A Multi-Regional Two-Stage Cournot Model for Analyzing Competition in the German Electricity Market

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Abstract

In this paper a model based analysis of competition in the German electricity market is presented. Applying a multi-regional two-stage model, which captures interregional transmission constraints and the impact of forward trading on spot market decisions, potential for exercising market power of the four dominant electricity producers has been found. Assuming *Cournot* behavior in the spot market, it has been shown to what extent network reinforcement between Germany and some of its neighboring countries and increased forward quantities lead to enhanced competition and decreasing market power potential within the German electricity market.

Key words: Competition analysis, Market power, Two-stage Cournot model, Forward markets, Interregional electricity exchange.

1 Introduction

As a consequence of the high market concentration due to mergers and acquisitions among generators, the German electricity market faces growing potential for market power. Over the last few years the four generating companies RWE Power AG, E.ON Energie AG, Vattenfall Europe AG and EnBW AG formed an oligopoly with RWE and E.ON having a dominant market position. Taking the acquisitions within Eastern Europe and Great Britain into consideration, there are no indicators that a change in the two firms' dominance could be expected.

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Considering concentration measures like the CR_n concentration ratio or the Hirschman-Herfindahl Index (HHI), Germany's electricity market can be regarded as highly concentrated. Given installed generation capacity, the CR_3 approximately amounts to 69%, whereas the CR_5 reaches about 80%. The HHI value yields approximately 1945. Even if traditional concentration measures can be inappropriate instruments to analyze competition (cf. e. g. Borenstein et al. (1999) and Borenstein and Shepard (2002)), at least they can indicate if market power problems probably might occur. Additionally, using ex post comparison of electricity prices and predicted competitive marginal costs, the actual degree of market power can be quantified, but it has limited ability to derive conclusions due to regarded changes in market structure and strategic behavior. Cf. for an analysis of the Californian electricity market Borenstein et al. (2000) and Muesgens (2004) for a similar approach regarding Germany.

Given the specific conditions in electricity markets, e.g. low elasticity of demand, non-storability, capacity constraints in generation and transmission and several alternatives for market behavior, model based analyses which take non-competitive market transaction into account explicitly, can therefore be more suitable to diagnose market power (cf. e. g. Smeers (1997) and Borenstein and Bushnell (1999)). Furthermore, structural and institutional aspects that influence companies' potential to exercise market power like increased interconnector capacities and the possibility to trade on forward markets should be addressed within the used model framework.

However, several electricity market models of strategic interaction, which take interregional transmission constraints into account have already been developed, cf. e. g. Amundsen et al. (1998), Day et al. (2002) and Metzler et al. (2003). Moreover, Chuang et al. (2001) and Murphy and Smeers (2002) introduce investment in dynamic models of strategic behavior. For a recent overview, cf. Neuhoff et al. (2005) and the references therein. Most of the existing game theoretic models for analyzing market power, applying either a *Cournot* or a supply-functions approach. As *Cournot* models are usually easier to solve, even if technical constraints regarding generation and transmission are considered, this type of game has often been modeled. Furthermore, as the *Cournot-Nash* solution is representing an upper bound for possible supply-function equilibria, the calculated market outcome can be interpreted as a maximum impact of non-cooperative strategic behavior.

In addition to the consideration of network constraints within the various models, the impact of forward trading on generators' optimal decisions have been analyzed e. g. in Green (1999), Newbery (1998), Powell (1993) and Fleten and Lie (2000). The theoretical framework for this type of models have mainly been developed by Allaz (1987), Allaz (1992) and Allaz and Vila (1993), who described a sequential two-stage game, where oligopolistic producers decide bout optimal forward quantity before physical production occurs. Assuming a non-competitive spot market, forward trading is thus predicted to enhance competition, due to a decrease in producers' potential to exercise market power.

Regarding Germany's electricity market structure, potential for exercising market power of the four dominant producers are supposed. Taking interregional electricity exchange and forward trading into account, a multi-regional two-stage *Cournot* model has therefore been developed to analyze competition in the German electricity market. Following the Allaz (1987) and Allaz and Vila (1993) approach, the impact of increasing forward quantities on spot market results has been calculated. Additionally to the analyzed forward market impact, the model has also been applied to changes in interregional transmission capacities.

The paper is organized as follows. In section 2 a short overview regarding two aspects of the German market structure is given. The mathematical formulation of the developed model is described in Section 3. In section 4 exemplary results regarding changes in cross-border capacities and forward contract quantities are presented. Finally, conclusions are drawn in section 5.

2 The German electricity market

Germany is highly integrated within the European electricity market, having various interconnections with its neighboring countries. Until the market was liberalized in 1998, it was characterized by vertically integrated utilities, supplying residential and industrial consumers. With the opening of Germany's electricity market, several changes regarding structural and operational aspects can be observed.

2.1 Interregional electricity exchange

Regarding the central location of Germany, interregional electricity exchange has been continuously increased over the last years. Sharing borders with France, Luxembourg, Belgium, the Netherlands, Denmark, Sweden, Poland, Czech Republic, Austria and Switzerland, Germany's gross electricity exchange has grown from approximately 72 TWh in 1995 to approximately 100 TWh in 2003 and 96 TWh in 2004, respectively (cf. UCTE (2005)).

As interregional transmission in Europe was mainly coordinated to balance variations in demand and supply on the inter-country level, it has recently become more important regarding trading aspects. Due to legally unrestricted international electricity trade possibilities, cross-border exchange is projected to serve common economic purposes, particularly to reduce interregional price differences. However, beside the legal framework, technical aspects concerning transmission and production have to be taken into account, when market structure and regionally varying electricity prices in Europe are to be analyzed.

2.2 Spot and derivatives market

The European Energy Exchange AG (EEX) in Leipzig is operating a day-ahead spot market for physical contracts since 2000. Within a double-sided call auction, market participants submit bits for the quantity they want to purchase and to sell the following day. Single hour contracts of 0.1 MW delivery capacity and block contracts for multiple hours of 1 MW delivery capacity can be traded each day until noon. After collecting all bits in a closed order book, EEX aggregates individual supply and demand curves to determine a uniform market clearing price. Physical delivery can be executed in each of the five transmission system operator (TSO) zones. In absence of transmission congestion, the spot market price is the same for all of Germany. Given the possible trading options at the established spot market, the market clearing price can therefore be regarded as a reference for other market segments.

Considering the amount of electricity traded at the EEX, it can be observed that spot market quantity has continuously increased since 2000. While quantity amounts to approximately 14 TWh in 2001, the traded quantity is about 25 TWh in 2002 and 48 TWh in 2003. In the year 2004 a total of approximately 59 TWh was contracted through the physical spot market in Germany. Regarding total electricity consumption, the traded spot market volume was about 11% in 2004.

Beside the day-ahead market, the EEX also established a derivatives market in 2001. As spot market contracts call for physical delivery of electricity the next day, derivative contracts usually are fulfilled financially. After financial settlement, the contracted quantity can be obtained at the spot market. More general, derivatives enclose both futures contracts with financial settlement only and forward contracts which call for delivery or purchase of the committed electricity quantity. At the EEX base load and peak load futures and forwards can be traded, respectively. Among other things, the contracts are standardized concerning the delivery period, i. e. monthly, quarterly and yearly respectively, the load profile, the place of delivery, the contract volume, which is 1 MW for each hour committed and the tradeable period for this contract.

Considering given market risks like uncertain demand and price, derivatives can be used for risk hedging and speculative reasons. As e. g. Allaz (1987) has already shown, forward contracts can also be used strategically by oligopolistic producers in non-competitive markets to enhance spot market position. In 2003 a quantity of approximately 342 TWh has been traded at the EEX derivatives market, whereas approximately 338 TWh were committed in 2004, showing a ratio of about 88% base load contracts.

3 The model

For analyzing competition in the German electricity market, a multi-regional, two-stage *Cournot* model has been developed. The German electricity market is considered to be a 4 player oligopoly facing a competitive fringe and being physically interconnected to its European neighboring countries. Figure 1 depicts regions and transmission lines covered by the model. Electricity markets within the German neighboring regions are assumed to be fully competitive. Transmission capacities are supplied by a Single Transmission System Operator (TSO) and are based on average Net Transfer Capacities (NTC) for the years 2002 to 2004 provided by the European Electricity System Operators (ETSO) (cf. Table 1). Power plant portfolios for RWE Power AG, E.ON Energie AG, Vattenfall Europe AG, EnBW AG and the competitive fringe are modeled on a unit basis, whereas portfolios for the neighboring countries are represented on a higher aggregation level. Electricity demand is separated in peak and off-peak load distinguishing summer, winter and intermediate periods. The electricity suppliers solve a two-stage optimization problem. In the first stage, generators sell forward contracts in the German market that call for delivery in the second stage. In the second stage, producers maximize their profits in the spot market, taking the forward market decisions, generation and transmission constraints into account. For the analysis presented in this paper, a deterministic version of the *Cournot* model is applied, solving an one-shot game with exogenous variations of forward contract cover and interregional transmission investments.

3.1 Demand side

Time varying electricity demand in the several countries is represented by approximated load duration curves. To capture different load situations in a year, the load duration curves are decomposed into two load (peak, off-peak) and three time segments (summer, winter, intermediate). For Germany, load varies from 40275 MW in the summer off-peak load segment to 68331 MW in the winter peak load segment. Peak load contains demand values for weekdays from 08:00 a. m. to 08:00 p. m. whereas the off-peak load segment contains the hours on weekends and the hours from 08:00 p. m. to 08:00 a. m. on weekdays. Hence, peak load covers 960 hours and off-peak load 1960 hours each time segment, respectively. Demand values are based on data for the year 2000 provided by the Union for Co-ordination of Transmission for Electricity (UCTE). Figure 2 exemplary presents the decomposition of the load duration curve for Germany.

Demand curves for each region, load and time segment in the spot market are modeled applying an inverse constant elasticity demand function. Equilibrium electricity price $P_{t,s,r}(S_{t,s,r}) : \mathbb{R}^+ \mapsto \mathbb{R}^+$ is a function of the form:

$$P_{t,s,r}(S_{t,s,r}) = P^{\text{ref}}_{t,s,r} \left(\frac{P_{t,s,r}(S_{t,s,r})}{S^{\text{ref}}_{t,s,r}} \right)^{\frac{1}{\epsilon}} \tag{1}$$

with $S_{t,s,r}$ being total supply in each time segment t, each load segment s and each country r. The demand curves are calibrated by using reference prices for each demand segment and each country. Reference prices for e. g. Germany were calculated from European Energy Exchange AG (EEX) data for the year 2002. According to the demand segment specification, averaged system marginal prices lie at 13.31 €/MWh for the summer off-peak and 34.98 €/MWh for the intermediate peak load segment, respectively. Price elasticity of demand ϵ is assumed to be -0.25 within the different load segments. Figure 3 depicts exemplary inverse demand curves for different load situations in Germany.

3.2 Supply side

On the supply side, real technical and economical data for specification of the different types of fossil fired power plants and non-fossil power plants are taken. The overall production capacities are assumed to be given. Specific operation cost for each type of unit are calculated on the basis of fuel prices, additional operation and maintenance cost and electrical efficiencies. Power plant efficiencies are based on fuel type and the date of unit commissioning. However, the technologically oriented representation of production capacities facilitates a relatively realistic approximation of the generation structure within the several countries.

The differentiated electricity generation portfolios of the four German supplying companies on the one hand and the more aggregated generation portfolios for the nine neighboring countries on the other hand, included in the model, represent almost 95 % of the installed generation capacity in each country. Ordering the different production units regarding their variable production costs, a country-specific merit order curve can be constructed. Figure 4 depicts the merit order curve for Germany based on the installed capacities for 2005.

For analyzing the potential to exercise market power in the German electricity market, the given market structure has to be taken into account. Therefore, the overall installed generation capacity has to be allocated among strategic players. According to the analysis of the given horizontal capital ownerships among utilities, the strategically controlled production capacities can be derived. Due to focusing on the German market and assuming that electricity markets in the neighboring countries are fully competitive, only the major German generation companies are represented in detail. Furthermore, capital ownership across borders has been neglected, thus German suppliers utilize domestic capacities only. Table 2 gives an overview to the individual generation capacities owned by the four strategic players in Germany and the aggregated capacities of the neighboring countries.

To derive individual merit oder curves or marginal cost curves, for each strategic player and fringe supply, respectively, installed generation capacity has been adjusted to given technical and seasonal availability. Average planned unit outage for conventional power plants and time varying water inflow for run of river and lake power plants, respectively, has been taken into account to distinguish time depending availability. Furthermore, pumped storage capacities are assumed to be available in the peak load segment only. This assumption has been made due to the static structure of the model. As power plants are not dispatched dynamically, pumped storage capacities are assumed to pump in off-peak periods. Moreover, pump losses $\phi_{t,s^-,r}$, with $s^- \in \{\text{off} - \text{peak}\}$ are derived from historical data. Hence, merit order curves for peak and off-peak load differ considerably for particular players and countries, respectively. As a result, each company is represented by six different marginal cost curves. Similarly, six varying marginal cost curves for each of the German neighboring countries has been constructed. Figures 5 and 6 present the marginal cost curves for E.ON Energie AG and Vattenfall Europe AG, respectively, which are based on average available generation capacities.

As the model is formulated in Mixed Complementarity Problem (MCP) format, here the stepwise marginal cost functions are approximated by strictly increasing polynomials. Marginal cost functions $C_{i,t,s}(x_{i,t,s}) : \mathbb{R} \mapsto \mathbb{R}^+$ are of the form:

$$C_{i,t,s}(x_{i,t,s}) = c_1 x_{i,t,s}^4 + c_2 x_{i,t,s}^3 + c_3 x_{i,t,s}^2 + c_4 x_{i,t,s} + c_5 \tag{2}$$

where c_1 to $c_4 \in]-\infty, \infty[$ and $c_5 \in [0, \infty[$ are estimated by a least squares method algorithm. Generation by firm $i \in \mathbb{I}$ in time segment t and load segment s, $x_{i,t,s} \in [0, x_{i,t,s}^{\max}]$ is constrained by firm's available capacity $x_{i,t,s}^{\max}$. Following the assumption, that cross-border ownership is neglected, the firms' electricity production takes place in the country they are located.

3.3 Two-stage market structure

The model described has two stages. In the first stage, the forward market, German electricity suppliers decide about the amount of forward contracts they want to sell. These forward contracts call for delivery in the second stage. The second stage is the physical spot market, where generation takes place. However, a forward market is assumed to be operated in Germany only. This restriction is due to focusing on strategic interactions within the German electricity market and the assumption that market structures in neighboring countries are fully competitive.

German producers trade in the forward market before optimizing their generation program in the spot market. Spot market behavior of the four strategic players is assumed to be of *Cournot* type profit maximization. Fringe suppliers and generators in neighboring countries behave as price takers. Deciding about first stage contracting and second stage supply, taking fringe supply, interregional electricity trade as well as production and transmission constraints into account, producers face a constrained two-stage optimization problem, which can be solved backwards.

Solving the second stage optimization problem first, each oligopolistic supplier $i \in \mathbb{I}$ maximizes its profit $\Pi_{i,t,s,r}(s_{i,t,s,r}, f_{i,t,s}) : \mathbb{R}^n \mapsto \mathbb{R}$ by determining the optimal electricity output $s_{i,t,s,r}$. With suppressing indices for demand segments t (time), s (load) and r (country), profit for each player can be written as:

$$\max_{s_i} \Pi_i(s_i, f_i) = P(S)s_i + f_i(P^f - P(S)) - TC_i(s_i) \quad \forall\, i, t, s, r \qquad (3)$$

with $S = \sum_{i\in\mathbb{I}} s_i$ being aggregated supply by all generators. $TC_i(s_i) : \mathbb{R} \mapsto \mathbb{R}^+$ represents total generation cost for supply of player i in the spot market, whereas P^f is the forward price and $f_i(P^f - P(S))$ being the profit from selling forward contracts. When producers decide about their optimal output quantity in the second stage, P^f is a constant, hence the term f_iP^f can be ignored in the profit maximization.

On the second stage, firms' generation is constrained by its maximum available production capacity. The production constraint $g_i(x_i) : \mathbb{R} \mapsto \mathbb{R}$ has to be satisfied for each firm i in each demand segment

$$g_i(x_i) : x_i - x_i^{\max} \leq 0 \quad \forall\, i, t, s \qquad (4)$$

As interregional electricity trade is allowed, producers decide not only about the quantity they want to sell in their country r, but also about the amount they want to sell in foreign countries rr, i. e. export. Exports are denoted by $s^{\mathrm{rr}}_{i,t,s,r}$, with the superscript indicating the country of destination. The TSO supply transmission services at marginal cost of congestion. Therefore, the producers in country r have to take interregional transmission capacity constraints and possible congestion charge into account. The transmission constraint $e_{r,rr}(S_r^{\mathrm{rr}}, S_{rr}^{\mathrm{r}}) : \mathbb{R}^n \mapsto \mathbb{R}$ for each line $r \to rr$ of distinct countries, that has to be satisfied, is:

$$e_{r,rr}(S_r^{\mathrm{rr}}, S_{rr}^{\mathrm{r}}) : \left(\sum_{i^-} s_{i,r}^{\mathrm{rr}} + \sum_{i^+} s_{i,rr}^{\mathrm{r}} \right) - t_{r \to rr}^{\max} \leq 0 \quad \forall \, t, s \tag{5}$$

with i^- denoting suppliers located in country r and i^+ denoting suppliers located in country rr. Again, following the assumption that electricity markets in the neighboring countries are fully competitive, imports to Germany are priced at marginal production costs. Each interregional transmission line has a maximum capacity of $t_{r \to rr}^{\max}$, whereas inner-country transmission is assumed to be unconstrained. In addition, transport losses between district countries has being neglected. Total electricity supply per demand segment in a country r can therefore be written as:

$$S_r = \sum_{i^- \in \mathbb{I}} s_{i,r}^{\mathrm{r}} + \sum_{i^+ \in \mathbb{I}} s_{i,rr}^{\mathrm{r}} \quad \forall \, t, s, r \tag{6}$$

For Germany ($r^D E$), domestic electricity supply can also be described in more detail by distinguishing oligopoly supply on the one side and competitive fringe supply on the other side:

$$S_{r^D E} = \sum_i s_{i,r^D E}^{\mathrm{r^D E}} + s_{\mathrm{fringe,r^D E}}^{\mathrm{r^D E}} \quad \forall \, t, s \tag{7}$$

Considering production/supply and demand balance in each demand segment and each country, production has to be adjusted regarding network and pump losses. Contrary to the neglected additional transmission losses due to interregional trade, network losses within a country $\theta_{t,s,r}$ have been captured in the model. With pump losses $\phi_{t,s^-,r}$, production has to be:

$$x_i \geq \sum_r s_i, r(1 + \theta_r + \phi_r) \quad \forall \, i, t, s \tag{8}$$

which equals overall electricity demand in each segment and each country. Estimated network losses are derived from historical data, similarly to the estimation of pump losses for the off-peak periods.

However, when producers maximize their profit on the spot market by optimizing their output, they have to take the constraints $g_i(x_i)$ and $e_{r,rr}(S_r^{\mathrm{rr}}, S_{rr}^{\mathrm{r}})$ into account. The resulting nonlinear program with inequality constraints can be formulated in mixed complementarity format. For maximizing the second stage profit function (cf. Eq. (3)) for every player simultaneously, the first order *Karush-Kuhn-Tucker* conditions have been derived. In equilibrium, none of the players and generators, respectively, is willing to change its production program. Due to the form of the approximated marginal cost and demand functions, the resulting *Cournot-Nash* equilibrium represents an unique solution to the given problem.

Introducing a function $\mathcal{L}_{i,t,s,r}(s_{i,t,s,r}, \lambda_{i,t,s}, \tau_{r\to rr}) : \mathbb{R}^n \mapsto \mathbb{R}^n$ similar to a Lagrangian, the first order conditions of the nonlinear program that have to be satisfied are:

$$\begin{aligned}\frac{\partial \mathcal{L}_{i,t,s,r}(s_{i,t,s,r}, \lambda_{i,t,s}, \tau_{r\to rr})}{\partial s_{i,t,s,r}} &= \frac{\partial P_{t,s,r}(S_{t,s,r})}{\partial S_{t,s,r}} \frac{\partial S_{t,s,r}}{\partial s_{i,t,s,r}} s_{i,t,s,r} + P_{t,s,r}(S_{t,s,r}) \\ &- \frac{\partial P_{t,s,r}(S_{t,s,r})}{\partial S_{t,s,r}} \frac{\partial S_{t,s,r}}{\partial s_{i,t,s,r}} f_{i,t,s,r^-} \\ &- P_{t,s,r}(S_{t,s,r}) \frac{\partial f_{i,t,s,r^-}}{\partial s_{i,t,s,r}} - \frac{\partial TC(s_{i,t,s,r})}{\partial s_{i,t,s,r}} \\ &- \lambda_{i,t,s} - \sum_{r\to rr} \tau_{r\to rr} \leq 0 \quad \forall\, i,t,s,r \end{aligned} \tag{9}$$

complements

$$s_{i,t,s,r} \geq 0 \quad \forall\, i,t,s,r \tag{10}$$

and the inner product

$$\frac{\partial \mathcal{L}_{i,t,s,r}(s_{i,t,s,r}, \lambda_{i,t,s}, \tau_{r\to rr})}{\partial s_{i,t,s,r}} s_{i,t,s,r} = 0 \quad \forall\, i,t,s,r \tag{11}$$

Partial derivative, taking into account the given production constraint for a generator is:

$$\frac{\partial \mathcal{L}_{i,t,s,r}(s_{i,t,s,r}, \lambda_{i,t,s}, \tau_{r\to rr})}{\partial \lambda_{i,t,s}} = s_{i,t,s,r} - s^{\max}_{i,t,s,r} \leq 0 \quad \forall\, i,t,s \tag{12}$$

complements

$$\lambda_{i,t,s} \geq 0 \quad \forall\, i,t,s \tag{13}$$

and the inner product

$$\frac{\partial \mathcal{L}_{i,t,s,r}(s_{i,t,s,r}, \lambda_{i,t,s}, \tau_{r\to rr})}{\partial \lambda_{i,t,s}} \lambda_{i,t,s} = 0 \quad \forall\, i,t,s \tag{14}$$

It should be noted that, concerning definition in Eq. (4), the generation capacity constraint $g_i(x_i)$ is related to $x_{i,t,s}$. As $x_{i,t,s}$ and $s_{i,t,s,r}$ are linked by the production/supply balance (cf. Eqs. (8)), the supply variable $s_{i,t,s,r}$ is applied in Eq. (12) and (14), due to consistency in mathematical notation.

Partial derivatives, taking into account the given transmission constraint finally, results in:

$$\frac{\partial \mathcal{L}_{i,t,s,r}(s_{i,t,s,r}, \lambda_{i,t,s}, \tau_{r\to rr})}{\partial \tau_{r\to rr}} = \left(\sum_{i^-} s_{i,r}^{\mathrm{rr}} + \sum_{i^+} s_{i,rr}^{\mathrm{r}}\right) - t_{r\to rr}^{\max} \leq 0 \quad \forall\, r \to rr \tag{15}$$

complements

$$\tau_{r\to rr} \geq 0 \quad \forall\, r \to rr \tag{16}$$

and the inner product

$$\frac{\partial \mathcal{L}_{i,t,s,r}(s_{i,t,s,r}, \lambda_{i,t,s}, \tau_{r\to rr})}{\partial \tau_{r\to rr}} \tau_{r\to rr} = 0 \quad \forall\, r \to rr \tag{17}$$

Considering the constraints of given production and transmission capacities, Eq. (12) and Eq. (15) are associated with the variables $\lambda_{i,t,s}$ and $\tau_{r\to rr}$, respectively. $\lambda_{i,t,s}$ denotes the shadow variable or shadow price of the production constraint, whereas $\tau_{r\to rr}$ denotes the the shadow variable or shadow price of congestion of a transmission line between distinct countries. Due to the assumption that the TSO supplies transmission services at marginal congestion cost, $\tau_{r\to rr}$ can be interpreted as a congestion fee, generators have to take into account when maximizing spot market profit. Therefore, interregional trade decisions are determined by interregional price differences and marginal transmission cost.

Following the *Cournot* assumption that competitors are supposed to not react to player i's output decision, i. e. the conjectural variation is zero, the term $\partial S/\partial s_i$ in Eq. (9) can be ignored. This assumption also holds for the competitive fringe and the foreign generators concerning oligopolistic supply.

Regarding the dynamic effects, optimal second stage output depends on first stage contacting, as discussed above. Hence, f_i in Eq. (9) leads to $s_i(f_i) : \mathbb{R} \mapsto \mathbb{R}$, indicating the influence of forward market decisions on spot market supply. Producers can thus use forward contracts strategically to influence their spot market position. A larger forward market position, that calls for delivery in the spot market ($f_i > 0$) induces an increased output quantity of firm i and therefore an increase in i's market share. This is more obvious by calculating the second stage marginal revenue with forward contracts $MR_i(s_i, f_i) : \mathbb{R} \mapsto \mathbb{R}$. Forward contracts shift marginal revenue upwards. As price elasticity is negative ($\epsilon < 0$), an additional unit of electricity sold forward will have a positive effect on marginal revenue. This strategic incentive of forward trading leads to increased second stage supply by each oligopolistic player and hence to a decrease in spot market price.

How forward trading can influence second stage behavior and thus the resulting spot market equilibrium, can be well shown by rearranging the first order condition in Eq. (9) (indices suppressed). Applying market share ϑ_i and price elasticity of demand ϵ, player i's constrained profit maximization condition is:

$$P(S)\left(1+\frac{\vartheta_i}{\epsilon}-\frac{\vartheta_i}{\epsilon}\frac{f_i}{s_i}\right)=C_i(s_i)+\lambda_i+\sum_{r\to rr}\tau_{r\to rr}\quad\forall\, i,t,s,r \tag{18}$$

where $C_i(s_i)$ denotes marginal cost of second stage generation s_i (cf. Eq. (2)) and λ_i and $\tau_{r\to rr}$ indicate the shadow variables of the given production and transmission constraints, respectively.

As first stage contracting shifts second stage marginal revenue upwards, forwards can be used as strategic instruments to improve spot market position. Beside the risk hedging motive, which leads to either a long or a short position in the forward market, e. g. induced by uncertain residual demand, due to stochastic wind power supply, strategic forward trading calls for delivery in the spot market, assuming *Cournot* behavior.

The influence of the pre-committed forward quantity on the second stage generation is indicated by the term f_i/s_i in Eq. (18). Thus, f_i/s_i can be interpreted as the degree of contract cover, firm i has realized in the forward market, due to risk hedging and strategy. Assuming $f_i/s_i = 0$, the oligopolist does not trade forward and is playing the *Cournot* game in the spot market. Assuming on the other hand, $f_i/s_i = 1$, i. e. the oligopolist's physical output is fully contracted through the forward market, he ends up as a price taker, loosing all of his market power. By varying $f_i/s_i \in [0; 1]$ exogenously, different forward market strategies, i. e. degree of contract cover, can be simulated.

Concerning the general approach of modeling the two-stage game of forward trading and spot market supply, the resulting second stage *Cournot-Nash* equilibrium is taken into account by the producers, when optimizing the degree of contract cover. For optimizing first stage contracting, players consider given uncertainty and their risk aversion on the one side and the strategic use of forwards on the other side. However, for the analysis described here, first stage contracting is simulated by varying the degree of contract cover exogenously without deriving optimal forward decisions explicitly. Moreover, due to the assumed approximation of the merit order curves by a polynomial of higher degree, an analytical solutions for the first stage optimum, to be implemented in complementarity format, seems to be difficult.

4 Exemplary model results

The model described above has been applied to analyze competition in the German electricity market. Given the current market structure, German electricity suppliers form a four player oligopoly with a competitive fringe. To what extend the four dominante oligopolistic producers RWE Power AG, E.ON Energie AG, Vattenfall Europe AG and EnBW AG can exercise market power depends on various factors. Beside the type of market behavior, absolut fringe supply possibilities and the assumptions made regarding anticipation towards fringe reaction, the potentials for exercising market power depend highly i) on the possibilities to limit price increase by electricity imports and ii) the option to trade specific production quantities on a forward market. In the following subsections, exemplary model results considering this two aspects are presented.

4.1 Base case

Assuming that the liberalized German electricity market is not integrated in the European UCTE network and assuming furthermore that there is no possibility for forward trading, a one stage *Cournot-Nash* equilibrium in quantities for the physical spot market can be calculated. Given this restrictive assumptions, the derived market equilibrium represents the potentials for exercising market power by the four oligopolistic suppliers as an upper bound for possible market manipulation. Figure 7 presents resulting market prices in the defined demand segments. The price elasticity of demand ϵ is assumed to be -0.25.

Considering the potentials to increase market prices by withholding capacity, i. e. reducing supply, the German electricity market seems not to be perfectly competitive. Under the given assumptions, dominant producers are able to increase prices between factors of approximately 2.0 (summer off-peak period) and 2.6 (winter peak period), compared to a calculated perfectly competitive equilibrium. Electricity price e. g. in the summer off-peak segment increases therefore from 15.84 €/MWh in the perfectly competitive case to 31.27 €/MWh under *Cournot* behavior. In the winter peak segment prices change from 28.40 €/MWh (competitive) to 74.74 €/MWh (*Cournot*), cf. Figure 7. The observable price increases result from significant mark-ups, which can be realized by the oligopolistic producers. Table 3 presents minimum and maximum values of the *Lerner-Index* and overall profit under different assumptions regarding producers' behavior in the base case.

It can be seen that the competitive fringe profits substantially from strategic behavior of the four dominant producers in Germany. As the competitive fringe behaves as a price taker, its generation is increased significantly due to higher electricity prices. Moreover, within the peak load segments, the *Lerner-Index* of fringe supply results in values greater than zero, indicating a situation in which prices exceed marginal cost. This can be explained with limitations in their generation capacity. Even if electricity prices are above marginal generation cost, fringe suppliers are not able to extend their production further.

Regarding overall efficiency of electricity generation, it can be shown that strategic behavior leads to unbalanced marginal cost among generators and therefore to a suboptimal allocation of production factors. The observable shift in generation from RWE, E.ON, Vattenfall and EnBW to fringe producers, increases dead weight losses additionally. Considering the existing power plant portfolios, it is evident that relatively high priced gas and oil units are utilized by the competitive fringe in equilibrium.

4.2 Interregional transmission

Given the actual situation, where Germany is integrated into a large European electricity network having various interconnection to its neighboring countries, the restrictive assumption in the base case have to be relaxed. Moreover, with reinforcing the internal European electricity market, the European Union aims to strengthen competition among generators and to improve overall efficiency. Regarding the interregional transmission possibilities, competition analyses have to take into account the potentials to limit price increases due to exercised market power by electricity imports.

Allowing for interregional electricity exchange, i. e. extending the options to optimize spot market decisions for the German players and the generators in foreign countries, by modeling existing transmission lines (cf. Table 1), leads to significant changes in results. Regarding the exchange possibilities, foreign generators can profit from market power induced price increases in Germany by exporting electricity to the German market. Thereby foreign electricity exports keep pressure on prices in Germany, preventing for mark-ups observable in the base case scenario. Figure 8 presents a price comparison for the *Cournot-Nash* equilibria in the base case (Cournot (BC)), in the case where interregional electricity exchange is allowed (Cournot (i)) and the corresponding perfectly competitive equilibrium with transmission (Competitive (i)).

As can be seen, interregional electricity exchange forces down prices in the Cournot (i) scenario by approximately 32% for the summer off-peak period and 40% for the winter peak period, compared to the Cournot (BC) equilibrium in the base case. Nevertheless with these price decreases, the large German players are able to raise market prices by factors of between approximately 1.3 (summer off-peak) and 1.6 (winter peak) over the competitive equilibrium. According to the observable price changes, values for the *Lerner-Index* and the overall profit decrease also, cf. Table 4. It can be noted, that in equilibrium the profits decrease, assuming both *Cournot* and competitive behavior, except a slight increase in profit of RWE Power AG in the competitive case. Due to interregional trade, this effect can be lead back to profitable exports to neighboring countries and domestic price changes, which can possibly cause positive effects on profit. However, a detailed presentation of results regarding exchange values and regional specific numbers is omitted here.

Considering the current structure of the European transmission grid, e. g. Haubrich et al. (2001) analyzed the cross-border capacities to identify critical bottlenecks within the internal European market. As was seen in comparison of base case results with the scenario where interregional exchange was allowed, congestion in transmission lines can negatively influence regional price adjustment and therefore be a crucial factor to prevent market power mitigation. Taking into account transmission reinforcement projects that have been already identified by the European Commission within the Trans-European Energy Networks (TEN-E) priority projects, several bottlenecks can be identified for German cross-border trade.

Following Haubrich et al. (2001), the interconnections among Belgium/Germany and the Netherlands as well as Denmark and Germany can be regarded as highly congested all over the year. Additionally, the cross-border link between France and Germany shows occasionally congestion, particularly in summer. Beside the already mentioned interconnections within the BeNeLux region, transmission lines between Belgium and France have been identified as critical bottlenecks, which may have an impact on market outcome in Germany. Thus, applying the model for analyzing the competition enhancing effects of transmission capacity expansion between Germany and its neighboring countries, the following reinforcement projects are considered.

- Germany ⟺ the Netherlands, 700 MW
- Germany ⟺ France, 600 MW
- Germany ⟺ Denmark, 1250 MW
- Belgium ⟺ the Netherlands, 1000 MW
- Belgium ⟺ France, 1000 MW

Increasing the congested German cross-border transmission capacities leads to increased pressure on the dominant firms to lower mark-ups and hence to a decrease in market price. As possibilities to export electricity into the German market grow, potentials for exercising market power decline. The competition enhancing effect of interregional electricity exchange has already been observed by comparing the base case results with the situation where interregional transmission is considered. The resulting effects on prices, due to the specified grid enlargement are presented in Figure 9. The *Cournot-Nash* equilibrium with capacity expansion is denoted by Cournot (i+), whereas Competitive (i+) represents the corresponding perfectly competitive equilibrium. It can be seen that the strategically influenced electricity price is reduced by approximately 5% in the summer off-peak period, whereas the price reduction in the winter and intermediate peak periods amounts to 10%, compared to the *Cournot-*

Nash equilibrium considering the current transmission capacities (Cournot(i)).

Again, the potentials to increase market price by withholding capacities and supply respectively, can also be analyzed by calculating the *Lerner-Index*, cf. Table 5. As expected, *Lerner-Index* and profit is reduced, due to enhanced imported competition by foreign electricity supply in the German market.

Summarizing, the results indicate that reinforcement of the above considered transmission lines within the internal European electricity market mitigates the potentials to exercise market power in Germany. Hence, the reduction of network congestion is therefore suitable to enhance competition and therefore to lower electricity prices in Germany, given its oligopolistic market structure.

4.3 Forward trading

Beside the positive impact of interregional transmission possibilities on competition, particularly in non-competitive market environments, Allaz (1992) and Allaz and Vila (1993) have shown that forward trading can have a similar effect. Since most of the liberalized electricity markets have institutionalized forward and futures markets, market power analyses should take these trading options into account. Considering the 2001 established derivatives market at the European Electricity Exchange in Germany, domestic and foreign European electricity producers and consumers are enabled to use the traded products for various purposes. As RWE Power AG, E.ON Energie AG, Vattenfall Europe AG and EnBW AG are all trading participants in the spot and the derivatives market at the EEX, it can be considered that these players use the trading options to improve their market position.

As mentioned above, forwards and futures can be used for risk hedging and strategic motives (cf. also e. g. Allaz, 1987). Within the analysis described here, the distinction between risk hedging and strategic motives can be neglected, as the main focus lies on the impact of increased forward trading on the spot market equilibrium in Germany. Thereby only positive forward quantities $f_i \geq 0$ that call for delivery in the spot market are considered, i. e. dominant producers are assumed to be short on the forward market (cf. Subsection 3.3).

For analyzing the competitive effects of increasing forward quantities, the amount of pre-committed physical production has been varied exogenously. To cover the range between no contracts and a situation where the producers are fully contracted on the forward market, the degree of contract cover (f_i/s_i) has been varied between 0% and 100%. A degree of contract cover of 0% yields the usual *Cournot-Nash* equilibrium on the spot market, whereas a degree of contract cover of 100% leads to the perfect competitive market outcome (cf. Eq. (18)). The calculation is executed by changing the ratio in 5% steps for all oligopolistic players simultaneously. A simulation of asymmetric contract cover scenarios for individual players has not been considered here (cf. e. g. Ellersdorfer, 2005).

However, the scenarios analyzed here are based on the case where interregional electricity exchange is allowed, considering current interconnection capacities. The presented scenario is denoted by Cournot (ii), whereas the corresponding scenario without forward trading is Cournot (i), described in the previous subsection. Implementing a forward market in Germany and allowing for forward trading provides oligopolistic players with instruments to influence their spot market position. When oligopolists use forward contracts for strategic reasons, which call for delivery, they increase their physical production and, hence lower spot market prices. It should be noted that the identical results can be predicted, if producers sell forward contracts for risk hedging reasons. Figure 10 presents the impact on electricity prices in the different demand segments when the oligopolistic producers increase their contract quantity simultaneously.

It can be observed that the price decrease is nearly linear in the different demand segments, except for the summer and intermediate peak periods, which show a little break. Reaching a contract ratio of 100%, prices went down to the competitive level. Hence, oligopolistic producers loose whole of their market power and behave as price takers, respectively. Figure 11 presents exemplary values for the *Lerner Index* in the winter off-peak period. As the degree of contract cover increases, price mark-up decreases.

As the amount of pre-committed production quantity grows, spot market supply increases, leading to the shown significant price reductions. Cf. Figure 12 for production in the winter off-peak period and Figure 13 for the intermediate peak segment. Despite growing spot market supply, producers are worse off when they all increase their forward quantity simultaneously, due to a compensating price effect. Thus, individual and industry profits are cut down. Figure 14 presents the four large German producers' and fringe's profits.

Considering the induced impact on electricity prices, mark-ups and production quantities, it can be observed that the implementation of a forward market can have positive effect on the market outcome in Germany. When the German dominant electricity suppliers use forward contracts, which call for the delivery in the spot market either for strategic or risk hedging motives, enhanced competition is predicted. Moreover, forward trading as it is specified here, can be assumed to decrease dead weight loss and have a positive effect on social welfare. Beside enhancing the possibilities for interregional electricity exchange within the internal European market, a strengthening of derivative trading options is considered to mitigate market power in Germany.

Following the above argumentation that both interregional electricity exchange and forward trading can lead to enhanced competition in Germany, it is obvious that network investment improves market outcome in a situation where oligopolistic firms additionally pre-commit spot market production. To render an exemplary analysis of how network investment effects electricity prices quantitatively, a scenario in which cross-border capacity between Germany and the Netherlands is being enlarged by 3000 MW has been calculated (Cournot (ii+)). Increasing the interconnection capacity in steps of 150 MW each, it can be seen that, depending on the level of contract cover, capacity enlargement can have different effects on prices, both in Germany and the Netherlands.

Figure 15 presents the development of electricity prices in the summer peak period in Germany. Again, given the current transmission capacities, i. e. network investment is zero, the Cournot (ii) result is determined. Assuming that bilateral transmission capacity to the Netherlands is going to be enlarged, the price within the German market decreases when contract cover is low, whereas price increases slightly when firms are fully contracted. Thereby, electricity price falls by approximately 2.0 €/MWh when playing the usual *Cournot-Nash* game, whereas price increases by approximately 1.0 €/MWh in the perfectly competitive equilibrium. The observable price increase in Germany is induced by higher electricity exports by German suppliers to the Netherlands. Given the current price differences between both countries, German producers find it favorable to shift specific amounts of production from the German to the Dutch market. Moreover, due to this behavior, electricity prices in Germany and the Netherlands were equalized from an additional cross-border capacity of 2250 MW, i. e. an overall capacity of 5190 MW. Electricity price in the summer peak period is thereby 25.1 €/MWh within both countries. Cf. Figure 16 for the price development in the Dutch market.

Regarding the exemplary price development in the Dutch market, it can be seen that investments in cross-border transmission capacities do not always yield better market outcome, at least not in every country. Depending on producers' market behavior, electricity exchange expansion can also lead to increasing market prices in some countries. As was already described for the perfect competitive equilibrium in the German market, a similar impact on prices can be seen for the Dutch market, assuming *Cournot-Nash* behavior of the four German suppliers. Whereas price adjustment between Germany and the Netherlands was mainly induced by equalization of marginal generation cost, the price increase in the Netherlands is caused particularly by the relative small size of the Dutch market compared to Germany. Although the price increase is only slight, two related effects can be described to contribute to this result. First, the enlargement of the bilateral transmission capacity enables the oligopolistic German producers to exercise market power even in the Netherlands, secondly, the high electricity prices in Germany induce rising exports by Dutch producers to the German market.

Assuming competitive behavior and high degree of contract cover, electricity prices in the Netherlands decrease by approximately 1.6 €/MWh in the summer peak period (cf. Figure 16). As can be observed, price cuts are not linear, but show a broken development. While price changes remain nearly flat until approximately 60% of contract cover, prices decrease from a pre-commitment ratio of approximately 70%. However, given the current cross-border capacities, prices in the summer peak period are projected to reach about 26.7 €/MWh, whereas considering network enlargement, prices amount to 25.1 €/MWh, as has also been seen in Germany.

Regarding the analyzed exemplary capacity reinforcement of the German-Dutch transmission lines, it can be noticed that increased forward trading of the German producers has a stronger impact on German electricity prices than the grid enlargement by 3000 MW. Nevertheless, bilateral network investment can lead to enhanced competition in non-perfect competitive market structures. Regarding the reduction of transmission congestion between Germany and other neighboring countries, e. g. France with a completely different generation structure, might yield alternative results.

5 Conclusions

The model based analysis of competition in the German electricity market has shown that there are potentials to exercise market power by the four dominant producers RWE Power AG, E.ON Energie AG, Vattenfall Europe AG and EnBW AG. It has also been discussed how network reinforcement and forward trading influences producers' market decisions and to what extent these factors contribute to market power mitigation in Germany.

Regarding the competition enhancing effects of interregional electricity exchange and increasing amount of pre-committed production quantities, it can be concluded that market power analyses at least for Germany should take these aspects into account.

Within the analysis, both network enlargement and forward trading decisions were determined exogenously, i. e. no explicit optima for transmission investment nor contracting were derived. Aside endogenous investment for network infrastructure, which requires a different type of model, optimal forward trading decisions for the German producers can be derived within the described model structure, but with linearized demand and marginal cost functions. Spot market equilibria therefore depend on German producers' strategic and risk hedging incentives.

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Figures and Tables

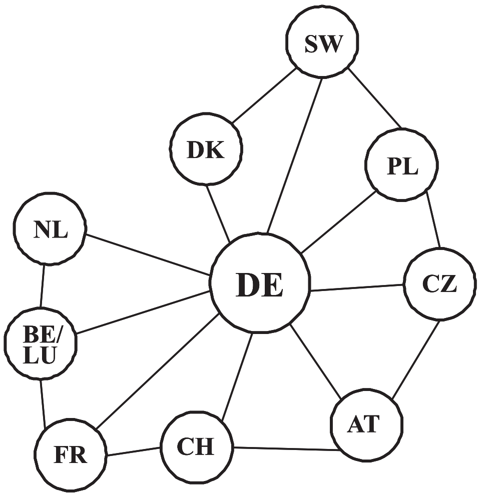

Fig. 1. Regions and transmission lines covered by model

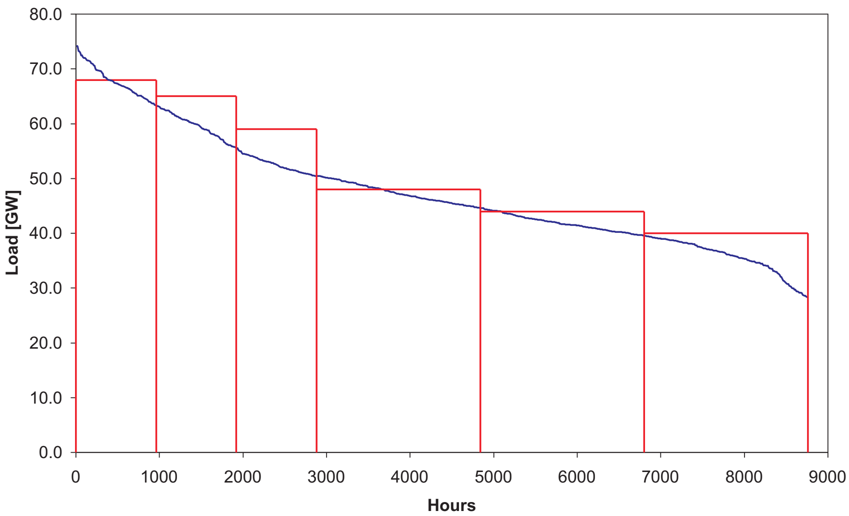

Fig. 2. Approximation of load duration curve for Germany, 2000

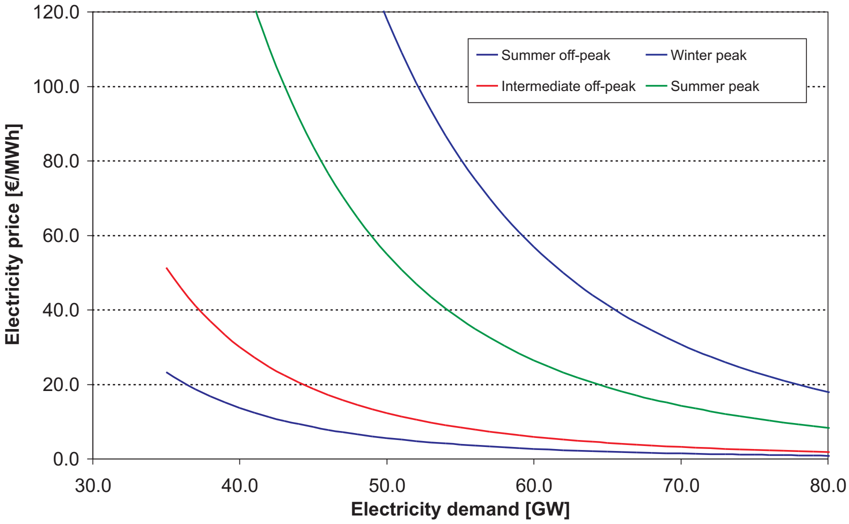

Fig. 3. Inverse demand curves for different time segments in Germany

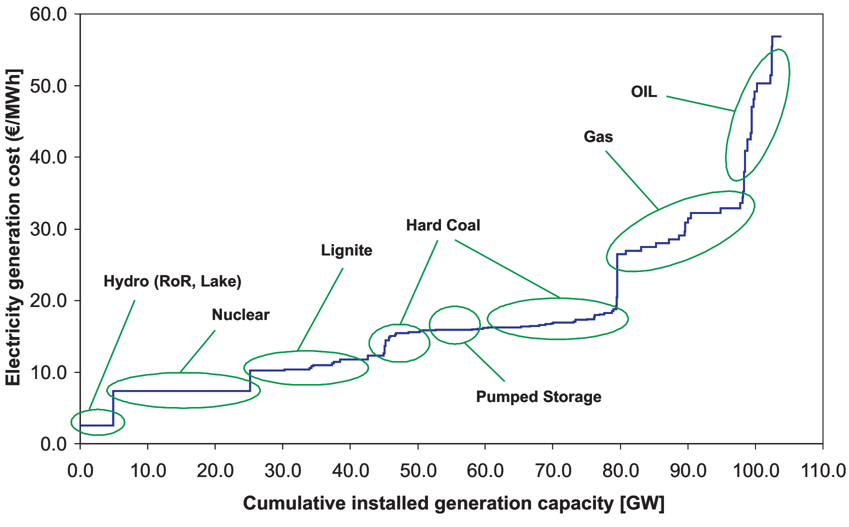

Fig. 4. Merit order curve for Germany, 2005

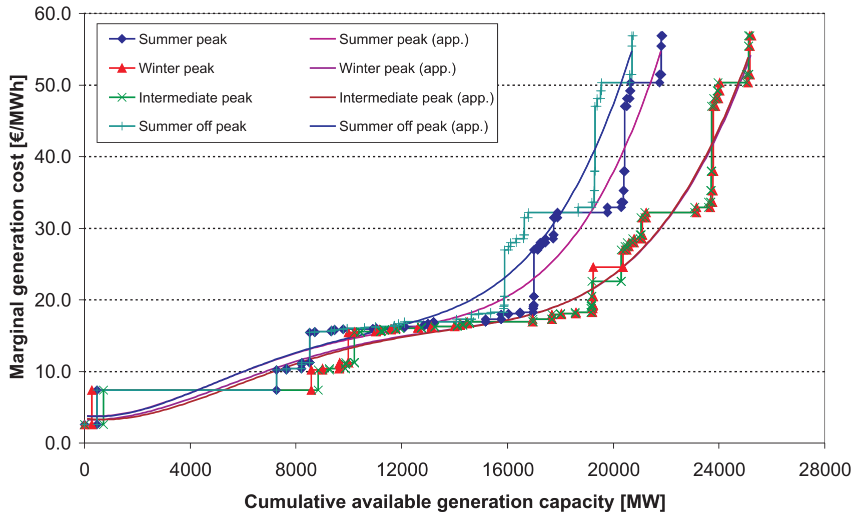

Fig. 5. Marginal cost curves and approximation for E.ON Energie AG

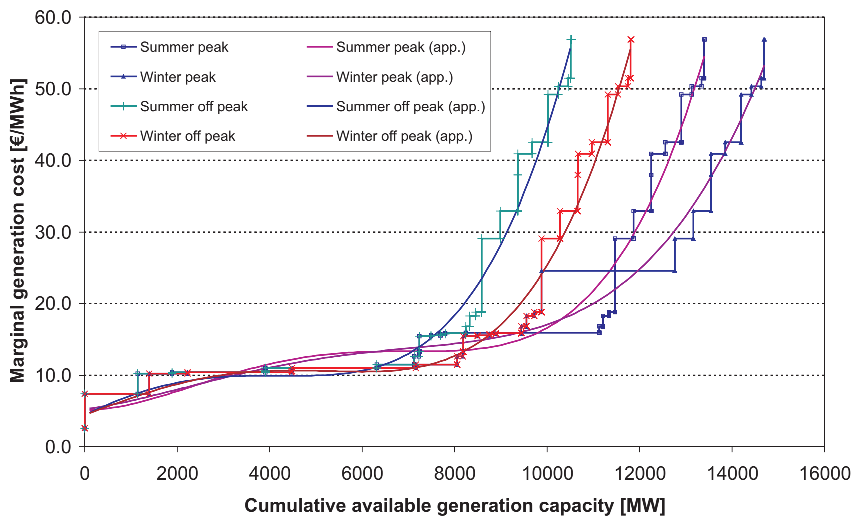

Fig. 6. Marginal cost curves and approximation for Vattenfall Europe AG

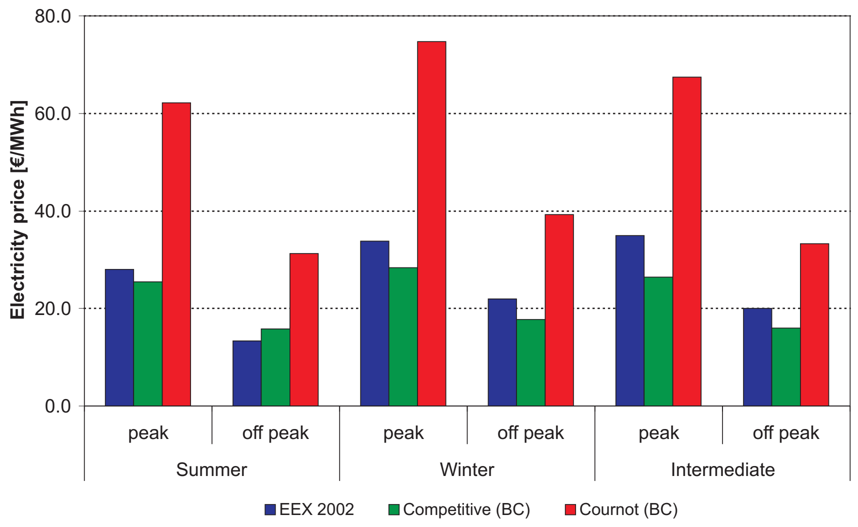

Fig. 7. Electricity prices in Germany - no transmission, no forward trading - Scenario: Cournot (BC)

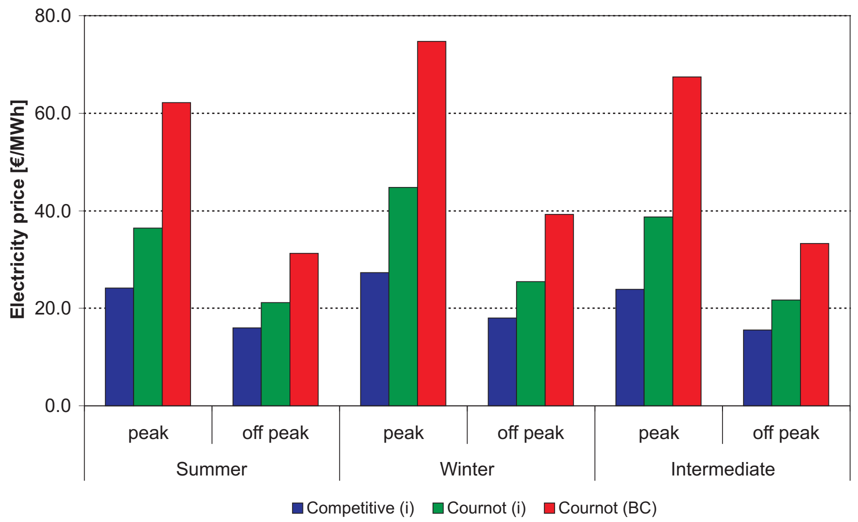

Fig. 8. Electricity prices in Germany - transmission considered, no forward trading - Scenario: Cournot (i)

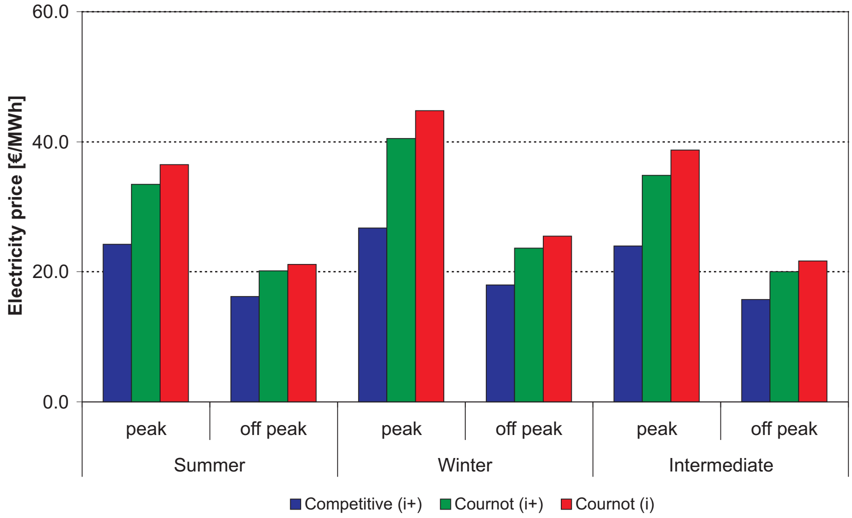

Fig. 9. Electricity prices in Germany - transmission enlargement, no forward trading - Scenario: Cournot (i+)

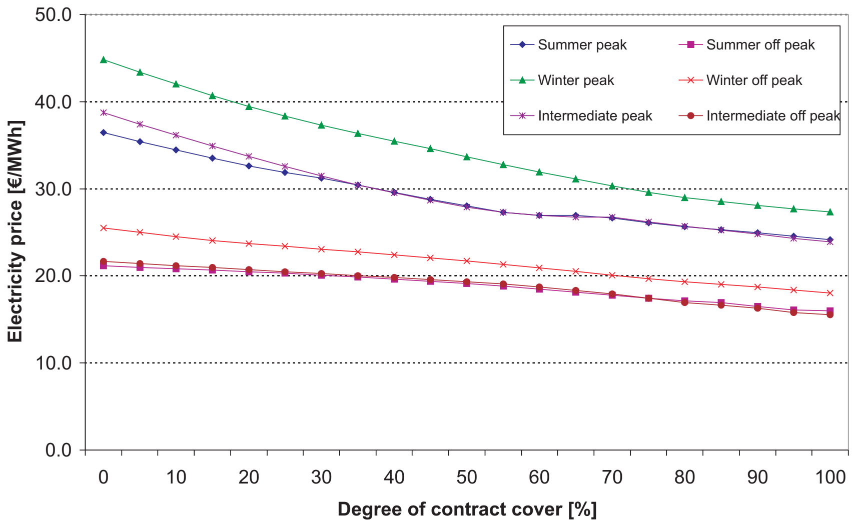

Fig. 10. Electricity prices in Germany - transmission considered, increasing forward quantities - Scenario: Cournot (ii)

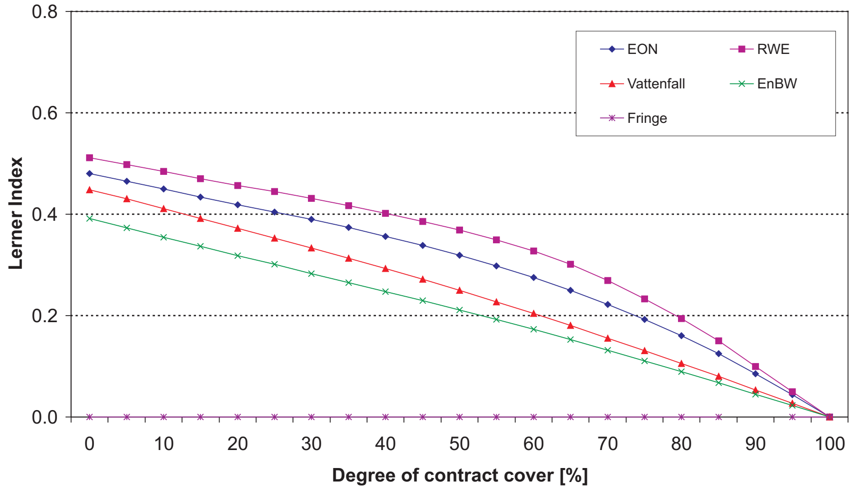

Fig. 11. Lerner Index of German producers in the winter off-peak period - transmission considered, increasing forward quantities - Scenario: Cournot (ii)

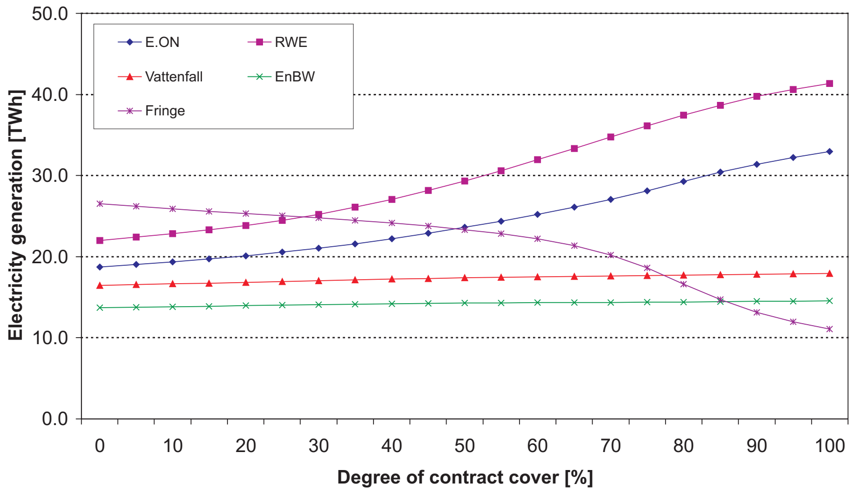

Fig. 12. Electricity generation of German producers in the winter off-peak period - transmission considered, increasing forward quantities - Scenario: Cournot (ii)

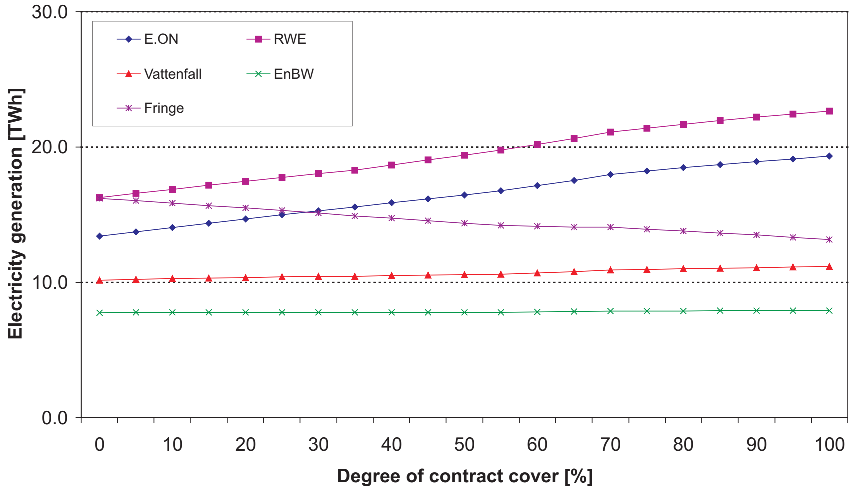

Fig. 13. Electricity generation of German producers in the intermediate peak period - transmission considered, increasing forward quantities - Scenario: Cournot (ii)

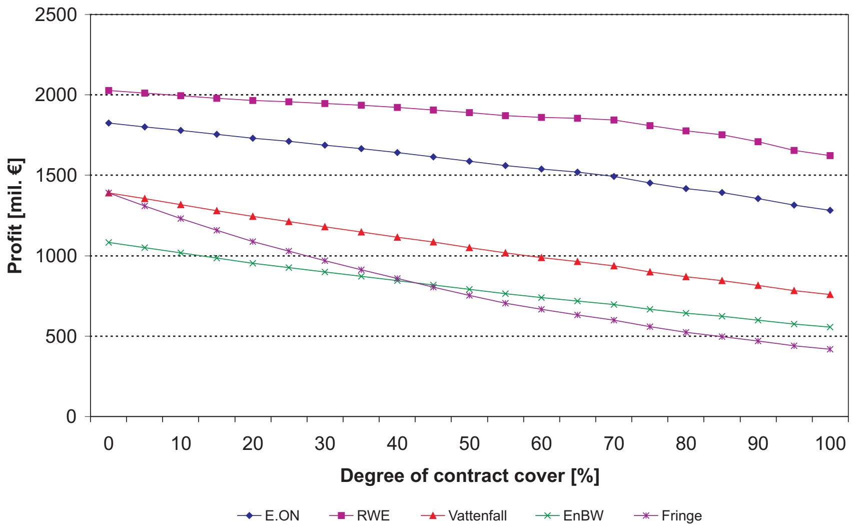

Fig. 14. Profits of German producers - transmission considered, increasing forward quantities - Scenario: Cournot (ii)

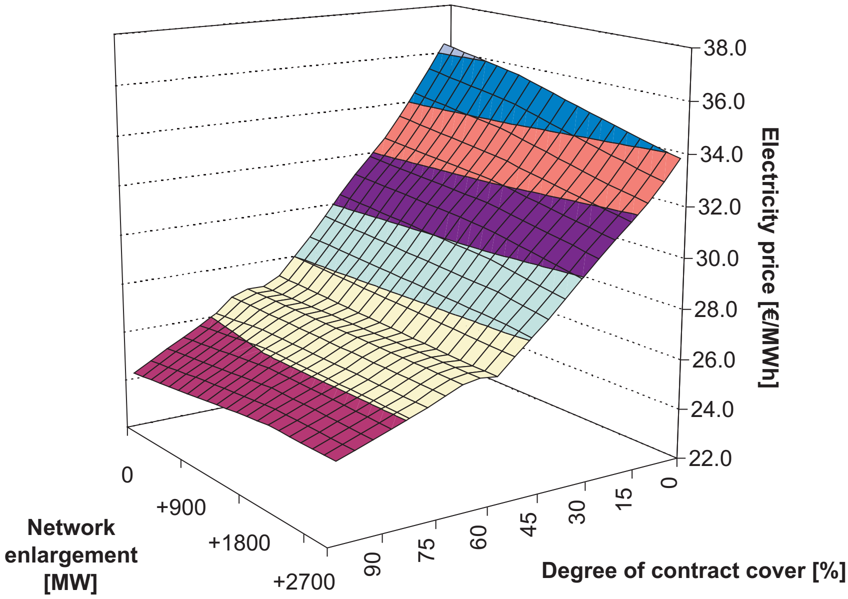

Fig. 15. Electricity price in the summer peak period in Germany - transmission enlargement, increasing forward quantities - Scenario: Cournot (ii+)

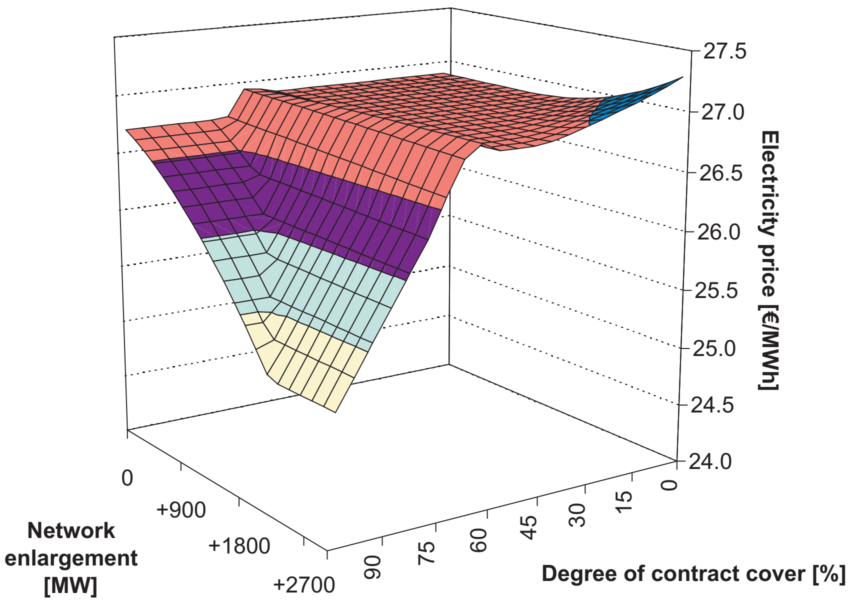

Fig. 16. Electricity price in the summer peak period in the Netherlands - transmission enlargement, increasing forward quantities - Scenario: Cournot (ii+)

Table 1
Interregional transmission capacities among countries [MW]

	DE	FR	BE/LU	NL	DK	SW	PL	CZ	AT	CH
DE	∞	3120	760	2940	1750	460	1242	1512	1460	3630
FR	3120	∞	1150	-	-	-	-	-	-	590
BE/LU	760	1150	∞	1030	-	-	-	-	-	-
NL	2940	-	1030	∞	-	-	-	-	-	-
DK	1750	-	-	-	∞	924	-	-	-	-
SW	460	-	-	-	924	∞	240	-	-	-
PL	1242	-	-	-	-	240	∞	658	-	-
CZ	1512	-	-	-	-	-	658	∞	234	-
AT	1460	-	-	-	-	-	-	234	∞	370
CH	3630	590	-	-	-	-	-	-	370	∞

Table 2. Installed generation capacities of strategic players and fringe in Germany and neighboring countries [MW]

Fuel type	RWE	E.ON	Vattenfall	EnBW	Fringe	FR	BE/LU	NL	DK	SW	PL	CZ	AT	CH
Hard coal	7249	9461	1729	3288	7161	7200	2502	4196	5722	879	20064	1652	1335	-
Soft coal	10554	1425	6932	453	718	-	-	-	-	5	8269	7320	428	-
Gas	4297	3808	870	1083	8809	5898	6882	15440	2178	557	947	1808	3806	226
Oil	188	1779	1429	617	1375	8526	341	669	1313	3625	162	284	340	311
Nuclear	5499	8473	1421	4272	597	63200	5738	449	-	9050	-	3471	-	3230
Hydro														
- RoR, Lake	741	1320	9	447	2390	20971	146	129	39	16024	629	1057	10054	12304
- Pumped	793	1110	2883	368	263	4302	2307	-	-	427	1484	1145	1846	907

Table 3
Lerner-Index (LI) and profit [mil.€] of German producers - no transmission, no forward trading

		RWE	E.ON	Vattenfall	EnBW	Fringe
LI	min/max	0.69/0.82	0.66/0.80	0.65/0.72	0.53/0.59	0.00/0.25
Profit	Cournot	3421	3272	2847	2265	3784
	Compet.	1635	1324	802	588	483

Table 4
Lerner-Index (LI) and profit [mil.€] of German producers - transmission allowed, no forward trading

		RWE	E.ON	Vattenfall	EnBW	Fringe
LI	min/max	0.48/0.65	0.44/0.61	0.43/0.52	0.36/0.43	0.00/0.00
Profit	Cournot (i)	2027	1824	1390	1082	1390
	Compet. (i)	1651	1261	753	554	420

Table 5
Lerner-Index (LI) and profit [mil.€] of German producers - transmission enlarged, no forward trading

		RWE	E.ON	Vattenfall	EnBW	Fringe
LI	min/max	0.45/0.60	0.42/0.57	0.41/0.47	0.33/0.38	0.00/0.00
Profit	Cournot (i+)	1836	1634	1220	936	1112
	Compet. (i+)	1601	1240	749	553	416