MODELLING THE INTERACTION OF THE ELECTRICITY MARKET AND THE ENVIRONMENT

IMPACT ASSESSMENT OF LIBERALISATION AND CLIMATE POLICY

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Abstract

The European electricity market faces two main challenges: the liberalisation process and climate policy. The liberalisation process of the European electricity market leads to increased competition between utilities. The emissions trading system intends to reduce greenhouse gas emissions. Therefore, only those utilities will gain a compared market advantage that can produce electricity with cost efficient and environmental friendly technologies. This paper investigates the impacts of the European emissions trading system on the electricity market. It turns out that emissions trading leads to higher electricity prices and triggers a substitution process from coal to gas and renewable technologies.

Keywords: Electricity market liberalisation, European Emissions Trading, market impacts

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Introduction

The liberalisation of electricity markets—the introduction of competition, the reduction of external, particularly political interferences and adjustments, and the opening of the market for new providers—is a worldwide phenomenon. Although the reasons for an opening of markets vary from country to country, the main goal apart from higher production efficiency is to offer customers lower electricity prices.

Though only a few countries in the world have accomplished a complete liberalisation, it can be observed, however, that most countries aim for a complete opening of the electricity market in the near future. In Europe, all EU member states shall liberalise the electricity market according to the 1997 directive of the European Commission (Directive 96/92/EC). The directive provides that European electricity markets should already have been opened up to an average of 25 percent in 1999.

The directive is, however, converted differently into an actual policy in different countries, and the progress of liberalisation of electricity markets in Europe vary between countries. In Germany, the market was liberalised in 1999, whereby the markets in Norway, Sweden and the United Kingdom had already been completely opened up by then. Austria and Denmark have liberalised their electricity markets almost completely as well (see Table 1). Spain is likewise aiming at an imminent opening of the market. France and Italy have not yet decided when they intend to open the market for external competition. These countries are characterized by the predominant position of a few electricity produces, i.e. a rather uncompetitive monopoly and/or duopoly prevail (France: EdF, Italy: Elettrogen and Enel). This unequal distribution of market opening and liberalisation of the electricity markets in Europe involve some competition distortions – some utilities already face complete competition, whereas others can continue operating in a monopolistic position. Since utilities have to compete with each other after the opening of the market, providers, in order to survive, need to alter their behaviour. In Germany, for example, utilities reacted very dynamically after the liberalisation of the electricity market in 1999 by firm mergers and strategic behaviour. A rise of the market shares of certain producers might lead to a rather uncompetitive market structure, which will not reduce, but rather increase electricity tariffs. Whether an electricity supplier is able to convert strategies in the electricity sector depends on the market situation, in particular on the dominant market conditions. Thus the market entrance conditions on the different levels of the current market (production, trade (and selling)) play a crucial role.

Furthermore, also electricity trading options can offer additional incentives for the practice of market power, unless uniform price structuring for tradable electricity is created. In Germany for example, a federation agreement regulates the prices for the power trade. However, it has been observed in the past that due to strategic market behaviour, providers for third party access of extraneous electricity were completely delayed or refused. In its second benchmark report, the European Commission criticizes that competition distortions and market power can arise through high entrance net access fees, which obstruct the entrance of new providers. The different market opening degrees diminish the advantages for the customer.

European climate policy is dominated by two main challenges: the European emissions trading system[1] and policies to increase renewable energy. Europe reacts on the challenges of climate change by establishing a European wide emissions trading system. Within the first phase from 2005 until 2007, all 25 European countries will be able to trade emission allowances (European Commission (2003)). The European emissions trading system starts in 2005, the first phase lasts from 2005 until 2007 and is restricted to emissions of CO2. The

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[1] Commission of the European Communities: Proposal for a Directive of the European Parliament and the Council establishing a scheme for greenhouse gas emission allowance trading within the Community and amending council dierctive 96/61/EC, COM (2001) 581 final. Brussles: Commission of the European Communities, 2001

idea of emissions trading is very charming: to reach the overall goal of emissions at minimal economic costs. However, the success of such a system significantly depends on the design, the organization and the monitoring process. The European Parliament and the Council decided that each Member State should allocate the initial allowances on the basis of its National Allocation Plan (NAP). Up to now, some, but not all European Countries including Germany, have notified their NAP to the European Commission. The German NAP may undermine the effectiveness of the European trading systems because of two reasons: firstly, only grant emitters are affected. Secondly, the past is counted as (past) early actions without concrete proof whether these initiatives were made in order to reach concrete emissions reduction targets. The European Commission has recently criticised this and asked Germany to change this procedure.

The European Union has issued a white paper to support the increase of renewable energy for electricity production.[2] The share of renewable energy for electricity production should reach an amount of 12 percent until 2010. The individual European countries have committed to accomplish concrete targets of renewable energy contribution until 2010 for electricity production. In order to reach that target, specific countries apply different policy tools. Belgium, Spain, France and Portugal support a feed in tariff (similar to Germany) to compensate higher costs of electricity production by renewable. Other countries like Finland, the Netherlands and Sweden support tax relaxations to give incentives for electricity production through renewable resources. A quota system regulates the share of renewable energy for electricity production; licences can be traded similar to the emissions trading system. Such a system is favoured by Austria, Italy and England. Germany has implemented a renewable energy law (EEG) [3], which specifies the share of renewable energy and supports electricity production by renewable energy through concrete feed-in tariffs. The share of

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[2] See European Commission (1997)

[3] Law to support renewable energy, German: Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare Energien-Gesetz-EEG) of March 2000.

renewable energy for electricity production should be increased by 20 percent by 2020 and by 50 % by 2050.

The main aim of this paper is to investigate the impacts of a European emissions trading system on the electricity market. We apply a game theoretic model for the European electricity market EMELIE (Electricity Market Liberalisation In Europe).[4] EMELIE is calibrated to the main European energy suppliers, which are linked by capital flows. These firms produce electricity through different technologies, considering others' and their own capacities, and variable production costs. Within this context, the analysis focuses on the impacts of strategic action by firms, which is compared to the case without strategic action, i.e. when the market is fully competitive. We especially investigate the impacts of a European emissions trading system on the electricity market.

Newberry (2002, 2002a, 2002b) studied potentials and opportunities for European utilities in a liberalised market. Day and Bunn (1999) investigated these aspects by a game theoretic model of market power and strategic actions of firms in the UK. Bower and Bunn (1999) assess trade opportunities within a pool versus a bilateral trade system in the electricity market of the UK. Admundsen and Bergman (2002) studied these issues for the Norwegian and Swedish power market. Here, transmission and transport pricing plays a crucial role. Experiences in Scandinavia and the UK suggest that a uniform tariff is preferred over distance charges. Moreover, market opportunities and grid owners significantly influence trade. Dawson and Shuttleworth (1997) studied transmission pricing in Norway and Sweden. Green (1997) examined this effect for the UK. Cardell et al (1994) investigated the negative effects of market power and transmission constraints on trading by an imperfect competition model for North American electricity suppliers.

Diverse authors have examined different non-cooperative games within various markets. Murphy et al (1986) demonstrate how mathematical programming approaches can be used to

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[4] A first version of EMELIE is applied to study economic impacts of the German electricity market in Lise et al (2003). The first application to the European market is given by Kemfert et al (2002). See also Kemfert (2004)

determine oligopolitistic market equilibria. Salant and Shaffer (1999) illustrate the theoretical impacts on production and social welfare via two-stage Cournot-Nash equilibrium solutions, where learning by doing and investments in R&D determine marginal costs of identical agents differently. For Europe, Jing-Yuan and Smeers (1999) have modelled an oligopolistic electricity market with a sophisticated game theoretic model, calculating the Nash equilibria. More generally, Helman et al (1999) investigated different kinds of trade options and strategic price setting within the electricity market. Stern (1998) investigates the liberalisation of the European gas market.

Bower et al (2001) have simulated the liberalised German electricity market by an agent-based model. They conclude that mergers increase market power, increasing the electricity prices. Their model is very sensitive to the out-phasing of expensive oil-fired plants, nuclear energy, or to closing the borders to imports of (cheap) electricity. In all these instances, prices jump up considerably. Bigano and Proost (2002) conducted a four-country study (France, Germany, Belgium, the Netherlands) that is linked through electricity trade. The environmental impacts are quantified, where a 3-stage game is calculated in a partial equilibrium framework. They compare strategic action with perfect competition to conclude that phasing out nuclear energy leads to a substantial decrease in social welfare.

In a liberalised electricity market, electricity suppliers can act strategically, which influences electricity prices, due to changing market shares in favour of large firms. Furthermore, mergers can become attractive, as it increases the electricity price and hence profits. While enhancing competition in the electricity market, strategic behaviour determines the structure of the market and energy supply network (see also Kemfert, 1999, and Kemfert 2004).

The paper is organised as follows: we describe briefly the current situation of the European electricity market in the second section. Then, we give a short characterisation of the applied game theoretic modelling tool. The fourth section reports and explains the modelling results, the last section concludes. The Annex provides a detailed mathematical description of the model.

The Electricity Market in Europe

As the benchmark report of the European Commission of March 2003 testifies, the European electricity market can be characterised by increased market opening, improvements of unbundling of net owners and more transparent regulation methods[5]. Whereas Italy and the United Kingdom registered decreased electricity prices for large consumers, also Austria, Germany and the Netherlands observed increasing activities of customers. However, as not all countries have liberalised their electricity markets completely, some unsolved difficulties still emerge, as the degree of unbundling, increased market shares of dominant utilities in some European countries and the lack of infrastructure of inter country electricity trade.

Since the market conditions for the current providers are still very different in the individual countries in Europe, there is so far no clear tendency to observe in the development of the electricity market. In Germany, the liberalisation of the electricity market first led to sinking electricity tariffs, particularly for the main customers, due to increased competition. For the private customer range the prices reduced first. However so far, only a few private customers in Germany have changed providers (see Table 1). Therefore, within the private customer range in Germany, the electricity tariffs rose once again. In England, however, private customers frequently changed providers due to strong electricity tariff variations.

Through various developments of the electricity market in individual European countries and the additional competitive pressure on the particular providers, strong strategic behaviour of individual providers increases. Mergers of large power suppliers in Germany reduced and rather obstructed competition, since the free decentralised market access also is decreased for small electricity providers. Although France so far has opened its electricity market, the

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[5] See European Commission (2003).

largest French provider, EdF, dominates the electricity supply in France and increasingly also in Europe. Because the nationally controlled giant pursued a strong policy of expansion overseas, it is however hardly possible for current European providers to expand into the French market. Therefore the European commission has already demanded extra time to regulate the European market as uniformly as possible and to decrease market power by an independent adjustment authority.

The Applied Modelling Approach

We investigate the market developments in seven European countries using the game theoretic model EMELIE (Electricity Market Liberalisation In Europe). EMELIE can be classified as a computational game theoretic modelling tool that investigates strategic behaviour by firms within the fully liberalized European electricity market. In the first and final stage of the game, electricity suppliers play a Cournot-Nash game, optimizing their profits under cost constraints and demand restrictions. Demand is represented by an inverse demand function, which is continuously differentiable twice. In the second stage of the game, firms maximize their profits given the strategic production behaviour of other actors. Electricity production is determined by variable production costs. Electricity can be traded, depending on capacity constraints, maximum net power, net access costs and transport costs. Market shares (which may change with merges or co-operation) play an important role. In the oligopolistic market structure, market shares and powers can influence prices, and prices are also influenced by the price elasticities of demand. An oligopolistic market structure is characterized by a mutual influence of prices due to market shares and power. In the Nash equilibrium, electricity firms, optimizing their profits, react strategically by enlarging their market shares, thus influencing prices and demand. A Nash equilibrium is reached by the selection of each player's optimal strategic action considering strategic behaviour by all other market actors. In a full competition case, each agent reacts as a price taker, equalizing prices and marginal costs to determine and optimize firms' profits. The Annex gives a mathematical description of the model.

The model is calibrated by providing the electricity retail price and the actual demand in a particular base year. In this paper we take the year 2000 as the base year. In the calibration of the model, production costs are minimised to see whether it is possible to meet the required demand. Below we refer to the results from this calibration as the reference case (REF).

The first case uses the assumptions of the perfectly competitive market, i.e. that firms are price takers and act as if they couldn't influence the market price. This case is referred to as the perfect competition case, COMP. The perfectly competitive outcome is equivalent to Bertrand oligopoly competition, i.e. when firms set prices taking the actions of the other firms into account.

In contrast to the perfectly competitive situation, in the second case, producers are assumed to act strategically. Each player decides on a production quantity taking the strategic choices of the other players into account. This is the Cournot-Nash oligopoly model, which is characterised by mutual, strategic reactions by market players. This result leads to a Nash equilibrium where the strategies of all market actors are the best responses to the actions of all other market players. However, a so-called competitive fringe consisting of the total sum of small-decentralised production units has been included, and this fringe is assumed to always behave as a price taker. Strategically behaving firms can influence prices by changing production. We refer to this as the STRA case.

The production of electricity depends on the production activities of other producer, the demand, and available production technologies and capacities. In addition to the main utilities of each country we take the great number of small-decentralised production units into account through a competitive fringe. As their sizes are small, they always act as price takers in the model.

The demand of electricity varies due to price changes. The model considers a one-stage game. We distinguish between peak and load production activities. The model takes into account 12 different productions; table 2 illustrates the different production capacities by each individual country. We apply conventional thermal power technologies as nuclear (N), coal (C), gas (G), lignite (L) and oil (O). Furthermore, we take five different types of combined heat and power production (CHP) type technologies into account: gas (CHP-G), coal (CHP-C), oil (CHP-O), biomass (CHP-B) and other fuels (CHP-X). Finally, we include renewable energy technologies as hydro (H) and wind power (W). We calibrate the EMELIE model by considering data for the benchmark year 2000: production capacities of the largest producers, variable production costs for different technologies, transmission capacities between countries, together with the wholesale market price and demand data. We consider the following European countries: Denmark, Finland, France, Germany, the Netherlands, Norway and Sweden.

Impacts of European Emissions Trading System on the Electricity Market

We apply the European Emissions trading system by simulating the impacts and reactions of European utilities if a certain permit price increases. The Permit price changes the variable production cost of each production technology. The higher the emission price, the higher the increase of variable production costs (Figure 1). Both scenarios lead to substantial electricity price changes. In the reference scenario (no emissions trading), the real reference price is far higher than the simulation results assuming perfect competition in both Belgium and Holland. The perfect competition scenario means that all firms produce at a marginal cost. Full competition does not allow for any strategic behaviour that could influence the electricity price (Table 3). Full competition leads to a similar low price within most countries. Only in Germany, the real electricity price reflects a full competitive situation. The oligopolistic scenario allows for strategic actions of utilities that increase the electricity price. But even in this scenario (STRA), the electricity price of Belgium and Netherlands was below the real electricity price in 2000. As most of the firms face higher marginal production costs than reflected by the simulated electricity price of the competition scenario (COM), firms loose gains. Only EDF and Vattenfall Sweden/Germany can profit from the full competitive situation, both because of the high share of nuclear power and low production costs. The oligopolistic market situation leads to higher electricity prices, so that all firms can increase gains and profits (Table 5).

With increasing emissions permit prices, electricity prices increase as well. Again, the electricity prices are even higher if an oligopolistic market situation is assumed. The increasing emissions certificate prices make technologies that produce a greater share of emissions more expensive. Coal power plants produce the greatest emissions, followed by oil and gas. France is characterised by a high share of nuclear power, with low variable production costs. Germany still has a high share of coal power, but also nuclear and renewable. Companies with a high share of coal power like RWE loose gains within a full competitive situation but also in an emissions trading market. Belgium produces electricity by both coal and nuclear power plants. In the overall European electricity market simulation, emissions trading leads to a substitution of coal technology in both gas and CHP (Figure 2). Germany intensifies imports from France and Sweden with increasing emissions permit prices, but also increases to export electricity to both Holland and Denmark.

Conclusions

The liberalisation of the European electricity market leads to an increased competition situation. However, due to firm mergers the current market can be classified as an oligopolistic market that leads to increased electricity prices. The emissions trading system increases electricity prices even further. In an oligopolistic market situation, firms benefit from emissions trading. Coal technologies are substituted by gas and renewable technologies.

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References

Amundsen, E. and Bergman, L. (2002) Will cross-ownership re-establish market power in the Nordic power market? *The Energy Journal* **23(2)**:73–95.

Bigano, A. and Proost, S. (2002) The opening of the European electricity market and environmental policy: does the degree of competition matter? Center for Economic Studies, Katholieke Universiteit Leuven. Available from: http://weber.ucsd.edu/~carsonvs/papers/602.pdf

Bower, J., Bunn, D. W. and C. Wattendrup (2001) A model-based analysis of strategic consolidation in the German electricity industry, *Energy Policy* **29**:987–1005.

Bower, J. and Bunn, D. (1999) A Model-Based Comparison of Pool and Bilateral Market Mechanisms for Electricity Trading, London.

Cardell, J., Hitt, C. C. and Hogan, W. W. (1996) Market Power and Strategic Interaction in Electricity Networks, Harvard Electricity Policy Group, Cambridge, Mass.

Dawson, Paul and Shuttleworth, Graham (1997) Efficient Transmission Pricing in Norway and Sweden, Report for NVE, National Economic Research Associates, London.

Day, C. and Bunn D. (1999) Generation Asset Divestment in the England and Wales Electricity market: A Computational Approach to Analysing Market Power, London.

European Commissions (1997): Communication from the Commission - Energy for the future: Renewable sources of energy - White Paper for a Community strategy and action plan**,** COM(97) 599, November 1997

European Commission (2003): Second Benchmarkreport of the implementation of the European Electricity and Gasmarket, Brussels.

Green, Richard (1997) Electricity Transmission Pricing An Internal Comparison, Department for Applied Economics and Fitzwilliam College, Cambridge.

Helman, U., Hobbs, J.B., Cardell, T., Luong, T. and Wander, M.T. (1999) Modelling Strategic Pricing in Bilateral and Poolco Electricity Markets: A Nash-Cournot Approach with Applications to US Eastern Interconnection, INFORMS national meeting, Philadelphia, Npv. 7-10

Jing- Yuan, W. and Smeers, Y. (1999) Spatial oligopolistic electricity models with Cournot Generators and regulated transmission prices. *Operations Research* **47(1)**:102–112.

Kemfert, C. (1999) Liberalisation of the German Electricity Market - Strategies and Opportunities. *Nota di Lavoro*, **95-1999**.

Kemfert, C.: The European Electricity market between liberalisation and climate policy, risks and challenges for the German electricity supply, Economic Bulletin, Volume 43, No.6, 2004 pp.241-153

Murphy, F. H., H. D. Sherali, et al (1986) A mathematical programming approach for determining ologopolistic market equilibrium. *Mathematical Programming* **24**:92–106.

Newberry (2000) Privatisation, Restructuring, and Regulation of Network utilities. MIT Press.

Newberry (2002a) Regulatory Challenges to European Electricity Liberalisation. Cambridge.

Newberry (2002b) Problems of Liberalisation of the energy utilities. *European Economic Review*, Vol. 4.

Salant, S. W. and Shaffer, G. (1999) Unequal treatment of Identical Agents in Cournot Equilibrium. *The American Economic Review* **89(3)**:585–604.

Stern, J (1998) Competition and Liberalisation in the European Gas Market: A Diversity of Models, London.

Tirole, Jean (1988) The Theory of Industrial Organisation. MIT Press, Cambridge, Massachusetts.

Annex I: Tables and Figures

Table 1: Liberalisation of the Electricity Market in Europe

Country	Percent of liberalisation	Date of complete liberalisation	Main providers	Market share of the main providers	Consumers who changed providers
Austria	100%	2003	EVN, Verbund, Wiener Stadtwerke	68%	5-10%
Belgium	35%	2007	Electrabel	97%	5-10%
Denmark	90%	2003	SK Power Company	75%	N/A
Finland	100%	1997	Fortrum, Ivo Group	54%	30%
France	30%	Discussion not ended	EDF	98%	5-10%
Germany	100%	1999	E.On, EnBW, RWE, Vattenfall	63%	10-20%
Greece	30%	Not discussed	AEH (public company)	100%	None
Ireland	97%	2007	ESB	97%	30%
Italy	35%	Not discussed	Elettrogen, Enel	79%	Less than 5%
Luxemburg	50%	2007	Cegetel	90%	N/A
Netherlands	33%	2003	Essent, Nea	64%	10-20%
Portugal	30%	Not discussed	EDP	85%	Less than 5%
Spain	45%	2003	Endesa, Hidroelectrica del Cantabrico, Iberdrola, Union Fenosa	79%	Less than 5%
Sweden	100%	1998	Sydkraft, Vattenfall	77%	N/A
UK	100%	1998	British Energy, Innogy, Powergen, Scottish and Southern Energy, Scottish Power	44%	80%

Source: Benchmark Report of the European Commission, see European Commissions (2003)

Table 2 Electricity production capacities in 2000

(TWh / year)	Denmark		Finland		France		Germany		Netherlands		Norway		Sweden	
	N	I	N	I	N	I	N	I	N	I	N	I	N	I
Nuclear	0	9.2	21.3	16.7	403.6	23.8	167.9	35.6	3.8	5.4	-	9.1	68.1	3.5
Coal	16.8	2.6	16.0	-	88.8	13.1	178.9	26.8	34.6	-	-	3.9	-	17.3
Lignite	-	1.5	-	-	-	2.4	99.3	-	-	-	-	-	-	0.4
Gas	-	2.7	6.3	0.4	13.2	18.5	157.7	10.2	61.2	-	-	0.5	-	1.5
Oil	-	2.8	8.7	1.8	85.6	10.3	64.1	3.5	8.5	-	-	2.5	22.8	1.4
CHP-G	8.6	0.2	8.1	0.06	-	0.2	10.2	3.5	39.8	-	-	2.1	0.6	5.8
CHP-C	7.1	1.0	6.6	0.2	-	1.3	52.1	2.9	-	-	-	2.0	2.5	5.0
CHP-O	-	0.3	0.7	0.3	-	0.06	2.6	0.07	-	-	-	0.4	2.9	0.1
CHP-B	-	0.2	4.7	0.2	-	-	-	0.05	5.4	-	-	0.3	2.1	0.6
CHP-X	-	1.0	6.5	0.4	29.9	0.8	32.9	1.2	-	-	0.9	0.6	4.5	1.1
Hydro	0.03	15.7	12.5	6.8	72.6	38.9	37.4	33.9	0.3	22.1	142.3	8.2	64.4	23.1
Wind	4.4	0.06	0.08	0.05	0.2	0.02	0.7	1.8	1.9	-	0.03	1.1	0.5	2.4
Total	*37.0*	*37.3*	*91.4*	*27.0*	*693.9*	*109.5*	*803.6*	*119.6*	*155.7*	*27.5*	*143.2*	*30.7*	*168.5*	*62.2*

Notes: *N* shows total domestic capacity and *I* refers to import capacity.

Table 3: Electricity Prices in Euro/MWh with different emission prces (E-price) of two different scenarios: fill competition (COMP) and oligopoly (STRA)

		E-Price=0		E-Price=5		E-Price =10		E-Price=20		E-Price=40	
Region	REAL 2000	COMP	STRA	COMP	STRA	COMP	STRA	COMP	STRA	COMP	STRA
Begium	39,65	15,38	22,29	15,79	25,32	16,22	27,98	17,96	34,63	21,19	42,55
Denmark	17,41	15,26	17,17	15,79	18,77	15,73	20,14	17,37	23,13	20,60	23,57
Finland	14,88	15,23	16,70	15,72	18,32	15,64	19,69	17,28	22,36	20,51	23,12
France	20,81	15,38	20,54	15,79	23,55	16,22	25,66	17,96	29,96	21,19	34,2
Germany	15,19	15,38	19,38	15,79	22,81	16,22	25,79	17,96	30,02	21,19	35,49
Holland	39,65	15,38	22,88	15,79	26,75	16,22	29,68	17,96	35,05	21,19	43,09
Norway	12,25	15,38	17,62	15,79	20,26	16,22	21,29	17,96	24,59	21,19	26,95
Sweden	14,26	16,46	18,80	16,73	21,44	17,17	22,47	18,91	24,77	22,37	28,13

Table 4: Trade Impacts of different emissions trading scenarios (permit price of 0,10,20,40 €/t CO2)

	Belgium	Denmark	Finland	France	Germany	Holland	Norway	Sweden
Trade E-Price =0								
Belgium	0	0	0	5,1608	0	-1,4091	0	0
Denmark	0	0	0	0	-3,5752	0	0,2972	0,7002
Finland	0	0	0	0	0	0	-0,125	-0,798
France	-5,1608	0	0	0	-5,2371	0	0	0
Germany	0	3,5752	0	5,2371	0	-2,3887	0	10,284
Holland	1,4091	0	0	0	2,3877	0	0	0
Norway	0	-0,2972	0,125	0	0	0	0	-4,4124
Sweden	0	-0,7002	0,798	0	-10,284	0	4,4124	0
Trade E-price =10								
Belgium	0	0	0	5,2811	0	-1,8169	0	0
Denmark	0	0	0	0	-1,2085	0	0,2601	0,3558
Finland	0	0	0	0	0	0	-0,0144	-0,8189
France	-5,2811	0	0	0	-6,4438	0	0	0
Germany	0	1,2085	0	6,4438	0	-3,9028	0	11,0004
Holland	1,8169	0	0	0	3,9028	0	0	0
Norway	0	-0,2601	0,0144	0	0	0	0	-4,5093
Sweden	0	-0,4943	0,8189	0	-11,0004	0	4,5093	0
Trade E Price =20								
Belgium	0	0	0	4,409	0	-1,5562	0	0
Denmark	0	0	0	0	-1,3469	0	0,2082	0,05027
Finland	0	0	0	0	0	0	-0,3575	-0,5009
France	-4,409	0	0	0	-5,863	0	0	0
Germany	0	1,3469	0	5,863	0	-4,2317	0	11,2336
Holland	1,5562	0	0	0	4,2317	0	0	0
Norway	0	-0,2082	0,3575	0	0	0	0	-5,048
Sweden	0	-0,5027	0,5009	0	-11,2336	0	5,048	0
Trade E-Price =40								
Belgium	0	0	0	3,7717	0	-1,3848	0	0
Denmark	0	0	0	0	-0,5288	0	0,2986	0,451
Finland	0	0	0	0	0	0	-0,2677	-0,2493
France	-3,7717	0	0	0	-8,9203	0	0	0
Germany	0	0,5288	0	8,9203	0	-4,3827	0	11,827
Holland	1,3848	0	0	0	4,3827	0	0	0
Norway	0	-0,2986	0,2677	0	0	0	0	-5,2327
Sweden	0	-0,451	0,2493	0	-11,872	0	5,2327	0

	Certificate Price =0		**Certificate Price=5**		**Certificate Price =10**		**Certificate Price=20**		**Certificate Price =40**	
Firm	COMP	STRA	COMP	STRA	COMP	STRA	COMP	STRA	COMP	STRA
FrinBEL	-540,8	74,6	-177,1	82,2	-291	94,3	7,3	110,7	-213,1	136,8
ElectBEL	-403	706,4	-177,6	797,4	-216	875,7	-75,8	1087,3	-30,9	1370,9
FrinDEN	-448,6	171,2	-110,8	220,1	-149,9	257,3	-148,5	324,9	-260,7	396,8
Elsam	-487,7	176,7	-182,1	145,6	-262,3	117,8	-230,1	117,1	-525,9	111,1
E2Energi	-194,8	129,8	-104,9	107,9	-438,8	76,1	-340,4	69,2	-415	55,9
FrinFIN	-434,8	276	-336,5	320,3	-361,8	338,7	-495,3	423,7	-342,9	491,6
Fortum	-399,9	319,8	-471,3	356,3	-275,6	379,4	-541	469,7	-2571,1	552,1
PVO	-531,7	156	-581,5	178,8	-482,6	185,5	-555,5	228,3	-465	271,6
FrinFRA	-163,5	371,6	-410,5	407,9	-151,6	427,5	-253	570,6	35,4	703,8
EDF	4674,2	5309,7	3732,2	6269,2	4002,7	7166,1	4146	8693,4	5210	10265,6
EONGER	52,7	1194,9	178,4	1365,5	323,5	1519,1	426,7	1764,8	597,3	1875
EnBW	-60,5	896,2	-97,3	830,4	-52,9	830,6	122,3	903,1	261,5	916,7
RWE	-271,8	502,3	-150,4	524,8	-95,1	567	-1,1	663,1	132,2	730
VattenGER	160,1	1285,2	189	1338,3	231,2	1418,4	312,5	1582,3	514,9	1623,3
FrinHOL	-485	266,7	-291,5	331,6	-311,1	369	-358,2	471,1	-192	517,8
ElectHOL	-580,6	35,2	-358,9	27,8	-606,7	23,6	-219,9	32,2	-135,7	20,7
NUON	-562	80,9	-349,2	84,9	-287,9	86,1	-209,4	110,1	-110,6	105,8
EONHOL	-577,1	38,3	-358,2	25,5	-302,8	16,5	-222,3	17,9	-135,5	12,1
Essent	-560,2	120,7	-332,8	125,5	-275,5	123,5	-192,1	157,1	-93,5	166,9
FrinNOR	327,7	1507,5	385,6	1736,1	413	1826,5	387,8	2115,3	1282,7	2143,3
Statkraft	142	693,6	251,1	783,5	232,4	833,2	416,5	965,7	567,6	976,7
FrinSWE	-238,9	381,6	-119,5	454,3	-93	520,8	25,8	618,1	173,5	642,3
VattenSWE	688,3	1217,6	318,1	1454,6	557,2	1653,8	379,5	1967,8	769,8	2061,1
Sydkraft	77,4	444,3	8	534,8	79	615,8	-13,5	739,2	61,2	775,5
Birka	7	345,4	-146	406,2	0,3	460,7	-93,7	539,6	-31,7	558,2

Table 5: Firm Payoffs in Mio Euro/a of different scenarios (COMP,STRA) and with different permit prices (0,5,10,20,40 €/t CO2)

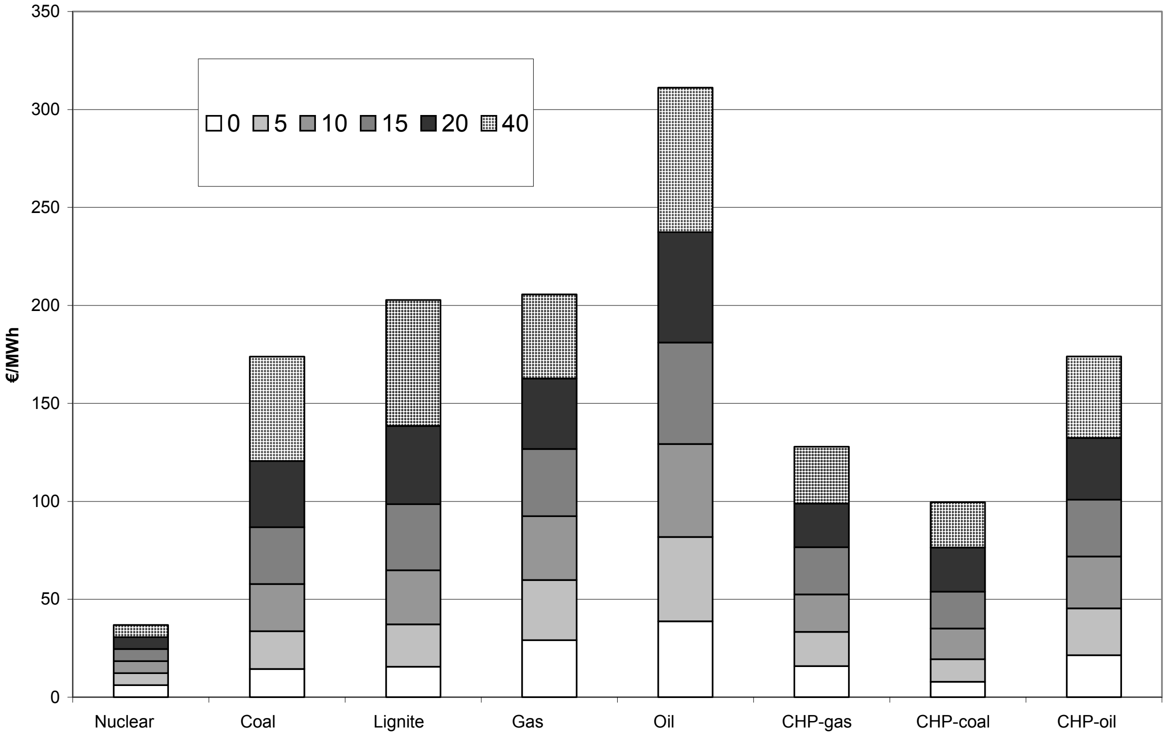

Figure 1: Variable production costs (€/MWh) of different technologies with increasing permit price (5,10,15,20,40 €/T CO2)

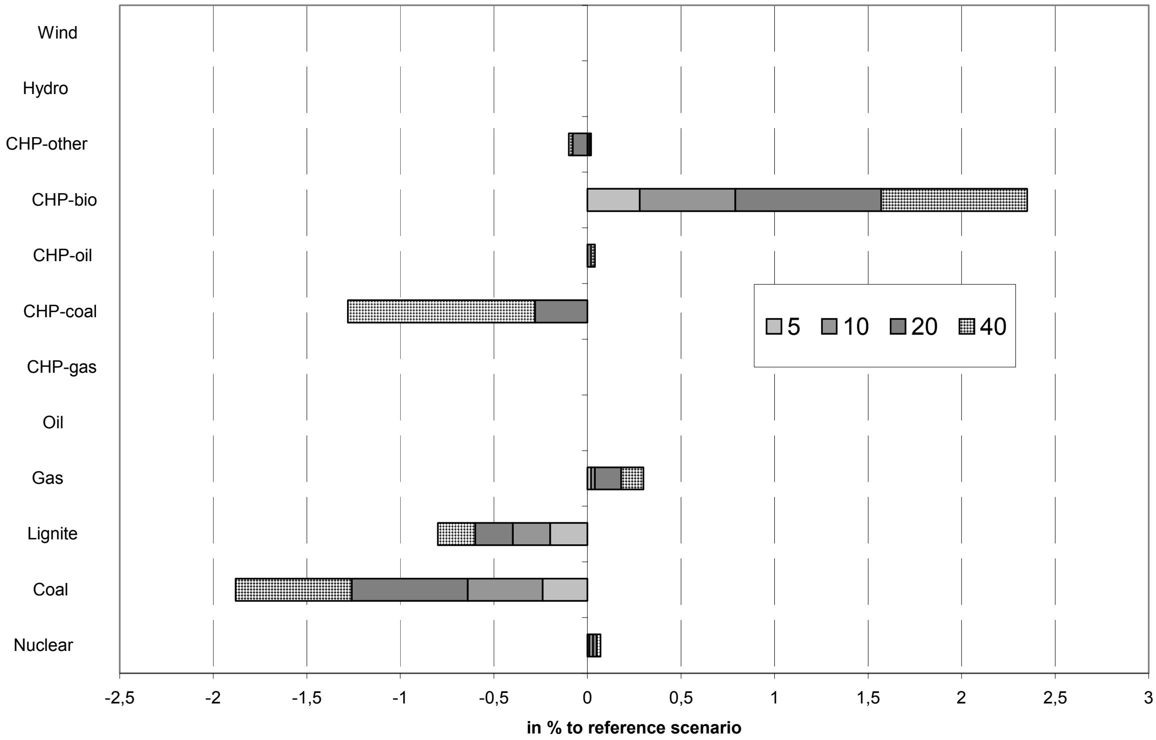

Figure 2: Technology share changes in comparison to the reference scenario of different permit price assumptions (5,10,20,40 €/t CO2)

Annex II: Mathematical Description of the EMELIE Model

The computational game theoretic model EMELIE is characterised by the following indices, parameters and variables:

Indices:

f	- Firms $f \in F$
i	- Technologies $i \in I$

Parameters:

c^{v}_{i}	- Variable production costs for technology i
d^{0}	- Reference demand for electricity
p^{0}	- Reference price for electricity
σ	- Price elasticity of electricity demand
$q^{max}_{i,f}$	- Maximum production capacity with technology i in firm f
λ	- Electricity net transport losses

Variables:

p	- Demand price for electricity
c^{m}_{f}	- Marginal and average costs of electricity production of firm f
s_f	- Supply of electricity by firm f
$q_{i,f}$	- Production of electricity by firm f with technology i

EMELIE is a partial general equilibrium model of a liberalised electricity market with multiple actors. On the supply side, electricity producing firms maximise their profits. On the electricity demand side consumers maximise utility. In equilibrium, prices p clear in national markets.

Note first that the market needs to be closed on the (consumer) demand side. This is achieved by the well-known inverse demand function:

$$\sum_{f \in F} s_f = d^0 \left(\frac{p}{p^0} \right)^{-\sigma} \perp 0 \leq p$$

(A.1)

Let us now consider the case with *strategic interaction* among firms on the supply side. In this case, electricity producing firms *f* maximise their net profits. They do this by choosing their strategies as represented by their supplies s_f simultaneously by assuming that other firms do the same. This is equivalent to maximising the profit firm *f* that can be obtained by supplying to the grid. This profit is the difference between incomes from supplied electricity minus the cost of production:

$$\text{Maximise } \Pi_f(S) = \left(p(S) - c_f^{\mathrm{m}} \right) s_f \qquad \text{(A.2)}$$

$$\text{where } S = \sum\nolimits_{f \in F} s_f \qquad \text{(A.3)}$$

where the dependence of the demand function *p*(.) on *S* constitutes “strategic action”, while from equations (A.1,A.3), the explicit functional form of *p*(.) can be derived.

The first order conditions for optimality of strategically acting firms follow directly from (1), by taking the partial derivatives with respect to s_f:

$$\forall f \in F : c_f^{\mathrm{m}} = p\left(1 - \frac{\vartheta_f}{\sigma} \right) \perp 0 \leq s_f \,, \qquad \text{(A. 4)}$$

The ‘⊥’ sign is used to denote the dual variable to this equation. The equation on the left-hand-side holds when firm *f* has a positive supply, a result which is well-known from the Karush Kuhn Tucker conditions and is a typical characteristic of a mixed complementarity problem (MCP).

Equation (A.4) shows the equalisation between marginal costs and marginal income. The individual market shares in equation (A.4) are conveniently determined by:

$$\forall f \in F : \vartheta_f = \frac{s_f}{\sum_{g \in F} s_g} \perp 0 \le \vartheta_f \qquad \text{(A.5)}$$

The marginal income in the case of strategic action is reduced by the factor "market share" divided by price elasticity of demand. The market share represents a monopoly mark-up. Power supply by firm *f* to the grid can be generated with various technologies *i*, like nuclear, coal, lignite, gas, oil, hydro, and so on. We assume here a λ% electricity transport loss, which is generally in the range of 0–5%.

$$\forall f \in F : (1-\lambda)\sum_{i \in I} q_{i,f} = s_f \perp 0 \le c_f^{\mathrm{m}} \qquad \text{(A.6)}$$

In order to fully define the model, we need to restrict firms' marginal costs. For this purpose we have used variable cost data per technology, which do not differ per firm. Then, a logical lower bound of marginal costs are these variable costs.

$$\forall i,f \in (I,F) : c_i^{\mathrm{v}} \le c_f^{\mathrm{m}} \perp 0 \le q_{i,f} \le q_{i,f}^{\max} \qquad \text{(A.7)}$$

where the available technology is restricted by an upper bound too.

Model (A.1,A.4–7) is used to calculate the *Nash equilibrium* in the case with strategic action, where market information is typically incomplete and we are dealing with the case of imperfect markets. This case of quantity competition shall be referred to as "STRA".

A model with perfect markets is established by replacing equation (A.4) by:

$$\forall f \in F : c_f^{\mathrm{m}} = p \perp 0 \le s_f \qquad \text{(A.4')}$$

Furthermore, in the case of equation (A.4'), equation (A.5) should be eliminated as well from the model, as market share ϑ_f is no longer a variable. Of course, the market shares now follow exogenously from the model. Model (A.1,A.4',A.6,A.7) is used to calculate the *competitive* *equilibrium* in the case without strategic action. This case is derived by reducing the demand function to an identity: $p(.)=p$. Here firms take market prices as given and we are dealing with the case of perfect markets. This case of price competition shall be referred to as "COMP". These model relations are written by the programming language GAMS, which decomposes the non-linear program as a mixed complementary problem (MCP). This is solved by the non-linear MCP-solving algorithm MILES, which is a mixed inequality and non-linear equation solver. Partially, MILES approximates linear sub-problems by Lemke's algorithm and solves the non-linear program by the generalised Newton algorithm iteratively with a backtracking line search. An optimal solution is found by maximising regional profit conditions reciprocally under all considered constraints.

It is also useful to verify whether the initial prices and demands are viable. This is done in the so-called "REF" case, where the production cost is minimised. This is expressed in the following equation.

$$\text{Minimise Cost}\left(q_{i,f}\right)=\sum\nolimits_{i\in I}\sum\nolimits_{f\in F} q_{i,f}c_i^{\mathrm{v}} \qquad \text{(A. 8)}$$

Model (A.1,A.6–8) is run as a non-linear programming problem to establish the REF case. The main outcomes of the model are regional prices, interregional trade flows and the optimal market shares of each electricity producer from which the regional concentration of the industry can be calculated in terms of the Hirschmann-Herfindahl index (HHI). HHI is a measure for (regional) competitiveness (see also Tirole, 1988, pages 221–223). For the industry as a whole, the Hirschmann-Herfindahl index is calculated as follows:

$$\mathrm{HHI}=10000\sum_{f\in F}\left(\frac{\sum\limits_{r\in R} s_{f,r}}{\sum\limits_{r\in R}\sum\limits_{f\in F} s_{f,r}}\right)^2 \qquad \text{(A. 9)}$$

A fourth possible market situation is where one firm is a leader and moves first, while the others are followers and move second in reaction to the chosen supply by the leader. The followers behave just like the STRA case (while the fringe behaves as COMP). The leader chooses its output knowing ultimately the outcome will lie on the follower's reaction function (A.4). The follower's reaction function is a constraint for the leader. The leader chooses its output to maximise profit given this constraint.

The first order condition of the leader can then be written as:

$$c_f^{\mathrm{m}} = p\left(1 - \frac{\vartheta_f}{\sigma} \Big/ \frac{dS}{ds_f}\right)$$

(A. 10)

where $dS/ds_f=1$ for the follower who behaves as in the STRA case, while $dS/ds_f > 1$ for the leader, which reduces the monopoly markup to the advantage of the leader. Hence, the outcome of the Stackelberg behaviour will lie between COMP and STRA.

Derivative dS/ds_f no longer cancels out in the case of the Stackelberg equilibrium, as the term in the aggregate demand $S = \Sigma\, s_f$ is built up from the supply of all firms, which can be expressed implicitly via (A.4) in the supply of the leading firm.

Let us now simplify the model of f to two firms, where i is the leader and j is the follower.[6]

Then the reaction function $s_j(s_i)$ can be derived by rewriting (A.4):

$$s_j = s_i\left(\frac{\sigma\left(p - c_j^{\mathrm{m}}\right)}{p - \sigma\left(p - c_j^{\mathrm{m}}\right)}\right)$$

$$S = s_i + s_j = s_i\left(1 + \frac{\sigma\left(p - c_j^{\mathrm{m}}\right)}{p - \sigma\left(p - c_j^{\mathrm{m}}\right)}\right) = s_i \frac{p}{\Omega_j};\ \text{where } \Omega_j = p - \sigma\left(p - c_j^{\mathrm{m}}\right)$$

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[6] To derive, mathematically, the FOC for the leader with n followers, is not an easy task, as expressing the reaction functions of each follower leads to n equations, with n variables. This can be aggregated to total demand, but the derivative w.r.t p is very complex. Nevertheless, the present approach already shows the advantage of moving first.

$$\frac{dS}{ds_i} = \frac{p}{\Omega_j} + s_i \sigma c_j^{\mathrm{m}} \frac{dp}{dS}\frac{dS}{ds_i}\frac{1}{\Omega_j^{\,2}}$$

$$\frac{dS}{ds_i} = \frac{p}{\Omega_j} \Bigg/ \left(1 - \frac{s_i c_j^{\mathrm{m}} \sigma}{\Omega_j^{\,2}}\frac{dp}{dS}\right) = \frac{p\Omega_j}{\Omega_j^{\,2} - s_i c_j^{m} \sigma \frac{dp}{dS}}$$

(A. 11)

we know from the definition of inverse demand (A.1) that:

$$\frac{dp}{dS} = \frac{-1}{\sigma}\frac{p}{S}$$

substituting this in (11) this leads to:

$$\frac{dS}{ds_i} = \frac{p\Omega_j}{\Omega_j^{\,2} + p c_j^{\mathrm{m}} \vartheta_i}$$

(A.12)

Finally substituting (A.12) in (A.10) and after rewriting the expression leads to:

$$c_f^{\mathrm{m}} = p\left(1 - \frac{\vartheta_f}{\sigma}\frac{\left(1-\sigma\gamma_f\right)^2 + \left(1-\gamma_f\right)\vartheta_f}{\left(1-\sigma\gamma_f\right)}\right);\ \text{where } \gamma_f = \frac{p - c_f^{\mathrm{m}}}{p};\ \text{the Lerner index} \qquad \text{(A.13)}$$

Equation (13) is used as the FOC for the Stackelberg leader, while the followers are competing in quantities (4), whereas the competitive fringe is a price taker (A.4’).