OR Spectrum
DOI 10.1007/s00291-015-0415-x

REGULAR ARTICLE

Perfect competition vs. strategic behaviour models to derive electricity prices and the influence of renewables on market power

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Received: 30 June 2014 / Accepted: 10 August 2015

Abstract A variety of fundamental modelling approaches exist using different competition concepts with and without strategic behaviour to derive electricity prices. To investigate the quality and practicability of these different approaches in energy economics, a perfect competition model, a Cournot model and a Bilevel model are introduced and applied to different situations in the German electricity market. The three electricity market approaches are analysed with respect to their ability to represent electricity prices and the possibility of market power abuse. Market prices are taken as a benchmark for model validity. As a result, the perfect competition model fits best to today's market situation in most hours of the year. The Bilevel approach explains prices in high load hours sometimes better than the competition model. But complexity and calculation time increase disproportionately. In addition to the analysis of model quality, we use three scenarios to quantify how a high renewable feed-in influences the ability to abuse market power. Results show that the ability to address market power strongly depends on the amount of installed capacities.

Keywords Electricity prices · Electricity market modelling · Perfect competition model · Cournot model · Bilevel model · Market power

1 Introduction

Companies in the energy sector face structural changes due to the liberalisation of electricity markets, the introduction of emission trading and the integration of renewable energies. In this context, complementarity models are an important and interesting approach to model player behaviour in electricity markets. There are several comple-

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Published online: 02 September 2015

mentarity model approaches and publications addressing this topic in energy markets. However, these models are often quite theoretical and an application to real markets is often lacking. In this paper, two complementarity approaches are used to model strategic behaviour of utilities and their impact on electricity prices. To obtain information about the validity and accuracy of the models, their results will be benchmarked with real market observations (hourly market prices) as well as with a standard competition model based on linear optimisation. Hence, the three different modelling approaches—perfect competition, Cournot competition and a Bilevel approach—will be compared based on real market data.

For this purpose, three scenarios are used to analyse the strengths and weaknesses of the different modelling approaches. As a first scenario, the modelling approaches are applied to the German electricity market for the year 2012.[1] This base scenario should show how good the different models can explain wholesale electricity prices, players' behaviour[2] and how they differ in the way of market modelling. Two further scenarios allow for the analysis of the impact of renewable energy penetration on the ability of conventional capacities to abuse market power. The potential to abuse market power depends (amongst others) on the amount of generation capacities, which is why we vary the amount of generation capacity. Therefore, in the second scenario, we have selected a historical market situation in Germany, the year 2001, where several papers claim that no market power was abused (see e.g. Möst and Genoese 2009; Müsgens 2006) and where the renewable generation capacity is still quite low. For this market situation, we analyse the differences in market results and check which model results are closest to reality. In the third scenario, we choose an expected future market situation, where the amount of renewable power feed-in is high. In this context, we want to know about the impact of renewables on the ability of conventional power plants to abuse market power especially in peak load times. This is especially relevant as the questions arise: how can capacities be financed when there are significant amounts of technologies in the market with marginal costs of zero and what will be their impact on market prices?

Summarising, it is the objective of the paper to apply different model concepts to demonstrate their ability to derive electricity prices and to compare their ability to explain market results. Additional to that the paper addresses the research question: what is the influence of renewable generation capacities on the ability to abuse market power? Therefore, the behaviour of the different models in the different scenarios will be compared to each other and some market power measures will be calculated. From these results, the significance of the models will be evaluated.

The article is organised as follows: after a short literature review about complementarity models in energy markets and about model application addressing market power questions in Sects. 2 and 3 the fundamentals of the developed and applied models are explained: a perfect competition approach, a Cournot approach and a Bilevel approach as well as the scenario assumptions. In Sect. 4 modelling results, the impact of renewables on the ability of conventional power plants to abuse market power and on different market power indicators are presented. Finally, a conclusion summarises the findings.

[1] The year 2012 is chosen as present year, as relevant data for power markets are available.

[2] In this paper, the players are utilities.

2 Application of complementarity models to electricity markets and of models addressing market power issues

In the following, a short literature overview in the three addressed working fields of this article will be given. First, complementarity models and their application to electricity markets, second, modelling of market power issues in electricity markets and third, the impact of renewable energies on market power as well as on electricity prices.

There are at least two reasons why complementarity models become more and more interesting for modelling energy markets. First, liberalisation and restructuring of energy markets necessitate approaches dealing with these new framework conditions. Second, significant progress has been made on using and solving complementarity formulations for real market applications.

Complementarity approaches allow the modelling of non-cooperative games in which each market agent can solve a separate but related optimisation problem, subject to system-wide constraints. Additionally, this model formulation allows the inclusion of constraints on both primal and dual variables, which traditional problems cannot handle. Some researchers believe that such improved models and algorithms in this area will, therefore, be fruitful and challenging areas of research (Gabriel et al. 2013, p. ix).

One of the earliest complementarity modelling approaches was applied to the UK power market and published in 1999 (Wolfram 1999). Within her paper, Wolfram could show that real market prices are significantly below predicted prices in the Cournot case. The field of congestion pricing in transmission networks is an application of Cournot competition to analyse the influence of market power on prices in congested zones. Hobbs formulated a Nash–Cournot competition model in Hobbs (2001) that also includes both Kirchhoff's laws of transmission. This model is applied to a simple example. Another important application of Cournot-based models is the coordination of hydro-thermal power plant portfolios. Scott and Read (1996) analyse the effects of contracts and of company structure within a medium-term market simulation model taking firms with thermal and hydropower plants into account. In this approach, they apply a dual dynamic programming methodology, with the sub-models at each stage being Cournot duopolies. In our contribution, we focus on the possibility to explain market results, while Scott and Read concentrate on the "gaming by mixed hydro-thermal firms". This shows that the variety of applications is quite broad and a good overview about different areas of application and models can be found in Ventosa et al. (2005).

Besides Cournot approaches, Bilevel problems have been applied to energy markets in the last years. Bilevel problems are optimisation problems constrained by other optimisation problems, which explicitly indicates a hierarchy (see e.g. Gabriel et al. 2013 for an intuitive introduction). This approach is helpful if market agents have to make decisions anticipating the equilibrium of the market. As Gabriel et al. (2013) state: "Anticipating the market equilibrium is necessary, for instance, to estimate the market clearing price, which in turn is used to establish the strategy of the agent (e.g., maximising profit)." Barroso et al. (2006) formulated a Bilevel problem where the upper level problem represents the profit maximisation of a strategic producer, while the lower level one represents the market clearing and the corresponding price formation. After developing the model, it is applied to a small example. Gabriel and Leuthold applied a Bilevel problem for 1 h to the electric power markets in Gabriel and Leuthold (2010). Model results for this single hour show significant deviations from the real market behaviour and this application can be classified as a quite small real world application.

It can be summarised that complementarity models are often used in the last years, but only for applications with a limited evidence. This comment should not weaken the above-mentioned papers, but should emphasise that application to real market situations is a valuable further research area, which should be addressed in this paper.

In contrast to these complementarity approaches, several papers addressing market power issues exist, which use less complex model approaches, sometimes only statistical analysis. The reason for that can be seen in the fact that with the liberalisation of the electricity markets the discussion about market power started and the issue of market power was controversially discussed.[3] In Europe, especially the markets in UK, Spain and Germany are addressed by several academic papers: a good and current overview about papers addressing market power is given in Wozabal and Graf (2013). Several papers are claiming that prices are sometimes above competitive levels (see e.g. Wolfram 1999; Müsgens 2006; Weigt and von Hirschhausen 2008), but also papers concluding that the exercise of market power cannot be confirmed or that criticise studies using the mark-up on these short-run marginal costs as indicator for the abuse of market power (see e.g. Möst and Genoese 2009; Ockenfels 2007; Ellersdorfer et al. 2007). Thus is also the objective of this contribution to use different competition concepts to analyse their ability to derive market prices. The comparison with real market data should thereby provide information about the competitiveness of the market.

To investigate market power in electricity markets, different methods have been developed and applied. A simple method is the calculation of market power measures like the concentration ratio[4] to investigate the market structure [e.g. Bundeskartellamt (Bataille and Thorwarth 2013)]. This measure has several shortfalls, such as not considering fluctuating demand, power plant restrictions, as it is not only developed for electricity markets. In market power literature, very often models are used to derive a price benchmark. This price benchmark is compared to observed market prices. Often the Lerner index is applied for an indicator calculation. In short, the Lerner index describes the mark-up of observed prices to model prices.[5] For the calculation of these benchmark prices, different model approaches can be applied which can be grouped in the following categories: competition models, agent-based simulations and game-theoretic models (refer to Chapter 3 in Ellersdorfer 2009).

Competition models Often ex-post analysis is applied and competitive benchmark results are compared with market outcomes. An early example can be found in Wol-

[3] Also, in the United States, especially after the California energy crisis in 2001 and 2002, an intense academic debate concerning whole sale electricity prices in California started and the interested reader is referred to e.g. Bushnell et al. (2002), Joskow and Kahn (2002), Mansur et al. (2002) and Kim and Knittel (2006). Most of these papers use empirical methods to analyse the abuse of market power and find indications for the abuse of market power during this crisis.

[4] For example, the concentration ratio is used by the German monopoly commission to test structural market power (independent from energy markets).

[5] For a short overview about market power indicators for electricity markets see e.g. Möst and Genoese (2009).

fram (1999). Wolfram studied the British electricity spot market in 1992 until 1994 and claimed significant mark-ups priced on top of marginal costs. Weigt and von Hirschhausen (2008) studied the German market and compared spot market prices on the European Energy Exchange (EEX) with prices based on a competitive benchmark model and found competitive base prices 11 % below the average price at the EEX.

Agent-based simulation In an agent-based simulation, the individual market participants are modelled. In contrast to competition or oligopolistic models, no market equilibrium is calculated. The market outcome is determined by the individual behaviour of the participants and the defined behaviour rules. An early application for the market in England and Wales can be found in Bunn and Oliveira (2001). A study about market power by Möst and Genoese (2009) used an agent-based simulation to approximate the marginal costs and the electricity prices of the electricity market in Germany in the years 2001–2006. It summarises that there is no observable market power abuse.

Game-theoretic models Game-theoretic models are already introduced above for different contexts (not only market power). As also papers addressing market power issues are mentioned above, no further papers will be highlighted here.

Few studies address the influence of renewables on the ability of conventional power plants to abuse market power, which is also addressed in this paper. For example, Traber and Kemfert (2009) applied a Cournot model to the German electricity market to analyse the influence of the renewable subsidies on the market position of the big players with respect to the network and the emission policies. The effect of the subsidies is divided into a substitution effect where conventional capacities are replaced and an allowance effect where emission prices are influenced. They conclude that there is nearly no influence because of the trading possibilities to neighbouring countries. Another paper was presented by Tanaka and Chen (2013) where the strategic behaviour in the renewable energy certificate (REC) market is investigated. It is shown that market power could have significant impacts on the REC and electricity prices. The differing conclusions between these two papers can be explained by the fact that different policy instruments for renewable support (REC vs. feed-in tariff) are assumed and additionally the investment possibility of the firm is different. Additionally, some papers exist analysing the influence of renewables on market prices. Very low prices occur as renewable generation is provided with marginal costs at zero and the compensation of renewables is paid outside the market, while a low demand occurs resulting in low prices. This phenomenon of low prices in combination with renewable feed-in is also called the merit-order effect of renewables. The interested reader is referred to Sensfuß et al. (2008) and Keles et al. (2012). Besides, Green and Vasilakos examine the impact of intermittent wind generation on hourly equilibrium prices and output in UK and conclude . . .” Above-average wind speeds lead to below-average prices, but annual revenues for British wind generators (producing more in the winter) are almost as great as for base load generators (Vasilakos and Green 2010).

Currently, market power plays a minor role in Europe, as wholesale electricity prices are very low.[6] Nevertheless, one current article deals with market power in Germany

[6] Market power has been an issue in the years 2004–2007 and several publications exist for this period, especially in Germany. Since 2008–2010, wholesale electricity prices have been quite low and very

(Bataille and Thorwarth 2013). The authors from the Monopolkommission concluded that the market power of the big players of the German electricity market some years ago is not present in 2012 anymore. The results are based on the calculation of the Residual Supply Index for data of 2012 for Germany and Austria. But they point out that the dynamics of the energy markets and changes in the market design can lead to other results in a little while. We pick up this statement as starting basis and analyse how market power will develop in the German electricity market, especially taking the growing amount of renewable feed-in into account and by comparing different modelling approaches to derive electricity prices.

3 Cournot and Bilevel approach to model the German electricity market

As stated in the research question in the introduction, we want to apply several model approaches to analyse player behaviour and the impact on wholesale electricity prices taking different generation situations into account. Three modelling approaches will be deduced and explained in the following. This includes one competitive modelling approach based on linear programming with inverse demand function, one Cournot model and one Bilevel model.

To formulate the models, the following indices, parameters and variables are needed.

Indices

h	Modelling hours
f	Firms taking part in competition
s	Power plant/station
s_f	Power plant/station of firm f

Parameters

$a(h)$	Intersection of linear demand
$b(h)$	Slope of linear demand
$\mathrm{oc}(h, s)$	Operation cost of power plant s in hour h
$\kappa(h, s)$	Capacity of power plant s in hour h

Variables

$g(h, s)$	Dispatch of power plant s in hour h
$\gamma(h, s)$	Dual variable of capacity constraint
$\delta(h, s)$	Dual variable of dispatch constraint.

A linear inverse demand function $f_{d,h}^{-1}$ is assumed $p(h) = f_{d,h}^{-1}(q(h)) = a(h) + b(h)q(h)$ with $p(h)$ as price and $q(h) = \sum_s g(h, s)$ as quantity in hour h. The linear inverse demand function is derived on the basis of historical prices $p_{\mathrm{eex}}(h)$,[7] historical

Footnote 6 continued
competitive, so that currently no publications claim that market power is observable. But household consumer electricity prices are one of the highest in Europe, especially due to the renewable energy act surcharge and taxes.

[7] Of the European Energy Exchange—https://www.eex.com/.

residual loads $\text{res}_l(h)$ (total demand minus generation of renewables in hour h) and an assumed elasticity ε. The use of historical data should allow for having a realistic picture of the demand. We chose two elasticities to cope with the influence of the elasticity on the ability to abuse market power, namely -0.075 and -0.25, which are commonly used in electricity markets (cf. Green 2007).[8]

For interpretation of the results of the complementarity models, a benchmark or reference model with perfect competition is used. This competition model is the starting point for the development of the complementarity models and is deliberately kept very simple. This means that general restrictions of a competitive electricity market model are not included for reasons of comparability (cf. Sect. 3.1). In this contribution, the simplifications are acceptable.

3.1 Competitive model of the electricity market with an inverse demand function

As derived in Gabriel et al. (2013), Chapter 3 a competitive market can be represented by social welfare maximisation. The social welfare can be calculated by

$$\text{Maximise}_{g(h,s)} \sum_h \left[\sum_s \text{oc}(h,s) g(h,s) - a(h) \sum_s g(h,s) - \frac{1}{2} b(h) \left(\sum_s g(h,s) \right)^2 \right] \tag{1}$$

(refer to the derivation in "Appendix" section or Example 3.4.2.1 in Gabriel et al. 2013). Of course, the dispatch of the power plants is limited by its capacity $\kappa(h,s)$. That leads to the following constraint:

$$0 \leq g(h,s) \leq \kappa(h,s) \quad \forall h, s. \tag{2}$$

To represent perfect competition in electricity market, this simplified model has been chosen. The decisions were made to ensure comparability to the following Cournot model including strategic behaviour. Optimisation models are in general more detailed (see e.g. Kunz 2013). Besides, capacity restriction and a fluctuating demand (which is considered here), optimisation models often include conditions to depict, for example, the following special characteristics in electricity markets[9]:

- load change restrictions: production quantities of conventional power plants can only change in a restricted range from 1 h to another

[8] In electricity markets, electricity demand is often assumed to be inelastic. In this contribution, we take two different elasticities into account: one nearly inelastic and one slightly more elastic. Slope and intersection are determined by: $b(h) = \frac{p_{\text{eex}}(h)}{\varepsilon \text{res}_l(h)}$, $a(h) = p_{\text{eex}}(h) - b(h)\text{res}_l(h)\ \forall h$. In case the residual load is zero slope $b(h)$ and intersection $a(h)$ are also zero $\forall h$.

[9] The interested reader is referred to Martinez (2008), who contributes to the formulation and implementation of production cost models for the modelling of liberalised electricity markets by addressing issues associated with the level of detail in the representation of the underlying power system, the accuracy of the results and the modelling effort.

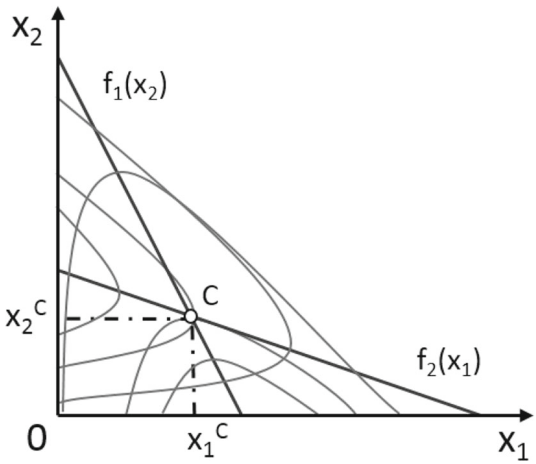
- shutdown periods: conventional power plants are scheduled for shutdown (e.g. revision) or unscheduled (e.g. accident) a couple of days in a year
- pump storage: inter-period restriction to model the storage level
- power grid: in load flow models also power grid restrictions are taken into account to consider physical load flows
- balancing energy: balancing energy has to be provided to ensure functionality of the grid
- as well as further restrictions, such as CO_2 reduction restrictions, load change costs, combined heat and power provision.

3.2 Cournot model of the electricity market with an inverse demand function

In contrast to a competitive market, Cournot competition describes an industry structure in which companies compete on the amount of output they will produce. The companies are economically rational and act strategically, usually seeking to maximise profit given their competitors' decisions. This means that each firm uses its knowledge of the inverse demand function to anticipate its own effect on the market price. However, each firm would have to make a guess about the other firm sales quantity to predict the market price (the price depends on total demand). The principle is pictured in Fig. 1 where the isoprofit curves of firm one and two are presented (the parabolic curves). Every isoprofit curve shows a fixed level of profit with different combinations of produced quantities (x_1, x_2) of firm one and two. The closer the curve is to the axes the higher is the profit. The functions through the maximum of all isoprofit curves depict the reaction function $(f_1(x_1),\ f_2(x_2))$ of each firm to the produced quantity of the competitor. The intersection of both reaction functions presents the Cournot equilibrium. In contrast to a perfect competition market, prices are higher in the Cournot case. For more information, confer the literature (e.g. Blum et al. 2006).

Within this contribution, we base our model on Gabriel et al. (2013), section 3.4.2.5. The total demand $q(h)$ is used to calculate the price $p(h)$ with the linear inverse demand function $f_{d,h}^{-1}(q(h)) = a(h)+b(h)q(h)$. Each firm f makes a guess about the quantity

Fig. 1 Cournot game with two firms (own representation based on Blum et al. 2006)



decisions $\bar{dp}(h, s_{\bar{f}})$ for every power plant of other firms $\bar{f} \neq f$, and chooses its own quantity for every power plant $g(h, s_f)$ to maximise its profit. In the following model for firm f, total demand $q(h)$ in hour h is understood by firm f to be equal to $\sum_{s_f} g(h, s_f) + \sum_{\bar{f} \neq f} \sum_{s_{\bar{f}}} \bar{dp}(h, s_{\bar{f}})$. The target function maximises revenues minus costs for firm f. Be aware that this optimisation problem holds for each firm:

$$\text{Maximise}_{g(h,s_f)} \sum_{h,s_f} g(h, s_f) f_{d,h}^{-1}(q(h)) - \sum_{h,s_f} oc(h, s_f) g(h, s_f) \tag{3}$$

$$\text{s.t.}$$

$$g(h, s_f) - \kappa(h, s_f) \leq 0 \quad \forall s_f, h \quad (\gamma(h, s_f)) \tag{4}$$

$$-g(h, s_f) \leq 0 \quad \forall s_f, h \quad (\delta(h, s_f)). \tag{5}$$

Note that each dual variable is indicated in parentheses to the right of its associated equation. Following the argumentation in Gabriel et al. (2013) and suggesting a linear inverse demand function as described above, we achieve the following complementary representation of the Nash–Cournot model:

$$\begin{aligned} 0 = \mathrm{oc}(h, s_f) - a(h) - b(h) \sum_{s} g(h, s) - b(h) \sum_{s'_f} g(h, s'_f) \\ - b(h) \sum_{s'_f} g(h, s'_f) - \delta(h, s_f) + \gamma(h, s_f) \quad \forall h, s_f, f \end{aligned} \tag{6}$$

$$0 \geq g(h, s_f) - \kappa(s_f) \perp \gamma(h, s_f) \geq 0 \quad \forall h, s_f, f \tag{7}$$

$$0 \geq -g(h, s_f) \perp \delta(h, s_f) \geq 0 \quad \forall h, s_f, f \tag{8}$$

where the alias index s'_f is used to index summations in Eq. (6) over all power plants of company f[10]. Equation (6) is composed by the operating costs[11] of electricity production (h, s_f), minus the market price $a(h) - b(h) \sum_s g(h, s)$ in hour h, plus a marginal revenue [slope $b(h)$ is negative] and some shadow prices of the restrictions. Equations (6)–(8) are the typical Karush–Kuhn-Tucker condition and hold for each firm f. To solve the model, the optimisation software GAMS is used.

3.3 Bilevel model of the electricity market with an inverse demand function

In the following, a Bilevel problem is introduced. Bilevel problems describe optimisation problems constrained by complementarity and other optimisation problems. Thus, they belong to the class of hierarchical optimisation. We have chosen this Bilevel approach due to two reasons:

[10] $\forall s_f, f$ indicates that this condition holds for every power plant s_f of firm f and for all elements of f (all firms).

[11] Operating costs include fuel costs, costs for CO_2 emissions (both dependent on fuel/emission prices and the efficiency of the plant) and further operating costs.

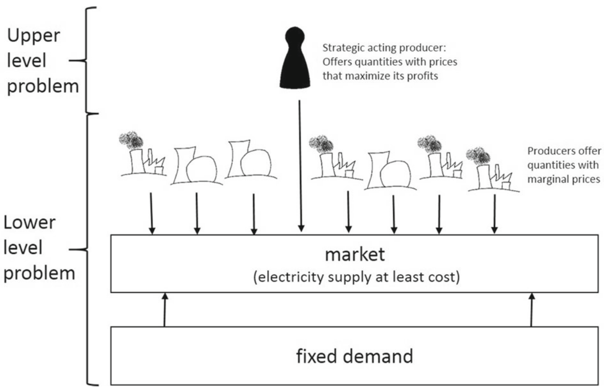


Fig. 2 Bilevel model: schematic representation

- Cournot models (as depicted above) often deduce too high prices and thus a modelling approach closer to competition is selected. Bilevel approaches allow for this purpose.
- As mentioned in the introduction, this paper should also serve as comparison of different modelling approaches and their ability to derive wholesale electricity prices. Bilevel approaches are an interesting approach to model players behaviour in electricity markets.

We base our Bilevel model on Barroso et al. (2006) and Gabriel et al. (2013). In our model, a price maker agent (who can affect market prices with its bids) is considered that trades electric energy in a day-ahead spot market. This describes a situation in which one large utility or in the case of market collusion several utilities can abuse market power. This means that a (or several) owner(s) uses its generating units in a strategic sense to alter the formation of the market clearing price. In contrast to a Stackelberg competition, the strategic player can influence the market clearing price over its price bids and not over the offered quantities. Therefore, a fixed demand to cover can be assumed. We selected this approach because the assumptions are more consistent with reality. The case of offering no quantities for one power plant can be achieved by price bids over the market clearing price (very high prices).

The lower level problem contains the clearing of the spot market as well as the bidding of the price-taking firms. Every other participant offers its quantities with the marginal costs at the central auction. The offers are ordered to determine the lowest price for electricity that covers the whole demand (merit-order principle) and thus represents a competitive market. The upper level problem depicts the profit maximising strategy of the price maker utility. In Fig. 2, the upper and lower problem as well as the main principle is illustrated.

We apply this model to a real scenario for 8760 h (1 year).

To set up the Bilevel model, we define the additional indices, parameters and variables:

Indices

ss Power plant/stations of firms acting strategically sm Power plant/stations of firms acting as price takers

i Generation levels

Parameters

M Constants for Foruntу-Amat and McCarl linearisation

Variables

$_{\text{fake}}(h, \text{ss})$	Strategic price offer for the stations ss of the strategic player in hour h
$p(h)$	price of electricity in hour h
$\phi_{\max}(h, s)$,$\phi_{\min}(h, s)$	Dual variable for capacity restriction, positive
$v(h, \text{ss}, i)$	Variable for linearisation of target function, positive
$q_{dp}(h, \text{ss}, i)$, $q_v(h, \text{ss}, i)$,$q_p(h, i)$	Binary variable for linearisation of target function.

The set of all power plants s is divided into the two sets ss (power plants of strategic player) and sm (power plants of prict taking producers).

3.3.1 Basic Bilevel problem

The lower level problem (9)–(10) pursues to maximise the social welfare (compare Sect. 3.1). The price-making producer bids with the variable $oc_{\text{fake}}(h, \text{ss})$ for its power plants ss. The other participants offer the known marginal costs $\text{oc}(h, \text{sm})$ for their power plants sm at the market:

$$\text{Maximise}_{g(h,s)} \left[\sum_{\text{ss}} \text{oc}_{\text{fake}}(h, \text{ss}) g(h, \text{ss}) + \sum_{\text{sm}} \text{oc}(h, \text{sm}) g(h, \text{sm}) \right.$$
$$\left. -a(h) \sum_{s} g(h, s) - \frac{1}{2} b(h) \left(\sum_{s} g(h, s) \right)^2 \right]. \tag{9}$$

The lower level problem is constraint by a power plant capacity restriction (10).

$$0 \leq g(h, s) \leq \kappa(h, s) \quad \forall s, h \quad (\phi_{\min}(h, s), \phi_{\max}(h, s)) \tag{10}$$

The *upper level problem* (11) seeks to maximise the profit of the strategically acting firm:

$$\text{Maximise}_{\{g(h,s)\} \cup \{\text{oc}_{\text{fake}}(h,\text{ss})\}} \sum_{h,\text{ss}} p(h) g(h, \text{ss}) - \sum_{h,\text{ss}} \text{oc}(h, \text{ss}) g(h, \text{ss}). \tag{11}$$

The objective function includes revenue minus costs. The revenue is computed by multiplying the energy sales $g(h, \mathrm{ss})$ and the market clearing price $p(h)$ obtained from the lower level problem (9)–(10). The upper level problem has no constraints other than those from the lower level problem and it is a nonlinear problem due to the term $p(h)g(h, \mathrm{ss})$.

We convert the Bilevel problem into an mixed-integer linear problem (MILP) to solve it with an appropriate solver (as nonlinear Bilevel problems cannot be solved directly). Three steps are necessary: First, the Karush–Kuhn–Tucker conditions are applied to reformulate the lower level optimisation problem as a system of equations. Second, the complementarity constraints are converted into equations and finally the nonlinear term $p(h)g(h, \mathrm{ss})$ is linearised. In the following, the three steps are described in detail.

(*A*) *Corresponding MPEC* If the lower level optimisation problem constraining the upper level problem is convex, it can be replaced by its corresponding Karush–Kuhn–Tucker (KKT) conditions (Bertsekas 1999). Note that for convex problems meeting appropriate constraints qualifications, KKT conditions are both necessary and sufficient optimality conditions (see Gabriel et al. 2013, p. 235). Since the lower level problem (9) and (10) is linear and thus convex, the Bilevel problem (11), (9) and (10) can be recast as an mathematical program with equilibrium constraints (MPEC) as indicated below.

First, we replace the lower level problem by its KKT conditions. We start with the derivative with respect to $g(h, \mathrm{ss})$

$$0 = \mathrm{oc}_{\mathrm{fake}}(h, \mathrm{ss}) - p(h) + \phi_{\max}(h, \mathrm{ss}) - \phi_{\min}(h, \mathrm{ss}) \tag{12}$$

and with respect to $g(h, sm)$

$$0 = \mathrm{oc}(h, \mathrm{sm}) - p(h) + \phi_{\max}(h, \mathrm{sm}) - \phi_{\min}(h, \mathrm{sm}). \tag{13}$$

The complementarity constraints are

$$0 \le \phi_{\max}(h, s) \perp \kappa(h, s) - g(h, s) \ge 0 \quad \text{and} \tag{14}$$

$$0 \le \phi_{\min}(h, s) \perp g(h, s) \ge 0. \tag{15}$$

(*B*) *Complementarity constraints* The complementarity constraints (14) and (15) in combination with integer variables are difficult to handle in GAMS. Thus, we use a binary formulation of the complementarity restrictions. Fortuny-Amat and McCarl developed a linearisation in their paper (Foruny-Amat and McCarl 1981). The complementarity constraints of the type

$$0 \le x \perp y \ge 0 \tag{16}$$

can be replaced by the following set of linear constraints

$$0 \le x \le Mu \tag{17}$$

$$0 \leq y \leq M(1-u) \tag{18}$$

being M large enough and u binary. Care should be exercised to select constant M to avoid numerical ill-conditioning (cf. Gabriel et al. 2013).[12]

(C) Nonlinear to linear To use a commercially available optimisation software, the nonlinear term $\sum_{h,\mathrm{ss}} p(h)g(h,\mathrm{ss})$ in Eq. (11) has to be transformed into mixed-integer linear constraints as shown in Barroso et al. (2006).[13]

For the strategic generation $g(h,\mathrm{ss})$ valid generation levels $\bar{dp}(h,\mathrm{ss},i)$ are defined. One can imagine this as selecting a discrete set of possible generation levels. The binary variable $q_{dp}(h,\mathrm{ss},i)$ equals 1 if the generation level i is selected and zero otherwise. This indicates the selected fixed generation level. $q_p(h,i)$ is a binary variable which equals 1 when the price $p(h) > 0$ and $q_v(h,\mathrm{ss},i)$ is a binary variable which equals 1 when the variable $v(h,\mathrm{ss},i) > 0$ where

$$v(h,\mathrm{ss},i) = \begin{cases} \bar{dp}(h,\mathrm{ss},i)p(h) & \text{if } q_{dp}(h,\mathrm{ss},i) = q_p(h,i) = 1 \\ 0 & \text{otherwise.} \end{cases} \tag{19}$$

So $\sum_{h,\mathrm{ss},i} v(h,\mathrm{ss},i)$ provides a linear expression for $\sum_{h,\mathrm{ss}} p(h)g(h,\mathrm{ss})$ under the following constraints

$$0 \leq p(h) \leq Mq_p(h) \tag{20}$$

$$g(h,\mathrm{ss}) = \sum_i q_{dp}(h,\mathrm{ss},i) \tag{21}$$

$$\sum_i q_{dp}(h,\mathrm{ss},i) = 1 \tag{22}$$

$$q_v(h,\mathrm{ss},i) \leq q_p(h) \tag{23}$$

$$q_v(h,\mathrm{ss},i) \leq q_{dp}(h,\mathrm{ss},i) \tag{24}$$

$$q_{dp}(h,\mathrm{ss},i) + q_p(h) - 1 \leq q_v(h,\mathrm{ss},i) \tag{25}$$

$$v(h,\mathrm{ss},i) \leq \bar{dp}(h,\mathrm{ss},i)p(h) \tag{26}$$

$$0 \leq v(h,\mathrm{ss},i) \leq Mq_v(h,\mathrm{ss},i). \tag{27}$$

For further information, consider Barroso et al. (2006), Appendix A and Gabriel and Leuthold (2010).

[12] On the one hand, Big M should be large enough, so that the model could be solved with big M method. But the solver may fail citing numerical difficulties or an ill-conditioned basis. Such events can be caused by poor scaling, which means that M is too big for the solver. For more details, the interested reader is referred to Spreen and McCarl (1968).

[13] Nonlinear optimisation problems can be solved depending on the type of model; however, nonlinear complementarity models applied to real market data can hardly be solved.

3.3.2 Computable Bilevel model for the electricity market

Using the results of the previous subsections, problem (11), (9) and (10) can be recast as a mixed-integer linear programming problem, easily solved using an appropriate MILP solver. The final model is formulated as minimising problem for solvability reasons (instead of profit maximisation) and is presented below.

$$\text{Minimise}_{\{g(h,s)\}\cup\{\text{oc}_{\text{fake}}(h,\text{ss})\}} \sum_{h,\text{ss}} \text{oc}(h,\text{ss})g(h,\text{ss}) - \sum_{h,\text{ss},i} v(h,\text{ss},i) \tag{28}$$

$$\text{s.t.}$$

$$0 \leq p(h) \leq Mq_p(h) \tag{29}$$

$$g(h,\text{ss}) = \sum_i q_{dp}(h,\text{ss},i) \tag{30}$$

$$\sum_i q_{dp}(h,\text{ss},i) = 1 \tag{31}$$

$$q_v(h,\text{ss},i) \leq q_p(h) \tag{32}$$

$$q_v(h,\text{ss},i) \leq q_{dp}(h,\text{ss},i) \tag{33}$$

$$q_{dp}(h,\text{ss},i) + q_p(h) - 1 \leq q_v(h,\text{ss},i) \tag{34}$$

$$v(h,\text{ss},i) \leq \bar{dp}(h,\text{ss},i)p(h) \tag{35}$$

$$0 \leq v(h,\text{ss},i) \leq Mq_v(h,\text{ss},i) \tag{36}$$

$$0 = \text{oc}_{\text{fake}}(h,\text{ss}) - p(h) + \phi_{\max}(h,\text{ss}) - \phi_{\min}(h,\text{ss}) \tag{37}$$

$$0 = \text{oc}(h,\text{sm}) - p(h) + \phi_{\max}(h,\text{sm}) - \phi_{\min}(h,\text{sm}) \tag{38}$$

$$l_{\text{res}}(h) = \sum_{h,s} g(h,s) \tag{39}$$

$$0 \leq \phi_{\max}(h,s) \leq Mv_{\max}(h,s) \tag{40}$$

$$0 \leq \kappa(h,s) - g(h,s) \leq M(1 - v_{\max}(h,s)) \tag{41}$$

$$0 \leq \phi_{\min}(h,s) \leq Mv_{\min}(h,s) \tag{42}$$

$$0 \leq g(h,s) \leq M(1 - v_{\min}(h,s)) \tag{43}$$

where $M \in \mathbb{R}$ is big enough. Equation (29) up to (36) represent the linearised part of the optimisation problem. Equation (37) up to (43) correspond to the lower level problem.

The model is applied to the German electricity market as described in the next subsection. It has to be taken into account that the basic model (lower level model) is very simple concerning the amount of restrictions. But this already results in 15 equations as constraints in the computable model. This illustrates that the effort for setting up such a model is already quite high. This is especially relevant when the model should be used for real market situations with 8760 h.[14] This is why ramping restrictions, starting costs, etc., are not considered.[15]

3.4 Scenarios and data assumption to investigate the influence of renewables on market power

As stated in the introduction, the three presented electricity market approaches should be used to analyse their ability to represent electricity prices and the possibility of market power abuse. Furthermore, the influence of renewable energy penetration on model results should be considered. This is especially interesting as the capacity of renewables is quite high in future years, but their availability could be quite low in a lot of hours during the year.[16]

Thus, the three models are applied to three scenarios: for the reference case, today's market data are used.[17] Today, nearly the same amount of renewable capacity (71 GW) is installed in comparison to conventional capacity (93 GW). A second scenario is chosen for a quite low renewable penetration in combination with a year with no market power[18] and therefore the year 2001 has been selected. In the third scenario, it is assumed that the expansion of renewables will continue as it is foreseen and planned by the German government. This scenario takes up the year 2033 where renewable capacity is estimated to be nearly the double (168 GW) of the conventional capacity (90 GW).[19] The data are based on official documents, such as in the German network development plan (NEP 2013). This situation is interesting as the question arises how conventional power plants can still refinance their total costs, which also depends on the ability to increase market prices above short-term marginal costs in times of low renewable feed-in or in other words when capacities are scarce.

In summary, we selected the three scenarios: past (2001), present (2012) and future (2033). The main characterisation of the scenarios concerning installed renewable and conventional capacities is summarised in Table 1.

[14] A reduction of hours per year could be an option (e.g. using typical day structures), but as demand and renewable feed-in vary from hour to hour and hourly resolution gets more and more important with higher renewable penetration. For a good modelling of the power plant dispatch and the analysis of market power, an hourly representation is preferable (Möst and Genoese 2009). The interested reader is also referred to Staffell et al. (2014), which shows how representative hours can be selected for a system with a high penetration of renewables.

[15] The Bilevel problem is non-convex due to linearization of the nonlinearity. The obtained solutions can usually only be guaranteed to be local solutions. We do modelling in the same way as in Gabriel and Leuthold (2010) and Barroso et al. (2006), who conclude that the solution is the Nash equilibrium. Additionally, we have made some checks with different starting solutions and come up with the conclusion that the solution is the global one.

[16] This means that nearly the same amount of conventional capacities is necessary, but resulting in significantly less full load hours and hence the question arises how these capacities can cover their fixed costs.

[17] 2013 cannot be used as reference year, as (some) data are only available for 2012 at the earliest.

[18] The electricity market in Germany was deregulated and nearly no market power was exercised in 2001 (cf. Möst and Genoese 2009).

[19] The year 2033 was selected as the net development plan for Germany (Netzentwicklungsplan 2013 2 (NEP13), cf. NEP 2013) is a common base in scientific work. The scenario 2033 B was chosen in this paper for modelling.

Table 1 Renewable and conventional capacities in different scenarios

Scenario name	Renewable capacities (GW)	Conventional capacities (GW)
Scenario past (2001)	9	93
Scenario present (2012)	71	93
Scenario future (2033)	168	90

Table 2 Data assumption in all scenarios

Scenario past	Source
Conventional power plants	Power plant list of Federal Network Agency of Germany for 2012
Installed renewable capacities	Ministry of economics Germany (Bundesverband Solarwirtschaft 2013)
Hourly load curve	Hourly load curve of 2012 scaled to the monthly values of 2001 (Entso-E 2013)
Gas, oil, coal price	Monthly values from the statistics of federal office of export control of Germany
Lignite, uranium price	Yearly values from the literature (Traber and Kemfert 2011)
CO_2 price	Price is zero (EU ETS was launched in 2005)
Price of electricity	Hourly prices from EEX 2001
Scenario present	Source
Conventional power plants	Power plant list of Federal Network Agency of Germany for 2012
Installed renewable capacities	European Wind Association
Hourly load curve	Hourly load curve of 2012 provided by Entso-E (Entso-E 2013)
Gas, oil, coal price	Monthly values from the statistics of federal office of export control of Germany
Lignite, uranium price	Yearly values from the literature (Traber and Kemfert 2011)
CO_2 price	Energate for the year 2012
Price of electricity	Hourly day-ahead prices from EEX 2012
Scenario future	Source
Conventional power plants	Power plants from 2012 are scaled to the capacities from NEP13
Installed renewable capacities	NEP13
Hourly load curve	Hourly load curve of 2012
Gas, oil, coal price	NEP13
Lignite, uranium price	The same as in 2012
CO_2 price	NEP13

Although the models seem to be quite simple, data need for the representation of the market situations is quite extensive. Data sources and assumptions are depicted in Table 2.[20]

[20] Be aware that load curve in 2033 may look different to that of 2012 due to the electrification of heat and transport as well as changes in the macro-economy. Due to simplicity, we assumed today's load curve for 2033.

All 8760 h are considered within each year, which increase data needs and calculation time.[21] Within the strategic behaviour models (Cournot and Bilevel), five players are distinguished: RWE, EON, Vattenfall, EnBW as well as the other companies, which are grouped together to one player.[22] In the Cournot model, all players behave in Cournot fashion. For the scenarios in the Bilevel model, we suppose that in a first case RWE, in a second case EON and finally in a third case a consortium of RWE and EON are the strategic companies.[23]

To reduce the calculation time of the models, generation capacities are grouped to technical classes. This means that not the single power plants are modelled but instead power plants are grouped together by energy carrier and efficiency factor[24] demand is based on the hourly load curve of 2012 and is adapted for the other years.[25]

4 Outcome of the complementarity model approaches in the different scenarios

In the following, we will compare and discuss results concerning the price duration curve of the different models and scenarios. In the second result chapter, we will show the principle differences in market outcome for single hours. This helps to interpret the causalities in the models.

4.1 Hourly prices as model benchmark

The price duration curve[26] is used to compare the different model results. We start with the scenario 2012 (today scenario) as it is based on today's situations and has thus

[21] Hourly fuel prices can be used for modelling. However, Wozabal and Graf (2013) states that ... 'However, the prices of electricity do not react to daily changes on the corresponding commodity markets, but rather to long term trends.' They propose to smoothen hourly values, but for reasons of simplicity we directly refer to monthly values. The interested reader is referred to Martinez (2008), who examined in detail, which data input has which impact on model outcome and quality.

[22] Market shares of the four utilities depend on the method of calculation and of system borders. The market share is often referred to different dimensions, e.g. installed capacities, energy production, or sales to final customers, etc. Taking capacity values as basis, EON has a market share of approximately 26 %, RWE 25 %, Vattenfall 14 % and EnBW 10 % (see Ellersdorfer 2009).

[23] These companies have the biggest share in conventional generation capacities in the year 2012. So the influence and the interest to influence prices on the electricity market is assumed to be higher compared with other market participants.

[24] Please notice that this is a common approach in electricity market modelling. Power plants are grouped together by energy carrier and divided into three different groups (per energy carrier) depending on their vintage, respectively, their efficiency. The efficiency factors depend on type, vintage, modernization, etc. and are taken from the database of the Chair of Energy Economics. Average availability factors are used to model (unplanned and planned) non-availabilities. For further details on modelling non-availabilities the interested reader is referred to Weber (2004).

[25] It is implicitly assumed that import-/export profiles will not significantly change between the scenarios. Of course, this is a an assumption, but the increase in total interconnector capacity in Germany until 2033 is very small taking the planned projects in the Ten-Year-Network-Development plan of the EU (2014) as reference. Besides, it is very difficult to estimate the change in import-/export profiles as it depends on a variety of factors (e.g. development of national capacities and merit orders, interconnector capacities, etc.).

[26] The price duration curve is the sorted hourly price curve of 1 year.

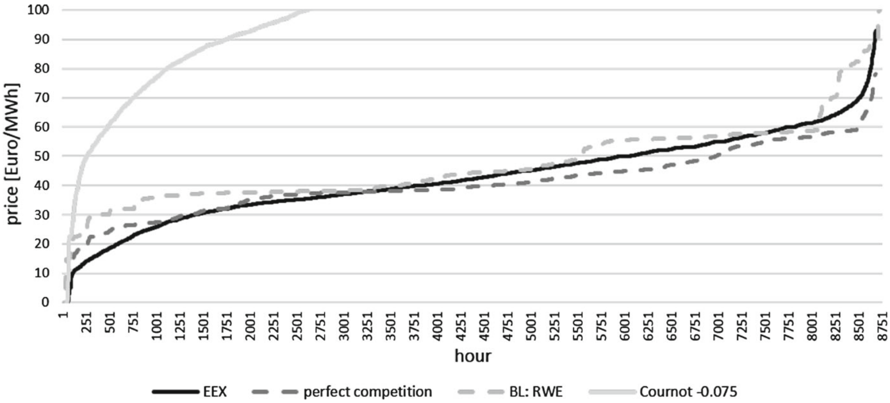


Fig. 3 Price duration curves in Cournot model and Bilevel model, 2012

the most realistic specifications. The price duration curves for the perfect competition model, the Cournot model, the Bilevel model (RWE) and real market results are depicted in Fig. 3.

The marginal costs in the perfect competition (PC) case are lower than in all other cases, which is intuitive. The reader should be aware that the competition model is a quite simple model, which does not take ramping restrictions, start-up costs etc. into account. If taking these restrictions into account, model quality further improves and marginal costs are nearly identical to real market prices (see e.g. Müller et al. 2013 or Möst and Genoese 2009). Noticeable is that the price in the Cournot model is significantly higher than real market prices. This means that the utilities do not behave in Cournot fashion or at least not in all hours of the year (same result as in Wolfram 1999). For the Bilevel case (BL), different behaviours are assumed. As mentioned above RWE, EON or RWE and EON can act as strategic players. In the diagram, RWE is assumed as strategic player. It is noteworthy that in base load, prices from the Bilevel model are significantly higher than in reality. In the mid-load, prices are quite comparable to the competitive case while in the peak load, market prices could better be explained by the Bilevel model. This is not surprising as the ability to abuse market power increases with scarce capacity, so that the competitive case, which in general fits best over the whole year, has some weaknesses in peak hours. Additionally, it has to be kept in mind that prices have to increase above marginal costs to refinance fixed costs or in other words to cover long-term marginal costs (Table 3). In total, as especially base load prices are too high in the Bilevel model, the competitive case can explain best the electricity prices—this is even more correct, when all restrictions are taken into account in the competitive model (which is not the case here but, for example, in Müller et al. 2013) and goes along with the literature that assumes in 2012 no market power was executed (cf. Bataille and Thorwarth 2013).

Results for different strategic actors in the Bilevel model for today are depicted in Fig. 4. Using EON instead of RWE does not change results significantly. In total, the price curve is a little bit lower, especially in base load, than in the case of RWE as strategic player. This can be traced back to the fact that RWE has some more base

Table 3 Year-average prices in the different models with elasticity −0.075

Year	EEX	Perfect competition	Cournot	Bilevel RWE	Bilevel EON	Bilevel RWE and EON
2001	24.05	23.91	103.02	31.02	27.71	37.82
2012	42.68	39.24	119.97	45.56	44.59	60.47
2033	–	60.94	161.0	63.32	61.81	66.41

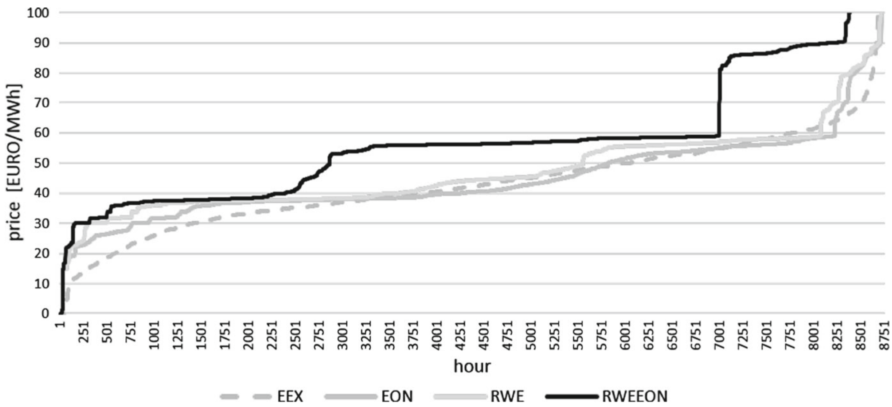


Fig. 4 Price duration curves in the Bilevel model with different strategic players, 2012

load capacities and thus can influence base load prices a little bit more. Taking both utilities acting as consortium together, prices are even higher in peak load than in the Cournot case. This is intuitive as market collusion leads to the ability to abuse more market power in peak load. It is interesting that the prices in the Bilevel model are not as smooth as in the other cases. Especially in the collusion case, the price curve is very steep for peak load. The steps in the price curve can be explained by the switch of one technology to the next in the merit order. As the Cournot model derives too high prices, the Bilevel model in the collusion case is even more unrealistic (as prices are higher than in the Cournot case). In total, this supports the statement that the competitive model fits best to represent the electricity market in 2012 and which can be seen as a fact that today's electricity market is for nearly all hours a competitive market.[27]

Table 4 confirms the graphical results. In Table 4, the Lerner index is calculated for the different scenarios and models. There are several indicators to analyse market power. In general, indicators measuring structural market power can be distinguished from indicators measuring the abuse of market power (for details see e.g. Möst and Genoese 2009). Structural market power is not of interest here and only the Lerner index (LI) as indicator for the abuse of market power is used:

[27] Because the Lerner-indices are negative for most years (except for the year 2012 with perfect competition) this could be used as a supportive argument that power plants are not profitable on average since market prices remain below marginal costs and that perfect competition is the most accurate description of the market structure.

Table 4 Lerner index in the different models

Benchmark	Year	PC	Cournot −0.25	Cournot −0.075	Bilevel RWE
Perfect competition	2001	–	−0.66	−2.35	−0.15
	2012	–	−0.83	−4.22	−0.30
	2033	–	−62.00	−196.21	−7.56
EEX spot market prices	2001	−0.22	−1.07	−2.98	−0.54
	2012	0.05	−0.45	−2.18	−0.42

$$\mathrm{L}_h^p = \frac{p_h - \mathrm{MO}_h}{\mathrm{p}_h} \tag{44}$$

whereby p_h is the market price in hour h and MO_h is the outcome from the models (marginal costs of the competitive model or prices from the strategic models). Instead of p_h also the marginal costs of the competitive model can be taken as reference, which is also done here. The closer the value of the Lerner index is to zero the more competitive is the market. If values are negative, modelled prices overestimate the market data. This means that the strategic models are less useful as benchmark for electricity prices. In general, it can be stated that the values of the Lerner index reflect the graphical interpretation. The indicator for the Cournot case is the highest (for all years and all elasticities), while the Bilevel RWE case is between the competitive case and the Cournot case. In the Table 4, real market data is taken as as well as perfect competition prices as comparison especially for future years.

Up to now, we have discussed today's situation. For the year 2001, several authors state that this is a year with very high competition. This can also be seen in our results where the Lerner index is very low for the comparison of marginal costs of the competitive model and real market data (see Table 4). The Lerner index is with about −0.22 near to zero. In contrast to that, the Cournot model produces too high prices and cannot be used as explanation for market prices. The Bilevel approach is a little better to the Cournot approach, especially when only RWE is acting as strategic player, nevertheless base load prices are too high.

In contrast to the years 2001 and 2012, in the analysed year 2033, no real market data exist. But, such a future year is interesting as the amount of fluctuating renewable energies nearly doubles (in comparison to today) and conventional capacities are still necessary to cover the demand. The question arises whether very high prices in a few hours can compensate for very low prices in hours with high renewable feed-in[28] so that conventional power plants can still be economically operated. Thus, we expect high price peaks for peak load power plants. Admittedly, our model results indicate for the competitive model as well as for the Bilevel model that nearly no price peaks occur (depicted in Fig. 5). On the contrary, model results show that nearly 1000 h of the year

[28] Very low prices occur as renewable generation is provided with marginal costs at zero and the compensation of renewables is paid outside the market, while a low demand occurs resulting in low prices. This phenomenon of low prices in combination with renewable feed-in is also called merit-order effect of renewables. The interested reader is referred to Sensfuß et al. (2008).

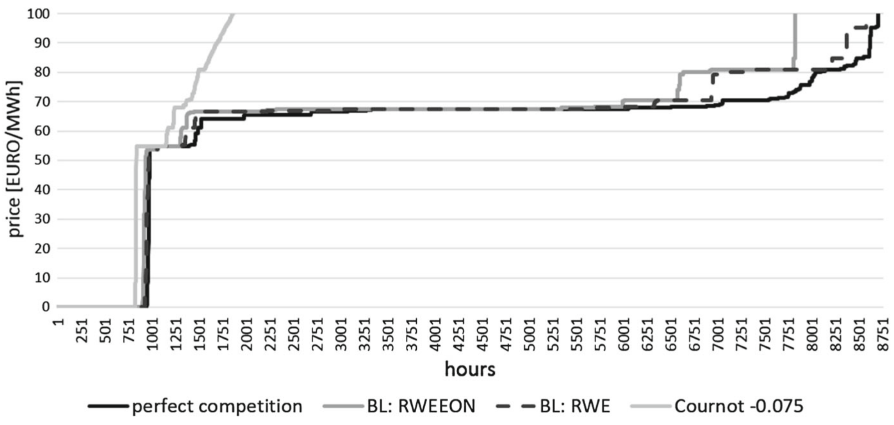


Fig. 5 Price duration curves 2033

prices are near to zero. This is a situation which is not comfortable for conventional power plants as fixed costs can hardly be recovered.[29] Nevertheless, it shows that the residual load is quite low or even negative in this future year. In the Cournot case, the situation is a little bit better, but we have to bear in mind that the model output of the Cournot case dramatically overestimated prices in 2001 and 2012, so that this can also be expected to be the case for the scenario 2033.

Of course, the following points have to be considered when discussing model results: first, neighbouring countries are not modelled which would especially in base load hours have an price increasing effect (as the oversupply could be sold to neighbouring countries). This would enhance the economic situation of the power plants. Second, conventional capacities are taken from the grid development plan, which are in the order of today's capacities (cf. Table 1). From our point of view, this figure seems to be quite high. Even a little bit smaller capacity would lead to higher price peaks in peak load times. This relation is also picked up in another context in the following subsection.

4.2 Market situation in single hours

To understand the strategic behaviour in the Cournot case and the Bilevel case in detail, we pick up some selected hours. We choose the merit order of hour 42 (2nd January 2012, 18 o'clock) in scenario today and the result of the Bilevel model: RWE (cf. Fig. 6). The abbreviation behind the number stands for the power plant technology [run-of-the-river power station (RoR), close cycle gas turbine (CCGT), open cycle gas turbine (OCGT), open cycle oil turbine (OCOT)]. RWE can influence the price only with power plants that have lower marginal costs than the potential price on the energy

[29] In the scenario future, capacities are assumed based on the grid development plan, which is currently a reference document for the development of capacities in Germany. However, it is unclear who will invest in these capacities and whether these capacities will be really installed. It has to be mentioned that prices should be in equilibrium, meaning that capacities will (maybe) be scarcer when prices are too low.

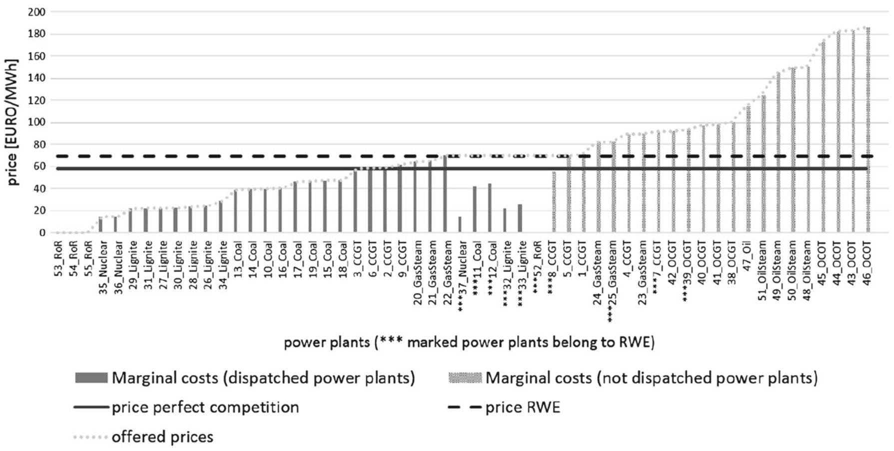


Fig. 6 Merit-order BL: RWE, 2012, h42

Table 5 Total costs of electricity supply and profit in scenario today (billion EUR)

Model	Total costs	Profit EON	Profit RWE	Profit Vattenfall	Profit EnBW
Perfect competition	14.8	1.6	1.6	1.8	0.7
Cournot game −0.25	21.1	3.2	3.2	4.0	1.8
BL: EON	16.1	1.8	1.9	2.1	0.8
BL: RWE	17.6	2.2	2.0	2.4	1.0
BL: RWE and EON	28.0	3.3	2.5	4.6	2.2

exchange. For example, the power plants 52_RoR and 37_Nuclear offer prices higher than marginal costs but lower than the price bid (here marginal costs) of power plant 5_CCGT. Some power plants of RWE are not dispatched that would be dispatched by offering marginal prices e.g. 8_CCGT (which is depicted in light grey colour, finely patterned).

So the strategic producer reduces sales but anyway increases total profit because the dispatched power plants heavily increase its profits. Since Vattenfall (as price-taking company in this model) owns a lot of lignite power plants which have low marginal costs, it also profits even more from higher market prices (in model BL: RWE and EON) (see Table 5, column “Profit Vattenfall”: profit increases from 1.6 billion euro in competition case up to 4.6 billion euro in case of RWE and EON act as strategic player). This is true for all model results: the profit increase is even higher for the price-taking company. This means that the companies abusing market power profit less from their behaviour. This is also a reason why the abuse of market power is not always a lucrative strategy and thus not self-evident.

High peak load prices are very important to refinance long-term production costs of conventional power plants. For this reasons, the relationship between residual load and model prices is illustrated in Fig. 7 for the present and the future scenario. It becomes obvious that real market prices (and model prices as well) increase significantly in high

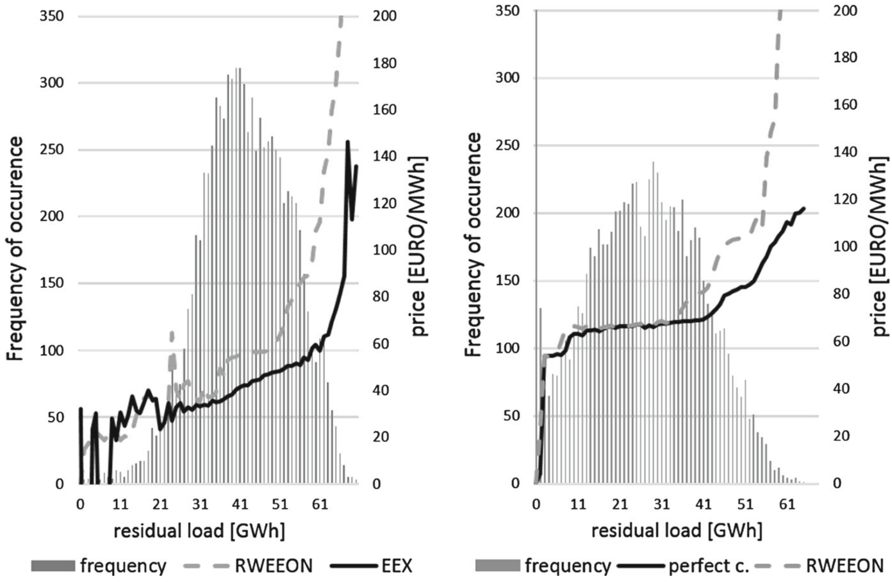


Fig. 7 Residual load and prices, Bilevel model, 2012 and 2033

load hours. The histogram depicts the frequency of occurrence of different residual load levels. From today to the future scenario, a strong left shift is visible due to higher renewable feed-in.

Extreme price peaks only occur in less than 10 h of 1 year in the present and the future scenario. But in the Bilevel model in 2033 price peaks appear already from a residual load of 61 GW (instead of 64 GW in today's scenario). This can be justified with the 3 GW lower conventional capacities in the future scenario (cf. Table 1). In case there are less conventional capacities available in the future (as we assume it) the abrupt price increases will appear more often. To a certain extent, this could be interpreted as a necessary utilisation of market power to operate power plants economically, since for a lot of hours in the year prices are close to zero.

5 Conclusion

Different approaches to model electricity markets and to simulate strategic behaviour have been introduced and afterwards applied to different situations in the German electricity market: a competition, a Cournot and a Bilevel model. The comparison of model prices to prices in a perfect competition model and real market prices show that there is a significant price overestimation in most hours of the year (especially in the Cournot case). The perfect competition model predicts market prices in most hours of the year best with some limitations due to comparability with the strategic behaviour models. Especially, as model results in the competition model will even improve when technical restrictions (up- and down times, ramping, etc.) are taken into account, this even supports our statement. In some high load hours, the results of the Bilevel model with one strategic player can sometimes explain price peaks better. But the modelling effort is quiet complex, because a nonlinear target function has to be linearised. In conclusion, the often used competition model still seems to be a state-of-the-art solution to model electricity markets for most research applications in competitive electricity markets, as in Germany but also in Central Europe. The results of the competitive model are quite close to reality and complexity and efforts are manageable. Obviously, the strategic models could maybe have more relevance for energy markets, where strategic behaviour has a higher importance such as in gas and oil markets. This should be addressed in future research.

The results of other authors that electricity markets in 2001 and 2012 are quite competitive can be confirmed by our results. We confirm that with an increasing renewable feed-in the possibility to abuse market power even decreases. But results are very sensitive to the assumed conventional capacities and further analysis should concentrate on the amount of installed capacities. With only a small reduction of conventional capacities, price peaks can occur more often, especially in high load hours. But these price peaks may not only be reasoned by market power abuse but also by the need to operate power plants economically.

Appendix: Social welfare calculation

The consumers surplus and the producers surplus added together is called the social welfare or the gain from trade and is a standard measure of market efficiency (Gabriel et al. 2013, p. 88). The consumers surplus is calculated by

$$\text{consumers surplus} = \int_0^{q^*} f_d^{-1}(q')dq' - p^*q^* \tag{45}$$

whereas $*$ stands for the equilibrium quantity and the resulting price. Since $q = \sum_{h,s} g(h,s)$ it is analogue $q^* = \sum_{h,s} dp^*(h,s)$ where $dp^*(h,s)$ is the produced quantity of power plant s in equilibrium. The symbols are declared in Sect. 3. The producer surplus is calculated by

$$\text{producers surplus} = p^*q^* - \sum_{h,s} \text{oc}(h,s^*)dp^*(h,s). \tag{46}$$

Therefore, the social welfare will be obtained by

$$\begin{aligned}\text{social welfare} &= \int_0^{q^*} f_d^{-1}(q')dq' - \sum_{h,s} \text{oc}(h,s^*)dp^*(h,s)\\ &= a(h)q^* + \frac{1}{2}b(h)q^{*2} - \sum_{h,s} \text{oc}(h,s^*)dp^*(h,s).\end{aligned} \tag{47}$$

In Sect. 3.1, the quantity q^* is found by maximisation of the social welfare.

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