tested under the new market structure as well. When the size of the fine increases to 37 GBP then the price of the certificate is increasing by 2 GBP and when the buy-out price is equal to 40 GBP then the price of the ROC increases by 4.07 GBP on average. These values are slightly higher than the increments in the original cases, which indicates that under separation the increased cost is passed more to the customers. The production quantities change more when a more inelastic demand is used. On average, the production is decreasing by 1255 MW and 2687 MW, which is smaller when there is integration. Increasing the buy-out price raises the price of electricity by smaller amounts under separation, compared to the original market structure. Meanwhile, the price of certificates increases more with separated power plants compared to the integrated case. This suggest that under separation there is greater competition in the electricity market, and the renewable firms have to compensate more in the certificates market.

Table 4.5 Increasing Buy-out Price with Separated Firms

Applied parameters					Simulation results		
ε	α	P_b	Demand	Cost	P_e	P_c	Q
		£/MWh			£/MWh	£/MWh	MW
0.1	7.9%	37	CED	avg.	37.58	36.44	60283
0.5	7.9%	37	CED	avg.	37.98	37.24	61623
0.1	7.9%	37	CED	random	37.53	35.63	58959
0.5	7.9%	37	CED	random	37.91	37.09	61369
0.1	7.9%	37	CED	max.diff.	37.58	36.51	60407
0.5	7.9%	37	CED	max.diff.	37.99	37.01	61233
0.1	7.9%	37	CED	min.diff.	37.55	36.79	60871
0.5	7.9%	37	CED	min.diff.	38.13	36.68	60688
0.1	7.9%	37	linear	avg.	37.64	36.51	60404
0.5	7.9%	37	linear	avg.	38.19	36.91	61061
0.1	7.9%	37	linear	random	38.97	42.58	70453
0.5	7.9%	37	linear	random	38.30	36.93	61099
0.1	7.9%	37	linear	max.diff.	37.62	36.62	60594
0.5	7.9%	37	linear	max.diff.	38.25	36.80	60887
0.1	7.9%	37	linear	min.diff.	37.60	36.74	60789
0.5	7.9%	37	linear	min.diff.	38.23	36.84	60960
0.1	7.9%	40	CED	avg.	37.74	37.79	57840
0.5	7.9%	40	CED	avg.	38.41	39.36	60236
0.1	7.9%	40	CED	random	37.64	37.38	57211
0.5	7.9%	40	CED	random	38.35	39.19	59978
0.1	7.9%	40	CED	max.diff.	37.70	38.18	58434
0.5	7.9%	40	CED	max.diff.	38.37	39.21	60003
0.1	7.9%	40	CED	min.diff.	37.74	37.78	57821
0.5	7.9%	40	CED	min.diff.	38.37	39.16	59925
0.1	7.9%	40	linear	avg.	37.84	38.26	58561
0.5	7.9%	40	linear	avg.	38.54	39.27	60098
0.1	7.9%	40	linear	random	39.03	45.44	69543
0.5	7.9%	40	linear	random	38.20	40.10	61374

Table 4.5 – continued

	Applied parameters				Simulation results		
ε	α	P_b £/MWh	Demand	Cost	P_e £/MWh	P_c £/MWh	Q MW
0.1	7.9%	40	linear	max.diff.	37.83	38.32	58644
0.5	7.9%	40	linear	max.diff.	38.45	39.43	60347
0.1	7.9%	40	linear	min.diff.	37.83	38.30	58620
0.5	7.9%	40	linear	min.diff.	38.52	39.29	60137

Table 4.6 shows the effect of the minimum requirement under separated market structure. If α is 10% then the price of the certificate increases by 3.92 GBP, and when the requirement almost doubled then the price of ROC increases by 41%, which is the same as the case of integrated power plants presented in Table 4.3. Again production changes more in the inelastic scenarios. In this case the increased quota decreases the production by 7627 MW and 16116 MW on average, and increases the electricity prices by 1.20 GBP/MWh and 3.31 GBP/MWh on average. As in the previous case, the changes are bigger as the demand elasticity increases.

Table 4.6 Increasing Minimum Requirement with Separated Firms

	Applied parameters				Simulation results		
ε	α	P_b £/MWh	Demand	Cost	P_e £/MWh	P_c £/MWh	Q MW
0.1	10.0%	34.3	CED	avg.	38.24	35.95	50691
0.5	10.0%	34.3	CED	avg.	39.43	40.53	57151
0.1	10.0%	34.3	CED	random	38.16	35.39	49893
0.5	10.0%	34.3	CED	random	39.34	40.41	56980
0.1	10.0%	34.3	CED	max.diff.	38.25	35.87	50577
0.5	10.0%	34.3	CED	max.diff.	39.21	40.75	57460
0.1	10.0%	34.3	CED	min.diff.	38.27	35.67	50299
0.5	10.0%	34.3	CED	min.diff.	39.30	40.51	57122
0.1	10.0%	34.3	linear	avg.	38.49	37.12	52344
0.5	10.0%	34.3	linear	avg.	39.40	40.92	57691
0.1	10.0%	34.3	linear	random	39.61	43.59	61462
0.5	10.0%	34.3	linear	random	39.39	41.31	58251
0.1	10.0%	34.3	linear	max.diff.	38.52	36.91	52037

Table 4.6 – continued

Applied parameters					Simulation results		
ε	α	P_b £/MWh	Demand	Cost	P_e £/MWh	P_c £/MWh	Q MW
0.5	10.0%	34.3	linear	max.diff.	39.31	41.08	57919
0.1	10.0%	34.3	linear	min.diff.	38.51	37.02	52196
0.5	10.0%	34.3	linear	min.diff.	39.41	40.90	57663
0.1	15.0%	34.3	CED	avg.	38.78	46.89	44073
0.5	15.0%	34.3	CED	avg.	43.16	50.76	47710
0.1	15.0%	34.3	CED	random	38.68	46.30	43517
0.5	15.0%	34.3	CED	random	42.90	50.98	47916
0.1	15.0%	34.3	CED	max.diff.	38.41	51.58	48480
0.5	15.0%	34.3	CED	max.diff.	42.26	52.62	49465
0.1	15.0%	34.3	CED	min.diff.	38.90	45.45	42720
0.5	15.0%	34.3	CED	min.diff.	43.20	50.29	47276
0.1	15.0%	34.3	linear	avg.	39.36	46.93	44113
0.5	15.0%	34.3	linear	avg.	42.96	50.76	47710
0.1	15.0%	34.3	linear	random	40.77	48.12	45236
0.5	15.0%	34.3	linear	random	43.36	50.82	47772
0.1	15.0%	34.3	linear	max.diff.	38.90	51.58	48480
0.5	15.0%	34.3	linear	max.diff.	42.33	52.62	49465
0.1	15.0%	34.3	linear	min.diff.	39.50	45.45	42720
0.5	15.0%	34.3	linear	min.diff.	43.12	50.27	47251

4.5.2 Results under more integrated market structure

In the last case, the market integration is increased. In the original oligopoly market there were 48 firms. Under the assumption of separation it increased to 54. Finally, in this situation one third of the firms will merge: 18 fossil-fuel plants will be together with one renewable power producer. In this scenario the number of firms is 36.

Table 4.7 The Base Results with Higher Concentration

Applied parameters					Simulation results		
ε	α	P_b £/MWh	Demand	Cost	P_e £/MWh	P_c £/MWh	Q MW
0.1	7.9%	34.3	CED	avg.	37.46	34.93	62346
0.5	7.9%	34.3	CED	avg.	37.77	34.90	62289

Table 4.7 – continued

Applied parameters					Simulation results		
ε	α	P_b £/MWh	Demand	Cost	P_e £/MWh	P_c £/MWh	Q MW
0.1	7.9%	34.3	CED	random	37.38	34.38	61354
0.5	7.9%	34.3	CED	random	37.72	34.73	61983
0.1	7.9%	34.3	CED	max.diff.	37.46	34.90	62296
0.5	7.9%	34.3	CED	max.diff.	37.69	34.85	62205
0.1	7.9%	34.3	CED	min.diff.	37.46	34.95	62374
0.5	7.9%	34.3	CED	min.diff.	37.72	34.74	62007
0.1	7.9%	34.3	linear	avg.	37.47	34.75	62019
0.5	7.9%	34.3	linear	avg.	37.83	34.78	62082
0.1	7.9%	34.3	linear	random	38.77	41.04	73238
0.5	7.9%	34.3	linear	random	37.99	34.70	61927
0.1	7.9%	34.3	linear	max.diff.	37.47	34.78	62077
0.5	7.9%	34.3	linear	max.diff.	37.79	34.85	62202
0.1	7.9%	34.3	linear	min.diff.	37.46	34.80	62115
0.5	7.9%	34.3	linear	min.diff.	37.81	34.81	62136

Table 4.7 presents the base result of the simulation with higher level of concentration. It is very similar to values in Table 4.1. The main difference is when the random cost is applied in the simulation. In these cases on average the production increases by 120 MW, the price of the electricity decreases by 4 pennies/MWh and the price of the renewable obligation decreases by 7 pennies/MWh. The differences between the linear and CED demand cases are negligible as in the previous scenarios.

Table 4.8 Increasing Buy-out Price with Higher Concentration

Applied parameters					Simulation results		
ε	α	P_b £/MWh	Demand	Cost	P_e £/MWh	P_c £/MWh	Q MW
0.1	7.9%	37	CED	avg.	37.57	36.57	60506
0.5	7.9%	37	CED	avg.	38.07	37.06	61318
0.1	7.9%	37	CED	random	37.51	35.79	59207
0.5	7.9%	37	CED	random	37.98	36.96	61155
0.1	7.9%	37	CED	max.diff.	37.58	36.51	60407
0.5	7.9%	37	CED	max.diff.	37.94	37.10	61390
0.1	7.9%	37	CED	min.diff.	37.62	36.06	59667

Table 4.8 – continued

Applied parameters					Simulation results		
ε	α	P_b £/MWh	Demand	Cost	P_e £/MWh	P_c £/MWh	Q MW
0.5	7.9%	37	CED	min.diff.	37.96	37.00	61223
0.1	7.9%	37	linear	avg.	37.64	36.54	60450
0.5	7.9%	37	linear	avg.	38.16	36.96	61148
0.1	7.9%	37	linear	random	38.92	43.02	71179
0.5	7.9%	37	linear	random	38.27	36.98	61190
0.1	7.9%	37	linear	max.diff.	37.62	36.62	60594
0.5	7.9%	37	linear	max.diff.	38.04	37.16	61487
0.1	7.9%	37	linear	min.diff.	37.60	36.74	60789
0.5	7.9%	37	linear	min.diff.	38.22	36.86	60983
0.1	7.9%	40	CED	avg.	37.70	38.14	58377
0.5	7.9%	40	CED	avg.	38.46	39.26	60082
0.1	7.9%	40	CED	random	37.64	37.38	57205
0.5	7.9%	40	CED	random	38.40	39.09	59819
0.1	7.9%	40	CED	max.diff.	37.74	37.80	57848
0.5	7.9%	40	CED	max.diff.	38.39	39.17	59947
0.1	7.9%	40	CED	min.diff.	37.74	37.78	57821
0.5	7.9%	40	CED	min.diff.	38.39	39.12	59873
0.1	7.9%	40	linear	avg.	37.88	37.97	58117
0.5	7.9%	40	linear	avg.	38.45	39.42	60330
0.1	7.9%	40	linear	random	39.06	45.23	69223
0.5	7.9%	40	linear	random	38.17	40.15	61444
0.1	7.9%	40	linear	max.diff.	37.83	38.32	58644
0.5	7.9%	40	linear	max.diff.	38.45	39.43	60343
0.1	7.9%	40	linear	min.diff.	37.82	38.38	58743
0.5	7.9%	40	linear	min.diff.	38.52	39.29	60137

If the buy-out price increases to 37 and 40 GBP under the assumption of increased concentration, then the price of the certificates increases by 1.94 GBP and 3.94 GBP. These changes are the smallest out of the three scenarios. The price of the electricity increases by 0.22 GBP/MWh and 0.46 GBP/MWh, which is smaller than in the original market structure presented in Table 4.2. This shows that the increasing market concentration under the environmental regulation can have positive effects on the welfare. The electricity production decreases by 1372 MW and 2918 MW on average.

Table 4.9 Increasing Minimum Requirement with Higher Concentration

Applied parameters					Simulation results		
ε	α	P_b £/MWh	Demand	Cost	P_e £/MWh	P_c £/MWh	Q MW
0.1	10.0%	34.3	CED	avg.	38.31	35.31	49783
0.5	10.0%	34.3	CED	avg.	39.43	40.53	57151
0.1	10.0%	34.3	CED	random	38.15	35.44	49975
0.5	10.0%	34.3	CED	random	39.28	40.55	57176
0.1	10.0%	34.3	CED	max.diff.	38.25	35.87	50577
0.5	10.0%	34.3	CED	max.diff.	39.30	40.57	57197
0.1	10.0%	34.3	CED	min.diff.	38.27	35.67	50299
0.5	10.0%	34.3	CED	min.diff.	39.40	40.31	56837
0.1	10.0%	34.3	linear	avg.	38.49	37.12	52344
0.5	10.0%	34.3	linear	avg.	39.40	40.92	57691
0.1	10.0%	34.3	linear	random	39.68	42.88	60465
0.5	10.0%	34.3	linear	random	39.40	41.28	58205
0.1	10.0%	34.3	linear	max.diff.	38.52	36.91	52037
0.5	10.0%	34.3	linear	max.diff.	39.31	41.08	57919
0.1	10.0%	34.3	linear	min.diff.	38.54	36.76	51827
0.5	10.0%	34.3	linear	min.diff.	39.40	40.90	57671
0.1	15.0%	34.3	CED	avg.	38.78	46.89	44073
0.5	15.0%	34.3	CED	avg.	43.16	50.76	47710
0.1	15.0%	34.3	CED	random	38.53	48.12	45229
0.5	15.0%	34.3	CED	random	42.47	52.01	48893
0.1	15.0%	34.3	CED	max.diff.	38.41	51.58	48480
0.5	15.0%	34.3	CED	max.diff.	42.26	52.62	49465
0.1	15.0%	34.3	CED	min.diff.	38.90	45.45	42720
0.5	15.0%	34.3	CED	min.diff.	43.20	50.29	47276
0.1	15.0%	34.3	linear	avg.	39.36	46.93	44113
0.5	15.0%	34.3	linear	avg.	42.96	50.76	47710
0.1	15.0%	34.3	linear	random	40.76	48.30	45403
0.5	15.0%	34.3	linear	random	42.89	52.14	49014
0.1	15.0%	34.3	linear	max.diff.	38.90	51.58	48480
0.5	15.0%	34.3	linear	max.diff.	42.33	52.62	49465
0.1	15.0%	34.3	linear	min.diff.	39.50	45.45	42720
0.5	15.0%	34.3	linear	min.diff.	43.12	50.27	47251

Table 4.9 presents the results of the simulation when the minimum requirement increases and there are only 36 firms in the market. The price of the certificates increases by 3.7 GBP on average when the minimum requirement increases to 10% and by 14.55 GBP when α is

equal to 15%. The price of electricity increases by 3.27 GBP/MWh when the quota almost doubled. This figure is the smallest from the results of all three market structures. This result suggests again that the increasing market concentration can have a beneficial effect when the environmental regulation is more aggressive. With the mergers, the firms can increase the economies of scale and scope at the same time. In this last case, the production decreases by 7969 MW and 16041 MW on average.

4.5.3 Electricity market predictions

The simulation model can be used to predict future outcomes as well. Figures 4.2 and 4.3 show how the price of electricity and green certificates change in four different scenarios.

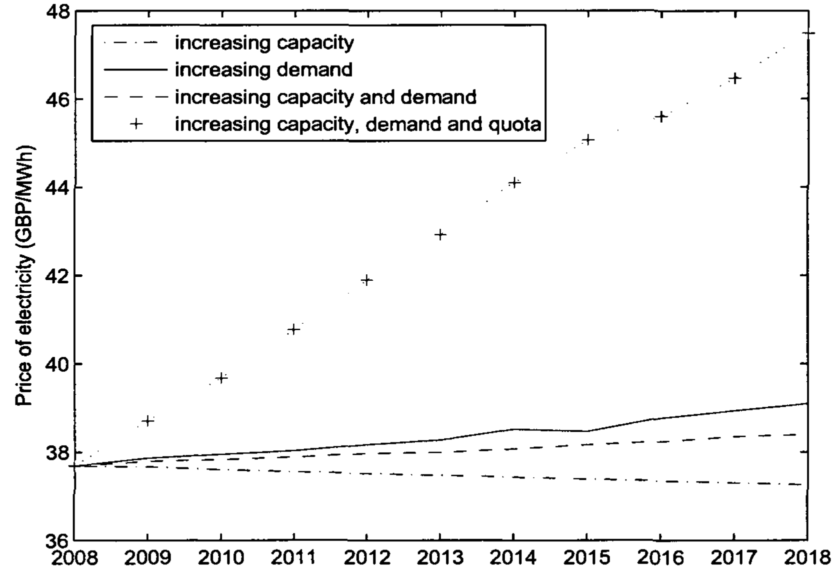

Figure 4.2 Electricity Price Forecast (CED demand, ε=0.5)

The first scenario is when only the capacity of the renewable electricity is increasing at a yearly rate of 1.5 percent. The growth rate is based on the information of the operator of the UK transmission grid, which expects that the renewable capacity will increase by 10 percent by 2015 (National Grid, 2008). The increasing capacity causes a moderate decrease in the price of electricity and a bigger decrease in the certificate prices. The second

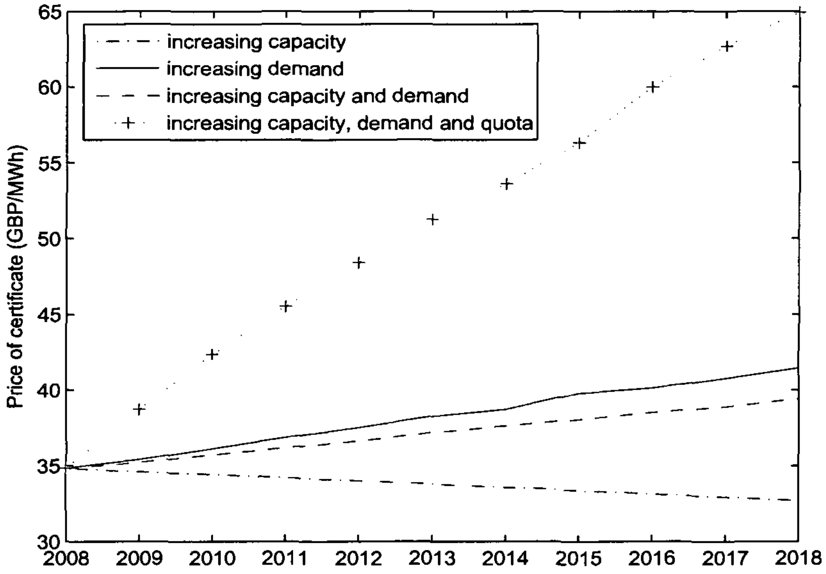

Figure 4.3 Green Certificate Price Forecast (CED demand, ε=0.5)

case is when only the demand is increasing at a yearly rate of 2.5 percent. The increasing demand could come, for example, from the introduction of electric vehicles into the households; a penetration rate of electric/plug-in hybrid vehicles of 1 percent would increase the electricity demand by 1560 MW in one hour in the UK (Webster, 1999). In this second case, the price of electricity increases by 0.3% yearly and the price of certificates increases with yearly 1.7% on average. The third case is when the green capacity increases together with the demand. In this case, the price of electricity has similar pattern as the previous scenario, but the growth rate is slightly smaller at 0.2% in a year. The price of the renewable obligation increases over the years by 1.2% yearly. The increased capacity alleviates the increasing pressure of increasing demand on prices. The final scenario is when the minimum requirement increases as well as demand and capacity. It is assumed that the quota will increase from year to year with 1.2 percentage points, which is the same as the growth rate of the last couple of years. The increasing quota increases the price of electricity by 2.3% yearly, which is the highest out of all the scenarios. The growth rate in the first years is higher than in the last ones. The price of certificates increases at a much higher rate. The increasing quota raises the price of ROC by 6.4% in a year. In all simulation scenarios all the renewable production capacity is used at their maximum level. Therefore, the increasing quota causes a shortage in the renewable electricity market which increases the prices more significantly. The first and third scenarios show that the increasing capacity can decrease this shortage and result in lower prices. These results have an important policy implication, that the increasing quota can raise the prices significantly if there are not enough renewable production capacities. If the regulatory authority set the long-term goal, then the yearly increase of the requirements should be adjusted to the available capacities.

4.6 Summary

The results with separated market structure confirm the results of the second case of the theoretical model in the previous chapter, where the price of electricity and certificates increases with the renewable requirement, and the production decreases at the same time. The results of the numerical calculation based on the UK electricity market structure show that the capacity limit in the renewable electricity sector has a major influence on market outcomes, because in all the cases the green production is at the maximum level. The limited capacity can constrain the market power under increasing market concentration, and limit the strategic actions. The results show that the increasing minimum requirement has an increasing effect on the renewable obligation prices, and electricity prices; meanwhile the electricity production decreases. The simulation results also suggest that even the increasing concentration can have a positive effect on the welfare (e.g. increase production, decrease prices). Finally, the simulation model shows that the change in the minimum requirement has stronger effects on the electricity price than the change of the penalty (i.e. the buy-out price). It means the minimum requirements determine the rough ROC prices, and the buy-out price can be used to do the fine tuning.

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APPENDICES

Appendix A

Definition of Variables and Statistical Outputs

Table A.1 The definition of the variables

Variable	Description
Q_e	Total electricity consumed in the last year in kWh
P_e	Average price of the electricity in USD/kWh
Y	Total combined income in the past 12 months
VAP	The total number of small household appliances (microwave oven, toaster, electric coffee maker, ceiling fan, color TV, VCR and DVD player, aquarium, cordless phone, answering machine, stereo equipment, personal computers, printer, fax, copier, portable electric heater, window AC unit, number of lights burning more than 12 hours a day)
w	The sum of the power/performance of small household appliances. The maximum hourly electricity consumption in Watts of the variable appliance stock.
FAP_1	Electric stove
FAP_2	Electric oven
FAP_3	The number of refrigerators
FAP_4	The number of separate freezers
FAP_5	Electric dishwasher
FAP_6	Electric clothes washer
FAP_7	Electric clothes dryer
FAP_8	Electric water heater
HC_1	Cooling Degree-Days to base 65. 1-04 TO 12-04
HC_2	Heating Degree-Days to base 65. 1-04 TO 12-04
HC_3	Type of Home: as report by Respondent
HC_{31}	The type of Home is mobile home
HC_{32}	The type of Home is detached family house
HC_{33}	The type of Home is attached family house
HC_{34}	The type of Home is apartment complex with 2-4 units
HC_{35}	The type of Home is apartment complex with more than 5 units
HC_4	Dwelling owned or rented
HC_5	Year Home Built
HC_6	Type of neighborhood
HC_{61}	Dummy=1 if the house in a city
HC_{62}	Dummy=1 if the house in a town
HC_{63}	Dummy=1 if the house in a suburb
HC_{64}	Dummy=1 if the house in a rural area
HC_7	Natural gas from underground pipe available

Continued on next page

Table A.1 – continued from previous page

Variable	Description
HC_8	Dummy if the main fuel for heating is electricity
HC_9	Dummy=1 if they have central airconditioning
HC_{10}	Any large trees shade home from afternoon sun
HC_{11}	Respondent perception of home insulation
HC_{111}	Dummy=1 if the house is not insulated
HC_{112}	Dummy=1 if the house is poorly insulated
HC_{113}	Dummy=1 if the house is adequately insulated
HC_{114}	Dummy=1 if the house is well insulated
HC_{12}	Total square footage
HC_{13}	Urban/rural dummy
HHC_1	The size of the household
HHC_2	The number of children under 12
HHC_3	The number of retired members above 65
HHC_4	Dummy=1 if someone at home all day on a typical weekday
HHC_5	Sex of the household head
HHC_6	Employment status of the household head
HHC_{61}	Dummy=1 if employment status is not employed
HHC_{62}	Dummy=1 if employment status is full-time employment
HHC_{63}	Dummy=1 if employment status is part-time employment
HHC_7	Household living with a spouse/partner
HHC_8	The race of the household head
HHC_{81}	Dummy=1 if race is White
HHC_{82}	Dummy=1 if race is Black
HHC_{83}	Dummy=1 if race is American Indian/Alaskan
HHC_{84}	Dummy=1 if race is Asian/Pacific Islander
HHC_{85}	Dummy=1 if race is Other
HHC_{86}	Dummy=1 if race is Hispanic
HHC_9	Dummy for home business
HHC_{10}	Number of vehicles
HHC_{11}	Government helped to pay some heating costs
HHC_{12}	Government helped to pay some cooling costs
HHC_{13}	Eligible for LIHEAP (Low Income Home Energy Assistance Program)
G_1	Census Region
G_{11}	Dummy=1 if census region is Northeast
G_{12}	Dummy=1 if census region is Midwest
G_{13}	Dummy=1 if census region is South
G_{14}	Dummy=1 if census region is West
G_2	Census Division
G_{21}	Dummy=1 if census division is New England
G_{22}	Dummy=1 if census division is Middle Atlantic
G_{23}	Dummy=1 if census division is East North Central
G_{24}	Dummy=1 if census division is West North Central

Continued on next page

Table A.1 – continued from previous page

Variable	Description
G_{25}	Dummy=1 if census division is South Atlantic
G_{26}	Dummy=1 if census division is East South Central
G_{27}	Dummy=1 if census division is West South Central
G_{28}	Dummy=1 if census division is Mountain
G_{29}	Dummy=1 if census division is Pacific

Table A.2 Descriptive Statistics of the Main Variables

	2001		1997		1993	
Variable	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Q_e	10619.83	7392.83	10064.59	7119.94	10299.42	7133.41
P_e	0.09	0.03	0.09	0.20	0.09	0.03
Y_{ps}	52670.13	60248.54	40939.90	47406.56	50712.46	74151.09
VAP	12.24	5.25	10.21	4.84	6.40	3.33
w	3557.53	1352.88	2262.37	995.14	2442.55	1093.20
FAP_1	0.60	0.48	0.60	0.48	0.63	0.48
FAP_2	0.59	0.49	0.60	0.48	0.63	0.48
FAP_3	1.18	0.41	1.15	0.38	1.15	0.38
FAP_4	0.38	0.56	0.36	0.55	0.39	0.57
HC_{12}	21.70	1404.90	1619.36	857.86	1927.44	1251.70
HHC_1	2.63	1.47	2.63	1.46	2.70	1.47
HHC_{13}	0.32	0.46	0.37	0.48	0.00	0.03

Table A.3 Estimation of Appliance Stock (Negative Binomial)

	2001		1997		1993	
VAP	Coef.	Std. Err.	Coef.	Std. Err.	Coef.	Std. Err.
Log(Y)	0.070[a]	0.007	0.071[1]	0.008	0.037[1]	0.005
HC_4	0.163[1]	0.013	0.156[1]	0.013	0.261[1]	0.014
HC_{62}	-0.008	0.014	-0.009	0.013	-0.031[2]	0.015
HC_{63}	0.021	0.014	0.026[3]	0.014	0.034[b]	0.014
HC_{64}	-0.038[1]	0.014	-0.045[1]	0.014	-0.077[1]	0.015
HC_{12}	4.59e-05[1]	3.88e-06	8.71e-06[1]	7.02e-06	5.25e-05[1]	4.58e-06
HHC_1	0.057[1]	0.006	0.059[1]	0.006	0.051[1]	0.006
HHC_2	-0.010	0.008	-0.019[2]	0.008	-0.010	0.008
HHC_3	-0.049[1]	0.009	-0.055[1]	0.009	-0.021[3]	0.011
HHC_5	0.000	0.010	0.005	0.010	0.018	0.011
HHC_{62}	0.038[1]	0.013	0.016	0.013	0.018	0.014
HHC_{63}	0.022	0.018	0.021	0.018	0.023	0.020
HHC_{82}	-0.013	0.017	-0.012	0.016	-0.037[2]	0.018
HHC_{83}	-0.095	0.060	-0.050	0.058	-0.007	0.072
HHC_{84}	-0.150[1]	0.029	-0.151[1]	0.031	-0.235[1]	0.034
HHC_{85}	-0.174[1]	0.048	-0.134[2]	0.056	-0.123	0.175
HHC_{86}	-0.156[1]	0.025	-0.187[1]	0.024	-0.174[1]	0.045
HHC_9	0.069[1]	0.018	0.104[1]	0.018	0.140[1]	0.019
HHC_{10}	0.064[1]	0.006	0.062[1]	0.006	0.088[1]	0.007
HHC_{13}	-0.032[c]	0.018	-0.057[1]	0.017	0.053	0.152
constant	1.304[1]	0.075	1.124[1]	0.080	0.898[1]	0.046
α	0.028	0.002	0.038	0.002	0.030	0.003
LR-test $\alpha = 0$ (Poisson)		241.46		368.84		241.46
p-value		0.000		0.000		0.000

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[a] Significant at 1% level.
[b] Significant at 5% level.
[c] Significant at 10% level.

Table A.4 ANOVA Analysis of Income and Electricity Consumption for 2001

lY_{ps}	Summary of lQ_e Mean
7.82728	8.6348278
9.03194	8.8641351
9.74531	8.9270524
10.2481	9.0428587
10.6392	9.0981533
11.113	9.2032856
11.6587	9.2699741
12.3629	9.4307293

Analysis of Variance	
F-statistics	68.33
Prob > F	0.0000

Table A.5 ANOVA Analysis of Income and Electricity Consumption for 1997

lY_{ps}	Summary of lQ_e Mean
8.18353	8.6083842
9.27302	8.8242624
9.93262	8.9434178
10.3866	8.9975791
10.7319	9.1318616
11.1427	9.2353015
11.6216	9.3303136
12.257	9.3777778

Analysis of Variance	
F-statistics	93.26
Prob > F	0.0000

Table A.6 ANOVA Analysis of Income and Electricity Consumption for 1993

lY_{ps}	Summary of lQ_e Mean
7.55683	8.6243945
8.92939	8.8117853
9.81212	9.0130503
10.4144	9.1162856
10.8704	9.1886426
11.3901	9.2042546
12.0600	9.3236894
12.7759	9.3807008

Analysis of Variance	
F-statistics	113.65
Prob > F	0.0000

Appendix B

Mathematical Derivations

Base case: The optimality for black producers

The first order condition (FOC) for the representative black producer is:

$$\frac{\partial \Pi_b}{\partial q_b} = a - c_b - bq_b^i - b(Q_{-i} + q_b^i) = 0 \tag{B.1}$$

where Q_{-i} is the production of other power plants, which is taken as exogenously given.

Base case: The optimality for green producers

The first order condition for the representative green producer is:

$$\frac{\partial \Pi_g}{\partial q_g} = a - c_g - bq_g^i - b(Q_{-i} + q_g^i) = 0 \tag{B.2}$$

where Q_{-i} is the production of other power plants, which is taken as exogenously given.

Base case: The first order conditions in the equilibrium

In the equilibrium the same type of firms will produce the same quantity because of the assumption of symmetry. The FOC in the equilibrium can be written as:

$$a - c_b - bq_b - b(q_b + (-1+m)q_b + nq_g) = 0 \tag{B.3a}$$

$$a - c_g - bq_g - b(mq_b + q_g + (-1+n)q_g) = 0 \tag{B.3b}$$

Base case: The price is higher when there is no green energy

If we subtract the price of electricity when there is no green energy from the case when there is renewable electricity in the market we get:

$$\frac{m(a-c_b)-(m+1)(a-c_g)}{(m+n+1)(m+1)} \quad | \quad c_g \leq c_b + \frac{a-c_b}{m+1} \tag{B.4}$$

If we substitute back the maximum value for c_g then we got zero. The difference will be always less than zero because c_g have negative sign, $(a-c_g)$ will be always bigger and bigger, which is subtracted from the same $m(a-c_b)$. This means the price is always higher when there is no green electricity in the market.

Case 1: The optimality for black producers

The first order condition for the representative black producer is:

$$\frac{\partial \Pi_b}{\partial q_b} = a - c_b - bq_b^i - b(Q_{-i} + q_b^i) = 0 \tag{B.5}$$

where Q_{-i} is the production of other power plants, which is taken as exogenously given.

Case 1: The optimality for green producers

The first order condition for the representative green producer is:

$$\frac{\partial \Pi_g}{\partial q_g} = a - c_g + t - bq_g^i - b(Q_{-i} + q_g^i) = 0 \tag{B.6}$$

where Q_{-i} is the production of other power plants, which is taken as exogenously given.

Case 1: The first order conditions in the equilibrium

In the equilibrium the same type of firms will produce the same quantity because of the assumption of symmetry. The FOC in the equilibrium can be written as:

$$a-c_b-bq_b-b(q_b+(-1+m)q_b+nq_g)=0 \tag{B.7a}$$

$$a-c_g+t-bq_g-b(mq_b+q_g+(-1+n)q_g)=0 \tag{B.7b}$$

The solution of this problem is:

$$q_b=\frac{a-c_b+n(c_g-c_b)-nt}{b(m+n+1)} \tag{B.8a}$$

$$q_g=\frac{a-c_g-m(c_g-c_b)+t(m+1)}{b(m+n+1)} \tag{B.8b}$$

Case 1: The condition for positive transfer

The denominator always positive the numerator will be positive if

$$m(n+\alpha)(a-c_b)-n(m+1-\alpha)(a-c_g)>0 \tag{B.9}$$

The first positive term takes the smallest value and the second negative term will be the largest if $\alpha=0$. Using this condition for α equation (B.9) can be rewritten as follows:

$$mn(a-c_b)-n(m+1)(a-c_g)>0\Rightarrow\frac{m}{m+1}>\frac{a-c_g}{a-c_b} \tag{B.10}$$

Case 1: The total production is bigger under environmental regulation

If we subtract equation (3.15c) from (3.9c) then we get:

$$\frac{-(a-c_b)m\alpha}{b(m+1)(m+1-\alpha)} \tag{B.11}$$

which will be always negative, so the production under feed-in tariff is always higher then without environmental regulation.

Case 2: The optimality for black producers

The first order condition for the representative black producer is:

$$\frac{\partial \Pi_b}{\partial q_b} = a - c_b - \alpha p_c - b q_b^i - b(Q_{-i} + q_b^i) = 0 \tag{B.12}$$

where Q_{-i} is the production of other power plants, which is taken as exogenously given.

Case 2: The optimality for green producers

The first order condition for the representative green producer is:

$$\frac{\partial \Pi_g}{\partial q_g} = a - c_g + p_c - \alpha p_c - b q_g^i - b(Q_{-i} + q_g^i) = 0 \tag{B.13}$$

where Q_{-i} is the production of other power plants, which is taken as exogenously given.

Case 2: The first order conditions in the equilibrium

In the equilibrium the same type of firms will produce the same quantity because of the assumption of symmetry. The FOC in the equilibrium can be written as:

$$a - c_b - \alpha p_c - b q_b - b(q_b + (-1+m) q_b + n q_g) = 0 \tag{B.14a}$$

$$a - c_g + p_c - \alpha p_c - b q_g - b(m q_b + q_g + (-1+n) q_g) = 0 \tag{B.14b}$$

The solution of these equations provides q_b and q_g.

$$q_b = \frac{a - c_b + n(c_g - c_b) - p_c(n+\alpha)}{b(m+n+1)} \tag{B.15a}$$

$$q_g = \frac{a - c_g - m(c_g - c_b) + p_c(m+1-\alpha)}{b(m+n+1)} \tag{B.15b}$$

Case 2: The total production is bigger under environmental regulation

If we subtract equation (3.23c) from (3.9c) then we get:

$$\frac{m\alpha(-(a-c_b)(3+m)n + (a-c_b)(m+3n+2mn)\alpha - (a-c_g)(1+m)n(1+2\alpha))}{b(1+m)\left(n\left(m+(-1+\alpha)^2\right)+m\alpha^2\right)} \tag{B.16}$$

Using condition (3.25) and substituting back the smallest value for $a - c_g$ we get the following expression:

$$\frac{(m\alpha + n(-3-2m+3\alpha))(a-c_b)}{b(1+m)\left(n\left(m+(-1+\alpha)^2\right)+m\alpha^2\right)} \tag{B.17}$$

which is always negative. $a - c_g$ has negative sign, so as $a - c_g$ increases then the difference will be more and more negative. This means that the environmental regulation increases the total production.

Case 2: The condition for positive $\partial_\alpha p_c$

Figure 3.2 shows that the partial derivative is increasing in α. If we substitute back the smallest value from condition (3.27) then we get for the numerator:

$$\frac{mn(1+m+n)((a-c_b)m + (a-c_g)n)}{m+n} > 0 \tag{B.18}$$

which is always positive. The denominator is always positive as well because it is a squared term. Equation (3.27) is sufficient condition for $\partial_\alpha p_c$ to be positive.

Case 2: The condition for positive $\partial_\alpha p_e$

The first term of equation (3.28) is always positive because $(mn+m(2-\alpha)\alpha-n(\alpha-1)^2)$ takes the smallest value if $\alpha=0$. In that case the numerator of the first term is $(m-1)n>0$. The second term of equation (3.28) is always negative because $(-n-mn+(m+n)\alpha^2)$ takes the largest value if $\alpha=1$. In that case the numerator is $n(1-m)<0$. The second term of the partial derivative is the largest negative number if $a-c_g=a-c_b$. In that case the numerator can be simplified in the following form:

$$2mn(n(\alpha-1)+m\alpha)(a-c_b) \tag{B.19}$$

which takes positive values if (3.27) is true. The denominator is always positive because it is a squared term. Equation (3.27) is sufficient condition for $\partial_\alpha p_e$ to be positive.

Case 2: The condition for negative $\partial_\alpha q_b$

The first term of equation (3.29) is always negative because $\alpha\leq 1$. The second term takes the maximum value if $\alpha=0$. In that case the numerator of the partial derivative can be simplified into the following form:

$$n^2((m+1)(a-c_g)-2m(a-c_b))<0 \tag{B.20}$$

which takes always negative values because $a-c_b\geq a-c_g$ and $2m\geq> m+1$. The denominator is always positive because it is a squared term. This means the$\partial_\alpha q_b$ is always negative.

Case 2: The condition for positive $\partial_\alpha q_g$

Figure 3.4 shows that the partial derivative is increasing in α. If we substitute back the smallest value from condition (3.27) then we get for the numerator:

$$\frac{m^2 n(1+m+n)((a-c_b)(m-n)+2(a-c_g)n)}{(m+n)^2} \tag{B.21}$$

which is always positive if $m \geq n$. The denominator is always positive because it is a squared term. Equation (3.27) is sufficient condition for $\partial_\alpha q_b$ to be positive.

Case 2: The condition for positive $\partial_\alpha Q$

The first term of equation (3.31) is always negative because $((m+n)((\alpha-1)^2-1)-(m-1)n)$ takes the largest value if $\alpha = 0$. In that case the numerator of the first term is $-(m-1)n(m+n)mn < 0$. The second term of equation (3.28) is always positive because $(n(m+1)-(m+n)\alpha^2)$ takes the smallest value if $\alpha = 0$. In that case the numerator is $n(m+1) > 0$. The second term of the partial derivative is the largest positive number if $a-c_g = a-c_b$. In that case the numerator can be simplified in the following form:

$$-2mn(n(\alpha-1)+m\alpha)(a-c_b) \tag{B.22}$$

which takes negative values if (3.27) is true. The denominator is always positive because it is a squared term. Equation (3.27) is sufficient condition for $\partial_\alpha Q$ to be negative.

Appendix C

Data Used in the Simualtion

Table C.1 Main Power Generators in the UK

Company Name	Station Name	Fuel	Capacity (MW)	Year	ROC
AES	Kilroot	coal/oil	520.0	1981	no
Alcan	Lynemouth	coal	420.0	1995	no
	Fort William	hydro	72.0	1929	no
	Kinlochleven	hydro	19.5	1907	yes
Ardrossan Windfarm	Ardrossan	wind	24.0	2004	yes
Baglan Generation Ltd	Baglan Bay	gas turbine	575.0	2002	no
Barking Power	Barking	CCGT	1000.0	1994	no
Beaufort Wind Ltd	Bears Down	wind	10.0	2001	yes
	Bein Ghlas	wind	8.0	1999	yes
	Bryn Titli	wind	10.0	1994	yes
	Carno	wind	34.0	1996	yes
	Causeymire	wind	48.0	2004	yes
	Kirkby Moor	wind	5.0	1993	yes
	Lambrigg	wind	7.0	2000	yes
	Llyn Alaw	wind	20.0	1997	yes
	Mynydd Gorddu	wind	10.0	1996	yes
	Novar	wind	17.0	1997	yes
	Taff Ely	wind	9.0	1993	yes
	Tow Law	wind	2.0	2001	yes
	Trysglwyn	wind	6.0	1996	yes
	Windy Standard	wind	22.0	1996	yes
	North Hoyle	wind/offshore	60.0	2003	yes
	Farr	wind	92.0	2006	yes
	Ffynnon Oer	wind	32.0	2006	yes
Braes of Doune Windfarm	Braes of Doune	wind	72.0	2006	yes
British Energy	Dungeness B	nuclear	1040.0	1983	no
	Hartlepool	nuclear	1190.0	1984	no
	Heysham1	nuclear	1160.0	1984	no
	Heysham 2	nuclear	1235.0	1988	no
	Hinkley Point B	nuclear	820.0	1976	no

Continued on next page

Table C.1 – continued from previous page

Company Name	Station Name	Fuel	Capacity (MW)	Year	ROC
	Sizewell B	nuclear	1188.0	1995	no
	Hunterston B	nuclear	820.0	1976	no
	Torness	nuclear	1230.0	1988	no
	Eggborough	coal	1960.0	1967	no
	Aberdare District Energy	gas	10.0	2002	no
	Bridgewater District Energy	gas	10.0	2000	no
	Sevington District Energy	gas	10.0	2000	no
	Solutia District Energy	gas	10.0	2000	no
Cemmaes Windfarm Ltd	Cemmaes	wind	15.0	2002	yes
Centrica	Barry	CCGT	230.0	1998	no
	Glanford Brigg	CCGT	260.0	1993	no
	Killingholme	CCGT	665.0	1994	no
	Kings Lynn	CCGT	340.0	1996	no
	Peterborough	CCGT	405.0	1993	no
	Roosecote	CCGT	229.0	1991	no
	South Humber Bank	CCGT	1285.0	1996	no
	Glens of Foudland	wind	26.0	2005	yes
	Barrow Offshore Windfarm	wind/offshore	90.0	2006	yes
Citigen (London) UK Ltd	Charterhouse St. London	gas/gas oil CHP	16.0	1995	no
Cold Northcott Windfarm Ltd	Cold Northcott	wind	7.0	1993	yes
Coolkeeragh ESB Ltd	Coolkeeragh	CCGT	408.0	2005	no
Corby Power Ltd	Corby	CCGT	401.0	1993	no
Coryton Energy Company Ltd	Coryton	CCGT	732.0	2001	no
Derwent Cogeneration	Derwent	gas CHP	236.0	1994	no
Drax Power Ltd	Drax	coal	3870.0	1974	no
	Drax GT	gas oil	75.0	1971	no
EDF Energy	Sutton Bridge	CCGT	800.0	1999	no
	Cottam	coal	2008.0	1969	no

Continued on next page

Table C.1 – continued from previous page

Company Name	Station Name	Fuel	Capacity (MW)	Year	ROC
	West Burton	coal	1972.0	1967	no
	West Burton GT	gas oil	40.0	1967	no
EPR Ely Limited	Elean	straw/gas	38.0	2001	yes
EPR Glanford Ltd	Glanford	meat & bone	13.0	1993	yes
EPR Eye Ltd	Eye. Suffolk	AWDF	13.0	1992	yes
EPR Thetford Ltd	Thetford	poultry litter	39.0	1998	yes
E.On UK	Kingsnorth	coal/oil	1940.0	1970	no
	Ironbridge	coal	970.0	1970	no
	Ratcliffe	coal	2000.0	1968	no
	Grain	oil	1300.0	1979	no
	Grain GT	gas oil	55.0	1978	no
	Kingsnorth GT	gas oil	34.0	1967	no
	Ratcliffe GT	gas oil	34.0	1966	no
	Taylor's Lane GT	gas oil	132.0	1979	no
	Connahs Quay	CCGT	1380.0	1996	no
	Cottam Development Centre	CCGT	400.0	1999	no
	Enfield	CCGT	392.0	1999	no
	Killingholme	CCGT	900.0	1993	no
	Steven's Croft	biomass	44.0	2007	yes
	Rheidol	hydro	49.0	1961	no
	Askam	wind	4.6	1999	yes
	Bessy Bell	wind	5.0	1995	yes
	Blood Hill	wind	2.3	1992	yes
	Bowbeat	wind	31.2	2002	yes
	Deucheran Hill	wind	15.8	2001	yes
	Hare Hill	wind	5.1	2004	yes
	High Volts	wind	7.8	2004	yes
	Holmside	wind	5.1	2004	yes
	Lowca	wind	4.6	2000	yes
	Oldside	wind	5.4	1996	yes
	Out Newton	wind	9.1	2002	yes
	Rheidol	wind	2.0	1997	yes
	Scroby Sands	wind/offshore	60.0	2005	yes
	Siddick	wind	4.2	1996	yes
	St Breock	wind	5.0	1994	yes
	Stags Holt	wind	18.0	2007	yes
	Rhyd-y-Groes	wind	7.0	1992	yes
	Blyth Offshore	wind/offshore	4.0	2000	yes

Continued on next page

Table C.1 – continued from previous page

Company Name	Station Name	Fuel	Capacity (MW)	Year	ROC
Fenland Windfarms Ltd	Deeping	wind	16.0	2006	yes
	Glass Moor	wind	16.0	2006	yes
	Red House	wind	12.0	2006	yes
	Red Tile	wind	24.0	2007	yes
Fred Olsen	Crystal Rig Windfarm	wind	50.0	2003	yes
	Haverigg III	wind	3.0	2005	yes
	Paul's Hill	wind	64.4	2005	yes
	Rothes	wind	51.0	2004	yes
Gaz de France	Shotton	gas CHP	180.0	2001	no
Great Orton Windfarm Ltd	Great Orton	wind	4.0	1999	yes
HG Capital	Tyr Mostyn & Foel Goch	wind	21.0	2005	yes
Immingham CHP LLP	Immingham CHP	gas CHP	741.0	2004	no
International Power / Mitsui	Indian Queens	gas oil/kerosene	140.0	1996	no
	Dinorwig	pumped storage	1728.0	1983	no
	Ffestiniog	pumped storage	360.0	1961	no
	Rugeley	coal	1006.0	1972	no
	Rugeley GT	gas oil	50.0	1972	no
	Deeside	CCGT	500.0	1994	no
	Saltend	CCGT	1200.0	2000	no
K/S Winscales	Winscales 1	wind	2.0	1999	yes
	Winscales 2	wind	7.0	2005	yes
Llangwyryfon Windfarm Ltd	Llangwyryfon	wind	9.0	2003	yes
Magnox Electric Ltd	Oldbury	nuclear	434.0	1967	no
	Wylfa	nuclear	980.0	1971	no
	Fellside CHP	gas CHP	180.0	1995	no
	Maentwrog	hydro	28.0	1928	no
Premier Power Ltd	Ballylumford B	gas/oil	360.0	1968	no
	Ballylumford C	CCGT	616.0	2003	no
RES-Gen Ltd	Dyffryn Brodyn	wind	6.0	1994	yes
	Four Burrows	wind	5.0	1995	yes

Continued on next page

Table C.1 – continued from previous page

Company Name	Station Name	Fuel	Capacity (MW)	Year	ROC
	Forss	wind	2.0	2003	yes
	Forss2	wind	5.0	2007	yes
	Lendrum's Bridge	wind	13.0	2000	yes
	Altahullion	wind	26.0	2003	yes
	Altahullion2	wind	12.0	2007	yes
	Black Hill	wind	29.0	2006	yes
	Lough Hill	wind	8.0	2007	yes
RGS Energy Ltd	Knapton	gas	40.0	1994	no
Rocksavage Power Co. Ltd	Rocksavage	CCGT	748.0	1998	no
RWE Npower Plc	Aberthaw B	coal	1586.0	1971	no
	Tilbury B	coal	1063.0	1968	no
	Didcot A	coal/gas	1958.0	1972	no
	Aberthaw GT	gas oil	51.0	1971	no
	Cowes	gas oil	140.0	1982	no
	Didcot GT	gas oil	100.0	1972	no
	Fawley GT	gas oil	34.0	1969	no
	Littlebrook GT	gas oil	105.0	1982	no
	Tilbury GT	gas oil	68.0	1968	no
	Little Barford GT	gas oil	17.0	2006	no
	Fawley	oil	968.0	1969	no
	Littlebrook D	oil	2055.0	1982	no
	Didcot B	CCGT	1390.0	1998	no
	Great Yarmouth	CCGT	420.0	2001	no
	Little Barford	CCGT	665.0	1995	no
	Braevallich	hydro	2.0	2005	yes
	Cwm Dyli	hydro	10.0	2002	yes
	Dolgarrog High Head	hydro	18.0	2002	yes
	Dolgarrog Low Head	hydro	15.0	2002	yes
	Garrogie	hydro	2.0	2005	yes
	Inverbain	hydro	1.0	2006	yes
	Kielder	hydro	6.0	2006	yes
	Burgar Hill	wind	5.0	2007	yes
	Hameldon Hill	wind	5.0	2007	yes
Scottish & Southern Energy plc	Mullardoch Tunnel	hydro	2.4	1955	yes
	Fasnakyle	hydro	69.0	1951	no

Continued on next page

Table C.1 – continued from previous page

Company Name	Station Name	Fuel	Capacity (MW)	Year	ROC
	Fasnakyle Compensation Set	hydro	8.0	2006	yes
	Deanie	hydro	38.0	1963	no
	Culligran	hydro	17.0	1962	yes
	Culligran Compensation Set	hydro	2.0	1962	yes
	Aigas	hydro	20.0	1962	yes
	Kilmorack	hydro	20.0	1962	yes
	Lubreoch	hydro	4.0	1958	yes
	Cashlie	hydro	11.0	1959	yes
	Lochay	hydro	45.0	1958	no
	Lochay Compensation Set	hydro	2.0	1959	yes
	Finlarig	hydro	16.5	1955	yes
	Lednock	hydro	3.0	1961	yes
	St. Fillans	hydro	16.8	1957	yes
	Dalchonzie	hydro	4.0	1958	yes
	Achanalt	hydro	3.0	1956	yes
	Grudie Bridge	hydro	18.7	1950	yes
	Mossford	hydro	18.7	1957	yes
	Luichart	hydro	34.0	1954	no
	Orrin	hydro	18.0	1959	yes
	Torr Achilty	hydro	15.0	1954	yes
	Foyers	pumped storage	300.0	1974	no
	Foyers Falls	hydro	5.2	1968	yes
	Mucomir	hydro	2.0	1962	yes
	Ceannacroc	hydro	20.0	1956	yes
	Livishie	hydro	17.0	1962	yes
	Glenmoriston	hydro	39.0	1957	no
	Quoich	hydro	18.0	1955	yes
	Invergarry	hydro	20.0	1956	yes
	Kingairloch	hydro	3.5	2005	yes
	Cassley	hydro	10.0	1959	yes
	Lairg	hydro	3.5	1959	yes
	Shin	hydro	18.7	1958	yes
	Loch Dubh	hydro	1.0	1954	yes
	Sloy	hydro	152.5	1950	no
	Sron Mor	hydro	5.0	1957	yes
	Clachan	hydro	40.0	1955	no
	Allt-na-Lairige	hydro	6.0	1956	yes

Continued on next page

Table C.1 – continued from previous page

Company Name	Station Name	Fuel	Capacity (MW)	Year	ROC
	Nant	hydro	15.0	1963	yes
	Inverawe	hydro	25.0	1963	no
	Kilmelfort	hydro	2.0	1956	yes
	Loch Gair	hydro	6.0	1961	yes
	Lussa	hydro	2.4	1952	yes
	Striven	hydro	8.0	1951	yes
	Gaur	hydro	7.9	1953	yes
	Cuaich	hydro	2.5	1959	yes
	Loch Ericht	hydro	2.2	1962	yes
	Rannoch	hydro	45.0	1930	no
	Tummel	hydro	34.0	1933	no
	Errochty	hydro	75.0	1955	no
	Clunie	hydro	61.2	1950	no
	Pitlochry	hydro	15.0	1950	yes
	Artfield Fell	wind	20.0	2005	yes
	Hadyard Hill	wind	120.0	2005	yes
	Spurness	wind	8.3	2004	yes
	Tangy	wind	19.0	2002	yes
	Dalswinton	wind	30.0	2008	yes
	Drumderg	wind	32.0	2008	yes
	Minsca	wind	37.0	2008	yes
	Bessy Bell	wind	9.0	2008	yes
	Bin Mountain	wind	9.0	2008	yes
	Tappaghan	wind	20.0	2008	yes
	Beatrice	wind/offshore	10.0	2007	yes
	Chliostair	hydro	1.1	1960	yes
	Cuileig	hydro	3.2	2002	yes
	Kerry Falls	hydro	1.3	1951	yes
	Loch Dubh	hydro	1.2	1954	yes
	Nostie Bridge	hydro	1.3	1950	yes
	Storr Lochs	hydro	2.4	1952	yes
	Peterhead	gas/oil	1540.0	1980	no
	Fife Power Station	CCGT	123.0	2000	no
	Keadby	gas/oil	749.0	1994	no
	Medway	CCGT	688.0	1995	no
	Ferrybridge C	coal/biomass	1955.0	1966	no
	Fiddlers Ferry	coal/biomass	1961.0	1971	no
	Ferrybridge GT	gas oil	34.0	1966	no
	Fiddlers Ferry GT	gas oil	34.0	1969	no

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Table C.1 – continued from previous page

Company Name	Station Name	Fuel	Capacity (MW)	Year	ROC
	Chickerell	gas/oil	45.0	1998	no
	Burghfield	gas/oil	47.0	1998	no
	Thatcham	light oil	10.0	1994	no
	Five Oaks	light oil	8.9	1995	no
	Chippenham	gas	10.0	2002	no
	Wheldale	mines gas	8.0	2002	no
	Arnish	diesel	3.0	2001	no
	Barra	diesel	2.1	1990	no
	Bowmore	diesel	6.0	1946	no
	Kirkwall	diesel	16.2	1953	no
	Lerwick	diesel	67.2	1953	no
	Loch Carnan. South Uist	diesel	10.0	1971	no
	Stornoway	diesel	26.0	1950	no
	Tiree	diesel	2.5	1945	no
Scottish Power	Carsfad	hydro	12.0	1936	yes
	Drumjohn	hydro	2.0	1985	yes
	Earlstoun	hydro	14.0	1936	yes
	Glenlee	hydro	24.0	1935	no
	Kendoon	hydro	24.0	1936	no
	Tongland	hydro	33.0	1935	no
	Bonnington	hydro	11.0	1927	yes
	Stonebyres	hydro	6.0	1927	yes
	Cruachan	pumped storage	440.0	1966	no
	Cockenzie	coal	1152.0	1967	no
	Longannet	coal	2304.0	1970	no
	Damhead Creek	CCGT	792.0	2000	no
	Pilkington - Greengate	gas	10.0	1998	no
	Ravenhead	gas	9.0	1999	no
	Rye House	CCGT	715.0	1993	no
	Shoreham	CCGT	400.0	2000	no
	Beinn an Tuirc	wind	30.0	2001	yes
	Beinn Tharsuinn	wind	30.0	2007	yes
	Black Law	wind	124.0	2005	yes
	Callagheen	wind	17.0	2006	yes
	Carland Cross	wind	6.0	1992	yes
	Coal Clough	wind	10.0	1992	yes
	Coldham	wind	16.0	2006	yes
	Corkey	wind	5.0	1994	yes

Continued on next page

Table C.1 – continued from previous page

Company Name	Station Name	Fuel	Capacity (MW)	Year	ROC
	Cruach Mhor	wind	30.0	2004	yes
	Dun Law	wind	17.0	2000	yes
	Elliots Hill	wind	5.0	1995	yes
	Hagshaw Hill	wind	16.0	1995	yes
	Hare Hill	wind	13.0	2000	yes
	Penryddian & Llidiartywaun	wind	31.0	1992	yes
	Rigged Hill	wind	5.0	1994	yes
	Wether Hill	wind	18.0	2007	yes
	Whitelee	wind	23.0	2007	yes
	Wolf Bog	wind	10.0	2008	yes
Seabank Power Limited	Seabank 1	CCGT	812.0	1998	no
	Seabank 2	CCGT	410.0	2000	no
South East London Combined Heat & Power Ltd	SELCHP ERF	waste	32.0	1994	no
Spalding Energy Company Ltd	Spalding	CCGT	860.0	2004	no
Teesside Power Ltd	Teesside Power Station	CCGT	1875.0	1992	no
Uskmouth Power Company Ltd	Uskmouth	coal/biomass	363.0	2000	no
Vattenfall Wind Power	Kentish Flats	wind/offshore	90.0	2005	yes
Western Power Generation	Lynton	gas oil	2.0	1961	no
	Princetown	kerosene	3.0	1959	no
	Roseland	kerosene	5.0	1963	no
	St Marys	gas oil	6.0	1958	no
Yorkshire Windpower Ltd	Ovenden Moor	wind	9.0	1993	yes
	Royd Moor	wind	7.0	1993	yes

Table C.2 Other Small Power Producers in the UK

Station type	Fuel	Capacity (MW)	ROC
Renewable sources and combustible wastes	wind	433.0	yes
	landfill gas	901.0	yes
	sewage gas	152.0	yes
	hydro	129.4	yes
	waste	294.0	yes
	other	216.0	yes
CHP schemes	various fuels	2183.4	no
CHP schemes	mainly gas	1562.0	no
Other autogenerators	various fuels	985.0	no

Table C.3 Production Costs Used in the Simulation

Fuel	Min. cost GBP/MWh	Max. cost GBP/MWh	Source
AWDF	66	68	RAoE
biomass	66	68	RAoE
CCGT	25	25.7	RAoE
coal	32.8	33.3	RAoE
coal/biomass	32.8	33.3	RAoE
coal/gas	37.9	38.6	RAoE
coal/oil	33.5	34.5	RAoE
diesel	33.5	34.5	RAoE
gas	25.7	36.4	RAoE
gas CHP	14.52	37.75	OECD
gas oil	34.1	36.4	RAoE
gas oil/kerosene	34.1	36.4	RAoE
gas turbine	25.7	36.4	RAoE
gas/gas oil CHP	14.52	37.75	OECD
gas/oil	34.1	36.4	RAoE
hydro	23.23	46.46	OECD
kerosene	33.5	34.5	RAoE
landfill gas	25.7	36.4	RAoE
light oil	33.5	34.5	RAoE
mainly gas	25.7	36.4	RAoE
meat & bone	66	68	RAoE
mines gas	25.7	36.4	RAoE
nuclear	22.6	24.4	RAoE
oil	33.5	34.5	RAoE
other	38.24	44.54	OECD
poultry litter	66	68	RAoE
pumped storage	23.23	46.46	OECD
sewage gas	25.7	36.4	RAoE
straw/gas	66	68	RAoE
various fuels	66	68	RAoE
waste	66	68	RAoE
wind	47.8	53.5	RAoE
wind/offshore	63.4	71.9	RAoE

OECD - OECD Nuclear Energy Agency and International Energy Agency (2005)
RAoE - The Royal Academy of Engineering (2004)

Appendix D

Matlab Codes

kalibracio.m

```
clear;
%adat=load('/home/mmatyi/matlab.test');
adat=load('/home/mmatyi/work/tezis/tema3/export.txt');
% ceg_azon eromu_azon kapacitas megujulo-1 min_koltseg max_koltseg
adat2=load('/home/mmatyi/work/tezis/tema3/zold_szegely.txt');
% koltseg capacitas
adat3=load('/home/mmatyi/work/tezis/tema3/fekete_szegely.txt');
% koltseg capacitas




list_p0=30:1:50;    %41      %horgony pont ar (EUROSTAT)
list_q0=36000:2000:60000;   %61527; %horgony pont mennyiseg (DUKES)
list_epszilon=[0.1 0.5];   %rugalmassag
list_kereslet_mod=[0 1];    %1-linearis kereslet, 0-konstant rugalmassag
list_koltseg_mod=[1 2 3 4 5 6]; %1-minimum koltseg, 2-maximum koltseg,
                                %3-atlag koltseg, 4-veletlen koltseg,
                                %5-max ktg diff, 6-min ktg diff
kalib_pe=40;
kalib_q=62000;
kalib_pc=40;
kalib_range=0.20;


erzekenyseg=0.1;
max_ciklus=150;
alfa=0.079; %0.055;     %0.079;
buyout=34.3; %32.33;    %34.3;

ge=sortrows(adat2,1);
ge=[ge cumsum(ge(:,2))];
be=sortrows(adat3,1);
be=[be cumsum(be(:,2))];
kereses={'q0','p0','epszilon','kereslet_mod','koltseg_mod',...
    'num_firm','elapsed time','iteration','P_e','P_c','Q','Q_b',...
    'Q_g','Capacity','Capacity_b','Capacity_g','HHI production',...
    'HHI production black','HHI production green','HHI capacity',...
    'HHI capacity black','HHI capacity green'};
kereses2={'q0','p0','epszilon','kereslet_mod','koltseg_mod',...
    'num_firm','elapsed time','iteration','P_e','P_c','Q','Q_b',...
    'Q_g','Capacity','Capacity_b','Capacity_g','HHI production',...
    'HHI production black','HHI production green','HHI capacity',...
    'HHI capacity black','HHI capacity green'};
```

```
kereslet_mod=0;

for kukac=3:3
koltseg_mod=list_koltseg_mod(kukac);

for r=1:max(size(list_epszilon))
epszilon=list_epszilon(r);
for s=1:max(size(list_q0))
q0=list_q0(s); %kereslet_mod=list_kereslet_mod(s);
for t=1:max(size(list_p0))
p0=list_p0(t);

tic


pc=1;
num_firm=max(adat(:,1));
num_plant=size(adat,1);
oszlop=size(adat,2);
index=zeros(num_firm,2);
termeles_b=[ones(num_firm,1) zeros(num_firm,max_ciklus)];
termeles_g=[ones(num_firm,1) zeros(num_firm,max_ciklus)];
capacity=zeros(num_firm,3);




for i=1:num_plant
    if adat(i,4)==0
        index(adat(i,1),1)=index(adat(i,1),1)+1;
    else
        index(adat(i,1),2)=index(adat(i,1),2)+1;
    end;
end;

i=1;
for j=1:num_firm
    %valtozo=genvarname(['firm' num2str(j)]);
    command=['tmpfirm' num2str(j) '=adat(i,2:oszlop);'];
    eval(command);
    i=i+1;
    while (i≤num_plant) && (adat(i,1)==j)
        command=['tmpfirm' num2str(j) '=[tmpfirm' num2str(j) ...
            '; adat(i,2:oszlop)];'];
        eval(command);
        i=i+1;
    end;
    command=['tmpfirm' num2str(j) '=[tmpfirm' num2str(j) ...
        ' koltseg(tmpfirm' num2str(j)  '(:,oszlop-3),tmpfirm' ...
        num2str(j)  '(:,oszlop-2),tmpfirm' num2str(j)  ...
        '(:,oszlop-1),koltseg_mod) zeros(size(tmpfirm' num2str(j) ...
        ',1),3)];'];
    eval(command);
    command=['firm' num2str(j) '=sortrows(tmpfirm' num2str(j) ...
```

```
        ',[3 oszlop]);'];
    eval(command);
    command=['firm' num2str(j) 'b=firm' num2str(j) '(1:index(j,1),:);'];
    eval(command);
    command=['firm' num2str(j) 'b(:,7)=cumsum(firm' num2str(j) ...
        'b(:,2));'];
    eval(command);
    command=['firm' num2str(j) 'g=firm' num2str(j) ...
        '(index(j,1)+1:index(j,1)+index(j,2),:);'];
    eval(command);
    command=['firm' num2str(j) 'g(:,7)=cumsum(firm' num2str(j) ...
        'g(:,2));'];
    eval(command);
    command=['if size(firm' num2str(j) 'b,1)>0, capacity(j,1)=firm' ...
        num2str(j) 'b(size(firm' num2str(j) 'b,1),7);, end;'];
    eval(command);
    command=['if size(firm' num2str(j) 'g,1)>0, capacity(j,2)=firm' ...
        num2str(j) 'g(size(firm' num2str(j) 'g,1),7);, end;'];
    eval(command);
end;

capacity(:,3)=capacity(:,1)+capacity(:,2);

j=3;
kontrol=0;
while  (max(abs(termeles_b(:,j-2)-termeles_b(:,j-1)))>erzekenyseg || ...
        max(abs(termeles_g(:,j-2)-termeles_g(:,j-1)))>erzekenyseg) ...
        && (j<max_ciklus)
    if (kontrol==0) && j==3
        j=j-1;
        kontrol=1;
    end;
    for i=1:num_firm

        if exist('tmpblack','var')
            clear tmpblack tmpgreen;
        end;
        command=['tmpblack=firm' num2str(i) 'b;'];
        eval(command);
        command=['tmpgreen=firm' num2str(i) 'g;'];
        eval(command);

        if size(tmpblack,1)>0
            if i<2
                egyeb_black=sum(termeles_b(i+1:num_firm,j-1));
            else
                egyeb_black=sum(termeles_b(1:i-1,j))+sum(...
                    termeles_b(i+1:num_firm,j-1));
            end;

            k=1;
            a=kereslet_mod;
            b=epszilon;
            c=p0;
```

```
        d=q0;
        e=tmpblack(k,6);
        f=egyeb_black+sum(termeles_g(:,j-1))+black_edge(kereslet(...
            kereslet_mod,epszilon,p0,q0,egyeb_black+sum(...
            termeles_g(:,j-1))),be)+green_edge(kereslet(...
            kereslet_mod,epszilon,p0,q0,egyeb_black+sum(...
            termeles_g(:,j-1))),tgc(egyeb_black,sum(termeles_g(...
            :,j-1)),alfa,buyout),ge);
        g=tgc(egyeb_black,sum(termeles_g(:,j-1)),alfa,buyout);
        h=alfa;
        tmpblack(k,8)=fminbnd(@(x) profitb_k(x,a,b,c,d,e,f,g,h),...
            0,tmpblack(k,2));

        while (tmpblack(k,2)>tmpblack(k,8)) && (k<size(tmpblack,1))
            k=k+1;
            e=tmpblack(k,6);
            f=egyeb_black+sum(termeles_g(:,j-1))+tmpblack(k-1,7)+...
                black_edge(kereslet(kereslet_mod,epszilon,p0,q0,...
                egyeb_black+sum(termeles_g(:,j-1))+tmpblack(...
                k-1,7)),be)+green_edge(kereslet(kereslet_mod,...
                epszilon,p0,q0,egyeb_black+sum(termeles_g(...
                :,j-1))+tmpblack(k-1,7)),tgc(egyeb_black+...
                tmpblack(k-1,7),sum(termeles_g(:,j-1)),alfa,...
                buyout),ge);
            g=tgc(egyeb_black,sum(termeles_g(:,j-1)),alfa,buyout);
            h=alfa;
            tmpblack(k,8)=fminbnd(@(x) profitb_k(...
                x,a,b,c,d,e,f,g,h),0,tmpblack(k,2));
        end;
        termeles_b(i,j)=sum(tmpblack(:,8));
        command=['firm' num2str(i) 'b(:,8)=tmpblack(:,8);'];
        eval(command);
    end;

    if size(tmpgreen,1)>0
        if i<2
            egyeb_green=sum(termeles_g(i+1:num_firm,j-1));
        else
            egyeb_green=sum(termeles_g(1:i-1,j))+sum(termeles_g(...
                i+1:num_firm,j-1));
        end;
        k=1;
        e=tmpgreen(k,6);
        f=egyeb_green+sum(termeles_b(:,j))+black_edge(kereslet(...
            kereslet_mod,epszilon,p0,q0,egyeb_green+sum(...
            termeles_b(:,j))),be)+green_edge(kereslet(...
            kereslet_mod,epszilon,p0,q0,egyeb_green+sum(...
            termeles_b(:,j))),tgc(sum(termeles_b(:,j)),...
            egyeb_green,alfa,buyout),ge);
        g=tgc(sum(termeles_b(:,j-1)),egyeb_green,alfa,buyout);
        h=alfa;
        tmpgreen(k,8)=fminbnd(@(x) profitg_k(x,a,b,c,d,e,f,g,h),...
        0,tmpgreen(k,2));
```

```
            while (tmpgreen(k,2)>tmpgreen(k,8)) && (k<size(tmpgreen,1))
                k=k+1;
                e=tmpgreen(k,6);
                f=egyeb_green+sum(termeles_b(:,j))+tmpgreen(k-1,7)+...
                    black_edge(kereslet(kereslet_mod,epszilon,p0,q0,...
                    egyeb_green+sum(termeles_b(:,j))+tmpgreen(...
                    k-1,7)),be)+green_edge(kereslet(kereslet_mod,...
                    epszilon,p0,q0,egyeb_green+sum(termeles_b(:,j))+...
                    tmpgreen(k-1,7)),tgc(sum(termeles_b(:,j)),...
                    egyeb_green+tmpgreen(k-1,7),alfa,buyout),ge);
                g=tgc(sum(termeles_b(:,j-1)),egyeb_green,alfa,buyout);
                h=alfa;
                tmpgreen(k,8)=fminbnd(@(x) profitg_k(...
                    x,a,b,c,d,e,f,g,h),0,tmpgreen(k,2));
            end;
            termeles_g(i,j)=sum(tmpgreen(:,8));
            command=['firm' num2str(i) 'g(:,8)=tmpgreen(:,8);'];
            eval(command);
        end;
    end;
    j=j+1;


end;

termeles=termeles_b(:,j-1)+termeles_g(:,j-1);
total_black=sum(termeles_b(:,j-1))+black_edge(kereslet(kereslet_mod,...
    epszilon,p0,q0,sum(termeles_b(:,j-1)+termeles_g(:,j-1))),be);
total_green=sum(termeles_g(:,j-1))+green_edge(kereslet(kereslet_mod,...
    epszilon,p0,q0,sum(termeles_b(:,j-1)+termeles_g(:,j-1))),tgc(sum(...
    termeles_b(:,j-1)),sum(termeles_g(:,j-1)),alfa,buyout),ge);
share=zeros(num_firm,6);

share(:,1)=capacity(:,1)/sum(capacity(:,1));
share(:,2)=capacity(:,2)/sum(capacity(:,2));
share(:,3)=capacity(:,3)/sum(capacity(:,3));
share(:,4)=termeles_b(:,j-1)/sum(termeles_b(:,j-1));
share(:,5)=termeles_g(:,j-1)/sum(termeles_g(:,j-1));
share(:,6)=termeles(:)/sum(termeles);


if abs(kereslet(kereslet_mod,epszilon,p0,q0,total_black+total_green)-...
        kalib_pe)<kalib_range*kalib_pe && abs(tgc(total_black,...
        total_green,alfa,buyout)-kalib_pc)<kalib_pc*kalib_range && ...
        abs(total_black+total_green-kalib_q)<kalib_q*kalib_range
    kereses=[kereses; {q0 p0 epszilon kereslet_mod koltseg_mod ...
        num_firm toc j-1 kereslet(kereslet_mod,epszilon,p0,q0,...
        total_black+total_green) tgc(total_black,total_green,alfa,...
        buyout) total_black+total_green sum(termeles_b(:,j-1)) sum(...
        termeles_g(:,j-1)) sum(capacity(:,3)) sum(capacity(:,1)) sum(...
        capacity(:,2)) sum(share(:,6).*share(:,6)) sum(...
        share(:,4).*share(:,4)) sum(share(:,5).*share(:,5)) sum(...
        share(:,3).*share(:,3)) sum(share(:,1).*share(:,1)) sum(...
        share(:,2).*share(:,2))}];
```

```
end;
    kereses2=[kereses2; {q0 p0 epszilon kereslet_mod koltseg_mod ...
        num_firm toc j-1 kereslet(kereslet_mod,epszilon,p0,q0,...
        total_black+total_green) tgc(total_black,total_green,alfa,...
        buyout) total_black+total_green sum(termeles_b(:,j-1)) sum(...
        termeles_g(:,j-1)) sum(capacity(:,3)) sum(capacity(:,1)) sum(...
        capacity(:,2)) sum(share(:,6).*share(:,6)) sum(...
        share(:,4).*share(:,4)) sum(share(:,5).*share(:,5)) sum(...
        share(:,3).*share(:,3)) sum(share(:,1).*share(:,1)) sum(...
        share(:,2).*share(:,2))}];

end;
end;
datum=clock;
fajlnev=['/home/mmatyi/work/tezis/tema3/test/k-' num2str(datum(1)) ...
    '-' num2str(datum(2)) '-' num2str(datum(3)) '_' num2str(datum(4))...
    '_' num2str(datum(5)) '_' num2str(round(datum(6)))];
save(fajlnev,'kereses2');
end;
datum=clock;
fajlnev=['/home/mmatyi/work/tezis/tema3/test/kk-' num2str(datum(1))...
    '-' num2str(datum(2)) '-' num2str(datum(3)) '_' num2str(datum(4))...
    '_' num2str(datum(5)) '_' num2str(round(datum(6)))];
save(fajlnev,'kereses');
end;
```

szimulacio_present.m

```
clear;
%adat=load('/home/mmatyi/matlab.test');
adat=load('/home/mmatyi/work/tezis/tema3/export.txt');
%adat=load('/home/mmatyi/work/tezis/tema3/kulon.txt');
%adat=load('/home/mmatyi/work/tezis/tema3/egyutt.txt');
% ceg_azon eromu_azon kapacitas megujulo-1 min_koltseg max_koltseg
adat2=load('/home/mmatyi/work/tezis/tema3/zold_szegely.txt');
% koltseg capacitas
adat3=load('/home/mmatyi/work/tezis/tema3/fekete_szegely.txt');
% koltseg capacitas
adat4=load('/home/mmatyi/work/tezis/tema3/horgonypontok20090501.txt');
%q0 p0 kereslet_mod koltseg_mod epszilon alfa buyout




erzekenyseg=0.01;
max_ciklus=300;
alfa=0.079;
buyout=34.3;

ge=sortrows(adat2,1);
ge=[ge cumsum(ge(:,2))];
be=sortrows(adat3,1);
```

```
be=[be cumsum(be(:,2))];
kereses={'q0','p0','epszilon','alfa','buyout','kereslet_mod',...
    'koltseg_mod','num_firm','elapsed time','iteration','P_e','P_c',...
    'Q','Q_b','Q_g','Capacity','Capacity_b','Capacity_g',...
    'HHI production','HHI production black','HHI production green',...
    'HHI capacity','HHI capacity black','HHI capacity green'};

for r=1:size(adat4,1)
q0=adat4(r,1);
p0=adat4(r,2);
kereslet_mod=adat4(r,3);
koltseg_mod=adat4(r,4);
epszilon=adat4(r,5);
alfa=adat4(r,6);
buyout=adat4(r,7);
tic

pc=1;
num_firm=max(adat(:,1));
num_plant=size(adat,1);
oszlop=size(adat,2);
index=zeros(num_firm,2);
termeles_b=[ones(num_firm,1) zeros(num_firm,max_ciklus)];
termeles_g=[ones(num_firm,1) zeros(num_firm,max_ciklus)];
capacity=zeros(num_firm,3);



for i=1:num_plant
    if adat(i,4)==0
        index(adat(i,1),1)=index(adat(i,1),1)+1;
    else
        index(adat(i,1),2)=index(adat(i,1),2)+1;
    end;
end;

i=1;
for j=1:num_firm
    command=['tmpfirm' num2str(j) '=adat(i,2:oszlop);'];
    eval(command);
    i=i+1;
    while (i≤num_plant) && (adat(i,1)==j)
        command=['tmpfirm' num2str(j) '=[tmpfirm' num2str(j) ...
            '; adat(i,2:oszlop)];'];
        eval(command);
        i=i+1;
    end;
    command=['tmpfirm' num2str(j) '=[tmpfirm' num2str(j) ...
        ' koltseg(tmpfirm' num2str(j)  '(:,oszlop-3),tmpfirm' ...
        num2str(j)  '(:,oszlop-2),tmpfirm' num2str(j)  ...
        '(:,oszlop-1),koltseg_mod) zeros(size(tmpfirm' num2str(j)...
        ',1),3)];'];
    eval(command);
    command=['firm' num2str(j) '=sortrows(tmpfirm' num2str(j) ...
```

```
        ',[3 oszlop]);'];
    eval(command);
    command=['firm' num2str(j) 'b=firm' num2str(j) '(1:index(j,1),:);'];
    eval(command);
    command=['firm' num2str(j) 'b(:,7)=cumsum(firm' num2str(j) ...
        'b(:,2));'];
    eval(command);
    command=['firm' num2str(j) 'g=firm' num2str(j) ...
        '(index(j,1)+1:index(j,1)+index(j,2),:);'];
    eval(command);
    command=['firm' num2str(j) 'g(:,7)=cumsum(firm' num2str(j) ...
        'g(:,2));'];
    eval(command);
    command=['if size(firm' num2str(j) 'b,1)>0, capacity(j,1)=firm' ...
        num2str(j) 'b(size(firm' num2str(j) 'b,1),7);, end;'];
    eval(command);
    command=['if size(firm' num2str(j) 'g,1)>0, capacity(j,2)=firm' ...
        num2str(j) 'g(size(firm' num2str(j) 'g,1),7);, end;'];
    eval(command);
end;

capacity(:,3)=capacity(:,1)+capacity(:,2);

j=3;
kontrol=0;
while  (max(abs(termeles_b(:,j-2)-termeles_b(:,j-1)))>erzekenyseg ...
        || max(abs(termeles_g(:,j-2)-termeles_g(:,j-1)))>erzekenyseg)...
        && (j<max_ciklus)
    if (kontrol==0) && j==3
        j=j-1;
        kontrol=1;
    end;
    for i=1:num_firm

        if exist('tmpblack','var')
            clear tmpblack tmpgreen;
        end;
        command=['tmpblack=firm' num2str(i) 'b;'];
        eval(command);
        command=['tmpgreen=firm' num2str(i) 'g;'];
        eval(command);

        if size(tmpblack,1)>0
            if i<2
                egyeb_black=sum(termeles_b(i+1:num_firm,j-1));
            else
                egyeb_black=sum(termeles_b(1:i-1,j))+...
                    sum(termeles_b(i+1:num_firm,j-1));
            end;

            k=1;
            a=kereslet_mod;
            b=epszilon;
            c=p0;
```

```
    d=q0;
    e=tmpblack(k,6);
    f=egyeb_black+sum(termeles_g(:,j-1))+black_edge(...
        kereslet(kereslet_mod,epszilon,p0,q0,egyeb_black+...
        sum(termeles_g(:,j-1))),be)+green_edge(kereslet(...
        kereslet_mod,epszilon,p0,q0,egyeb_black+...
        sum(termeles_g(:,j-1))),tgc(egyeb_black,sum(...
        termeles_g(:,j-1)),alfa,buyout),ge);
    g=tgc(egyeb_black,sum(termeles_g(:,j-1)),alfa,buyout);
    h=alfa;
    tmpblack(k,8)=fminbnd(@(x) profitb_k(x,a,b,c,d,e,f,g,h),...
        0,tmpblack(k,2));

    while (tmpblack(k,2)>tmpblack(k,8)) && (k<size(tmpblack,1))
        k=k+1;
        e=tmpblack(k,6);
        f=egyeb_black+sum(termeles_g(:,j-1))+tmpblack(k-1,7)+...
            black_edge(kereslet(kereslet_mod,epszilon,p0,q0,...
            egyeb_black+sum(termeles_g(:,j-1))+...
            tmpblack(k-1,7)),be)+green_edge(kereslet(...
            kereslet_mod,epszilon,p0,q0,egyeb_black+sum(...
            termeles_g(:,j-1))+tmpblack(k-1,7)),...
            tgc(egyeb_black+tmpblack(k-1,7),sum(...
            termeles_g(:,j-1)),alfa,buyout),ge);
        g=tgc(egyeb_black,sum(termeles_g(:,j-1)),alfa,buyout);
        h=alfa;
        tmpblack(k,8)=fminbnd(@(x) profitb_k(...
            x,a,b,c,d,e,f,g,h),0,tmpblack(k,2));
    end;
    termeles_b(i,j)=sum(tmpblack(:,8));
    command=['firm' num2str(i) 'b(:,8)=tmpblack(:,8);'];
    eval(command);
end;

if size(tmpgreen,1)>0
    if i<2
        egyeb_green=sum(termeles_g(i+1:num_firm,j-1));
    else
        egyeb_green=sum(termeles_g(1:i-1,j))+sum(termeles_g(...
            i+1:num_firm,j-1));
    end;
    k=1;
    e=tmpgreen(k,6);
    f=egyeb_green+sum(termeles_b(:,j))+black_edge(kereslet(...
        kereslet_mod,epszilon,p0,q0,egyeb_green+sum(...
        termeles_b(:,j))),be)+green_edge(kereslet(...
        kereslet_mod,epszilon,p0,q0,egyeb_green+sum(...
        termeles_b(:,j))),tgc(sum(termeles_b(:,j)),...
        egyeb_green,alfa,buyout),ge);
    g=tgc(sum(termeles_b(:,j-1)),egyeb_green,alfa,buyout);
    h=alfa;
    tmpgreen(k,8)=fminbnd(@(x) profitg_k(x,a,b,c,d,e,f,g,h),...
        0,tmpgreen(k,2));
```

```
            while (tmpgreen(k,2)>tmpgreen(k,8)) && (k<size(tmpgreen,1))
                k=k+1;
                e=tmpgreen(k,6);
                f=egyeb_green+sum(termeles_b(:,j))+tmpgreen(k-1,7)+...
                    black_edge(kereslet(kereslet_mod,epszilon,p0,q0,...
                    egyeb_green+sum(termeles_b(:,j))+tmpgreen(...
                    k-1,7)),be)+green_edge(kereslet(kereslet_mod,...
                    epszilon,p0,q0,egyeb_green+sum(termeles_b(:,j))+...
                    tmpgreen(k-1,7)),tgc(sum(termeles_b(:,j)),...
                    egyeb_green+tmpgreen(k-1,7),alfa,buyout),ge);
                g=tgc(sum(termeles_b(:,j-1)),egyeb_green,alfa,buyout);
                h=alfa;
                tmpgreen(k,8)=fminbnd(@(x) profitg_k(...
                    x,a,b,c,d,e,f,g,h),0,tmpgreen(k,2));
            end;
            termeles_g(i,j)=sum(tmpgreen(:,8));
            command=['firm' num2str(i) 'g(:,8)=tmpgreen(:,8);'];
            eval(command);
        end;
    end;
    j=j+1;

end;

termeles=termeles_b(:,j-1)+termeles_g(:,j-1);
total_black=sum(termeles_b(:,j-1))+black_edge(kereslet(kereslet_mod,...
    epszilon,p0,q0,sum(termeles_b(:,j-1)+termeles_g(:,j-1))),be);
total_green=sum(termeles_g(:,j-1))+green_edge(kereslet(kereslet_mod,...
    epszilon,p0,q0,sum(termeles_b(:,j-1)+termeles_g(:,j-1))),tgc(...
    sum(termeles_b(:,j-1)),sum(termeles_g(:,j-1)),alfa,buyout),ge);
share=zeros(num_firm,6);
vegeredmeny=[ones(size(firm1b,1),1) firm1b; ones(size(firm1g,1),1) ...
    firm1g];
for i=2:num_firm
            command=['vegeredmeny=[vegeredmeny; i*ones(size(firm' ...
                num2str(i) 'b,1),1) firm' num2str(i) ...
                'b; i*ones(size(firm' num2str(i) 'g,1),1) firm' ...
                num2str(i) 'g];'];
            eval(command);
end;
vegeredmeny=sortrows(vegeredmeny,2);
share(:,1)=capacity(:,1)/sum(capacity(:,1));
share(:,2)=capacity(:,2)/sum(capacity(:,2));
share(:,3)=capacity(:,3)/sum(capacity(:,3));
share(:,4)=termeles_b(:,j-1)/sum(termeles_b(:,j-1));
share(:,5)=termeles_g(:,j-1)/sum(termeles_g(:,j-1));
share(:,6)=termeles(:)/sum(termeles);



kereses=[kereses; {q0 p0 epszilon alfa buyout kereslet_mod ...
    koltseg_mod num_firm toc j-1 kereslet(kereslet_mod,epszilon,p0,...
    q0,total_black+total_green) tgc(total_black,total_green,alfa,...
    buyout) total_black+total_green sum(termeles_b(:,j-1)) sum(...
```

```
    termeles_g(:,j-1)) sum(capacity(:,3)) sum(capacity(:,1)) sum(...
    capacity(:,2)) sum(share(:,6).*share(:,6)) sum(...
    share(:,4).*share(:,4)) sum(share(:,5).*share(:,5)) sum(...
    share(:,3).*share(:,3)) sum(share(:,1).*share(:,1)) sum(...
    share(:,2).*share(:,2))}];



end;
datum=clock;
fajlnev=['/home/mmatyi/work/tezis/tema3/test/sz-' num2str(datum(1))...
    '-' num2str(datum(2)) '-' num2str(datum(3)) '_' num2str(datum(4))...
    ':' num2str(datum(5)) ':' num2str(round(datum(6)))];
save(fajlnev,'kereses');
```

szimulacio_future.m

```
clear;
%adat=load('/home/mmatyi/matlab.test');
adat=load('/home/mmatyi/work/tezis/tema3/export.txt');
%adat=load('/home/mmatyi/work/tezis/tema3/kulon.txt');
%adat=load('/home/mmatyi/work/tezis/tema3/egyutt.txt');
% ceg_azon eromu_azon kapacitas megujulo-1 min_koltseg max_koltseg
adat2=load('/home/mmatyi/work/tezis/tema3/zold_szegely.txt');
% koltseg capacitas
adat3=load('/home/mmatyi/work/tezis/tema3/fekete_szegely.txt');
% koltseg capacitas
%adat4=load('/home/mmatyi/work/tezis/tema3/horgony.txt');
%adat4=load('/home/mmatyi/work/tezis/tema3/horgonypontok2.txt');
adat4=load('/home/mmatyi/work/tezis/tema3/horgonypontok20090501.txt');
%q0 p0 kereslet_mod koltseg_mod epszilon alfa buyout




erzekenyseg=0.01;
max_ciklus=300;
years=10;
black_capacity_factor=1; % 1, 1.5, 3%
green_capacity_factor=1.015; % 1, 1.5, 3%
demand_factor=1; % 1, 2.5 5%
alfa_factor=0; %0.012;
ge=sortrows(adat2,1);
ge=[ge cumsum(ge(:,2))];
be=sortrows(adat3,1);
be=[be cumsum(be(:,2))];
kereses={'year','black_capacity_factor','green_capacity_factor',...
    'demand_factor','q0','p0','epszilon','alfa','buyout',...
    'kereslet_mod','koltseg_mod','num_firm','elapsed time',...
    'iteration','P_e','P_c','Q','Q_b','Q_g','Capacity','Capacity_b',...
    'Capacity_g','HHI production','HHI production black',...
    'HHI production green','HHI capacity','HHI capacity black',...
```

```
    'HHI capacity green'};


for r=1:size(adat4,1)


kereslet_mod=adat4(r,3);
koltseg_mod=adat4(r,4);
epszilon=adat4(r,5);
alfa0=adat4(r,6);
buyout=adat4(r,7);

tic

pc=1;
num_firm=max(adat(:,1));
num_plant=size(adat,1);
oszlop=size(adat,2);
index=zeros(num_firm,2);
termeles_b=[ones(num_firm,1) zeros(num_firm,max_ciklus)];
termeles_g=[ones(num_firm,1) zeros(num_firm,max_ciklus)];
capacity=zeros(num_firm,3);



for i=1:num_plant
    if adat(i,4)==0
        index(adat(i,1),1)=index(adat(i,1),1)+1;
    else
        index(adat(i,1),2)=index(adat(i,1),2)+1;
    end;
end;

i=1;
for j=1:num_firm
    command=['tmpfirm' num2str(j) '=adat(i,2:oszlop);'];
    eval(command);
    i=i+1;
    while (i≤num_plant) && (adat(i,1)==j)
        command=['tmpfirm' num2str(j) '=[tmpfirm' num2str(j) ...
            '; adat(i,2:oszlop)];'];
        eval(command);
        i=i+1;
    end;
    command=['tmpfirm' num2str(j) '=[tmpfirm' num2str(j) ...
        ' koltseg(tmpfirm' num2str(j)  '(:,oszlop-3),tmpfirm' ...
        num2str(j)  '(:,oszlop-2),tmpfirm' num2str(j)  ...
        '(:,oszlop-1),koltseg_mod) zeros(size(tmpfirm' num2str(j) ...
        ',1),3)];'];
    eval(command);
    command=['firm' num2str(j) '=sortrows(tmpfirm' num2str(j) ...
        ',[3 oszlop]);'];
    eval(command);
```

```
    command=['firm' num2str(j) 'b=firm' num2str(j) '(1:index(j,1),:);'];
    eval(command);
    command=['firm' num2str(j) 'b(:,7)=cumsum(firm' num2str(j) ...
        'b(:,2));'];
    eval(command);
    command=['firm' num2str(j) 'g=firm' num2str(j) ...
        '(index(j,1)+1:index(j,1)+index(j,2),:);'];
    eval(command);
    command=['firm' num2str(j) 'g(:,7)=cumsum(firm' num2str(j) ...
        'g(:,2));'];
    eval(command);
    command=['if size(firm' num2str(j) 'b,1)>0, capacity(j,1)=firm' ...
        num2str(j) 'b(size(firm' num2str(j) 'b,1),7);, end;'];
    eval(command);
    command=['if size(firm' num2str(j) 'g,1)>0, capacity(j,2)=firm' ...
        num2str(j) 'g(size(firm' num2str(j) 'g,1),7);, end;'];
    eval(command);
end;

capacity(:,3)=capacity(:,1)+capacity(:,2);

for y=0:years
q0=adat4(r,1)*(demand_factor^y);
p0=adat4(r,2);
gc=green_capacity_factor^y;
bc=black_capacity_factor^y;
alfa=alfa0+y*alfa_factor;
j=3;
kontrol=0;
while  (max(abs(termeles_b(:,j-2)-termeles_b(:,j-1)))>erzekenyseg || ...
        max(abs(termeles_g(:,j-2)-termeles_g(:,j-1)))>erzekenyseg) ...
        && (j<max_ciklus)
    if (kontrol==0) && j==3
        j=j-1;
        kontrol=1;
    end;
    for i=1:num_firm

        if exist('tmpblack','var')
            clear tmpblack tmpgreen;
        end;
        command=['tmpblack=firm' num2str(i) 'b;'];
        eval(command);
        command=['tmpgreen=firm' num2str(i) 'g;'];
        eval(command);

        tmpblack(:,2)=bc.*tmpblack(:,2);
        %tmpgreen(:,2)
        tmpgreen(:,2)=gc.*tmpgreen(:,2);
        %tmpgreen(:,2)

        if size(tmpblack,1)>0
            if i<2
                egyeb_black=sum(termeles_b(i+1:num_firm,j-1));
```

```
        else
            egyeb_black=sum(termeles_b(1:i-1,j))+sum(...
                termeles_b(i+1:num_firm,j-1));
        end;

        k=1;
        a=kereslet_mod;
        b=epszilon;
        c=p0;
        d=q0;
        e=tmpblack(k,6);
        f=egyeb_black+sum(termeles_g(:,j-1))+black_edge(kereslet(...
            kereslet_mod,epszilon,p0,q0,egyeb_black+sum(...
            termeles_g(:,j-1))),be)+green_edge(kereslet(...
            kereslet_mod,epszilon,p0,q0,egyeb_black+sum(...
            termeles_g(:,j-1))),tgc(egyeb_black,sum(termeles_g(...
            :,j-1)),alfa,buyout),ge);
        g=tgc(egyeb_black,sum(termeles_g(:,j-1)),alfa,buyout);
        h=alfa;
        tmpblack(k,8)=fminbnd(@(x) profitb_k(x,a,b,c,d,e,f,g,h),...
            0,tmpblack(k,2));

        while (tmpblack(k,2)>tmpblack(k,8)) && (k<size(tmpblack,1))
            k=k+1;
            e=tmpblack(k,6);
            f=egyeb_black+sum(termeles_g(:,j-1))+tmpblack(k-1,7)+...
                black_edge(kereslet(kereslet_mod,epszilon,p0,q0,...
                egyeb_black+sum(termeles_g(:,j-1))+tmpblack(...
                k-1,7)),be)+green_edge(kereslet(kereslet_mod,...
                epszilon,p0,q0,egyeb_black+sum(termeles_g(...
                :,j-1))+tmpblack(k-1,7)),tgc(egyeb_black+...
                tmpblack(k-1,7),sum(termeles_g(:,j-1)),alfa,...
                buyout),ge);
            g=tgc(egyeb_black,sum(termeles_g(:,j-1)),alfa,buyout);
            h=alfa;
            tmpblack(k,8)=fminbnd(@(x) profitb_k(...
                x,a,b,c,d,e,f,g,h),0,tmpblack(k,2));
        end;
        termeles_b(i,j)=sum(tmpblack(:,8));
        command=['firm' num2str(i) 'b(:,8)=tmpblack(:,8);'];
        eval(command);
    end;

    if size(tmpgreen,1)>0
        if i<2
            egyeb_green=sum(termeles_g(i+1:num_firm,j-1));
        else
            egyeb_green=sum(termeles_g(1:i-1,j))+sum(termeles_g(...
                i+1:num_firm,j-1));
        end;
        k=1;
        e=tmpgreen(k,6);
        f=egyeb_green+sum(termeles_b(:,j))+black_edge(kereslet(...
            kereslet_mod,epszilon,p0,q0,egyeb_green+sum(...
```

```
                    termeles_b(:,j))),be)+green_edge(kereslet(...
                    kereslet_mod,epszilon,p0,q0,egyeb_green+sum(...
                    termeles_b(:,j))),tgc(sum(termeles_b(:,j)),...
                    egyeb_green,alfa,buyout),ge);
                g=tgc(sum(termeles_b(:,j-1)),egyeb_green,alfa,buyout);
                h=alfa;
                tmpgreen(k,8)=fminbnd(@(x) profitg_k(x,a,b,c,d,e,f,g,h),...
                    0,tmpgreen(k,2));

                while (tmpgreen(k,2)>tmpgreen(k,8)) && (k<size(tmpgreen,1))
                    k=k+1;
                    e=tmpgreen(k,6);
                    f=egyeb_green+sum(termeles_b(:,j))+tmpgreen(k-1,7)+...
                        black_edge(kereslet(kereslet_mod,epszilon,p0,q0,...
                        egyeb_green+sum(termeles_b(:,j))+tmpgreen(...
                        k-1,7)),be)+green_edge(kereslet(kereslet_mod,...
                        epszilon,p0,q0,egyeb_green+sum(termeles_b(:,j))+...
                        tmpgreen(k-1,7)),tgc(sum(termeles_b(:,j)),...
                        egyeb_green+tmpgreen(k-1,7),alfa,buyout),ge);
                    g=tgc(sum(termeles_b(:,j-1)),egyeb_green,alfa,buyout);
                    h=alfa;
                    tmpgreen(k,8)=fminbnd(@(x) profitg_k(...
                        x,a,b,c,d,e,f,g,h),0,tmpgreen(k,2));
                end;
                termeles_g(i,j)=sum(tmpgreen(:,8));
                command=['firm' num2str(i) 'g(:,8)=tmpgreen(:,8);'];
                eval(command);
            end;
        end;
        j=j+1;

    end;

    termeles=termeles_b(:,j-1)+termeles_g(:,j-1);
    total_black=sum(termeles_b(:,j-1))+black_edge(kereslet(kereslet_mod,...
        epszilon,p0,q0,sum(termeles_b(:,j-1)+termeles_g(:,j-1))),be);
    total_green=sum(termeles_g(:,j-1))+green_edge(kereslet(kereslet_mod,...
        epszilon,p0,q0,sum(termeles_b(:,j-1)+termeles_g(:,j-1))),tgc(sum(...
        termeles_b(:,j-1)),sum(termeles_g(:,j-1)),alfa,buyout),ge);
    share=zeros(num_firm,6);
    vegeredmeny=[ones(size(firm1b,1),1) firm1b; ones(size(firm1g,1),1) ...
        firm1g];
    for i=2:num_firm
                command=['vegeredmeny=[vegeredmeny; i*ones(size(firm' ...
                    num2str(i) 'b,1),1) firm' num2str(i) ...
                    'b; i*ones(size(firm' num2str(i) 'g,1),1) firm' ...
                    num2str(i) 'g];'];
                eval(command);
    end;
    vegeredmeny=sortrows(vegeredmeny,2);
    share(:,1)=capacity(:,1)/sum(capacity(:,1));
    share(:,2)=capacity(:,2)/sum(capacity(:,2));
    share(:,3)=capacity(:,3)/sum(capacity(:,3));
    share(:,4)=termeles_b(:,j-1)/sum(termeles_b(:,j-1));
```

```
share(:,5)=termeles_g(:,j-1)/sum(termeles_g(:,j-1));
share(:,6)=termeles(:)/sum(termeles);



kereses=[kereses; {y black_capacity_factor green_capacity_factor ...
    demand_factor q0 p0 epszilon alfa buyout kereslet_mod ...
    koltseg_mod num_firm toc j-1 kereslet(kereslet_mod,epszilon,p0,...
    q0,total_black+total_green) tgc(total_black,total_green,alfa,...
    buyout) total_black+total_green sum(termeles_b(:,j-1)) sum(...
    termeles_g(:,j-1)) sum(capacity(:,3)) sum(capacity(:,1)) sum(...
    capacity(:,2)) sum(share(:,6).*share(:,6)) sum(...
    share(:,4).*share(:,4)) sum(share(:,5).*share(:,5)) sum(...
    share(:,3).*share(:,3)) sum(share(:,1).*share(:,1)) sum(...
    share(:,2).*share(:,2))}];


end;
end;
datum=clock;
fajlnev=['/home/mmatyi/work/tezis/tema3/test/sz2-' num2str(datum(1)) ...
    '-' num2str(datum(2)) '-' num2str(datum(3)) '_' num2str(datum(4))...
    ':' num2str(datum(5)) ':' num2str(round(datum(6)))];
save(fajlnev,'kereses');
```

kereslet.m

```
function negativ=kereslet(a,b,c,d,e);
%a=kereslet-opcio, b=rugalmassag, c=horgony-ar, d=horgony-mennyiseg,
%e=termeles
if a==1
   negativ=(c/(1-b/(1+b)))*(1-(e*b)/(d*(1+b)));
elseif a==0
   negativ=c*((d/(e))^b);
end;

% if a==1
%     negativ=((c*(1+b)/b)-((e*c)/(d*b)));
% elseif a==0
%     negativ=c*((d/(e))^(1/b));
% end;
```

koltseg.m

```
function koltseg=koltseg(w,x,y,z);
if z==1
    koltseg=x;
elseif z==2
    koltseg=y;
elseif z==3
    koltseg=(x+y)./2;
elseif z==4
    tmpr=rand(size(x));
```

```
    koltseg=x+tmpr.*(y-x);
elseif z==5
    koltseg=(ones(size(w,1),1)-w).*x+w.*y;
elseif z==6
    koltseg=(ones(size(w,1),1)-w).*y+w.*x;
end;
```

profitb_k.m

```
function negativ=profitb_k(x,a,b,c,d,e,f,g,h);
%a=kereslet-opcio, b=rugalmassag, c=horgony-ar, d=horgony-mennyiseg,
%e=hatarktg, f-tobbiek termelese, g-tgc, h-alfa
if a==1
   negativ=x*e-x*(((c/(1-b/(1+b)))*(1-((f+x)*b)/(d*(1+b))))-h*g);
elseif a==0
   negativ=x*e-x*((c*((d/(x+f))^b))-h*g);
end;
```

profitg_k.m

```
function negativ=profitg_k(x,a,b,c,d,e,f,g,h);
%a=kereslet-opcio, b=rugalmassag, c=horgony-ar, d=horgony-mennyiseg,
%e=hatarktg, f-tobbiek termelese, g-tgc-ar, h-alfa
if a==1
   negativ=x*e-x*((1-h)*g+((c/(1-b/(1+b)))*(1-((f+x)*b)/(d*(1+b)))));
elseif a==0
   negativ=x*e-x*((1-h)*g+(c*((d/(x+f))^b)));
end;
```

black_edge.m

```
function black_edge=price(x,z);
% x=P_e z=be matrix
black_edge=0;
for i=1:size(z,1)
if x>z(i,1), black_edge=z(i,3); end;
end;
```

green_edge.m

```
function green_edge=price(x,y,z);
% x=P_e y=P_c z=ge matrix
green_edge=0;
for i=1:size(z,1)
if x+y>z(i,1), green_edge=z(i,3); end;
end;
```

tgc.m

```
function tgc=price(x,y,z,w);
% x=Q_b y=Q_g z=alfa w=P_buyout
if y==0
```

```
    y=0.0001
end;
tgc=w*z*(x+y)/y;
```