A MODEL OF THE EUROPEAN ELECTRICITY MARKET – WHAT CAN WE LEARN FROM A GEOGRAPHICAL EXPANSION TO EU20?

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Abstract

This paper presents the static computational game theoretic COMPETES (COmprehensive Market Power in Electricity Transmission and Energy Simulator) model version 2.0. This model can be used to study various policy question regarding economic and environmental effects of a fully opened European electricity market. The COMPETES model can take strategic interaction among electricity producing firms into account.

The strategic behaviour of generation companies can be reflected in the conjectures each company holds regarding the supply response of rival companies. These response functions simulate expectations concerning how rivals will change their electricity sales when prices change; these expectations determine the perceived profitability of capacity withholding and other strategies. In addition, COMPETES can solve the market outcome under price and quantity competition. COMPETES can also represent different systems of transmission pricing, among them fixed transmission tariffs, congestion-based pricing of physical transmission, and auction pricing of interface capacity between countries. CO2 costs can be brought in as an exogenous variable.

In this paper the COMPETES model is calibrated to twenty European countries, EU20 for short, namely Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Hungary, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, UK/England & Wales. These countries have been chosen because they are geographically adjoined, their electricity networks are well connected (UCTE, Nord Pool, UK), they are members of the European Union (except for Norway and Switzerland) and data is quite reliable (which would for instance not be the case for the Balkan countries).

The level of detail in the COMPETES model is quite extensive. The model contains various characteristics of 7531 power plants in the EU20 area (acquired from the database on World

Energy Power Plants). These characteristics comprise among others the generation capacity (of at least 10 MW), production technology, and plant ownership. Availability, energy efficiency, CO_2 emissions, and fuel costs per production technology are collected from other sources. Firms can own power plants in various countries and have in effect active cross-border ownership relations (and these data are compiled from company annual reports). The year is divided into 12 demand periods varying from a EU20-wide simultaneous super peak (3% of the time), peak, shoulder, and off peak (evenly distributed); and three seasons winter, summer, and spring/autumn (derived from UCTE data). Consumer demand is met under perfect competition, which results into market clearing prices and by assuming a price elasticity of –0.4, completes the affine consumer demand curve. Trade among the twenty countries is delimited by inter-connector transmission capacity (derived from ETSO data). The hydro production capacity is assumed to be as if it was a year with average rainfall throughout the year. Net losses from production to consumption are not considered in the model.

The COMPETES model is run for two scenarios to derive additional insights for covering the geographical EU20 area. The model simulations indicate the following. First, under perfect competition in the liberalised European electricity market, the price differences among countries largely tend to converge to each other. The prices in some countries are lower due to the presence of relatively cheap generation technologies and a limited ability to export to other countries. Second, the effect of market power of active cross ownership is studied. In the case where all large firms exercise market power, the model runs indicate that the biggest price responses are found in countries where the number of firms is low. However, due to the interlinkages among the markets, the price responses in the near monopoly markets are still relatively low.

Keywords: Electricity market; liberalisation; market power; game theory; environmental impacts; Europe.

JEL–classification: C7, D2, Q4, R3

1. INTRODUCTION

By the year 2007 all EU-15 member countries will have liberalised their electricity markets if they live up to their commitments according to EU Directive 96/92/EC. The European electricity market is currently in the midst of a drastic transformation from monopolistic, national and state-owned producers to a market with competing, private and often multinational firms. Although the speed and current state of this process varies widely across Europe, this process will definitely affect the structure of the European electricity market. In the present European electricity market we can see a whole range of different structures from a near-monopoly in France to highly competitive markets in the Nordic countries.

Yet little is known about the consequences of liberalisation. The main goal of liberalising the electricity market is to achieve more cost efficient production and lower electricity prices.

To study this complex process, we develop a static computational game theoretic model, which can study economic and environmental consequences of different market structures. The model allows us to answer questions about the wholesale price and demand for electricity, profits of electricity producers, and emissions to the environment. The model covers twenty European countries, namely Austria (AT), Belgium (BE), Czech Republic (CZ), Denmark (DK), Finland (FI), France (FR), Germany (DE), Hungary (HU), Italy (IT), Luxembourg (LU), Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Slovakia (SK), Slovenia (SI), Spain (ES), Sweden (SE), Switzerland (CH), UK/England & Wales (UK), which we for simplicity refer to as “EU20”.

The model captures different market structures depending on firm’s abilities to exercise market power. The two extreme cases are, on the one hand, perfect (or price) competition where firms do not exercise market power (also referred to as Bertrand equilibrium) and, on the other hand, strategic (or quantity) competition where firms fully exercise market power (also referred to as Cournot equilibrium). In between these two extreme market structures there are several possible oligopolistic market structures where firms exercise market power to a more limited extent.[1]

The COMPETES (COmprehensive Market Power in Electricity Transmission and Energy Simulator) model version 2.0, which is presented in this paper, is a simplified version of the original model in Hobbs *et al.* (2004a,b, 2006). The original model also allowed for congestion on six nodes in the Netherlands and two nodes in Belgium. This congestion is generally not observed in the national networks and it is therefore possible to simplify the model by considering one node per country. A similar model has been developed by Lise *et al.* (forthcoming) for eight Northwestern European countries, however, the calibration that model is based on more aggregate data.

Bower *et al.* (2001) have simulated the liberalised German electricity market using an agent-based model. They conclude that mergers increase market power leading to higher electricity prices. Their model is very sensitive to the out-phasing of expensive oil-fired plants, nuclear energy, and 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), which is linked through electricity trade. The environmental impacts are quantified and 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. Newberry (2001, 2002)

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[1] For instance, this is true for models with supply function equilibrium, where the firms do not fully exercise market power. Solving such models is computationally more demanding.

discusses the potential difficulties in liberalising the EU electricity market. He argues that, due to insufficient regulation, the targeted lower price effect can be offset.

The outline of this paper is as follows. The next section provides an elaborate introduction to the model. Section 3 presents some illustrative results to demonstrate the scope of the model. The final section concludes.

2. THE MODEL

2.1 Model description

COMPETES[2] covers the European electricity markets (Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Hungary, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, UK/England & Wales). It simulates strategic behaviour (oligopolistic competition) among the larger electricity generation companies. This strategic behaviour is based on the theory of Cournot and Conjectured Supply Functions (CSF) on electric power networks. These theories and their relation towards other theoretical approaches are discussed by Day *et al.* (2002). The specific theoretical approach and application within COMPETES is described more in-depth in the papers by Hobbs and Rijkers (2004) and Hobbs *et al.* (2004). And more recently in the model comparison project in Neuhoff *et al.* (2005) and in a study after the implications of coupling the Dutch and Belgian market by Hobbs *et al.* (forthcoming).

The strategic behaviour of the generation companies is reflected in the conjectures each company holds regarding the supply response of rival companies. These response functions simulate expectations concerning how rivals will change their electricity sales when prices change; these expectations determine the perceived profitability of capacity withholding and other strategies. COMPETES can also represent different systems of transmission pricing, among them fixed transmission tariffs, congestion-based pricing of physical transmission, and auction pricing of interface capacity between countries.

The representation of the electricity network in the model is aggregated to one node per country (see Figure 2.1). All individual generation units in the twenty countries are allocated to one of these nodes. Information on generation units, type of units and the corresponding capacities is mainly based on the WEPP database,[3] updated with public available information. Assumptions concerning generator availabilities and thermal efficiencies are estimated using ECN publications.

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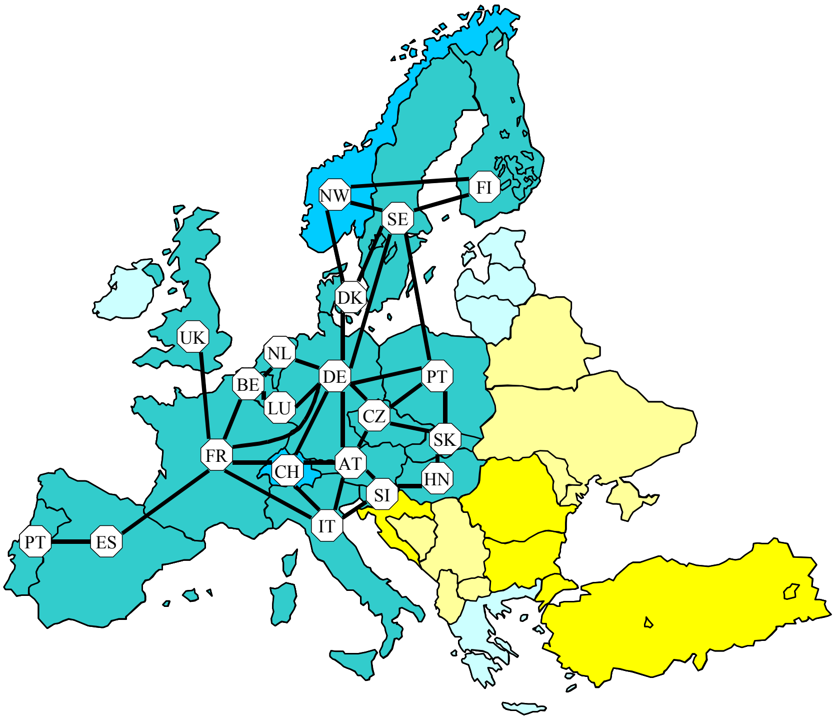
[2] COMPETES stands for COmprehensive Market Power in Electricity Transmission and Energy Simulator. This model is based on the theory of Cournot and Conjectured Supply Functions (CSF) competition on electric power networks, and is developed in cooperation with Benjamin F. Hobbs, Professor in the Whiting School of Engineering of The Johns Hopkins University.

[3] World Electric Power Plants database of 2001, UDI (2001).

Figure 2.1 *Physical representation of the electricity network in COMPETES 2.0*



Generators behaviour
Virtually all generation companies in the twenty countries are covered by the input data. Also CHP plants owned by energy suppliers and industrial CHP plants are included. The user can specify which generation companies are assumed to behave strategically and which companies will be allocated to the competitive fringe (i.e. the price takers). The model calculates the optimal behaviour of the generators by assuming that they simultaneously try to maximise their profits. Profits are determined as the income of sales (market prices multiplied by total sales) minus costs of transmission (if sale is not at the node of generation) minus the cost of generation. Cost of generation is calculated by using the short run marginal cost (operation and fuel costs). Start-up costs and fixed costs are not taken into account since these costs have no significant effect on the bidding behaviour of suppliers on the wholesale market.

Consumer behaviour
The model considers 12 different levels of demand, based on the typical demand during three seasons (winter, summer and autumn/spring) and four time periods (super peak, peak, shoulder and off-peak). The "super peak" period in the three seasons together consists of the 200 hours with the highest sum of the loads for the four considered countries. The three other periods have equal numbers of hours and represent the rest of the seasonal load duration curve. Altogether, the twelve periods represent all 8760 hours of a year. The consumers are assumed to be price sensitive by using decreasing linear demand curves depending on price. The model includes demand curves representing net wholesale loads on the high voltage grid.

Transmission system operator
The electricity network covering the twenty countries is represented by a DC load flow approximation. This approximation is a linear system that accounts only for the real power flows (not for reactive power) and is a simplification of the AC power flow model. Within this system both the current law and the voltage law of Kirchhoff apply. Using these two laws the flows within the electricity network can be uniquely identified using the net input of power at each node i.e. supply minus demand. Besides the physical network path-based constraints are defined using the available transmission capabilities (ATC) between the four countries. In the

current application these ATCs are set equal to the capacities that are available for the trade on the interconnections between the countries.

In the model generators or traders will buy network capacity when they want to transport power from one region to another. The total amount of transportation between two nodes can be limited due to the physical constraint or due to the limited availability of interconnection capacity between countries (see Figure 2.1). For the interconnectors it can be assumed that netting is or is not applied (anticipating that a power flow from, for example, Belgium to the Netherlands will increase the available interconnection capacity from Netherlands to Belgium).

Traders' behaviour

Between countries and nodes it can be assumed that arbitrageurs are active. An arbitrageur (or trader) is assumed to maximise its profits by buying electricity at a low price node and selling it to a high price node as long as the price differences between these nodes is higher than the cost for transporting the power between these nodes.

Input data

The most relevant input data used for the model that will influence the output data are the:

- Fuel prices assumed per country.
- Availability and efficiency per power plant for each generator.
- Demand load per season and period within each country.

The fuel prices are based upon a reference scenario developed by ECN for STATOIL (Van Oostvoorn *et al*., 2001). The generating units are taken from the WEPP database of UDI (Utility Data Institute, 2001) ownership relations are retrieved from the annual reports of the en-ergy companies and the generating unit characteristics are based on a study on innovations in production technologies (Lako and Ybema, 1997).

The level of detail in the COMPETES model is quite extensive. The model contains various characteristics of 7531 power plants (acquired from http://www.platts.com/, the database on World Energy Power Plants), among others the location, production technology, availability, and CO_2 emissions. Table 2.1 gives an overview of the main generators in the model including their market shares (firms with very small market shares are aggregated into the competitive fringes). Firms can own power plants in various countries and have in effect active cross-border ownership relations. The year is divided into 12 demand periods varying from lowest demand to a super peak (derived from data at http://www.ucte.org/, http://www.nordpool.com/, http://www.bmreports.com). Consumer demand is met under perfect competition, which results into market clearing prices and by choosing a price elasticity, completes the affine consumer demand curve. Trade among the four countries is delimited by inter-connector transmission capacity (derived from data at http://www.etso-net.org/). Net losses from production to consumption are assumed to be zero in the model.

Table 2.1 *Generation capacity and market shares in the twenty countries covered by COMPETES 2.0*

		Total	Market share			Total	Market share
AT	Comp_AT	8024	54%	IT	ENEL SPA	39065	56%
	VERBUND-AUSTRIAN HYDRO POWER	6782	46%		Comp_IT	17283	25%
		14806			EDISON SPA	7400	11%
BE	ELECTRABEL SA	11724	85%		ENDESA GENERACION	5251	7%
	Comp_BE	2075	14%		ELECTRABEL SA	1039	1%
		13799				*70038*	
CH	Comp_CH	*15715*	100%	LU	ELECTRABEL SA	*331*	100%
CZ	CEZ AS	11137	85%	NL	ELECTRABEL SA	4211	26%
	Comp_CZ	1938	14%		ESSENT ENERGIE PRODUCTIE BV	3953	25%
		13075			NUON NV	3414	21%
DE	Comp_DE	26350	26%		Comp_NL	2807	18%
	E.ON ENERGIE AG	24040	24%		E.ON ENERGIE AG	1591	10%
	RWE POWER	23433	24%			*15976*	
	VATTENFALL AB	14568	15%	NW	Comp_NW	17617	65%
	ENERGIE BADEN-WURTTEMBERG ENBW	9409	9%		STATKRAFT SF	9397	35%
	ELECTRICITE DE FRANCE	863	1%			*27014*	
	ESSENT ENERGIE PRODUCTIE BV	595	1%	PL	Comp_PL	24715	86%
		99258			ELECTRICITE DE FRANCE	2100	7%
DK	ELSAM A/S	3544	48%		ELECTRABEL SA	1512	5%
	ENERGI E2 A/S	3289	45%		VATTENFALL AB	513	2%
	Comp_DK	494	7%			*28840*	
		7327		PT	CIA PORTUGESA PRODUCAO ELEC	6910	72%
ES	Comp_ES	19253	36%		Comp_PT	1787	19%
	ENDESA GENERACION	14729	28%		RWE POWER	864	9%
	IBERDROLA SA	13623	26%			*9561*	
	UNION ELECTRICA FENOSA SA	3513	7%	SE	VATTENFALL AB	12603	43%
	ENERGIE BADEN-WURTTEMBERG ENBW	723	1%		Comp_SE	11544	39%
	RWE POWER	361	1%		FORTUM POWER & HEAT	2980	10%
		52201			E.ON ENERGIE AG	2117	7%
FI	Comp_FI	9486	71%			*29244*	
	FORTUM POWER & HEAT	3668	28%	SI	Comp_SI	2538	100%
	E.ON ENERGIE AG	142	1%	SK	SLOVENSKE ELEKTRARNE AS (SE)	6281	64%
		13296			ELECTRICITE DE FRANCE	3102	31%
FR	ELECTRICITE DE FRANCE	85502	85%		Comp_SK	465	5%
	Comp_FR	10302	10%			*9848*	
	ELECTRABEL SA	4457	4%	UK	Comp_UK	26635	47%
		100310			BRITISH ENERGY PLC	12061	21%
HN	ELECTRABEL SA	1817	61%		E.ON ENERGIE AG	7115	13%
	RWE POWER	544	18%		RWE POWER	6855	12%
	ELECTRICITE DE FRANCE	348	12%		ELECTRICITE DE FRANCE	4018	7%
	ENERGIE BADEN-WURTTEMBERG ENBW	185	6%			*56684*	
	E.ON ENERGIE AG	81	3%		Grand Total	*582836*	
		2975					

2.2 Model notation

Variables are designated as lower case Latin letters (primal variables) or lower case Greek letters (LaGrange or dual variables), while coefficients are given in upper case. Dual variables are not defined in this subsection, but are instead introduced within parentheses to the right of their constraints in the models of the next Section. Indices and their sets are represented by lower and upper case Latin letters, respectively.

This paper uses the model COMPETES version 2.0, which only deals with inter-country path-based transmission system, implicitly assuming that there is no congestion within the national distributions networks.

2.2.1 Indices and Sets

$c,c'\in C$	Set of countries.
$f,f'\in F$	Set of generation firms.
$h\in H(f,c)$	Set of generating units owned by f in country c.
$m\in M$	Set of constrained interfaces with net transfer capabilities.
$p\in P$	Set of periods {(w, super peak), (w, peak), (w, shoulder), (w, off peak), (s, super peak), (s, peak), (s, shoulder), (s, off peak), (m, super peak), (m, peak), (m, shoulder), (m, off peak)}

2.2.2 Primal Variables

If a variable x has an asterisk (x*), this indicates that the variable is exogenous to the generation firms and TSO, but endogenous to the market. An example can be a price variable p; a price taking firm naïvely views it as fixed, even though the full market model equilibrates price to order to equate supply with demand.

Generator's physical variables

g_{fchp}	MW generation by unit h owned by firm f in country c in period p.
s_{fcp}, s_{fcp}^*	MW sales by firm f in country c in period p.
s_{-fcp}, s_{-fcp}^*	MW sales by firms other than f in country c in period p.
$t_{fcc'p}$	MW power sales by f in country c' assigned to generation in country c in period p.

Hence, a firm can make inter-temporal decisions and has the choice among three different variables: How much and when where to generate and with which technology? How much and when where to sell? How much and when to transport from one country to another?

Arbitrager's variables

ap_{cp}	Net MW purchased by arbitragers in country c and transferred to other countries in period p.
as_{cp}	Net MW sold by arbitragers in country c and transferred from other countries in period p.
$t^{a}_{c'cp}$	MW power sales by arbitrager in country c' assigned to arbitrager purchases in country c in period p.

TSO's variables

z_{mp}	MW of flow through constrained interface m in period p.

Price variables

p^*_{cp}	€/MWh in country c during period p.
wt^*_{mp}	€/MWh for transfer capability for interface m during period p.

2.2.3 Coefficients and Functions

Producer's coefficients/functions

$C_{fchp}(g_{fchp})$	Total cost, in € per period p, of production by firm f located in country c with technology h during period p.
Ξ_{fcp}	An index defining whether generator f behaves competitively (Ξ_{fcp}=0) or strategically (Ξ_{fcp}=1) in country c during period p.
G_{fch}	MW production capacity of generator firm f in country c with technology h.
MC_{fchp}	€/MWh marginal cost of generation for unit h owned by f at c, if an affine $C_{fchp}(g_{fchp})$ is assumed.

TSO's coefficients

PTC_{mp}	Net MW transfer capability for interface constraint m during period p.

Arbitrager's coefficients

$PTCU_{cc'mp}$	MW of transfer capability in interface m consumed by a 1 MW transfer from country c to country c' based on the administratively defined path from c to c'.

Market coefficients/functions

$EFEE_{cc'p}$	Fixed €/MWh export fee for sales from country c to country c'. This can also be used to model grid access charges if all exports from c (including "exports" to c itself) are charged the same fee.
$P_{cp}(\Sigma_f s_{fcp})$	€/MWh inverse demand function at c during period p. $P_{cp}(.)$ is defined as $P_{cp}(\Sigma_{f\in F} s_{fcp}) = A_{cp} + B_{cp}\ (\Sigma_{f\in F} s_{fcp})$, where A_{cp} is the price intercept of the demand function and B_{cp} is the slope. If this function passes through point $\{P^0_{cp}, S^0_{cp}\}$ and has an elasticity of $\varepsilon_{cp} < 0$ at that point, then $A_{cp} = (1–1/\varepsilon_{cp})P^0_{cp}$ and $B_{cp} = P^0_{cp}/(S^0_{cp}\varepsilon_{cp})$.

2.3 Profit maximisation problems and market clearing conditions

2.3.1 Generator's Model

Each generator f maximises profit by choosing generation g_{fchp}, sales s_{fcp}, trade $t_{fcc'p}$ and injection into pumped storage i_{fchp}:

$$\max_{\substack{q_{fchp}, s_{fcp} \\ t_{fcc'p}, i_{fchp}}} \sum_{c\in C}\left[\left(\left(1-\Xi_{fcp}\right)p^*_{cp} + \Xi_{fcp}P_{cp}\left(\sum_{f\in F} s_{fcp}\right)\right)s_{fcp} - \sum_{h\in H(f,c)} C_{fchp}\left(g_{fchp}\right)\right] - \sum_{c'\in C}\left(EFEE_{cc'p} + \sum_{m\in M} wt^*_{mp}PTCU_{cc'mp}\right)t_{fcc'p} \tag{1}$$

Subject to

$$s_{fcp} - \sum_{c'\in C} t_{fc'cp} = 0 \qquad \left(\theta^S_{fcp}\right) \tag{2}$$

$$-\sum_{h\in H(f,c)} g_{fchp} + \sum_{c'\in C} t_{fcc'p} = 0 \quad \left(\theta^{G}_{fcp}\right) \tag{3}$$

$$g_{fchp} \le G_{fch} \quad \left(\mu_{fchp}\right) \tag{4}$$

$$q_{fchp}, s_{fcp}, t_{fcc'p} \ge 0 \tag{5}$$

The generator can exercise market power on the sales to the consumer including usage for pumped storage. The market-power mark-up can vary from Ξ_{fcp}=0, i.e. Bertrand competition (perfect competition) and Ξ_{fcp}=1 is equal to Cournot competition (oligopoly strategic competition). The cost of transport is the sum of TSO services and a fixed export fee. There are losses only once the electricity is being distributed for consumption including consumption via pumped storage. The generation capacity during peak demand can be increased for pumped storage hydro units according to the amount stored during the base demand. The amount of addition pumped storage is also delimited.

2.3.2 TSO Model

The TSO efficiently allocates scarce transmission capacity to the most highly valued transmission services. By “efficiently”, we mean that the value of services (as revealed by the market price of transmission, equalling the firms’ marginal willingness to pay) net of transmission operating costs is maximised. Inter-country flows are subject to simple upper bounds, representing the assumed available transmission capacity.

$$\max_{z_{mp}} \sum_{p\in P} U_p \sum_{m\in M} wt^{*}_{mp} z_{mp} \tag{6}$$

subject to

$$z_{mp} \le PTC_{mp} \quad \left(\psi_{mp}\right) \tag{7}$$

$$z_{mp} \ge 0 \tag{8}$$

Note also that it is not necessary to explicitly enforce mass balances at the nodes of the transmission network for the z_{mp}, as these will automatically be satisfied because of (3) and the market clearing constraints below.

2.3.3 Arbitrager

The arbitrager maximises profit based on price differences between nodes and transmission payments, subject to constraints that define between-country flow based on the amounts arbitraged:

$$\min_{t^{a}_{cc'p}} \sum_{p\in P} U_p \sum_{c\in C} \sum_{c'\in C} \left(EFEE_{cc'p} + \sum_{m\in M} wt^{*}_{mp} PTCU_{cc'mp} \right) t^{a}_{cc'p} \tag{9}$$

subject to

$$as_{cp} - \sum_{c'\in C} t^{a}_{cc'p} = 0 \quad \left(\theta^{aS}_{cp}\right) \tag{10}$$

$$-ap_{cp} + \sum_{c'\in C} t^{a}_{c'cp} = 0 \quad \left(\theta^{aP}_{cp}\right) \tag{11}$$

$$-as_{cp} + ap_{cp} = 0 \quad \left(\rho_{cp}\right) \tag{12}$$

$$as_{cp}, ap_{cp}, t^{a}_{cc'p} \ge 0 \tag{13}$$

2.3.4 Market Clearing and Consistency Conditions

$$p^*_{cp} = A_{cp} + B_{cp}\left(\sum_{f\in F} s_{fcp}\right) \tag{14}$$

$$z_{mp} = \sum_{c\in C}\sum_{c'\in C} PTCU_{cc'm}\left(t^a_{cc'p} + \sum_{f\in F} t_{fcc'p}\right) \quad \left(wt^*_{mp}\right) \tag{15}$$

The first market clearing condition (14) is simply the definition of the demand function. Condition (15) says that transmission services match the flows resulting from producers' actions.

2.4 Market equilibrium as a mixed linear complementarity problem

The complementarity model for calculating the market equilibrium is constructed by combining the following set of conditions:

- the first-order (Karush-Kuhn-Tucker) conditions for the profit-maximisation model for each generator *f*;
- the first-order conditions for the TSO model;
- the first-order conditions for the arbitrager model;
- the market clearing conditions.

The result, if properly formulated, will be a "square" system in which the number of conditions (either equalities or complementarity conditions) will equal the number of variables. Note that the set of variables will also include dual variables for the constraints (2)–(4), (7), (10)–(12), in addition to the decision variables defined above. In general, it will be possible to use some or all of the equality constraints to eliminate some variables and thus simplify the model.

The complementarity model can then be solved numerically (using the PATH solver in AIMMS) to obtain a solution for a given set of parameters. The model can also be analysed for properties such as existence and uniqueness of solutions, and for relationships among the variables. The mixed complementarity problem below is a linear one if the indicated derivatives are affine. The problem is square (there are as many equations as variables).

Before coming to the KKT conditions it is helpful to formulate the generator, TSO, and arbitrager problem as a Lagrangian, namely as follows:

$$\begin{aligned} L^{\text{Generator}}_f = \sum_{c\in C}\Bigg[& \left(\left(1-\Xi_{fcp}\right)p^*_{cp} + \Xi_{fcp}P_{cp}\left(\sum_{f\in F} s_{fcp}\right)\right)s_{fcp} - \sum_{h\in H(f,c)} C_{fchp}\left(g_{fchp}\right) \\ & - \sum_{c'\in C}\left(EFEE_{cc'p} + \sum_{m\in M} wt^*_{mp} PTCU_{cc'mp}\right)t_{fcc'p} \\ & - \theta^S_{fcp}\left(s_{fcp} - \sum_{c'\in C} t_{fc'cp}\right) \\ & - \theta^G_{fcp}\left(-\sum_{h\in H(f,c)} g_{fchp} + \sum_{c'\in C} t_{fcc'p}\right) \\ & - \mu_{fchp}\left(g_{fchp} - G_{fch}\right)\Bigg] \end{aligned} \tag{16}$$

$$L^{\text{TSO}} = \sum_{p\in P} U_p \sum_{m\in M} wt^*_{mp} z_{mp} - \psi_{mp}\left(z_{mp} - PTC_{mp}\right) \tag{17}$$

$$\begin{aligned} L^{\text{Arbitrager}} = \sum_{p\in P} U_p \sum_{c\in C} \Bigg\{ & \sum_{c'\in C}\left(-EFEE_{cc'p} - \sum_{m\in M} wt^*_{mp} PTCU_{cc'mp}\right) t^a_{cc'p} \\ & - \rho_{cp}\left(-as_{cp} + ap_{cp}\right) - \theta^{aS}_{cp}\left(as_{cp} - \sum_{c'\in C} t^a_{cc'p}\right) - \theta^{aP}_{cp}\left(-ap_{cp} + \sum_{c'\in C} t^a_{c'cp}\right) \Bigg\} \end{aligned} \tag{18}$$

The KKT conditions can be derived from (14)–(18) by taking the derivatives with respect to the primal variables and the Lagrange multipliers as denoted by the lower case Greek letters.

The KKT conditions:

Generators:

$$\forall g_{fchp}: \quad 0 \le g_{fchp} \perp \left[\theta^G_{fcp} - MC_{fchp} - \mu_{fchp}\right] \le 0 \tag{19}$$

$$\forall t_{fcc'p}: \quad 0 \le t_{fcc'p} \perp \left[\theta^S_{fc'p} - \theta^G_{fcp} - EFEE_{cc'p} - \sum_{m\in M} wt^*_{mp} PTCU_{cc'mp}\right] \le 0 \tag{20}$$

$$\forall s_{fcp}: \quad 0 \le s_{fcp} \perp \left[p^*_{cp} + \Xi_{fcp} P_{cp}{}'(.)\, s_{fcp} - \theta^S_{fcp}\right] \le 0 \tag{21}$$

$$\forall \theta^S_{fcp} \quad \theta^S_{fcp} \perp \left[s_{fcp} - \sum_{c'\in C} t_{fc'cp}\right] = 0 \tag{22}$$

$$\forall \theta^G_{fcp}: \quad \theta^G_{fcp} \perp \left[\sum_{c'\in C} t_{fcc'p} - \sum_{h\in H(f,c)} g_{fchp}\right] = 0 \tag{23}$$

$$\forall \mu_{fchp}: \quad 0 \le \mu_{fchp} \perp \left[g_{fchp} - G_{fch}\right] \le 0 \tag{24}$$

TSO:

$$\forall wt^*_{mp}: \quad 0 \le wt^*_{mp} \perp \left[z_{mp} - PTC_{mp}\right] \le 0 \tag{25}$$

Arbitrager:

$$\forall as_{cp}: \quad 0 \le as_{cp} \perp \left[\rho_{cp} - \theta^{aS}_{cp}\right] \le 0 \tag{26}$$

$$\forall ap_{cp}: \quad 0 \le ap_{cp} \perp \left[\theta^{aP}_{cp} - \rho_{cp}\right] \le 0 \tag{27}$$

$$\forall t^a_{cc'p}: \quad 0 \le t^a_{cc'p} \perp \left[\theta^{aS}_{cp} - \theta^{aP}_{cp} - EFEE_{cc'p} - \sum_{m\in M} wt^*_{mp} PTCU_{cc'mk}\right] \le 0 \tag{28}$$

$$\forall \theta^{aS}_{cp}: \quad \theta^{aS}_{cp} \perp \left[as_{cp} - \sum_{c'\in C} t^a_{cc'p}\right] = 0 \tag{29}$$

$$\forall \theta^{aP}_{cp}: \quad \theta^{aP}_{cp} \perp \left[\sum_{c'\in C} t^a_{c'cp} - ap_{cp}\right] = 0 \tag{30}$$

$$\forall \rho_{cp}: \quad \rho_{cp} \perp \left[ap_{cp} - as_{cp}\right] = 0 \tag{31}$$

Market clearing:

$$\forall p^*_{cp}: \quad p^*_{cp} = A_{cp} + B_{cp}\left(\sum_{f\in F} s_{fcp}\right) \tag{32}$$

$$\forall z_{mp}: \quad z_{mp} = \sum_{c\in C}\sum_{c'\in C} PTCU_{cc'm}\left(t^a_{cc'p} + \sum_{f\in F} t_{fcc'p}\right) \tag{33}$$

3. RESULTS

To study the type of outcomes that can be obtained with the COMPETES model version 2.0 the model has been further calibrated as follows. The generation capacities of the largest firms in the EU20 are derived from year reports. The remaining capacities are assigned to the price taking competitive fringes. Table 2.1 gives an overview of all firms considered in the model and the total amount of generation capacity each firm holds.

To solve the model, we have assumed that the competitive fringes can only sell in the market where they are located. Large firms can sell in the market where they are located and all countries to which they are directly connected. For instance, EdF can sell in almost all countries, except Norway, Finland and Portugal. Table 3.1 shows the result.

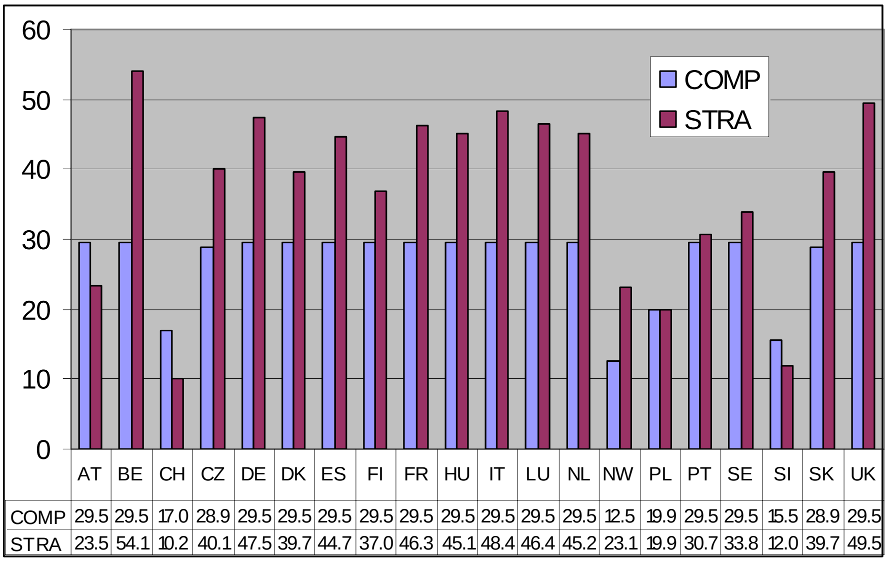
Table 3.1 *The countries where the large firms can sell electricity.*

	AT	BE	CH	CZ	DE	DK	ES	FI	FR	HU	IT	LU	NL	NW	PL	PT	SE	SI	SK	UK
BRITISH ENERGY PLC									√											√
CEZ AS	√			√	√										√				√	
CIA PORTUGESA PRODUCAO ELEC							√		√							√				
E.ON ENERGIE AG	√	√	√	√	√	√		√	√	√	√	√	√	√	√		√		√	√
EDISON SPA	√		√						√		√							√		
ELECTRABEL SA	√	√	√	√	√	√	√		√	√	√	√	√		√		√	√	√	√
ELECTRICITE DE FRANCE	√	√	√	√	√	√	√		√	√	√	√	√		√		√	√	√	√
ELSAM A/S					√	√		√						√			√			
ENDESA GENERACION	√		√				√		√		√					√		√		
ENEL SPA	√		√				√		√		√					√		√		
ENERGI E2 A/S					√	√								√			√			
ENERGIE BADEN-WURTTEMBERG ENBW	√	√	√	√	√	√	√		√	√	√	√	√		√	√	√		√	√
ESSENT ENERGIE PRODUCTIE BV	√	√	√	√	√	√			√	√	√	√	√		√		√	√		
FORTUM POWER & HEAT					√	√		√						√	√		√			
IBERDROLA SA							√		√							√				
NUON NV	√	√	√	√	√	√			√			√	√		√		√			
RWE POWER	√		√	√	√	√	√		√	√	√	√	√		√	√	√	√	√	√
SLOVENSKE ELEKTRARNE AS (SE)				√						√					√				√	
STATKRAFT SF						√		√						√			√			
UNION ELECTRICA FENOSA SA		√					√		√			√	√			√				
VATTENFALL AB	√		√	√	√	√		√	√			√	√	√	√		√		√	
VERBUND-AUSTRIAN HYDRO POWER	√		√	√	√					√	√							√		

We consider consecutively two cases based on the ability of firms to exercise market power, namely perfect competition (PC) and strategic competition (SC) scenarios. In PC demand is fixed in order to find the corresponding equilibrium prices, while a price demand elasticity of –0.4 is assumed in SC. The results are presented in terms of prices in Figure 3.1.

Inspection of Figure 3.1 yields that PC leads to nearly the same prices in 16 countries, while the prices are substantially lower in CH, NW, PL, SI. The prices are much lower in these four countries, due to (1) a relatively high share of (non-exporting) competitive fringe: CH (100%), NW (65%), PL (86%), SI (100%) and (2) the presence of relatively cheap generation technologies: hydro, nuclear & coal: CH (hydro 75%, nuclear 20%), NW (hydro 99%), PL (coal 90%), SI (hydro 25%, nuclear 25%, coal 40%).

Figure 3.1 *Average prices under perfect and strategic equilibrium.*



	AT	BE	CH	CZ	DE	DK	ES	FI	FR	HU	IT	LU	NL	NW	PL	PT	SE	SI	SK	UK
COMP	29.5	29.5	17.0	28.9	29.5	29.5	29.5	29.5	29.5	29.5	29.5	29.5	29.5	12.5	19.9	29.5	29.5	15.5	28.9	29.5
STRA	23.5	54.1	10.2	40.1	47.5	39.7	44.7	37.0	46.3	45.1	48.4	46.4	45.2	23.1	19.9	30.7	33.8	12.0	39.7	49.5

In order to study the effect of exercising market power Table 3.2 shows the price difference between PC and SC sorted in ascending order by the price difference.

Table 3.2 *Average prices under perfect and strategic competition, sorted towards the differences between the two scenarios.*

	Perfect competition (PC)	Strategic competition (SC)	Price difference
CH	17.04	10.17	-6.87
AT	29.51	23.47	-6.03
SI	15.50	12.02	-3.48
PL	19.88	19.88	0.00
PT	29.55	30.66	1.11
SE	29.51	33.83	4.32
FI	29.51	36.98	7.47
DK	29.51	39.66	10.15
NW	12.53	23.14	10.61
SK	28.91	39.71	10.80
CZ	28.91	40.12	11.20
ES	29.55	44.68	15.13
HU	29.51	45.14	15.63
NL	29.51	45.19	15.68
FR	29.51	46.29	16.78
LU	29.51	46.39	16.88
DE	29.55	47.45	17.90
IT	29.55	48.42	18.87
UK	29.55	49.53	19.98
BE	29.55	54.15	24.60

Inspection of Table 3.2 shows that the prices differ in all countries under strategic competition. Moreover the highest prices are found in the central European market, where Belgium tops the list, followed by the UK. The differences in prices are due to (1) the ability to exercise market power (determined by the market shares of large firms in the market), and (2) demand scarcity and accessibility of the market. The second argument plays a role for instance in the UK, where the market concentration is relatively low, but due to low accessibility still experiences a high price increase. The French market on the other hand is quite accessible from various sides and this reduces the impact of the near monopoly player EdF.

The prices in three adjoint countries (Austria, Slovenia and Switzerland) are decreasing. The market prices were already low in Switzerland and Slovenia, making them even more unattractive for exports under strategic competition.

It is remarkable to see that the price increases in the four geographically adjoint Nordic countries are quite similar. This is also the case for the Czech Republic and Slovakia.

4. CONCLUSIONS

This paper has presented the static COMPETES model. The COMPETES model is run for two scenarios to derive additional insights for covering the geographical EU20 area. The model simulations indicate the following. First, under perfect competition in the liberalised European electricity market, the price differences among countries largely tend to converge to each other. The prices in some countries are lower due to the presence of relatively cheap generation technologies and a limited ability to export to other countries. Second, the effect of market power of active cross ownership is studied. In the case where all large firms exercise market power, the model runs indicate that the biggest price responses are found in countries where the number of firms is low. However, due to the interlinkages among the markets, the price responses in the near monopoly markets are still relatively low.

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