Impact of Transmission Network Investments on Market Power in the German Electricity Market

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Abstract

In this paper a model based analysis of competition in the German wholesale electricity market is presented. Applying a multi-regional model which covers the interregional transmission constraints between Germany and its neighboring countries, potential for exercising market power by the four dominant electricity producers has been found. Assuming *Cournot* behavior in the spot market, it has been analyzed to what extent network investment can lead to enhanced competition. It has also been shown that the impact of transmission reinforcement on market power differs among interconnection lines due to the specific supply and demand structures within the considered markets.

Key words: Competition analysis, Market power, Cournot model, Transmission network investment, 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 system marginal costs, the actual degree of market power can be quantified, but it has limited ability to derive conclusions with regard to changes in market structure and strategic behavior. For an analysis of the Californian electricity market cf. Borenstein et al. (2000b) 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 aspects that influence companies' potential to exercise market power like actual interconnector capacities should be addressed within the model analyses.

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), Borenstein et al. (2000a) and Metzler et al. (2003). Moreover, Chuang et al. (2001) and Murphy and Smeers (2002) introduce network 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, especially when 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-functions equilibria, the calculated market outcome can be interpreted as a maximum impact of non-cooperative behavior, cf. Klemperer and Meyer (1989) and the restrictions described therein and Borenstein et al. (1999).

Regarding Germany's current electricity market structure, potential for exercising market power of the four dominant producers are supposed. Taking interregional electricity exchange into account, a multi-regional *Cournot* model has therefore been developed to analyze the impact of network reinforcement on competition in the German electricity market.

The paper is organized as follows. In section 2 two important aspects affecting the German wholesale market are described, i. e. interregional exchange and spot and derivatives markets. The mathematical formulation of the developed model is described in Section 3. In section 4 exemplary results regarding changes in cross-border capacities within Europe are presented. Finally, conclusions are drawn in section 5.

2 Changes in 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)).

Given the differences in region-specific generation and demand structures, electricity exchange varies between countries and over time. Figure 1 presents bilateral electricity exchange between Germany and its neighboring countries in 2004. It can be seen that Germany is a net importer with regard to France of between approximately 3.9 TWh in winter and 5.9 TWh in summer as well as the Czech Republic of 4.2 TWh in summer and 4.4 TWh in intermediate time, whereas it is a net exporter regarding the BeNeLux region of between approximately 4.9 TWh in summer and 8.7 TWh in winter. Concerning Poland, Austria and Switzerland, Germany is also a net exporter. The electricity exchange between Germany and Sweden and Germany and Denmark, respectively, is nearly balanced.

As interregional transmission in Europe was previously 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

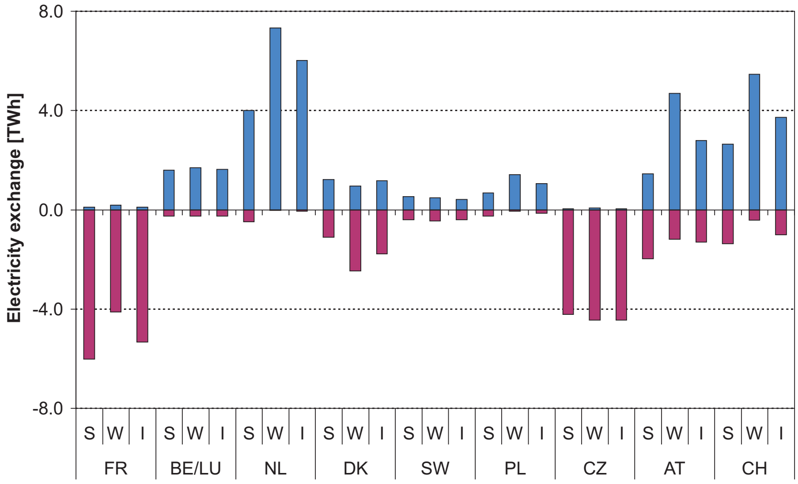

Fig. 1. Bilateral electricity exchange between Germany and its neighboring countries in summer, winter and intermediate time, 2004 – Export(+), Import(-)

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.

Considering the bilateral electricity exchange quantities, several transmission lines within the internal European market show occasional congestion. Beside e. g. Haubrich et al. (2001), who have analyzed transmission congestion in the former EU-15 countries including Switzerland and Norway, KEMA Consulting (2005) has focused on the European asseccion countries. The studies highlight that electricity trade is temporally affected by both cross-border and domestic network capacity bottlenecks.

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 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, 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.

3 The model

For analyzing competition in the German electricity market, a multi-regional *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 2 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 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 constrained optimization problem. Thereby producers maximize their profits in the spot market, taking generation and transmission constraints into account. For the analysis presented in this paper, the model is applied, varying interregional transmission capacities exogenously.

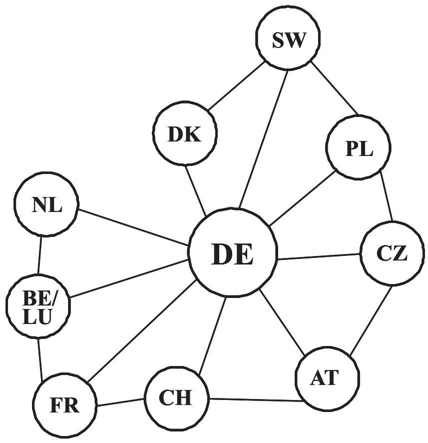

Fig. 2. Regions and transmission lines covered by model

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	∞

3.1 Demand side

Time varying electricity demand in each country 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 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. Demand values are based on data for the year 2000 provided by the Union for Co-ordination of Transmission for Electricity (UCTE), cf. UCTE (2000). They have been adjusted concerning the growth in electricity demand until 2005. Figure 3 presents the exemplary decomposition of the load duration curve for Germany.

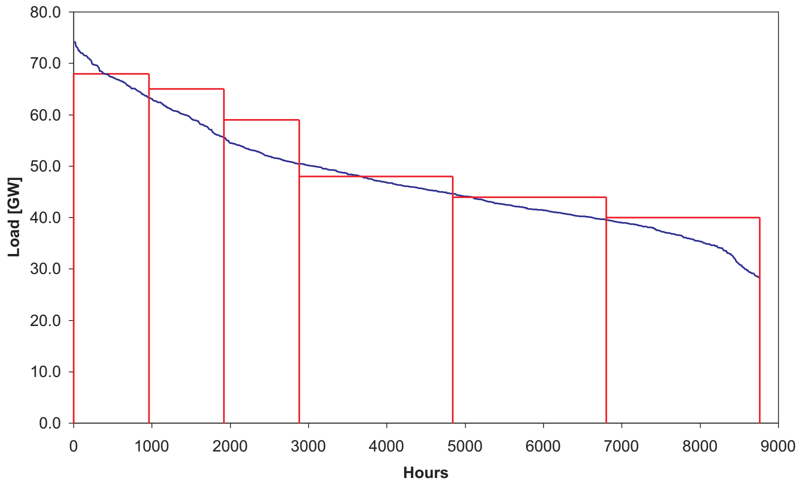

Fig. 3. Approximation of load duration curve for Germany, 2000

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:

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

with $S_{t,s,r}$ being total supply in each demand segment t and 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 data for the year 2002. According to the demand segment specification, average system marginal prices are 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 4 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

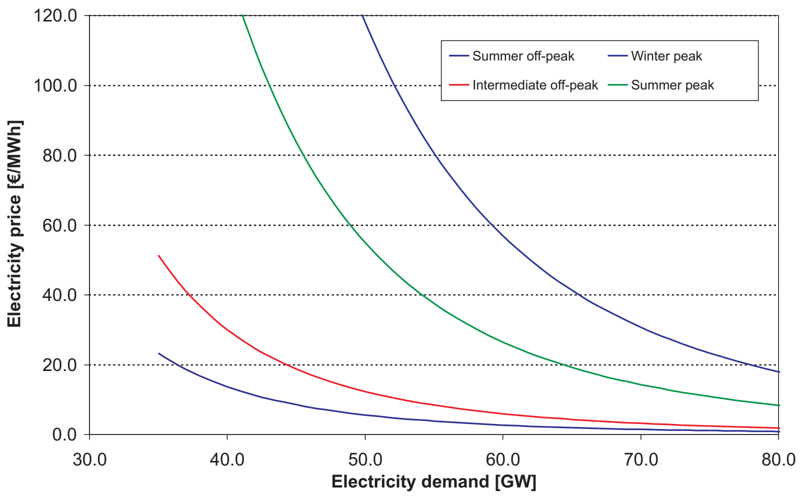

Fig. 4. Inverse demand curves for different time segments in Germany

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 determined analytically considering fuel type and date of unit commissioning. Due to the unit based representation of the German producers' power plant portfolios, this approach leads to 82 different variable cost categories. Regarding the generation structures within Germany's neighboring countries, power plant portfolios are represented on a higher aggregation level applying 18 different variable cost categories. 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 5 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

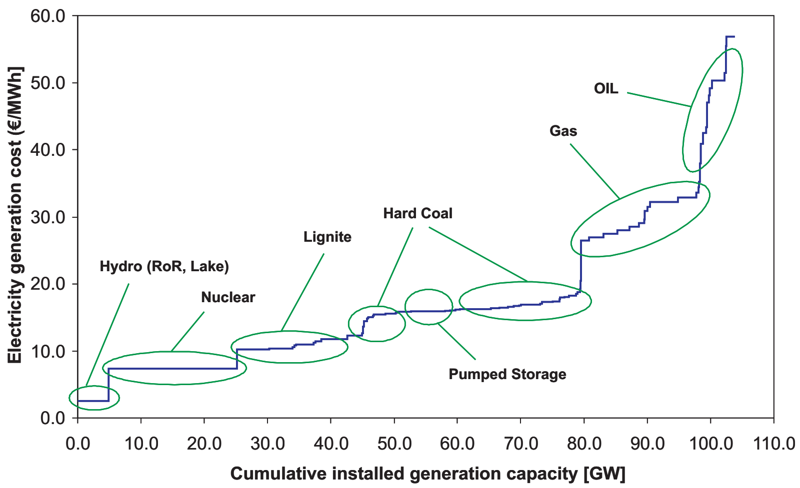

Fig. 5. Merit order curve for Germany, 2005

ownership across borders has been neglected, thus German suppliers utilize domestic capacities only. Table 5 at the end of this paper gives an overview of the individual generation capacities owned by the four strategic players and the competitive fringe in Germany and the aggregated capacities of the neighboring countries.

To derive individual merit order 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 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 and have been considered. 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 within each German neighboring country have been derived. Figures 6 and 7 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:

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

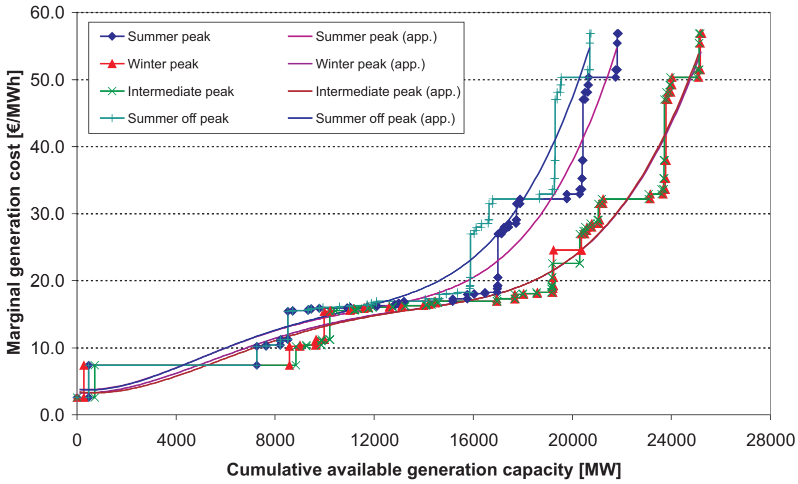

Fig. 6. Marginal cost curves and approximation for E.ON Energie AG

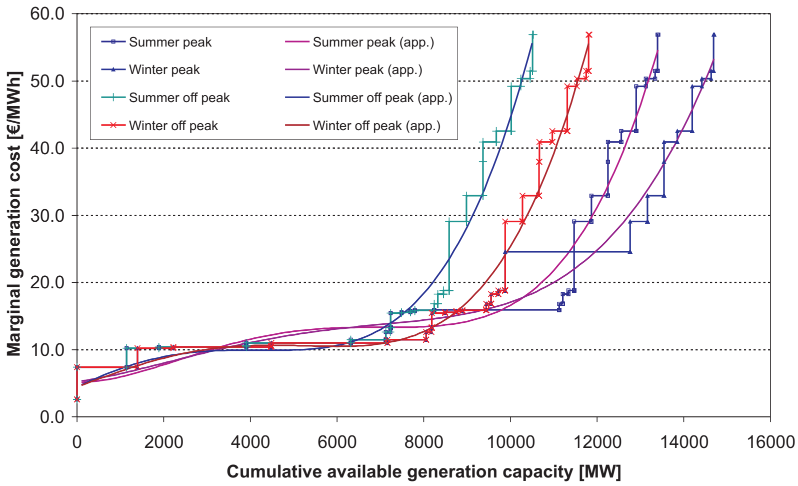

Fig. 7. Marginal cost curves and approximation for Vattenfall Europe AG

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 availably 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 Producers optimization program

Producers maximize their profits in the physical spot market, deciding about the optimal generation program. Spot market behavior of the four strategic players is assumed to be of *Cournot* type. Fringe suppliers in Germany and generators in neighboring countries are assumed to behave as price takers.

Given the limited production and transmission capacities and taking fringe supply and interregional electricity trade into account, generators face a constrained one-stage optimization problem.

Each oligopolistic supplier $i \in \mathbb{I}$ maximizes its profit $\Pi_{i,t,s,r}(s_{i,t,s,r}) : \mathbb{R}^n \mapsto \mathbb{R}$ 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:

$$\max_{s_i} \Pi_i(s_i) = P(S)s_i - TC_i(s_i) \quad \forall\, i, t, s, r \tag{3}$$

with $S = \sum_{i \in \mathbb{I}} s_i$ being aggregated supply by all generators. $TC_i(s_i)$ based on $TC_i(x_i) : \mathbb{R} \mapsto \mathbb{R}^+$ represents total generation cost for supply of player i in the spot market, being the antiderivative of the estimated marginal cost function in Eq. (2).

$$TC_i(x_i) = \frac{1}{5}c_1 x_i^5 + \frac{1}{4}c_2 x_i^4 + \frac{1}{3}c_3 x_i^3 + \frac{1}{2}c_4 x_i^2 + c_5 x_i + FC_i \quad \forall\, i, t, s \tag{4}$$

Thereby variable production costs are captured by the first five terms, whereas FC_i denotes fixed cost of electricity generation. Regarding the short model horizon, generation capacities are assumed to be given. Power plant investment and hence fixed cost can therefore be ignored for the optimization.

Firms' electricity generation x_i has to be:

$$x_i \geq \sum_r s_{i,r} \quad \forall\, i, t, s \tag{5}$$

and 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

$$g_i(x_i) : x_i - x_i^{\max} \leq 0 \quad \forall\, i, t, s \tag{6}$$

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 $s_{i,t,s,r}^{\mathrm{rr}}$, 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 charges 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 $r \rightarrow rr$ of distinct countries that has to be satisfied, is:

$$e_{r,rr}(S_r^{\mathrm{rr}}, S_{rr}^{\mathrm{r}}) : \left(\sum_{i^-} s_{i,r}^{\mathrm{rr}} + \sum_{i^+} s_{i,rr}^{\mathrm{r}} \right) - t_{r \rightarrow rr}^{\max} \leq 0 \quad \forall\, t, s \tag{7}$$

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 $t^{\max}_{r \to rr}$, 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:

$$S_r = \sum_{i^-} s^{\mathrm{r}}_{i,r} + \sum_{i^+} s^{\mathrm{r}}_{i,rr} \quad \forall\, t, s, r \tag{8}$$

For Germany (r^{DE}), 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:

$$S_{r^{DE}} = \sum_{i} s^{\mathrm{r}^{\mathrm{DE}}}_{i,r^{DE}} + s^{\mathrm{r}^{\mathrm{DE}}}_{\mathrm{fringe,r^{DE}}} \quad \forall\, t, s \tag{9}$$

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 $\phi_{t,s^-,r}$, Eq. (5) has to be extended to:

$$x_i \geq \sum_{r} s_{i,r}(1 + \theta_r + \phi_r) \quad \forall\, i, t, s \tag{10}$$

which equals overall electricity demand in each segment and each country. Estimated network losses are based on 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 $e_{r,rr}(S^{\mathrm{rr}}_r, S^{\mathrm{r}}_{rr})$ into account. The resulting nonlinear program with inequality constraints can be formulated in mixed complementarity format. For maximizing the profit function (cf. Eq. (3)) for each player simultaneously, the first order *Karush-Kuhn-Tucker* conditions have been derived. In equilibrium, none of the players and generators, respectively, are 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:

$$\frac{\partial \mathcal{L}_{i,t,s,r}(s_{i,t,s,r}, \lambda_{i,t,s}, \tau_{r \to rr})}{\partial s_{i,t,s,r}} = \frac{\partial P_{t,s,r}(S_{t,s,r})}{\partial S_{t,s,r}} \frac{\partial S_{t,s,r}}{\partial s_{i,t,s,r}} s_{i,t,s,r} + P_{t,s,r}(S_{t,s,r})$$

$$
\begin{aligned}
& - \frac{\partial TC(s_{i,t,s,r})}{\partial s_{i,t,s,r}} \\
& - \lambda_{i,t,s} - \sum_{r \to rr} \tau_{r \to rr} \leq 0 \quad \forall i,t,s,r
\end{aligned} \tag{11}
$$

complements

$$
s_{i,t,s,r} \geq 0 \quad \forall\, i,t,s,r \tag{12}
$$

and the inner product

$$
\frac{\partial \mathcal{L}_{i,t,s,r}(s_{i,t,s,r}, \lambda_{i,t,s}, \tau_{r \to rr})}{\partial s_{i,t,s,r}} s_{i,t,s,r} = 0 \quad \forall\, i,t,s,r \tag{13}
$$

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

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

complements

$$
\lambda_{i,t,s} \geq 0 \quad \forall\, i,t,s \tag{15}
$$

and the inner product

$$
\frac{\partial \mathcal{L}_{i,t,s,r}(s_{i,t,s,r}, \lambda_{i,t,s}, \tau_{r \to rr})}{\partial \lambda_{i,t,s}} \lambda_{i,t,s} = 0 \quad \forall\, i,t,s \tag{16}
$$

It should be noted that, concerning definition in Eq. (6), 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. (5) and (10), respectively), the supply variable $s_{i,t,s,r}$ is applied in Eq. (14) and (16), due to consistency in mathematical notation. Partial derivatives, taking into account the given transmission constraint, result in:

$$
\frac{\partial \mathcal{L}_{i,t,s,r}(s_{i,t,s,r}, \lambda_{i,t,s}, \tau_{r \to rr})}{\partial \tau_{r \to rr}} = \left(\sum_{i^-} s^{\mathrm{rr}}_{i,r} + \sum_{i^+} s^{\mathrm{r}}_{i,rr} \right) - t^{\max}_{r \to rr} \leq 0 \quad \forall\, r \to rr \tag{17}
$$

complements

$$
\tau_{r \to rr} \geq 0 \quad \forall\, r \to rr \tag{18}
$$

and the inner product

$$
\frac{\partial \mathcal{L}_{i,t,s,r}(s_{i,t,s,r}, \lambda_{i,t,s}, \tau_{r \to rr})}{\partial \tau_{r \to rr}} \tau_{r \to rr} = 0 \quad \forall\, r \to rr \tag{19}
$$

Considering the constraints of given production and transmission capacities, Eqs. (14) and (17) 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 $\tau_{r\rightarrow rr}$ 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, $\tau_{r\rightarrow rr}$ 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. (11) can be ignored. This assumption also holds for the competitive fringe and the foreign generators concerning oligopolistic supply.

Dominant producers' influence on market price due to strategic behavior can be well shown by rearranging the first order condition in Eq. (11) (indices suppressed). Applying market share ϑ_i and price elasticity of demand ϵ, player i's constrained profit maximization condition is:

$$P(S)\left(1+\frac{\vartheta_i}{\epsilon}\right) = C_i(s_i) + \lambda_i + \sum_{r\rightarrow rr} \tau_{r\rightarrow rr} \quad \forall\, i, t, s, r \tag{20}$$

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

The mark-up is thereby determined by the oligopolist's market share ϑ_i and the price elasticity of demand ϵ. As producers' strategically controlled generation capacity and related variable cost structures differ significantly among players, market shares and hence achievable price mark-ups are supposed to be asymmetric in equilibrium.

Due to the possibilities for interregional electricity trade, domestic market outcome can not be regarded as independent from neighboring countries' market structures. Regarding the differences in electricity generation portfolios and demand schedules, electricity trade can therefore provide significant profits from arbitrating price differences. Moreover, transmission network reinforcement is likely appropriate to improve price adjustment among countries.

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 extent 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 on the possibilities to limit price increase by electricity imports. In the following subsections, exemplary model results considering electricity transmission are presented.

4.1 Base case

Assuming firstly that the liberalized German electricity market is not integrated in the European UCTE network, a one-stage *Cournot-Nash* equilibrium in quantities for the physical spot market can be calculated. Given this restrictive assumption, 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 8 presents resulting market prices in the defined demand segments. The price elasticity of demand ϵ is assumed to be -0.25.

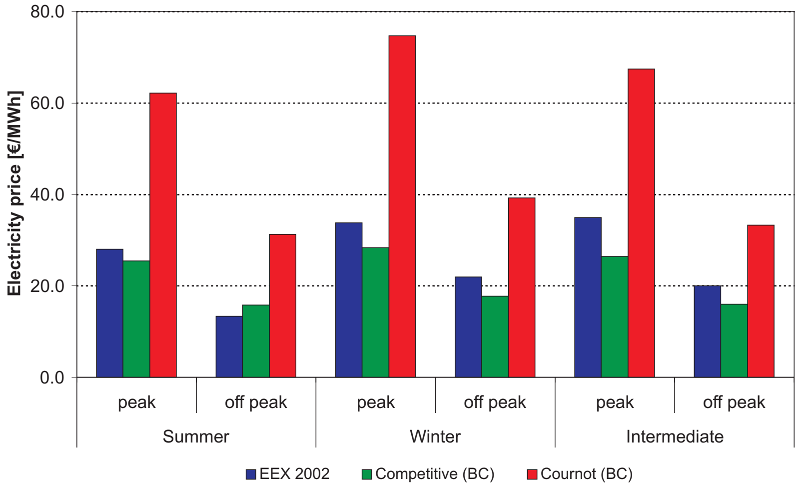

Fig. 8. Electricity prices in Germany – no transmission allowed, Scenario: Cournot (BC)

Considering the potentials to increase wholesale 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 8. The observable price increases result from significant mark-ups, which can be realized by the oligopolistic producers. Table 2 presents minimum and maximum values of the *Lerner-Index* which is defined as:

$$LI_i = \frac{\vartheta_i}{\epsilon} \equiv \frac{P(S) - C_i(x_i)}{P(S)} \quad \forall\, i, t, s \tag{21}$$

and overall profit under different assumptions regarding producers' behavior in the base case.

Table 2
Lerner-Index (LI) and profit [mill.€] of German producers – no transmission allowed

		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
Prof.	Cournot (BC)	3421	3272	2847	2265	3784
	Compet. (BC)	1635	1324	802	588	483

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 and network investment

Given the actual situation, where Germany is integrated into a large European electricity network having various interconnection to its neighboring countries, the restrictive assumptions 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 9 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 (TR)), and the corresponding perfectly competitive equilibrium with transmission (Competitive (TR)).

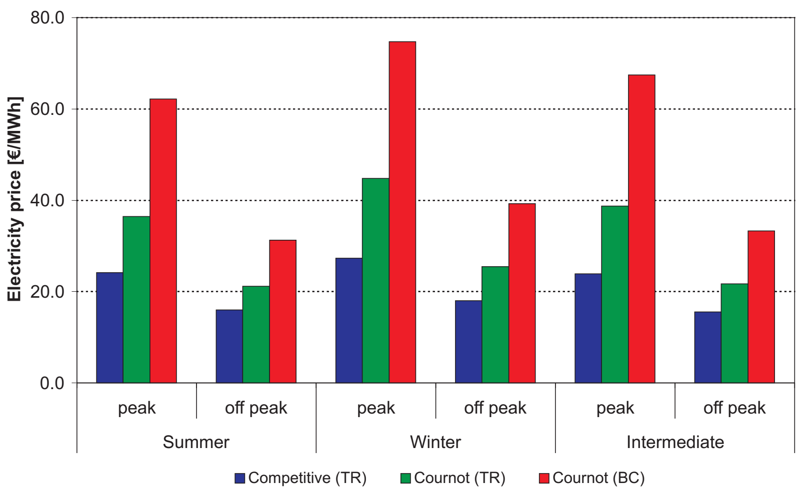

Fig. 9. Electricity prices in Germany – transmission allowed, Scenario: Cournot (TR)

As can be seen, interregional electricity exchange forces down prices in the Cournot (TR) 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 3. 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.

Table 3
Lerner-Index (LI) and profit [mill.€] of German producers – transmission allowed

		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
Prof.	Cournot (TR)	2027	1824	1390	1082	1390
	Compet. (TR)	1651	1261	753	554	420

Considering the current structure of the European transmission grid, e. g. Haubrich et al. (2001) and KEMA Consulting (2005) 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 is 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) and KEMA Consulting (2005), the North-Western European 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 occasional congestion, particularly in summer. For Germany's interconnections to Eastern Europe, the transmission lines to Poland are considered to be congested also. Beside the already mentioned interconnections within the BeNeLux region, transmission lines between Belgium and France and for South-Eastern Europe, Austria and Czech Republic 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 $\Longleftrightarrow$ The Netherlands, 700 MW
- Germany $\Longleftrightarrow$ France, 600 MW
- Germany $\Longleftrightarrow$ Denmark, 1250 MW
- Germany $\Longleftrightarrow$ Poland, 750 MW

• Belgium	$\Longleftrightarrow$	The Netherlands,	1000 MW
• Belgium	$\Longleftrightarrow$	France,	1000 MW
• Austria	$\Longleftrightarrow$	Czech Republic,	250 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 10. The *Cournot-Nash* equilibrium with capacity expansion is denoted by Cournot (TR+), whereas Competitive (TR+) represents the corresponding perfectly competitive equilibrium. It can be seen that the strategically influenced electricity price is reduced by approximately 6 % in the summer off-peak period, whereas the price reduction in the winter and intermediate peak periods amounts to 12 % and 13 %, respectively, compared to the *Cournot-Nash* equilibrium considering the current transmission capacities (Cournot (TR)).

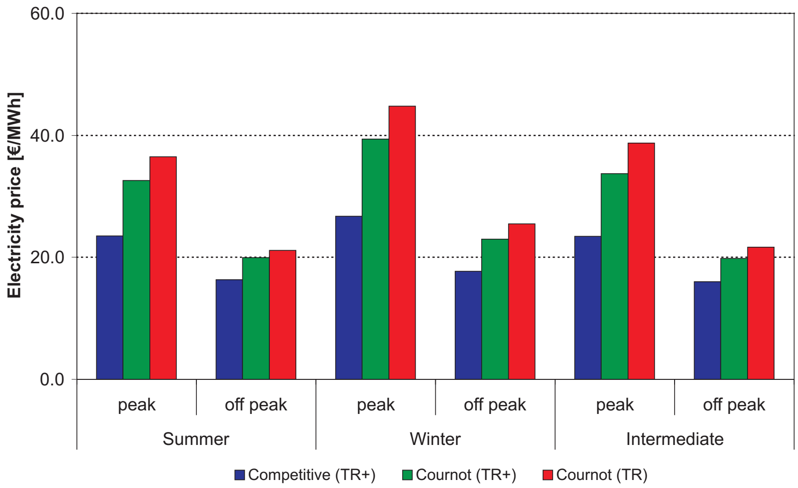

Fig. 10. Electricity prices in Germany – transmission network investment, Scenario: Cournot (TR+)

Although network reinforcement lowers the strategically influenced electricity prices in Germany, the oligopolistic players are still able to exercise market power and to increase prices significantly. Given the perfectly competitive market outcome (Competitive (TR+)), the electricity price in the summer, winter and intermediate peak periods of the Cournot (TR+) scenario lies 39 %, 47 % and 44 % above the competitive level. For the corresponding off-peak periods, price increases of 22 %, 30 % and 24 % can be observed.

Again, the potentials to increase market price by withholding capacities and supply, respectively, can also be analyzed by calculating the *Lerner-Index*, cf. Table 4. As expected, *Lerner-Index* and profit is reduced, due to enhanced imported competition by foreign electricity supply in the German market.

Table 4
Lerner-Index (LI) and profit [mill.€] of German producers – transmission network investment

		RWE	E.ON	Vattenfall	EnBW	Fringe
LI	min/max	0.44/0.59	0.41/0.55	0.39/0.46	0.32/0.37	0.00/0.00
Prof.	Cournot (TR+)	1772	1570	1170	899	1042
	Compet. (TR+)	1577	1221	737	544	401

In summary, 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 possible strategically influenced electricity prices in Germany, given its oligopolistic market structure.

4.3 Gradual network reinforcement

As has been shown, increased possibilities for interregional electricity exchange due to the above described transmission investment projects can lead to enhanced competition in Germany. To what extent gradual network investments between Germany and its neighboring countries can change market power potential has furthermore been analyzed considering exemplary bilateral cross-border transmission capacity enlargements.

Within the scenario Cournot (TR++), the transmission lines between Germany and France, The Netherlands, Denmark and Switzerland have been separately increased in 20 steps each of 100 MW, i. e. about 2000 MW overall (cf. Table 1 for initial capacity values). It can be observed that the enlargements of different transmission lines have specific effects on German electricity prices. Figures 11 and 12 present the price development in the summer and winter peak period, respectively, due to stepwise network investments. Whereas the increase of the cross-border capacity between German and Denmark leads to a decrease in electricity price by approximately 5.0 % in the summer peak segment, the price decrease due to network investment between Germany and The Netherlands amounts to approximately 4.2 %.

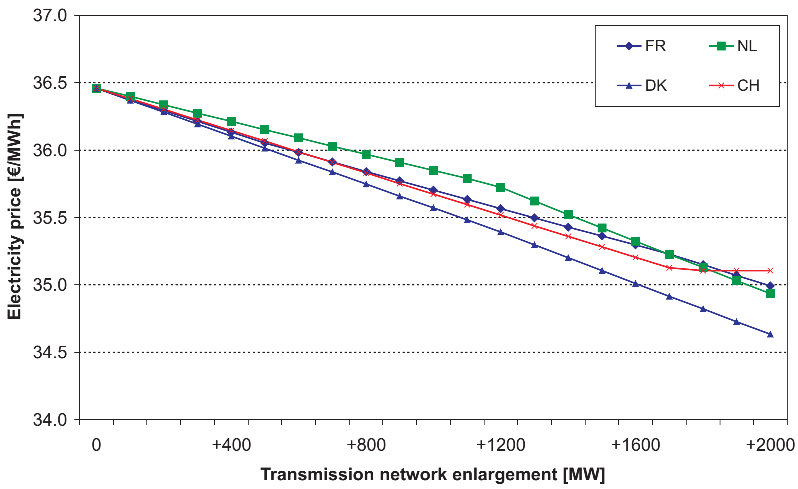

Fig. 11. Electricity prices in the summer peak period in Germany – gradual transmission network investment, Scenario: Cournot (TR++)

Regarding the interconnection capacity to Switzerland, the German electricity price keeps constant from a bilateral transmission capacity of 5430 MW onward. The same effect can be seen in the winter peak period. At a transmission capacity of 4530 MW, additional network enlargement to Switzerland does not lead to a further price decrease in Germany. Electricity price keeps constant on a level of 44.21 €/MWh (cf. Figure 12). This effect is determined by the specific supply and demand structures in the Swiss market. As marginal generation cost and hence electricity price in the winter peak period in Switzerland amounts to the German market price level, no additional electricity exchange is induced.

Similar to the price changes in the summer peak period, network investments in the cross-border capacity to Denmark lead to a greater price decrease in the winter peak segment in Germany than investments in the interconnection capacity to The Netherlands (cf. Figure 12). Whereas Germany/Denmark network investments amount to approximately 4.2 % price reduction, investments in the cross-border capacity to The Netherlands lead to approximately 3.7 % price decrease.

The increased possibilities for electricity exchange between Germany and its neighboring countries lead to higher pressure on electricity prices and hence to decreasing potential to exercise market power. Due to further growing export possibilities of foreign countries, German producers' ability to influence the market price is reduced. Figure 13 presents the *Lerner-Index* for the two dominant generators RWE Power AG and E.ON Energie AG in the winter peak period in Germany. It can be observed that the changes in the *Lerner-Index* show similar developments as the electricity price changes presented in Figure 12.

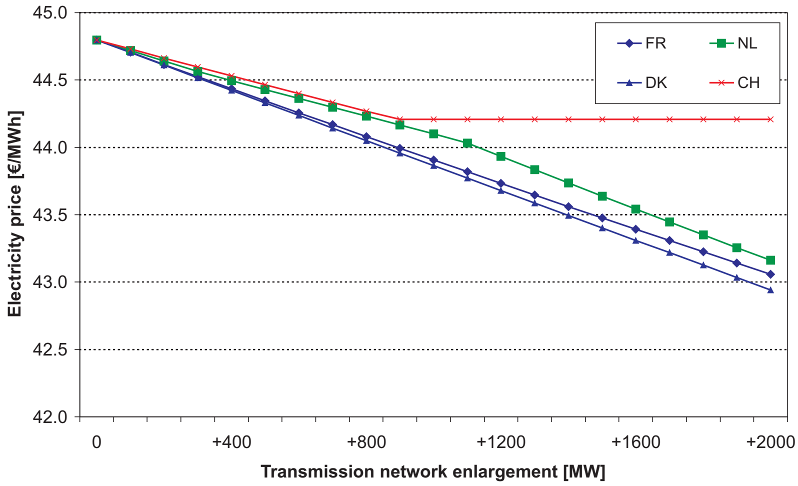

Fig. 12. Electricity prices in the winter peak period in Germany – gradual transmission network investment, Scenario: Cournot (TR++)

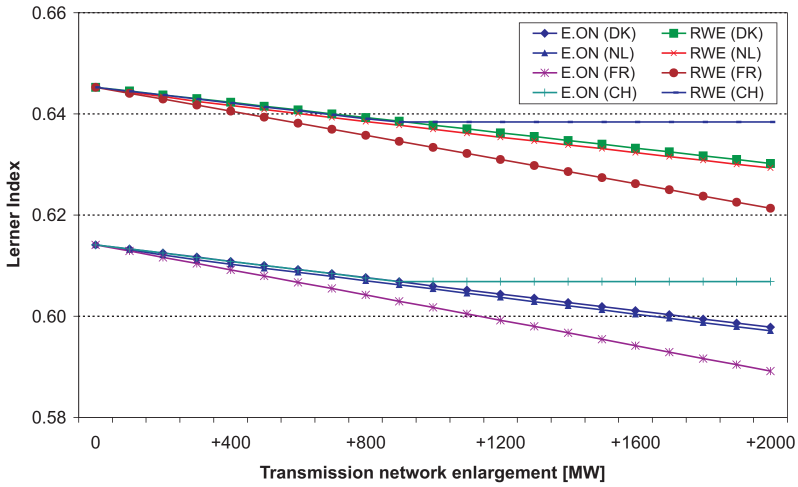

Fig. 13. Lerner-Index of RWE Power AG and E.ON Energie AG in the winter peak period – gradual transmission network investment, Scenario: Cournot (TR++)

Besides the potential to mitigate market power and therefore to enhance competition, the analysis has shown that the impact of transmission network investments on market outcome are determined by the specific supply and demand structures in the considered electricity markets. Given the different possible effects on market prices, the specific outcomes of various investments have to be taken into account when suitable bilateral interconnection reinforcement is to be implemented.

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 influences producers' market decisions and to what extent transmission investments contribute to market power mitigation in Germany.

Depending on the regarded investment projects, German market outcomes are determined by specific supply and demand structures within the considered countries. It has been shown that network investments in the cross-border capacity between Germany and Denmark lead to a stronger price reduction than e. g. investments in the interconnection capacity between Germany and The Netherlands, given strategic behavior of the German electricity producers.

Regarding the competition enhancing effects of interregional electricity exchange, it can be concluded that market power analyses at least for Germany should take this aspect into account. Within the analysis presented here, network enlargements were determined exogenously, i. e. no explicit optima for transmission investment were derived. Endogenous investment for network infrastructure requires a different type of model and therefore has not been the focus of this analysis.

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Table 5. 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