DISSERTATION

Price formation in electricity forward markets: An empirical analysis of expectations and risk aversion

ausgeführt zum Zwecke der Erlangung des akademischen Grades

eines Doktors der technischen Wissenschaften

unter der Leitung von

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eingereicht an der Technischen Universität Wien

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Wien, im März 2011

To my family

Acknowledgements

Sincere thanks go to my supervisors Prof. Reinhard Haas and Prof. Derek Bunn. The openness of Reinhard Haas and his comments enabled me to develop and perform research on this topic. While I was visiting Derek Bunn's research group at the London Business School my research made substantial progress. I owe the crucial ideas in this thesis to the inspiring atmosphere at his group and especially to the discussions with Derek Bunn and his comments.

Prof. Bernhard Böhm and Claus Huber took time during the past years to continuously discuss my work in progress. Before each meeting I was not only looking forward to their comments but also to having a nice time with them. Discussions with Benoît Sévi clarified initially intuitive ideas.

At the Night & Day Café, Manchester, UK, the band Delphic was recording a new song while I came up with the final outline of this thesis. This acoustic environment supported me substantially.

At the Energy Economics Group my colleagues created an atmosphere that rendered the years of my PhD studies particularly good. Thanks also to them.

Abstract

Futures and forward contracts are important means of risk reduction and transfer for market participants in liberalised electricity markets. This is reflected in high trading volumes – eventually exceeding actual physical demand. Sources of uncertainty and risks in power markets are manifold and range from short, medium and long term fundamental market uncertainties to open regulatory and policy decisions.

The theoretical literature on electricity futures markets has focused on the expectation formation of market actors. It demonstrates how forward prices arise from expected future spot prices. Further the literature maps the effect of risk aversion on the market outcome. Forward premia, so it reveals, emerge from the stochastic properties of spot prices.

The objective of this thesis is to integrate concepts of expectation formation and risk assessment of wholesale power market participants. By means of econometric models applied to the two major European electricity markets, the thesis analyses the determinants of futures prices and corresponding interactions between spots and forwards. The implications of these interactions for forward premia and its components are studied.

Firstly, the models reveal a combination of fundamental and behavioural pricing components of electricity forward prices. More precisely, the forwards are driven by estimates of future generation costs as well as current spot and forward prices of other maturities. Secondly, this complex price formation affects and interferes with the risk assessment of market participants and, in turn, influences their willingness to pay for risk reduction. Forward premia, the models show thirdly, are a compound function of fundamental, behavioural, market structure, dynamic and external shock components. Specifically, forward premia being affected by the unfavourable market structure in terms of concentration and market power effects unfolds market monitoring issues.

The results, so the conclusion, question the consistency of electricity futures price quotations. Moreover, there is an interaction effect with realised forward premia which contain behavioural pricing components. These insights cannot rule out inefficiencies in the analysed futures markets. In turn, futures prices and corresponding forward premia should be considered key elements when assessing transaction costs associated with electricity wholesale market restructuring.

Kurzfassung

Terminkontrakte stellen ein wichtiges Mittel zum Risikomanagement von Akteuren in liberalisierten Strommärkten dar. Dies widerspiegelt sich in Handelsvolumina, die die tatsächliche Nachfrage übersteigen. Die Bandbreite von Unsicherheit und Risiken in Strommärkten reicht von kurz-, mittel- und langfristigen Marktunsicherheiten bis offenen regulatorischen und politischen Entscheidungen.

Die theoretische Literatur zu Stromterminmärkten fokussiert auf die Erwartungsbildung und auf Konsequenzen von Risikoaversion. Terminpreise werden über Erwartungen künftiger Spotpreise und Forwardprämien über die stochastischen Eigenschaften der Spotpreise erklärt.

Das Ziel dieser Arbeit ist Konzepte der Erwartungsbildung und der Risikoeinschätzung zu integrieren. Konkret werden ökonometrische Modelle auf die zwei wichtigsten europäischen Strommärkte angewandt um Einflussparameter von Terminpreisen sowie Wechselwirkungen zwischen kurz- und langfristigen Preisen untersuchen zu können. Des Weiteren werden entsprechende Implikationen für die Forwardprämien dargestellt und erklärt.

Die Modelle zeigen eine Kombination von fundamentalen und verhaltensbezogenen Einflüssen auf die Terminpreise. Der Terminmarktpreis wird sowohl von Erwartungen bezüglich künftiger Erzeugungskosten als auch von aktuellen Spot- und Terminpreisen anderer Fristigkeiten beeinflusst. Diese komplexe Preisbildung beeinflusst und vermischt sich mit der Risikobeurteilung der Marktteilnehmer und affektiert deren Zahlungsbereitschaft zur Reduktion entsprechender Risiken. Die Modelle zeigen, dass Forwardprämien eine Funktion von fundamentalen, verhaltensökonomischen, strukturellen und dynamischen Komponenten sind. Weiters beeinflussen externe Schocks die Forwardprämie. Effekte von Marktkonzentration und Marktmacht werfen Fragen zum Marktmonitoring auf.

Zusammenfassend hinterfragen die Ergebnisse die Konsistenz von Terminpreisnotierungen. Ineffizienzen können daher in den untersuchten Terminmärkten nicht ausgeschlossen werden. Terminpreise und korrespondierende Forwardprämien sollten als wesentliche Elemente von Transaktionskosten interpretiert werden, die es bei der Beurteilung von liberalisierten Strommärkten zu berücksichtigen gilt.

Executive summary

Motivation

Breaking up the regulated monopoly of electricity supply in the European Union (EU) in 1997 into the potentially competitive segments of generation and supply and the regulated natural monopoly businesses of transmission and distribution has led to an unprecedented transformation of the industrial organisation of the power sector. Final customers and suppliers can, since liberalisation, freely source their electricity, generators may and actually do enter new business fields, electricity has become a tradable commodity and, accordingly, organised market places have emerged. Thus, the usage and utilisation of the interregional power network has changed. Not only contributes it to one of its original functions – security of supply – but also has to abide by the laws of economics – arbitrage and profit maximisation – nevertheless still bounded by the constraining forces of physics: Kirchhoff's laws.

No pain no gain. Generators have to make decentralised investment decisions in an environment of various short and long term (market and regulatory) uncertainties, consumers are exposed to a supply side prone to the exercise of market power due to the physical features of the commodity electricity (and its generation technologies), supply and demand side characteristics yield a highly volatile market result, and, above all, the EU power market has to deliver policy targets related to competitiveness, supply security and climate change. Hence, as with any market, the sources of risk – and demands for compensation – are manifold.

Theories of industrial organisation, regulation and financial markets have proposed various treatments of these risks. This thesis is concerned with one potential cure: The forward market, which should contribute to market completeness – a necessary condition for the optimality of competitive markets – and the facilitation of risk management and risk transfer. Specifically, it focused on the empirical assessment of major European long-term futures and forward markets. The attractiveness of long-term markets from a risk management point of view is reflected in high trading volumes on these markets – eventually exceeding physical demand.

High trading volumes and, correspondingly, high market liquidity are generally considered as indications of mature and well-functioning markets. Yet it is crucial to gain deeper insight into the price formation process – not at least because of the special characteristics of the physical commodity electricity, associated consequences for the market structure, and its importance for the overall economy. These insights enable an efficient and effective design of the markets and its regulatory and legislative provisions.

Research questions

In particular, the following questions are addressed in this thesis:

1. How are expectations formed in long-term markets?
2. What are the drivers of futures and forward prices?
3. What is the effect of trading of risk averse market actors on the futures-spot bias?
4. How do market structure and supply and demand shocks affect risk assessment and market outcomes?
5. What, in turn, are the determinants of the forward premium?
6. What are the implications for market efficiency?

Methodology

Some of the above questions are assessed by a review of the theoretical literature and by a simple analytical equilibrium modelling approach. Most of this thesis is, however, concerned with empirical analyses of the two main European power markets: The Central-Western European and the Scandinavian power market. Both reduced-form regression and vector autoregression models are applied throughout this thesis.

Theory

Forward markets deliver two main functions in an economy: They provide and aggregate information about future prices and allow for hedging price risks (Newbery and Stiglitz, 1981). Electricity forward prices arise from an equilibrium in expectations and risk aversion (Keynes, 1930) amongst agents with heterogeneous needs for hedging spot price uncertainty. The forward price $F_{t,T}$ quoted at time t for delivery at time T is thereby viewed as being determined as the expected spot price $E(S_T)$ plus an ex ante forward premium $FP_{t,T}$. In essence, the forward premium constitutes the costs of the hedge in order to insure a fixed price ahead of the delivery (i.e. the futures price).

Price formation in electricity forward markets: The case of year-ahead futures prices

The analysis shows that year-ahead baseload electricity prices do depend on year-ahead generation costs in line with economic theory on equilibrium relationships for forward pricing. The year-ahead generation costs can be interpreted as the market's best estimate of future electricity prices. Second, electricity forward prices are also influenced by current spot prices. Moreover, the recent trend of spot prices has a significant impact on the futures price.

This suggests the existence of a behavioural pricing component in the forward market. Trading strategies of market participants seem to rely partly on current spot prices instead of fundamental modelling approaches. Finally, although the EEX and Nord Pool market are physically only weakly interconnected – resulting in different price levels – main characteristics with regard to price formation on the year-ahead forward markets are alike although the supply and demand side characteristics in the EEX market differ significantly from the fundamentals in the Nord Pool market.

Clearly, the significant influence of current spot market prices on futures prices in both markets questions the forecasting power of the forward price (i.e. the consistency of the forward price). Hence, it is important to study the relationship between current spot and forward prices in detail.

Interaction between spot and forward prices

Clearing on spot and futures markets is a result of market forces and their interactions which might suggest a simultaneous evolution. Clearly, a link between current spot and current forward prices should not be anticipated due to the fact that electricity is not storable. Finding a corresponding relationship, however, would reveal a strong behavioural pricing component prevailing in the markets.

Benth et al. (2009) contend that the lacking storability of electricity implies that spot prices are not affected by available information about future price changes (i.e. price changes in the forward contract market). However, the results of this thesis suggest the opposite. In fact, the prevalence of behavioural components in the electricity markets' price formation is discernible since different product types (i.e. spots and various forwards) mutually influence each other.

Specifically, Granger-non causality tests have revealed significant interactions among spot price returns and month-, quarter-, and year-ahead futures price returns casting doubt on a clear distinction between short and long term markets. This suggests the existence of behavioural pricing components and rejects claims on a supposedly exogeneity – caused by the non-storability of electricity – of spot prices on the one hand and forward prices on the other. Furthermore, these results are confirmed by VAR regression models. More specifically, the movement of the electricity price system can, to a large extent, be explained by exogenous supply and demand side variables driving the electricity prices. Still, there are strong interactions between the electricity price series confirmed by significant regression coefficients in the VAR models (which accords with Granger non-causality tests). The results of the regression models cast doubts on the predictive power of forward prices and, in turn, on market efficiency. Besides these behavioural pricing components risk aversion contributes to the lacking informational function of the forwards via the emergence of a forward premium.

Components of the forward market premium in electricity

A multifactor analysis of electricity forward premia determinants gave insights into some important propositions on the electricity forward premium. In general several significant new effects have been shown:

- The ex post nature of the analysis was controlled for by including a margin shock variable in the regressions, and this was indeed significant in both the peak and baseload monthly ex post risk premia.
- As a derived commodity, electricity translates a substantial amount of the underlying fuel's market price of risk (i.e. the peak forward premium is in fact determined partly due to the gas market).
- As part of the energy commodity trading bundle, oil market sentiment spills over, in that increased oil price volatility increases the forward premium.
- Market concentration appears to have a double influence on power prices – in addition to its potential effect on spot prices, it increases the forward premium. It seems

therefore that whilst the theoretical effect of forward contracting may be to make the spot market more competitive, generators are able to compensate for this through a higher forward premium.

- The effects of scarcity (reserve margin), spot volatility and skewness were significant and consistent with propositions on the positive effects of market risk aversion.

The forward premium in electricity is a complex function of fundamental, behavioural, dynamic, market conduct and shock components. It is clearly an oversimplification in practice to analyse it only in terms of the stochastic properties of the spot prices (variance and skewness). Only part of the risk can be attributed to the electricity sector per se, but in that, risk aversion to scarcity, volatility and extreme events, as well as behavioural adaptation and oil sentiment spillovers characterises agent behaviour. Furthermore, market concentration appears to translate market power effects into the risk premium, which may have important market monitoring implications since forward markets have, so far, been considered to be procompetitive. Policy makers and regulators seek to increase consumer welfare. In the context of electricity markets this is associated with measures aiming to reduce the forward premium. The reserve margin plays a crucial role since increased scarcity increases spot prices (which is amplified in the case of concentrated markets) and, moreover, also the forward premium. Hence, consumers take a "double hit" if the margin reduces, and if this is due to strategic withholding, then it is an important anti-trust concern. In general, some of the insights presented here suggest that forward premia should be considered key elements of a transaction cost view of market efficiency in power trading.

Conclusions

The analyses carried out contribute to an assessment of the deregulation exercise of the European power sector. Firstly, the main drivers of year-ahead futures prices at the two analysed major European power markets (the EEX and Nord Pool power exchanges) were analysed. It was followed by a high-frequency analysis of the interaction between spot and forward prices of different maturities and their drivers. Finally, the price of risk inherent in the long-term markets was studied by a multifactor analysis of month-ahead forward premia and their corresponding determinants. These analyses have revealed several new effects as briefly summarised above.

What are the implications for the performance of electricity wholesale markets? Firstly, the conducted analyses give insights into the structure of the market participants. The performed analyses suggest that futures market results are largely determined by market actors with a physical position (i.e. generators, retailers and large consumers). This is indicated by the magnitude of realised forward premia in the order of 10% on a monthly basis. The premium would represent the willingness to pay for risk reduction if systematic forecast errors were neglected (i.e. market participants forming rational expectations). Forward premia are also affected by external shocks. Still, it is possible to contend that short-end forward premia are determined by risk averse buyers due to their magnitude and significant trend effects in the time to maturity evolution.

Sufficient short selling of futures contracts of "outside" speculators, that is, market actors without a physical position, would bring down these premia to a level determined by transaction costs. Yet increased trading activities in markets can cause price volatility to increase. Forward premia should decrease in absolute terms if the number of speculative trades grows. It might, however, have implications for the price of risk due to an increased short-term volatility. These implications are not clear cut in an electricity price system characterised by repercussions among the price series. They suggest further investigation.

Speculative trading activities in energy commodity markets have caused a lively public debate about its effects on price levels, especially since prices in the crude oil market rose to unprecedented highs in 2008. Sole speculative trading can be ruled out to be responsible for the electricity futures price formation for reasons outlined above. Still, prices on long-term markets are driven by expectations and corresponding trades bring about an equilibrium market price. In essence, these trades on derivative markets are zero sum games. Hence, if markets "don't get it right" it is also an issue of market participants' expectations.

The analysis in this thesis has revealed that the futures price formation and, correspondingly, the expectation formation of the market participants are a compound mix of rational and several behavioural components. As market equilibrium is linked to equilibrium in expectations the existence of behavioural effects applies for all groups of market participants. Future research could build a formal model of different groups of market actors detailing psychological biases. This could shed light on the specific short and long positions taken in the forward markets. Moreover, this would allow testing for expectations induced trend (herding) effects.

Futures prices are affected by behavioural pricing components and a – due to changing degrees of risk aversion – time-varying market price of risk. In combination with shock (i.e. uncertainty) induced errors these influences yield, in terms of forecasting power, a biased futures price. On the month-ahead level this adds up to forward prices being on average in the order of 10% above subsequent spot prices. This unfolds market monitoring issues. The analyses suggest that market power effects of concentrated supply structures spill over to forward premia due to a risk averse demand. Lacking transparency on the positions entered by market actors not only makes empirical analysis an elusive task but also determines information asymmetries. Information asymmetry though renders an inefficient resource allocation on markets (Stiglitz, 2001).

The spill over of market power effects into the forward premium, in turn, has essential monitoring implications since forward markets have, so far, been considered to be procompetitive. Analyses concerning market power effects in electricity markets focus typically on spot markets only. Whereas these studies do confirm the crucial role of excess supply capacities and of strategic withholding on spot market results the impact of margin and mark ups on risk aversion is not considered.

Publications of the USA based Commodity Futures Trading Commission (CFTC) list long and short open interests of different types of traders. If such market transparency programmes were implemented in the European electricity futures markets this would decrease asymmetries and increase the data base for new descriptive analysis and new theories on decision making of market participants. In fact, publication on aggregated trader category levels would take into account the trade-off between reducing asymmetries and releasing sensitive business related information.

The analyses in this thesis have relied on aggregated market data – basically settlement prices of different commodities and fundamental supply and demand quantities. The insights could be enlarged by the inclusion of data related to the positions taken, at least on aggregate, by hedgers and speculators and market concentrations. The robustness of the results could be increased by assessing additional forward contract maturities and taking into account higher granularities of daily or intra-daily price time series. Still, this would necessitate far higher transparency levels.

New empirical insights can frame new theories of decision making under risk. This thesis provided empirical insights into the price formation in electricity futures markets. They suggest expanding existing equilibrium models considering oligopolistic market environments, psychologically based behavioural concepts and different information levels.

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Abbreviations

AIC	Akaike information criterion
APX	Amsterdam Power Exchange
Belpex	Belgian Power Exchange
CCGT	Combined cycle gas turbine plant
CFTC	Commodity Futures Trading Commission
CO_2	Carbon dioxide
CUSUM	Cumulative sum of recursive residuals
EC	European Commission
EEX	European Energy Exchange
ETS	Emission trading scheme
EU	European Union
EXAA	Energy Exchange Austria
GWh	Gigawatt hour
HC	Hard coal fired plant
HQ	Hannan–Quinn information criterion
ISO	Independent transmission system operator
ITO	Independent transmission operator
MC	Marginal costs
MR	Marginal revenue
MWh	Megawatt hour
OLS	Ordinary least squares
OTC	Over the counter
PolPX	Polish Power Exchange
SC	Schwarz criterion
SRMC	Short run marginal costs
t	Metric ton
VAR	Vector autoregression

Symbols

a,b	Cost parameters
A	Coefficient of absolute risk aversion
ARA	Amsterdam/Rotterdam/Antwerp ports
b	Regression coefficient
c	Generation costs
Cov	Covariance
cy	Convenience yield
ε	Residual
E	Expectation
η	Electrical efficiency
n	Number of observations
f	CO_2 emission factor
F	Forward price
FC	Fixed costs
FP	Forward premium
Log	Logarithm
N	Number of market actors
π	Profit
p	Price
PRIM	Primary energy
Q	Quantity (generation, demand)
r	Interest rate
s	Storage costs
S	Spot price
σ^2	Variance
Skew	Skewness
TC	Total costs
U	Utility function
Var	Variance
x	Vector of exogenous parameters
y	Price vector

Indices

Base	Baseload
D	Demand
F	Forward
i, j	Index for market participants
P	Generator
Peak	Peak load
R	Retailer
S	Spot
S	Speculator
t, T	Time interval/period
W	Wholesale spot market

1 Introduction

1.1 Motivation

Breaking up the regulated monopoly of electricity supply in the European Union (EU) in 1997 into the competitive segments of generation and supply and the regulated businesses of transmission and distribution has led to an unprecedented transformation of the industrial organisation of the power sector. Final customers and suppliers can, since liberalisation, freely source their electricity, generators may and actually do enter new business fields, electricity has become a tradable commodity and, accordingly, organised market places have emerged. Thus, the usage and utilisation of the interregional power network has changed. Not only contributes it to one of its original functions – security of supply – but also has to abide by the laws of economics – arbitrage and profit maximisation – nevertheless still bounded by the constraining forces of physics: Kirchhoff's laws.

No pain no gain. Generators have to make decentralised investment decisions in an environment of various short and long term (market and regulatory) uncertainties, consumers are exposed to a supply side prone to the exercise of market power due to the physical features of the commodity electricity (and its generation technologies), supply and demand side characteristics yield a highly volatile market result, and, above all, the EU power market has to deliver policy targets related to competitiveness, supply security and climate change. Hence, as with any market, the sources of risk – and demands for compensation – are manifold.

Theories of industrial organisation, regulation and financial markets have proposed various treatments of these risks. This thesis is concerned with one potential cure: The forward market, which should contribute to market completeness – a necessary condition for the optimality of competitive markets – and the facilitation of risk management. The attractiveness of long-term markets from a risk management point of view is reflected in high trading volumes on these markets – eventually exceeding physical demand.

High trading volumes and, correspondingly, high market liquidity are generally considered as indications of mature and well-functioning markets. Yet it is crucial to gain deeper insight into the price formation process – not at least because of the special characteristics of the physical commodity electricity, associated consequences for the market structure, and its importance for the overall economy. These insights enable an efficient and effective design of the markets and its regulatory and legislative provisions.

1.2 Core research questions

This thesis analyses electricity forward and futures markets. Specifically it assesses the price formation in these markets. Key objectives are to gain insights on major price and risk drivers and to conclude on market efficiency. In particular, the following questions are addressed:

1. How are expectations formed in long-term markets?
2. What are the drivers of futures and forward prices?
3. What is the effect of trading of risk averse market actors on the futures-spot bias?
4. How do market structure and supply and demand shocks affect risk assessment and market outcomes?
5. What, in turn, are the determinants of the forward premium?
6. What are the implications for market efficiency?

1.3 Methodology

Some of the above questions will be assessed by a review of the theoretical literature and by a simple analytical equilibrium modelling approach. Most of this thesis is, however, concerned with empirical analyses of the two main European power markets: The Central-Western European and the Scandinavian power market. Both reduced-form regression and vector autoregression models will be applied throughout this thesis.

1.4 Structure

The remainder or this thesis is structured as follows:

The following **Chapter 2** unfolds the research problem. It briefly summarises the electricity liberalisation process in the EU with a focus on the regulatory provisions, discusses and reviews economic theory with respect to the price formation in liberalised power markets. Thereby, it focuses on the pricing in forward markets and different theoretical and methodological approaches. Then the social function of forward markets is discussed and a simple two-stage equilibrium model is introduced. This model focuses on the price risk management using forward contracts and explains stylised facts with respect to the emergence of the futures-spot bias.

Chapters 3, 4 and **5** contain the specific empirical analyses mentioned above. These analyses answer distinct though interlinked research questions. Common background information to all analyses is provided in Chapter 2. In each case chapters 3 to 5 contain a detailed motivation and introduction, describe the specific methodological approach and analysed data, present results and draw corresponding conclusions. **Chapter 3** analyses the price formation in year-ahead futures markets, **Chapter 4** discusses the links between spot prices and futures prices of different maturities and **Chapter 5** assesses the drivers of the forward premium.

Overall conclusions from the analyses are drawn in **Chapter 6**. **Appendix A** contains an additional robustness analysis of the model of the ex post forward premium presented in Chapter 5. **Appendix B** dynamises a sub analysis of Chapter 5. **Appendix C** derives the forward market equilibrium presented in section 2.3.2. Finally, **Appendix D** describes the classical Cournot duopoly solution.

2 Liberalisation, price formation and risk management

This chapter summarises the electricity liberalisation process in the European Union (EU) whereas it focalises on the main regulatory provisions. Furthermore the implications for the price formation in power markets are discussed. Particularly, it focuses on the pricing in forward and futures markets and associated theoretical and methodological approaches. The social function of forward markets is reviewed and a simple two-stage equilibrium model is introduced. This model concentrates on the price risk management using forwards and futures aiming to explain stylised facts with respect to the emergence of the futures-spot bias.

2.1 Liberalisation of energy markets

Liberalisation efforts of the electricity supply industry all over the world aimed at fostering an efficient energy supply due to the introduction of competition. The liberalisation process in the EU started in the late 1980s and early 1990s with the first electricity directive concerning common rules for the internal market in electricity being adopted in 1996 (European Commission, 1997).

2.1.1 Electricity market liberalisation in the EU

With the signing of the Single European Act, which came into effect in 1987, the objective to create one common European market became part of the Treaties of the European Communities. Also for services of general economic interest (e.g. energy, communications) the creation of a single market was considered as a necessary condition to improve the range and quality of these services. Specifically, in its communication on services of general interest in Europe, the European Commission states that "market forces produce a better allocation of resources and greater effectiveness in the supply of services, the principal beneficiary being the consumer, who gets better quality at a lower price".[1] Still, the communication recognises that market mechanisms are sometimes limited in their ability to employ all potential benefits (European Commission, 1996).

For the case of electricity supply European Commission (1996) considers the opening up of electricity markets for competition necessary to allow for an increased international competitiveness of the European industry due to reduced energy costs. This constitutes the main motivation for market liberalisation. Because of a gradual market opening, in turn, lower

[1] The expected price decrease has, of course, to be assessed against the regulated case. In this sense a lower price has to be considered as a relative and not an absolute price decrease.

prices should also result for household consumers. The communication does not call for privatisation of the energy sector. Instead, it focuses on the creation of competitive integrated markets.

The restructuring of the electricity sector in the EU was finally triggered by the Directive 96/92/EC of the European Parliament and of the Council concerning common rules for the internal market in electricity. Specifically, this directive contained three major provisions (European Commission, 1997):

- Regulating a minimum level of separation (unbundling) of the network (transmission and distribution grid):
  The formerly vertically electricity supply businesses had to separate their transmission and distribution activities from generation and supply by means of unbundling of accounts. In general, unbundling is of crucial importance in order to avoid possible distortion of competition, discrimination and cross subsidies between different segments of the supply chain (Haas et al., 2009).
- Specification of network access models:
  The directive foresaw two forms of third party access, negotiated or regulated, as well as a single buyer procedure.
- Opening up of former supply monopolies to allow eligible customers free choice of their suppliers:
  First, large customers with an annual consumption 40 GWh were eligible to choose their supplier. This consumption limit was gradually decreased to 9 GWh six years after the directive entered into force.

As recognised by European Commission (2007a) the minimum requirements set out by the directive resulted in a diverse implementation and, hence, in considerable differences regarding the level of market opening among the Member States. Furthermore, these minimum legal requirements were not sufficient for implementing truly competitive markets. Hence, a follow up directive[2] containing stricter rules and responsibilities for the electricity supply industry – and also for national authorities – entered into force in 2003 (European Commission, 2003):

[2] Directive 2003/54/EC of the European Parliament and of the Council. Official Journal of the European Union L176/37.

- Unbundling:
  In addition to the unbundling of accounting and management the directive called for legal unbundling. Hence, the transmission and distribution systems must be operated through legally separate entities.
- Network access:
  Access to the system must be organised through a regulated third party access based on published, objective and non discriminating tariffs monitored and methodologically set by a regulatory authority.
- Market opening:
  The provisions pursued full market opening with non-household customers being eligible from July 2004 and household customers from July 2007 on.

However, European Commission (2007b) questioned that, even after the second directive had been implemented, electricity prices were the result of a truly competitive market environment. Furthermore, insufficient unbundling provisions, discriminated third party network access and lacking regulatory competences were observed. Considering this unsatisfying process of achieving the internal market in electricity a third directive was set in force in 2009 – yet again containing stricter rules. These rules have to be implemented in national legislation by 2011. The most important provisions concern the unbundling of integrated utilities (European Commission, 2009):

- Unbundling:
  The new directive calls for ownership unbundling as the preferred way to remove non-competitive incentives of integrated incumbents. Possible alternatives to ownership unbundling are the independent transmission system operator (ISO) which has control over the network but ownership retains at the integrated utility and the independent transmission operator (ITO) where the ownership and control of the network retain within the integrated company subject to stricter regulation and oversight.
- Furthermore, the competences and tasks of national regulators are increased and provisions to stipulate cross border trade and investments are reinforced.

Liberalisation of the sector clearly effects the price formation of the commodity electricity. In the former pre-liberalised times prices were regulated and equalled the average costs of power generation. The next section will discuss price formation in liberalised markets.

2.1.2 Price formation in liberalised electricity markets [3]

In a competitive power market the price of electricity on the wholesale market is determined by the generation costs of the marginal technology; that is the short run marginal costs of the most expensive plant needed to meet demand. The price equals the so called system marginal costs.[4]

The short run marginal costs mainly consist of the costs for input fuels (e.g. natural gas) and CO_2 certificates and to a lesser extent of other variable costs (e.g. operation and maintenance cost). In this thesis, without affecting the results of the analysis in the following chapters, short run marginal costs of different power plant technologies are modelled by considering fuel and CO_2 costs only.

When the generation capacity Q of all power plants in an electricity market is ordered by short run generation costs c the total supply curve results. Since in a first approximation the individual generation technologies have constant marginal costs until their capacity limit the total supply curve is a stepped and discontinuous function of total capacity. As the utilisation of the power plant park increases, typically, the supply curve is steeply increasing since the individual plants eventually rely on more expensive fuels and are characterised by a decreasing efficiency. Figure 2.1 shows a stylised supply curve where the generation costs are plotted against the generation capacity. Typically run of river hydro power plants are characterised by generation costs close to zero, followed by nuclear power plants, lignite, gas and coal fired plants with oil fired plants usually constituting the most expensive generation technologies.

The equilibrium electricity price is finally determined by the intersection of the supply and the demand curve. As electricity demand can, in the short-term, be modelled as being inelastic to price resulting in a vertical demand curve, competitive electricity markets can be modelled by minimising the total generation costs to meet a given demand. Figure 2.1 illustrates price formation in a competitive power market for two different demand levels (low, high).

[3] This section is based on Haas, Redl and Auer (2009).

[4] For a detailed description of price formation in liberalised electricity markets see, e.g., Stoft (2002).

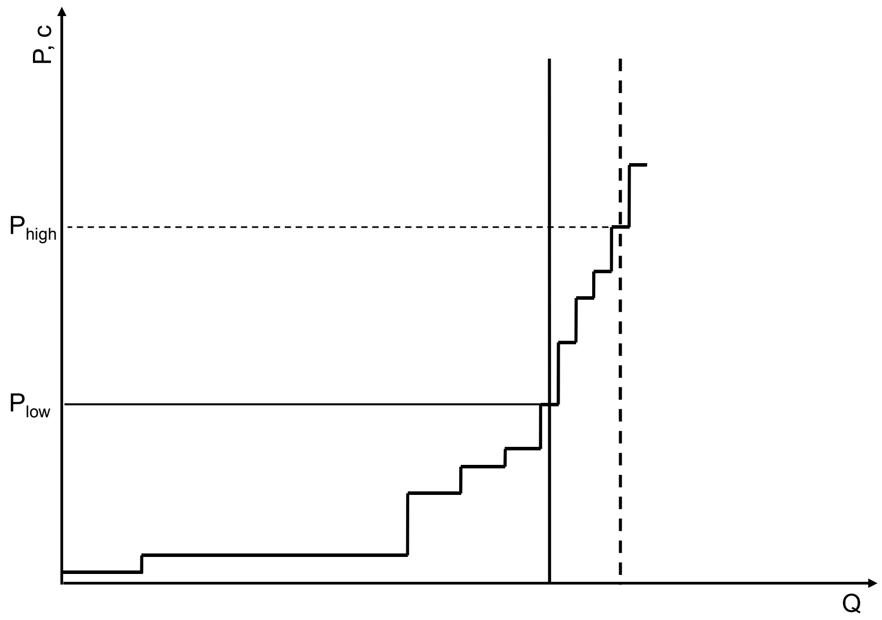

Figure 2.1. Price formation in a competitive electricity market. For the low and high demand case the wholesale prices, P_{low} and P_{high} respectively, equals system marginal costs. That is, the short run generation costs of the most expensive plant needed to meet demand.

The intersection of supply and demand in Figure 2.1 implies that the last power plant type needed to meet demand is utilised partly only. All technologies with lower generation costs operate at maximum capacity. As supply and demand curves change over time (e.g. due to seasonal factors or input price fluctuations) wholesale prices are characterised by volatile and seasonal patterns.

This principle of system marginal cost pricing is, for example, mirrored in the concept of uniform pricing auctions of organised wholesale electricity markets where all generators needed to meet demand receive the clearing price. The difference between this price and the individual generation costs is the contribution margin which allows for the coverage of fixed costs. Summing this contribution margin for all operating generators yields the producer surplus.[5]

2.1.3 Price formation in electricity forward markets

This thesis is concerned with price formation in futures/forward markets. That is, markets where price formation and delivery are distinct. Hence, delivery is deferred. Delivery can take

[5] There is a lively debate whether producers can recover their fixed investment costs in a fully liberalised and competitive power market. This thesis does not touch upon this issue. However, it should be pointed out that new power plants are characterised by high efficiencies and – within their load segment – should rarely constitute the marginal plant. In the long term the equilibrium price on a liberalised competitive power market equals the long run marginal costs of new power plants. For a discussion see Stoft (2002).

place up to years after the corresponding prices where agreed on the market. Clearly, this brings about complications in the price formation process. The above chapter, however, has not considered these specificities. Instead, I implicitly assumed a generally effective price formation process for both short term markets – also termed as spot markets – and long term futures or forward markets. This corresponds to the presumption of risk neutral market actors forming rational expectations in a competitive environment. This section therefore shows, given these assumptions, that prices on short and long term markets are equal. The following chapters, however, will relax these conjectures.

Figure 2.2 depicts the price convergence. In a risk neutral and competitive environment rational market actors will, in equilibrium, agree on the forward price *F* based on the intersection of the forecast of future (price inelastic) electricity demand Q_s and the expected upward sloping supply curve. This price equals the expected future spot price *S* when Q_s and the corresponding supply will finally materialise. The traded volume on the forward market Q_F corresponds to this expected demand $E(Q_s)$. Random shocks causing deviations of Q_s from $E(Q_s)$ cause similar deviations of *S* from *F* (Borenstein et al., 2008). Given the above assumptions, these deviations would have an expected value of zero. Any systematic price differences would be eliminated by arbitrageurs buying in the cheaper and selling in the more expensive market. These additional trading volumes would cause price convergence.

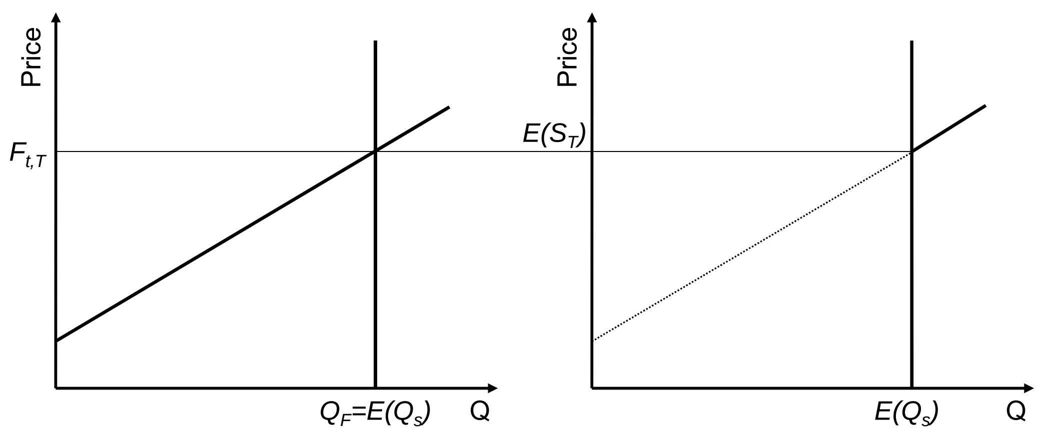

Figure 2.2. Equilibrium of forward and expected spot prices. Source: Borenstein et al. (2008)

Within the wider context of the financial behaviour of energy derivatives economic theory provides two main approaches for pricing forward contracts. The first is dating back to Kaldor (1939) where current spot prices, interest rates, storage costs and a convenience yield are used to determine a no-arbitrage condition between spot and futures prices:

$$F_{t,T} = S_t e^{(r+s-cy)(T-t)} \tag{2.1}$$

where $F_{t,T}$ is the futures price at time t for delivery in T, S_t is the spot price at time t, r is a constant interest rate, s are storage costs and cy is the convenience yield obtained from holding the physical commodity.[6] If the futures price deviated from this relationship, arbitrageurs could secure riskless profits. More specifically, arbitrageurs would buy in the cheaper market and sell in the more expensive market. As more market participants become aware of this opportunity, arbitrage would be eliminated due to induced changes of the demand and supply for spot and forward products.

However, the characteristics of electricity render its forward price formation rather special. The most crucial aspect is the nonstorability of power which precludes the above classic cost of carry equilibrium of spots and forwards. This nonstorability is amplified by the necessity of an exact match of supply and demand in order to guarantee stability of the electricity system.[7,8] Instead, expanding the price formation process depicted in Figure 2.2, it is usual to consider equilibrium in expectations and risk aversion (Keynes, 1930) amongst agents with heterogeneous needs for hedging spot price uncertainty. The forward price $F_{t,T}$ quoted at time t for delivery at time T is thereby viewed as being determined as the expected spot price $E(S_T)$ plus an ex ante forward premium $FP_{t,T}$ (Redl and Bunn, 2010):

$$F_{t,T} = E(S_T) + FP_{t,T} \tag{2.2}$$

Expected spot prices reflect market participants' expectations of fundamental supply and demand conditions during the delivery period of the forward contract (as depicted in Figure 2.2). Differences between forward and expected future spot prices are then a compensation for bearing the price risk (Bessembinder 1992, Bessembinder and Lemmon 2002, Longstaff and Wang 2004). The forward premium is thereby considered the net hedging cost of risk averse producers, retailers or other market participants.[9,10] In essence, the forward premium

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[6] See e.g. Telser (1958) for the concept of convenience yield for futures pricing.

[7] From an economic point of view the non-storability implies high storage costs yielding – according to equation (2.1) – high futures prices.

[8] Nonetheless, the cost of carry approach is used in the electricity literature (see e.g. Clewlow and Strickland (2000), Stoft et al. (1998) on arbitrage pricing of electricity futures).

[9] Fama (1984) states that equation (2.2) is simply a definition of the premium. Section 2.3 will present a model describing the emergence of this premium.

[10] The terms "forward premium" and "risk premium" are used interchangeably in many papers. However, it is important to stick to the definition: The risk premium is the negative of the forward premium. Hence, the forward premium is the difference between the futures price and the expected spot price whereas the risk premium is simply the opposite.

constitutes the costs of a hedge in order to insure a fixed price ahead of the delivery (i.e. the futures price).

Besides equilibrium approaches for forward price modelling stochastic models are frequently applied to determine the magnitude of inherent market risk (See Weron (2008), Kolos and Ronn (2008), Benth and Koekebakker (2008) and the references therein). In this thesis a structural approach for modelling forward prices is employed to study the relationship between forward and spot prices and gain insights on fundamental influence factors.

Testing the expectations theory challenges the empirical researcher. Prices, clearly, can only be observed ex post. However, equation (2.2) contains two non-observable ex ante terms. Hence, assessing both the forecasting power of forward prices (i.e. testing the consistency of expected prices) and the premium (i.e. testing the significance and magnitude of the price of risk) is a highly interlinked and intriguing problem. Still, equation (2.2) also presents two natural alternatives circumventing this inference problem. First, an ex ante spot price model can capture the price expectation formation allowing the deduction of the premium. Second, expanding equation (2.2) by the realised spot price allows a direct estimation of the premium. Some words of caution: Relocating the inference problem does not, however, resolve all empirical challenges. Chapter 5 will present a detailed motivation why the latter of the two above mentioned alternatives is, nevertheless, a careful approach paving the way for relevant and robust conclusions on the price formation in electricity forward markets.

A remark on nomenclature is overdue: Throughout this thesis the terms futures and forwards are used interchangeably. However, these two types of contracts differ – most importantly in terms of their settlement. Forward contracts, which are typically settled with physical delivery of the underlying commodity, yield cash flows (i.e. forward price times quantity) at the maturity date. In contrast, futures contracts, which are typically settled financially and traded at organised exchanges, comprise cash flows during the remaining time to maturity according to the change in the market value of the contract (i.e. the price changes of the contract). Since futures prices converge to the spot price due to arbitrage reasons this continuous settlement causes that e.g. for the purchase of the commodity at maturity simply the prevailing spot price has to be paid (Cox et al., 1981). In reality this daily settlement is paid out of a deposit (the margin) traders are required to leave at the exchanges. Cox et al. (1981) show that for constant interest rates futures and forward prices are, in fact, equal. Hence, this thesis implicitly assumes non-stochastic interest rates when referring to futures or forwards.[11]

2.2 The social function of forward markets

Forward markets deliver two main functions in an economy: They provide and aggregate information about future prices and allow for hedging price risks (Newbery and Stiglitz, 1981). That is, they contribute to market completeness – which is a necessary condition for competitive markets to be Pareto optimal – and facilitate risk management and risk transfer.[12]

The current electricity futures price is the market's best estimate (adjusted for forward premia) of the future price of this commodity. This, in turn, provides information to market participants and allows an adjustment of (future) production and consumption decisions. However, as pointed out by Newbery and Stiglitz (1981), information on the market may be biased due to conflicting benefits of privately versus socially available information.

The most important function of futures markets is the facilitation of risk management (hedging) of risk averse market actors. For example, a generator can sell power forward for future delivery and effectively lock in a fixed sale price at the time of the forward trade. Clearly, this illustration shows that forward markets provide a means for hedging *price risk*, whereas the risk of demand fluctuations cannot be cured by forwards. To also hedge the *quantity risk*[13] more sophisticated derivatives, namely option contracts, need to be entered by the respective generator.[14] The next section will show the effects of hedging on the price formation and profit distribution using an analytical model.

[11] Given the short time to delivery of the considered contracts a constant interest rate may indeed be a safe assumption.

[12] With the work of Allaz (1992) another social function of forward markets entered the economic debate: The strategic role of forwards in an oligopolistic market environment and its (positive) effect on efficiency. However, this result has been questioned by the theoretical literature and not been resolved by empirical studies. Hence this ambiguous function is not treated in this section. Instead, I refer to section 5.2.1.1 for a discussion of the strategic effects of forward markets and section 5.6 for an empirical analysis.

[13] Similarly, unexpected generation unit outages cause supply fluctuations representing another component of quantity risk.

[14] This thesis, however, is primarily concerned with the treatment of futures markets and, hence, the assessment of the facilitation of *price* risk management.

2.3 Price risk management using forward contracts: A simple analytical model

This section is concerned with the effects of forward trading on the profit distribution of risk averse power generators in an uncertain market environment. The model is kept as simply as possible in order to focus on the risk hedging function of forward markets. For more elaborated models see, e.g., Danthine (1978), Anderson and Danthine (1981), Newbery and Stiglitz (1981), and Bessembinder and Lemmon (2002).[15]

The model contains N_P risk averse producers acting competitively in the spot and forward market. The total cost function of each identical supplier i is a function of the individual output Q_{Pi} and fixed costs FC and is set to $TC_i = FC + \frac{a}{2}(Q_{Pi})^2$. The passive demand side is modelled via an inelastic demand function with expected mean demand Q^D which is normally distributed with demand variance σ_D^2. Uncertainty about demand is resolved when the spot market clears.

2.3.1 Spot market equilibrium

Taking into account the previously agreed forward positions the ex post profit π_{Pi} of producer i equals

$$\pi_{Pi} = P_W Q_{Pi}^W + P_F Q_{Pi}^F - TC_i \tag{2.3}$$

where P_W is the wholesale spot price, P_F is the forward price, and Q_{Pi}^W and Q_{Pi}^F denote the quantities sold by producer i on the spot and forward market respectively. Clearly, generator i's total physical production Q_{Pi} is the sum of Q_{Pi}^W and Q_{Pi}^F. The first order condition yields the profit maximising quantity sold in the spot market by producer i:[16]

$$\frac{\partial \pi_{Pi}}{\partial Q_{Pi}^W} = 0 = P_W - a(Q_{Pi}^W + Q_{Pi}^F) \tag{2.4}$$

$$Q_{Pi}^W = \frac{P_W}{a} - Q_{Pi}^F \tag{2.5}$$

Given that forward contracts are in sum zero net supply[17] and equating total production to total demand yields the equilibrium spot price:

---

[15] The presented model keeps the notation of Bessembinder and Lemmon (2002) as much as possible since their model is discussed in detail in section 5.2.1.2.

[16] It is easy to verify that the second order condition for a maximum is fulfilled.

[17] $\sum_{i=1}^{N_P} Q_{Pi}^F + \sum_{j=1}^{N_S} Q_{Sj}^F = 0$

$$P_W = a\frac{Q^D}{N_P} \tag{2.6}$$

2.3.2 Forward market equilibrium [18]

Participants on the forward market include the producers and N_S risk averse speculators *j* who do not take a physical position in the spot market.[19] Market actors are assumed, for simplicity, to maximise the well-known mean-variance utility function:[20]

$$U(\pi_{i,j}) = E(\pi_{i,j}) - \frac{A}{2}Var(\pi_{i,j}) \tag{2.7}$$

where $E(\pi_{i,j})$ is the expected value of the profit of generator *i* and speculator *j* respectively and $Var(\pi_{i,j})$ is the variance of the respective profit distribution.[21] Using (2.5) and the properties of variances and covariances[22] yields the following function for expected utility for producer *i*[23]

$$U(\pi_{Pi}) = \frac{1}{2a}E(P_W^2) - E(P_W)Q_{Pi}^F + P_F Q_{Pi}^F - FC - \frac{A^2}{8a^2}Var(P_W) - \frac{A}{2}{Q_{Pi}}^{F^2}Var(P_W) + \frac{A}{2a}Q_{Pi}^F Cov(P_W^2, P) \tag{2.8}$$

and for speculator *j*[24]

$$U(\pi_{Sj}) = -E(P_W)Q_{Sj}^F + P_F Q_{Sj}^F - \frac{A}{2}{Q_{Sj}}^{F^2}Var(P_W) \tag{2.9}$$

The first order conditions give the profit maximising quantity sold (or bought) in the forward market:[25]

---

[18] For a stepwise derivation of the forward market equilibrium see Appendix C.

[19] For simplicity, the model just includes producers and speculators in the forward stage. More sophisticated models may also include retailers (e.g. Bessembinder and Lemmon (2002)). Since the aim of this section is to point out the risk hedging function of forward markets the results would not be altered if retailers where included in the model. Clearly, speculators could be considered to be part of the total system demand. Hence, a passive demand side representation is taken into account in the spot market stage.

[20] This utility function constitutes a strong assumption. Particularly, returns need to be distributed normally and agents are assumed to maximise utility functions with constant absolute risk aversion. See Newbery and Stiglitz (1981) and Newbery (1988) for a detailed discussion of the limitations of the mean variance approach. Clearly, it seems reasonable that risk averse agent's are also concerned with the volatility of the expected profits – measured in this case by the variance of profits. The linear form of the above model yields normality of the return distribution.

[21] In this model market participants form rational expectations. Hence, they know the true distribution of power demand. This is a strong assumption. Nevertheless, this model formulation allows best focusing on the hedging part of the forward bias.

[22] $Var(x)=E(x^2)-E^2(x)$ and $Cov(x,y)=E(xy)-E(x)E(y)$.

[23] $E(\pi_{Pi}) = \frac{1}{2a}E(P_W^2) - E(P_W)Q_{Pi}^F + P_F Q_{Pi}^F - F$ and $Var(\pi_{Pi}) = \left(\frac{1}{4a^2} + Q_{Pi}^{F^2}\right)Var(P_W) - \frac{1}{a}Q_{Pi}^F Cov(P_W^2, P_W)$

[24] The speculator maximises $\pi_{Sj} = (P_F - P_W)Q_{Sj}^F$.

[25] Again, it is easy to verify that the second order conditions for a maximum are fulfilled.

$$Q_{Pi}^{F} = \frac{P_F - E(P_W)}{AVar(P_W)} + \frac{1}{2a}\frac{Cov(P_W^2, P_W)}{Var(P_W)} \tag{2.10}$$

for the producer and

$$Q_{Sj}^{F} = \frac{P_F - E(P_W)}{AVar(P_W)} \tag{2.11}$$

for the speculator. Since forward markets are in sum zero net[26] supply the market clearing forward price can be calculated:

$$P_F = E(P_W) - \frac{AN_P}{2a(N_P + N_S)} Cov(P_W^2, P_W) \tag{2.12}$$

Inserting (2.12) in (2.10) and (2.11) finally yields

$$Q_{Pi}^{F} = \frac{Cov(P_W^2, P_W)}{Var(P_W)}\left(\frac{1}{2a} - \frac{N_P}{2a(N_P + N_S)}\right) \tag{2.13}$$

and

$$Q_{Sj}^{F} = -\frac{Cov(P_W^2, P_W)}{Var(P_W)}\frac{N_P}{2a(N_P + N_S)} \tag{2.14}$$

2.3.3 Simulation of market equilibria

In the following the main results of the above sections are simulated by normalising demand Q^D to 100 MWh, setting N_P and N_S to 20 and 10 respectively, A to 0.5, a to 4 €/MWh^2 and FC to 0. The standard deviation of demand σ^D is varied between 0 and 10 (i.e. up to 10% of mean demand). Given these assumptions the expected value of the spot market wholesale price P_W equals 20 €/MWh.

If producers cannot hedge their production on the forward market expected profits are solely determined by spot market transactions. In this case, setting the demand standard deviation σ^D to 5, the expected value of the profit $E(\pi_{Pi})$ of producer i equals 50 € and the standard deviation of expected profits equals 5 €.[27] If producers can hedge their transactions on the spot market, which by definition of risk averse market actors is what they do, the expected value of the profit $E(\pi_{Pi})$ of producer i reduces to 47.3 €. On the other hand the standard deviation of expected profits reduces to 3.3 €.[28] The forward price P_F is downward biased and amounts to 18.3 €/MWh. The price difference to the spot price constitutes the cost of the

[26] $\sum_{i=1}^{N_P} Q_{Pi}^F + \sum_{j=1}^{N_S} Q_{Sj}^F = 0$

[27] The absolute numbers in this example are not of importance. Instead, the relative performance of the spot market and the market with spot and forward contracts matters.

[28] This results from the trade-off of the mean-variance maximisation.

hedge. Figure 2.3 plots the probability density functions of the expected profits for the two cases.

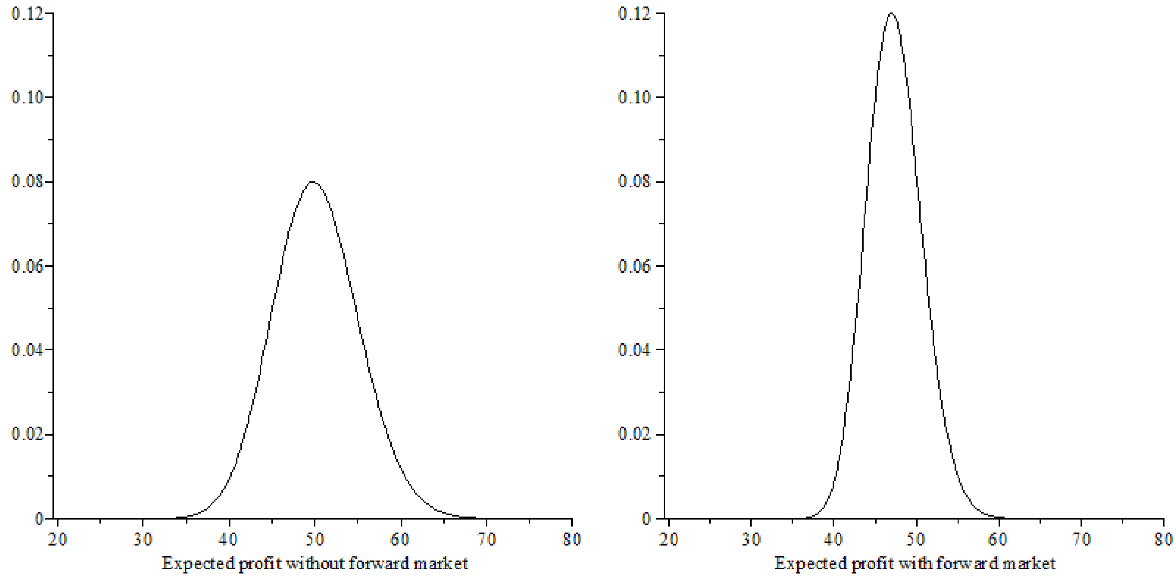

Figure 2.3. Probability density function of expected profits of producer *i* when relying solely on the spot market (left) and when hedging profits by contracting on the forward market as well (right).

The magnitude of the forward premium depends on the standard deviation of demand since demand is the only source of uncertainty in this model. Figure 2.4 plots the relative forward premium (i.e. the difference between the forward and spot price relative to the spot price) as a function of the relative demand standard deviation (i.e. the ratio of standard deviation to expected value of demand). The premium is a concave function of demand volatility and increases (in absolute values) nonlinearly.

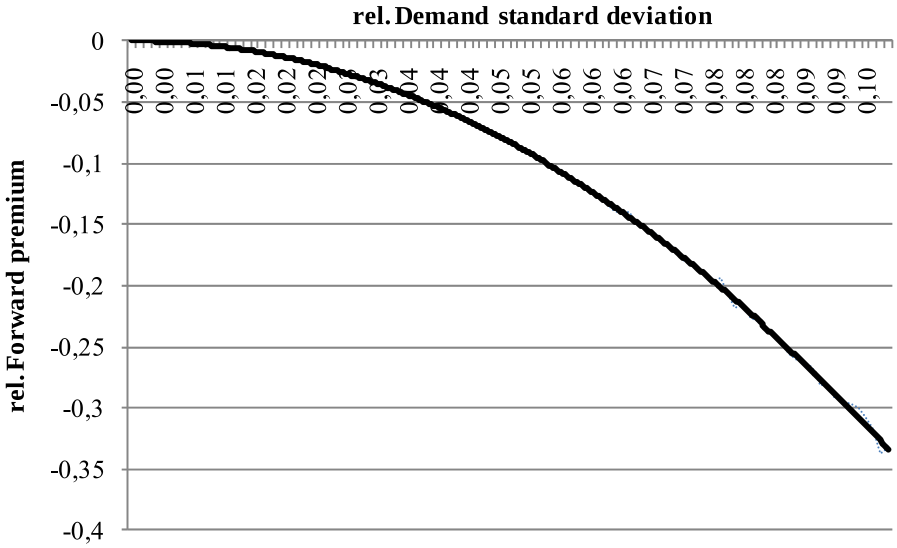

Figure 2.4. Relative forward premium as a function of relative demand standard deviation.

This result critically depends on the risk aversion of the modelled producer's as well as the assumed utility function. However, the main objective is to show that spot and forward prices can diverge in equilibrium. This applies also, as was the case in the model above, for rational market actors and can most easily be shown assuming this type of market participants. Expanding this, Chapter 5 will present an empirical analysis of a comprehensive set of forward premia determinants. As will be seen, the functional relationship is far more complex than the model in this section would seem to suggest.

Before this analysis can be performed it is, however, necessary to understand the empirical price formation in the forward markets. The next two chapters will study this issue in detail.

3 Price formation in electricity forward markets: The case of year-ahead futures prices [29]

Due to the high relevance of long-term electricity markets for risk management reasons pointed out in the previous chapter the determination of influence factors on the price formation on these markets is of great importance. For pricing of these contracts an important fact concerns the non-storability of electricity. In this case, according to economic theory, forward prices are related to expected spot prices which are built on fundamental market expectations. Therefore, in this chapter the crucial impact parameters on year-ahead forward electricity prices are assessed by an empirical analysis of electricity prices at two of the biggest European power exchanges: the European Energy Exchange (EEX) based in Leipzig, Germany, and the Nord Pool Power Exchange, based in Oslo, Norway.[30] The analysis is based on considerations of expectation formation of market participants. Specifically, reduced form regression models aim to give insights on the expectation and price formation. As will be seen, the price formation in the considered markets is influenced by historic spot market prices yielding a biased forecasting power of long-term contracts.

This chapter proceeds as follows: The next section introduces the market setting and the analysed data set. Section 3.2 focuses on an econometric analysis of year-ahead forward prices. Finally, section 3.3 concludes.

3.1 Market setting and data analysis

The European electricity market is still characterised by several different price areas. Reasons for this price divergence can be found, among others, in limited cross-border transmission capacities (European Commission, 2005). In turn, varying generation conditions between many Member States of the European Union result in different electricity wholesale price levels. However, several regional electricity markets have emerged within the European Union as some countries are not separated by permanent cross-border transmission capacity bottlenecks causing prices to converge. Figure 3.1 summarises the status of the year 2009.

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[29] A concise version of this analysis has been published in Redl et al. (2009).

[30] As mentioned the terms futures and forwards are used interchangeably in this thesis. Nevertheless, long-term contracts traded at the EEX are called futures whereas Nord Pool terms its contracts with delivery periods lasting at least one month forwards.

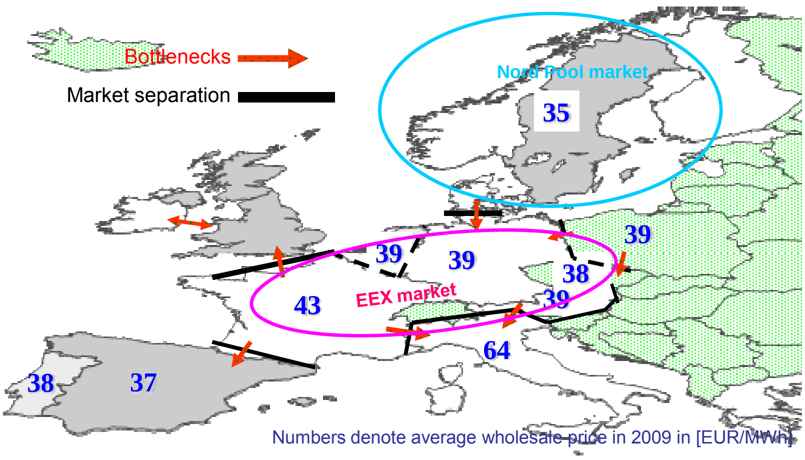

Figure 3.1. European electricity markets, corresponding wholesale price averages in 2009 and bottlenecks in the cross-border transmission grids. Source: Various power exchanges

One of these regional markets is the Western/Central European market comprising Austria, Germany, France and, to a certain extent, Switzerland forming the biggest market in Continental Europe. As these countries are not separated by permanent cross-border transmission capacity bottlenecks, electricity can be traded virtually without limitations between these countries. This causes prices to converge due to arbitrage reasons. Figure 3.2 depicts this convergence.

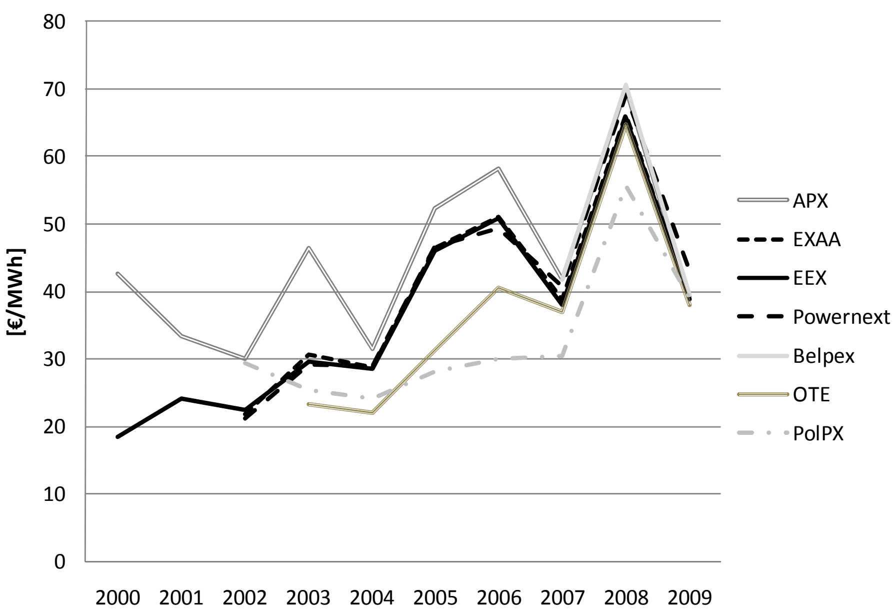

Figure 3.2. Average yearly wholesale prices in the Western European Power market. Source: Various power exchanges

The EEX is the leading exchange in this sub market.[31] Another very important regional market is the Nordic electricity market consisting of Denmark, Finland, Norway and Sweden where a single exchange – the Nord Pool – has been established. Figure 3.3 depicts the price evolution of monthly averages of spot and year-ahead base load electricity prices at the EEX and Nord Pool power exchanges from December 2004 to December 2009.

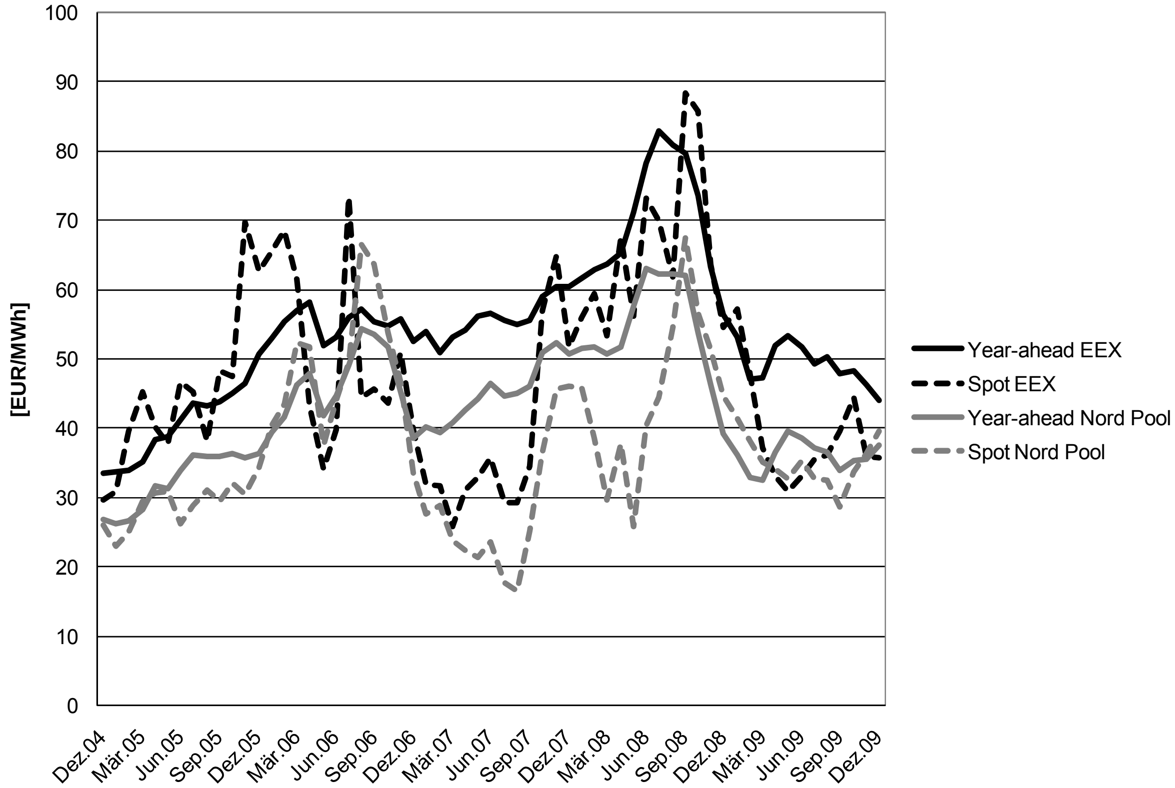

Figure 3.3. Evolution of monthly averages of spot and forward prices for base load electricity at EEX and Nord Pool. Source: EEX, Nord Pool

Spot and forward prices were rising continuously until mid 2006 at the EEX. Since fossil fuelled power plants constitute the price setting technologies in the EEX market, increasing power prices reflected rising primary energy prices. The highest increases could be observed during 2005 due to the commencement of the European Emission Trading Scheme (EU-ETS).[32] Prices for CO_2 emission allowances started trading from 8 EUR/t CO_2 and rose dramatically during 2005 peaking several times at 30 EUR/t CO_2. Spot prices at the EEX were falling, with a short exception, from March 2006 onwards mainly due to a massive drop-

[31] In early 2007 implicit auctions between France, Belgium and the Netherlands have been introduced leading to a coupling of these markets thereby effectively removing the market separation in North Western Europe and extending the Central European market.

[32] As CO_2 emissions from energy activities are part of the EU-ETS, market prices of emission allowances represent opportunity costs which affect electricity generation costs of fossil fuelled power plants.

off in emission allowance prices. Still, year-ahead prices have maintained their high level from early 2006 because of high gas and later on high (2008-) forward emission allowance prices. In 2008 EEX spot prices again reached the level of the forward price due to a price jump on the spot market for CO_2 allowances when the second EU-ETS period started in January 2008. Prices were falling from mid/end 2008 on due to falling primary energy prices (mainly triggered by falling oil prices).

Nord Pool prices follow a different pattern. The Scandinavian power market is mainly characterised by hydro and nuclear generation with 76% of total generation in 2007 stemming from these two generation sources whereas hydro and nuclear generation corresponds to 59% in the Central European sub market.[33] In times of high hydro generation in Scandinavia only highly efficient plants are needed to satisfy demand resulting in lower pool prices compared to the EEX. Still, low hydro availability implying congested transmission grids and increased generation in inefficient thermal power plants, causes prices soaring above EEX levels.

Compared to spot prices, year-ahead forward prices follow a less volatile regime for both markets whereas Nordic prices are generally lower than their EEX counterparts due to the mentioned differences in the power plant park structures. At first sight, spot and forward prices show a higher correlation in the Scandinavian market most likely due to the high amount of hydro storage capacity especially in Norway (see e.g. Gjolberg and Johnsen (2001), and Botterud et al. (2002)).

Figure 3.4 shows crucial influence parameters for European forward electricity prices, namely futures prices for hard coal (North-western Europe port prices – ARA ports), natural gas (Zeebrugge hub), CO_2 allowances (EUA) and year-ahead base load futures traded at the EEX and Nord Pool. A positive relationship between CO_2, natural gas and electricity futures as well as a weak correlation between mainly stable coal and rising electricity futures quotations can be observed.

[33] See, e.g., Nordel (2008) and UCTE (2008) on detailed statistics about the considered markets.

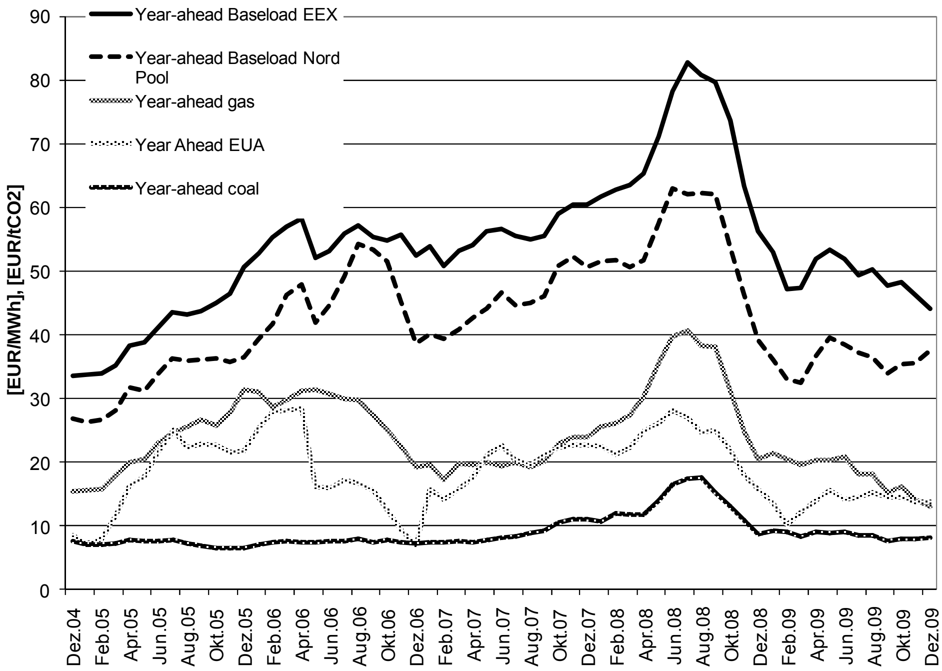

Figure 3.4. Monthly averages of year-ahead coal, gas and CO_2 emission allowance prices vs. EEX and Nord Pool year-ahead base load futures. Source: EEX, Nord Pool

Marginal generation costs are relevant for price formation in competitive electricity markets.[34] Due to the dominance of fossil fuelled power plants, generation costs of these technologies crucially determine electricity prices. Hence, (short run) year-ahead marginal costs of conventional thermal power plants are calculated by formula (3.1) using input data shown in Figure 3.4:[35]

$$SRMC_{t,T} = \frac{p_{PRIM,t,T}}{\eta} + \frac{p_{CO2,t,T} f_{CO2}}{\eta} \tag{3.1}$$

where $SRMC_{t,T}$ are short run (year-ahead) marginal costs [EUR/MWh], p_{PRIM} are primary energy prices [EUR/MWh], p_{CO2} are CO_2 emission allowance prices [EUR/t CO_2], f_{CO2} is the CO_2-emission factor of the fuel [t CO_2/MWh$_{\text{primary}}$] and η is the efficiency of the plant.

As discussed in section 2.1.3 futures prices are related to expected spot prices. Hence, within the framework of rational expectations one would first expect a prominent influence of generation costs of price setting technologies built on forward prices of input parameters. Indeed, year-ahead electricity futures traded at the EEX show a high correlation with generation costs of gas-fired plants (CCGT) and coal-fired power stations (HC) (see Table

[34] For a general discussion see Chapter 2.

[35] Variable operation and maintenance costs are neglected.

3.1). However, EEX year-ahead prices also show a high correlation with current spot prices indicating adaptive expectation formation behaviour of market participants in the futures market where the spot price serves as an estimator of year-ahead electricity prices.[36,37] A similar link between forward prices and generation costs of fossil fuelled plants prevails in the Nordic market (see Table 3.1). An adaptive price formation component can also be observed in this market given the correlation between forward and current spot prices. As mentioned earlier, the high amount of reservoirs in the Nord Pool area can serve as an explanation.

Table 3.1. Correlation coefficients between monthly averages of EEX and Nord Pool year-ahead base load prices and explanatory variables from December 2004 to December 2009.

	Correlation coefficient	
	EEX	Nord Pool
$\text{Year-ahead}_{\text{Base } t,T}$ / $\text{SRMC}_{\text{CCGT\_Zeebrugge } t,T}$	0.74	0.75
$\text{Year-ahead}_{\text{Base } t,T}$ / $\text{SRMC}_{\text{HC\_ARA } t,T}$	0.86	0.81
$\text{Year-ahead}_{\text{Base } t,T}$ / Spot_{t}	0.61	0.57

In the following, the year-ahead forward price at EEX and Nord Pool will be explained with the abovementioned variables by performing econometric analyses.

3.2 A model for year-ahead electricity prices

Comparing the abovementioned variables to futures prices suggests that futures prices at both exchanges are strongly influenced by both spot market prices and year-ahead generation costs for CCGT and HC plants. Generation costs, determined from input prices shown in Figure 3.4 according to (3.1), represent fundamental explanatory variables of the model. To be able to account for non-linear effects quadratic cost terms are included additionally. The current spot price represents an explanatory variable to incorporate adaptive behaviour of market participants into the model. All time series exhibit clear trends and thus must be considered to represent non-stationary processes which is confirmed by unit root tests. As the hypothesis of a cointegrated relationship has to be strongly rejected (by an Engle-Granger test with an ADF

[36] Karakatsani and Bunn (2008) show that British spot prices are significantly influenced by lagged spot prices – this autoregressive price effect could indicate market inefficiency.

[37] As will be discussed in chapters 4 and 5, a link in electricity spot and forward prices may emerge from a link in storable fuels serving as production inputs (coal and gas). Still, the correlation among the exogenous variables in (3.2) is low (about 20% for spots and generation costs) indicating a prominent influence of the spot price on the futures price itself.

test statistic of -1.57) the time series are transformed into first differences to avoid spurious regression results. The following regression model (3.2) is estimated by ordinary least squares (OLS) to test the above hypothesis for futures prices at the EEX and the Nord Pool exchange:

$$\Delta LnYearAhead_{Base,t,T} = b_1 + b_2 \Delta LnSRMC_{CCGT,t,T} + b_3 (\Delta LnSRMC_{CCGT,t,T})^2 + b_4 \Delta LnSRMC_{HC,t,T} + b_5 \Delta LnSpot_t + b_6 \Delta LnSpot_{t-1} + \varepsilon_t \tag{3.2}$$

where $\Delta LnYearAhead_{Base,t,T}$ is the growth rate of the year-ahead futures price, $\Delta LnSRMC_{CCGT,t,T}$ and $\Delta LnSRMC_{HC,t,T}$ are the growth rates of year-ahead generation costs of gas and hard coal fired power plants respectively, and $\Delta LnSpot_t$ and $\Delta LnSpot_{t-1}$ are the growth rates in the spot market for observation t and its one month lag respectively. Table 3.2 shows the results of the econometric model for the EEX and Nord Pool markets.

For EEX, year-ahead generation costs of CCGT and HC plants, quadratic generation costs of CCGT plants as well as spot market prices provide a good explanation of the year-ahead electricity price. All diagnostic test statistics of the residuals are not significant. The significant influence of current spot prices indicates an adaptive expectation formation component on the futures market. The generation costs of CCGT plants exert a non-linear influence on the year-ahead electricity price as strong increases of these costs do not pass through to the electricity price due to fuel-switching in times of high generation costs of CCGT plants (e.g. at times of high gas prices). Indeed, the clean spark spread gets negative during some months in the analysed sample. Whereas, the clean dark spread stays positive during these months. This is an indication for the potential to switch fuels. Put differently, positive clean spark spreads suggest that gas fired power plants are, given positive CO2 prices and low gas prices, inframarginal technologies. Decreasing spreads bring about fuel switching towards technologies with positive spreads – i.e. coal fired plants in our example. Hence, b_3 in equation (3.2) shows a negative sign.[38]

Similarly, the model provides a good explanation for Nord Pool's year-ahead forward prices. All diagnostic test statistics of the residuals are insignificant. Electricity prices are strongly dependent on generation costs also in the Nordic market. Nevertheless, current spot prices significantly influence forward prices most likely due to the high amount of hydro storage.

[38] Model (3.2) tests the expectations theory (2.2). Implicitly, a constant forward premium is assumed in model (3.2). This is a critical assumption. I will specifically deal with the evolution of a – time-varying – market price of risk in Chapter 5. Determining a significant influence of modelled expectations (of future generation costs) on futures prices verifies equilibria in expectations. This applies also for non-linear cost effects. Clearly, demand side induced non-linear effects (elasticity of demand) may add to the explanation of futures prices. Nonetheless, given a more detailed mix of the supply stack brought about by the EU-ETS corresponding changes of the stack due to time-varying spreads are crucial for explaining a non-linear behaviour of futures prices.

The effect of generation costs of CCGT plants is non-linear. When generation costs of these plants rise, the pressure on power prices is lowered due to the large amount of flexible hydro storage capacity and associated opportunity cost considerations. All results are shown in Table 3.2.

Table 3.2. Results of regression analysis (3.2) for *Δ Ln Year-ahead* base load futures traded during February 2005 to December 2009 at the EEX and Nord Pool exchanges (t-statistics in brackets). All tests are based on heteroscedasticity consistent standard errors. *, **, *** denotes significance on the 10%, 5% and 1%-level.

Coefficient	Variable	EEX	Nord Pool
b_1	Constant term	0.01 (1.78)*	0.01 (1.77)*
b_2	Δ Ln $SRMC_{CCGT\ t,T}$	0.23 (4.11)***	0.12 (1.78)*
b_3	$(\Delta$ Ln $SRMC_{CCGT\ t,T})^2$	-0.58 (1.81)*	-0.99 (-2.48)**
b_4	Δ Ln $SRMC_{HC\ t,T}$	0.25 (3.64)***	0.46 (5.23)***
b_5	Δ Ln $Spot_t$	0.03 (1.74)*	0.09 (2.67)***
b_6	Δ Ln $Spot_{t-1}$	0.04 (2.26)**	0.05 (1.61)
R^2 (R^2_{corr})		0.76 (0.74)	0.77 (0.75)
DW		1.24	1.57
Serial correlation	χ^2_{12} (p-value)	0.071	0.744
Functional form	χ^2_1 (p-value)	0.114	0.311
Normality	JB (p-value)	0.183	0.848
Heteroscedasticity	χ^2_5 (p-value)	0.974	0.314
Observations		59	59

In order to determine the robustness of the regression results presented in Table 3.2 – where coefficient estimates of the exogenous variables are assumed constant over time – recursive estimates are computed. This estimation technique calculates the dynamic evolution of the coefficients by continuously re-estimating the regression model by using ever larger observations starting with *n+1* observations for the first estimate and including one additional observation for each repeated estimate.[39]

Figure 3.5 depicts the results of the cumulative sums of the recursive residuals (CUSUM test) and the cumulative sum of squared residuals (CUSUM of Squares test) for both markets. For Nord Pool both tests clearly show stability of the regression parameters during the sample period for the 5% significance level. For EEX, the CUSUM test also indicates parameter stability. For the CUSUM of squared residuals the test indicates partial variance instability of the regression equation (3.2) as the sum grazes the 5% significance line during parts of 2008. To finally check robustness recursive coefficients are analysed next.

[39] *n* denotes the number of exogenous variables in the regression model.

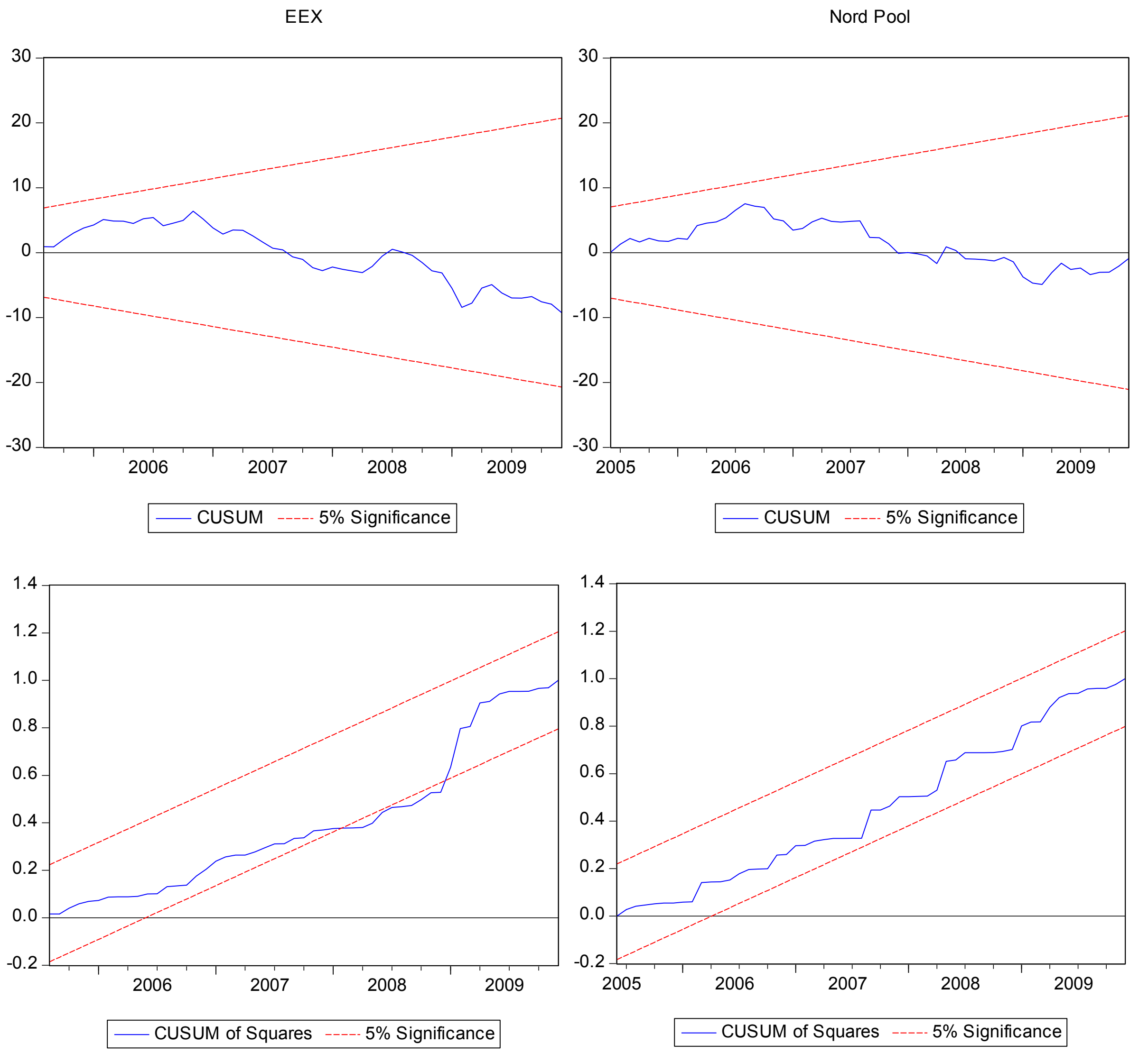

Figure 3.5. CUSUM and CUSUM of squares test for regression model (3.2) for EEX (left) and Nord Pool (right).

Figure 3.6 presents graphs of the recursively estimated regression coefficients for EEX. Clearly the parameters behave rather unstable at the beginning of the sample period since the degrees of freedom of the model are low. However, as the sample size increases, the estimates of the coefficients show a low variation which is an indicator of parameter stability. Also the significance of the coefficients shows the expected trend behaviour. Specifically, the coefficients for gas and coal generation costs behave in a volatile manner during 2006 whereas from 2007 on the pattern is smooth: Due to the price jump of carbon allowances from the EU-ETS period I to period II year-ahead forward prices for the latter apply from 2007 on. As can be seen in Figure 3.6 the coefficients are indeed stable as of 2007. The quadratic generation costs of gas fired CCGT plants get significant only at the end of the sample period. This is most likely due to dynamic evolution of the ratio of gas to coal generation costs since more fuel switching towards coal fired plants occurs. Overall, the analysis of recursive estimates for EEX has confirmed the robustness of the results presented in Table 3.2.

Similarly, Figure 3.7 presents graphs of the recursively estimated regression coefficients for Nord Pool. As expected the parameters behave rather unstable at the beginning of the sample period due to the low number of degrees of freedom of the model but, as the sample size increases, converge quickly as the estimates of the coefficients show a low remaining variation. This is a clear indicator of parameter stability. Similarly to EEX, the price jump in the year-ahead carbon market affects the coefficients for gas and coal generation costs whereas these coefficients behave in stable manner as of 2007. Also all regression coefficients are statistically significant apart from the first set of observations. Overall, the analysis of recursive estimates for Nord Pool has confirmed the robustness of the results presented in Table 3.2. In fact, in terms of parameter stability the Nord Pool model slightly outperforms the EEX model.

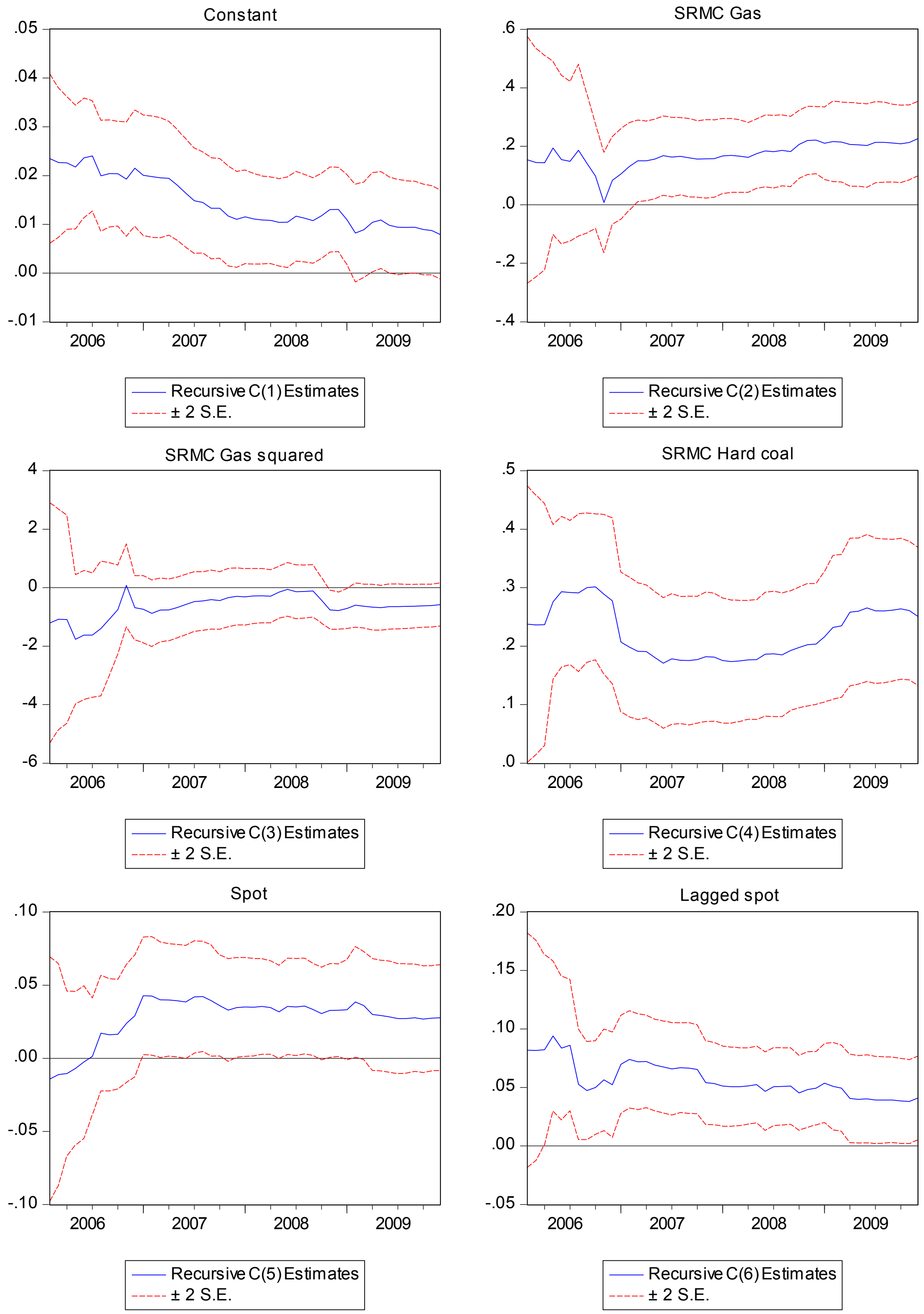

Figure 3.6. Recursive estimates of the coefficients of model (3.2) for EEX

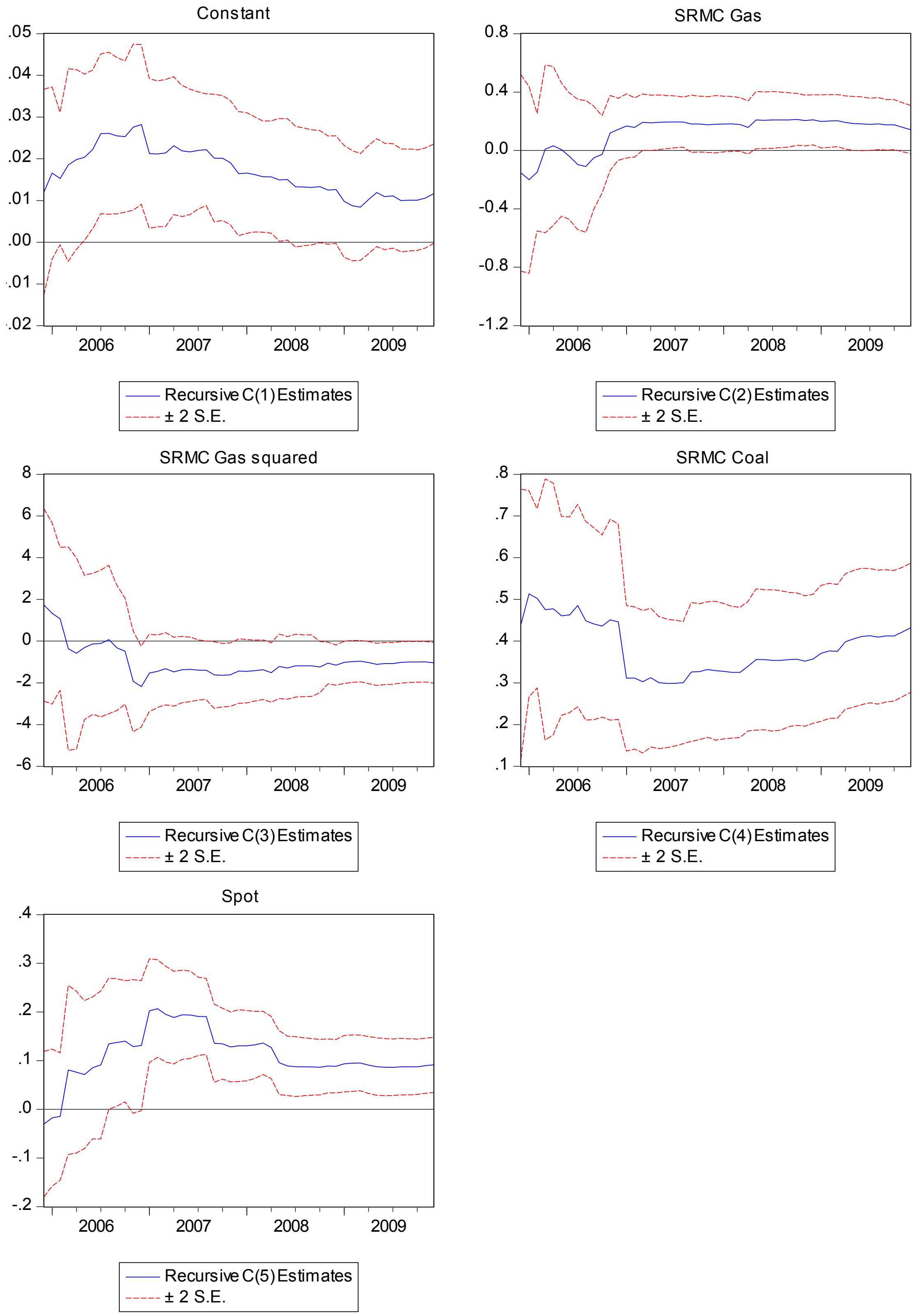

Figure 3.7. Recursive estimates of the coefficients of model (3.2) for Nord Pool

Interestingly, at both exchanges, the influence of gas and coal fired generation technologies on electricity prices cannot be distinguished according to a Wald test. The hypothesis of both power plant types equally influencing forward prices (i.e. $b_2=b_4$ in equation (3.2)) cannot be rejected on a 5% significance level with a χ_{1DOF}-statistic of 0.05 (p-value of 0.82) for EEX and a χ_{1DOF}-statistic of 3.58 (p-value of 0.06) for Nord Pool. Most likely the introduction of the EU-ETS contributes to this result yielding a higher competitiveness of gas fired generation technologies in baseload generation.

With the introduction of the EU-ETS controversial discussions among market participants on the role of allowance prices and their influence on electricity prices have started. Commonly, allowance prices were considered as being the prime mover of electricity wholesale prices although this influence was interpreted as the result of the exercise of market power. Why, it was argued, would freely allocated emission allowances increase the power price? Still, simple opportunity cost considerations can resolve this alleged puzzle.

With the empirical model (3.2) it is, however, not possible to assess a potential differing influence of fuel and CO_2 costs on the electricity price directly since splitting up of the fuel cost and CO_2 cost component according to equation (3.1) would lead to multicollinearity problems when estimating (3.2) by OLS. Instead, to be able to obtain insights regarding the relative influence of CO_2 costs on electricity prices the year-ahead fuel costs and year-ahead CO_2 costs (i.e. the two components of equation (3.1)) are regressed against year-ahead forward prices separately for CCGT and HC plants:

$$\Delta LnYearAhead_{Base,t,T} = b_1 + b_2 \Delta LnFuelCost_{CCGT,t,T} + b_3 \Delta LnCO_2Cost_{CCGT,t,T} + \varepsilon_t \tag{3.3}$$

$$\Delta LnYearAhead_{Base,t,T} = b_1 + b_2 \Delta LnFuelCost_{HC,t,T} + b_3 \Delta LnCO_2Cost_{HC,t,T} + \varepsilon_t \tag{3.4}$$

where in equation (3.3) $\Delta LnYearAhead_{Base,t,T}$ is the growth rate of the year-ahead futures price, $\Delta LnFuelCost_{CCGT,t,T}$ is the growth rate of the fuel cost component of the year-ahead generation costs of gas fired power plants and $\Delta LnCO_2Cost_{CCGT,t,T}$ is the growth rate of the CO_2 cost component of year-ahead generation costs of gas fired power plants. Similarly, equation (3.4) estimates the year-ahead futures price on the fuel and CO_2 cost components of coal fired power plants. Table 3.3 shows the detailed results of the econometric models for the EEX and Nord Pool markets.

According to the model results both fuel costs and CO_2 costs significantly influence forward prices at the EEX and the Nord Pool. This, clearly, is to be expected. As CO_2 emissions from energy activities are part of the EU-ETS, market prices of emission allowances represent opportunity costs which affect electricity generation costs of fossil fuelled power plants. Hence, given CO_2 emitting price setting technologies, CO_2 costs are part of electricity wholesale prices. This result applies irrespective of the allocation mechanism of CO_2 emission allowances.

Table 3.3. Results of regression analysis (3.3) and (3.4) for *Δ Ln Year-ahead* base load futures traded during December 2004 to December 2009 at the EEX and Nord Pool exchanges (t-statistics in brackets). All tests are based on heteroscedasticity consistent standard errors. *, **, *** denotes significance on the 10%, 5% and 1%-level.

Coefficient	Variable	EEX		Nord Pool	
		CCGT	HC	CCGT	HC
b_1	Constant term	0.001 (1.16)	0.003 (0.72)	0.01 (0.86)	0.003 (0.63)
b_2	Δ Ln Fuel cost $_{t,T}$	0.35 (6.03)***	0.40 (6.94)***	0.36 (4.33)***	0.52 (7.27)***
b_3	Δ Ln CO_2 cost $_{t,T}$	0.10 (2.24)**	0.13 (2.96)***	0.17 (2.79)***	0.19 (3.11)***
R^2 (R^2_{corr})		0.64 (0.63)	0.62 (0.61)	0.57 (0.56)	0.66 (0.65)
DW		1.30	1.24	1.36	1.19
Serial correlation	χ^2_{12DOF} (p-value)	0.181	0.228	0.116	0.0043
Functional form	χ^2_{1DOF} (p-value)	0.02	0.007	0	0.001
Normality	χ^2_{2DOF} (p-value)	0.817	0.404	0.774	0.13
Heteroscedasticity	χ^2_{2DOF} (p-value)	0.487	0.67	0.035	0.04
Observations		60	60	60	60

3.3 Conclusions

Due to lacking storage possibilities, no exact relationship between current spot and forward prices can be formulated. Instead, forward prices are built on expectations of market participants, updated by applying forward premia. The analysis on year-ahead electricity prices in this chapter has revealed three corresponding results concerning the expectation formation worth emphasising.

First, year-ahead baseload electricity prices do depend on year-ahead generation costs in line with economic theory on equilibrium relationships for forward pricing. The year-ahead generation costs can be interpreted as the market's best estimate of future electricity prices. Second, electricity forward prices are also influenced by current spot prices. Moreover, the recent trend of spot prices has a significant impact on the futures price.

This suggests the existence of a behavioural pricing component in the forward market. Trading strategies of market participants seem to rely partly on current spot prices instead of fundamental modelling approaches. Finally, although the EEX and Nord Pool market are physically only weakly interconnected – resulting in different price levels – main characteristics with regard to price formation on the year-ahead forward markets are alike although the supply and demand side characteristics in the EEX market differ significantly from the fundamentals in the Nord Pool market.

Clearly, the significant influence of current spot market prices on futures prices in both markets questions the forecasting power of the forward price (i.e. the consistency of the forward price). Hence, it is of interest to study the relationship between current spot and forward prices and market participants' corresponding risk assessment in more detail. The next chapter will specifically assess the interaction of spots and forwards. Chapter 5 will, in turn, study the implications for the price of risk inherent in forward price quotations.

4 Interaction between spot and forward prices

Assuming rational expectations and risk-neutral market actors, future spot prices should only deviate from forward prices in case of unexpected shocks. Therefore, under these stringent assumptions, spot prices in the delivery period S_T should equal forward prices $F_{t,T}$ plus a white noise error term ε_t with zero mean:

$$F_{t,T} = E_t(S_T | \Omega_t) \Rightarrow S_T = F_{t,T} + \varepsilon_t \tag{4.1}$$

The results of the empirical models presented in Chapter 3 question the predictive power of the year-ahead forward price however as it depends on current spot prices. Therefore, this chapter will explore this relationship more closely. A traditional approach to test hypothesis (4.1) is to run a regression where the spot price is regressed against a constant and the futures price. If the forward price were an unbiased predictor of the future spot price the regression coefficients of the constant term and the futures price should not be statistically different from zero and one respectively.

Price time series often exhibit a non-stationary behaviour. To avoid spurious regression results differences of the time series have to be considered which, however, eliminates important long run information. Nevertheless, if the time series are cointegrated OLS estimation can be used without taking differences of the relevant time series (Engle and Granger, 1987).

This structural approach necessitates a clear distinction between exogenous and endogenous variables. However, the distinction might not be clear cut in the case of spot and forward markets. Clearing on these markets is a result of market forces and their interactions which precludes that one development on one market is fixed and determines the development on the other market. Instead, a simultaneous evolution may be assumed. Furthermore, Gjolberg and Brattested (2011) point out additional econometric and fundamental problems associated with tests of equations similar to (4.1).

Interestingly, for electricity spot and forward markets the distinction is not as clear cut as commonly recognised. A link between current spot and current forward prices might not be anticipated due to the fact that electricity is not storable. Finding a corresponding relationship may, accordingly, suggest a behavioural pricing component prevailing in the markets. Fundamentally, power prices are affected by production costs, demand, and market power (Bunn, 2004, Weron, 2006). The inputs to electricity production (gas, coal and CO2 permits) are, however, storable.[40] Hence, links between electricity spots and forwards can emerge from the fact that electricity is a derived commodity.[41] This necessitates a careful variable selection for an empirical analysis of prices (and corresponding links).

The relations between electricity spots and forwards may not only emerge from links in storable fuels. Also, counter to the implications of rational pricing models, behavioural biases (e.g. caused by employing heuristics or anchoring decisions) are reasonably to be expected to prevail in electricity markets.[42]

Interestingly, despite rich literature on explicit stochastic spot and forward price models and empirical analyses of the properties of risk premia, few studies specifically dealt with (high-frequency and short-term) interactions of electricity spot and futures prices. Bunn and Gianfreda (2009) estimate the integration of different regional European spot and futures electricity markets using Granger, cointegration and impulse response tests and find significant interactions among European spot markets and also among European futures markets. Similarly, Bunn and Fezzi (2008) and Fell (2010) study in detail the interactions between carbon, fuel and electricity spot prices. However, the above studies do not assess interactions between electricity spots and forwards in the same regional market. I specifically seek to address this issue in the following. Shawky et al. (2003) constitutes a first exception for electricity. They estimate an EGARCH and a VAR model and find that conditional volatility and shocks to spot returns determine the relation between spots and forwards. Most of the empirical literature available on price interactions studies, obviously, oil prices. Ng and Pirrong (1996) provide an early analysis for petroleum products using non-linear error correction models and find (current) futures prices leading (current) spot prices. Newer work on oil includes Kaufmann and Ullman (2009) and Bekiros and Diks (2008).[43] Depending on the sample and applied methodology results differ – generally, they suggest mixed lead/lag relation between spots and forwards. Finally, Gronwald et al. (2010) apply Granger causality tests on European CO2 spot and futures prices finding a bi-directional relationship.

Figure 4.1 depicts the evolution of daily EEX spot and forward (month-ahead, quarter-ahead and year-ahead) prices. Generally, stable market periods can be distinguished from trending

[40] Chapter 3 has shown that fossil fuelled power plants are price setting in the EEX market.

[41] Douglas and Popova (2008) show that gas inventory levels can affect electricity day-ahead forward premia by influencing the moments of electricity prices. This chapter aims to analyse the effect of storable fuels on the futures prices themselves.

[42] See Chapter 5 for a detailed analysis.

[43] See also the references therein.

market periods whereas a similar behaviour between spot and futures prices can be observed. Given the existence of potential links as argued above, a natural question arising concerns the information flows (causal relation) between the current spot and forward prices. Does the spot follow the forward? Is it vice versa? Is one series (at least weakly) exogenous? Evidence from the literature (mainly available on oil price analyses only) suggests mixed evidence on lead/lag relationships.[44] Therefore, Granger causality tests and a vector autoregression (VAR) model will be applied in the following to assess these questions. Furthermore, the VAR model will be expanded by exogenous variables driving the electricity price series (and its links).

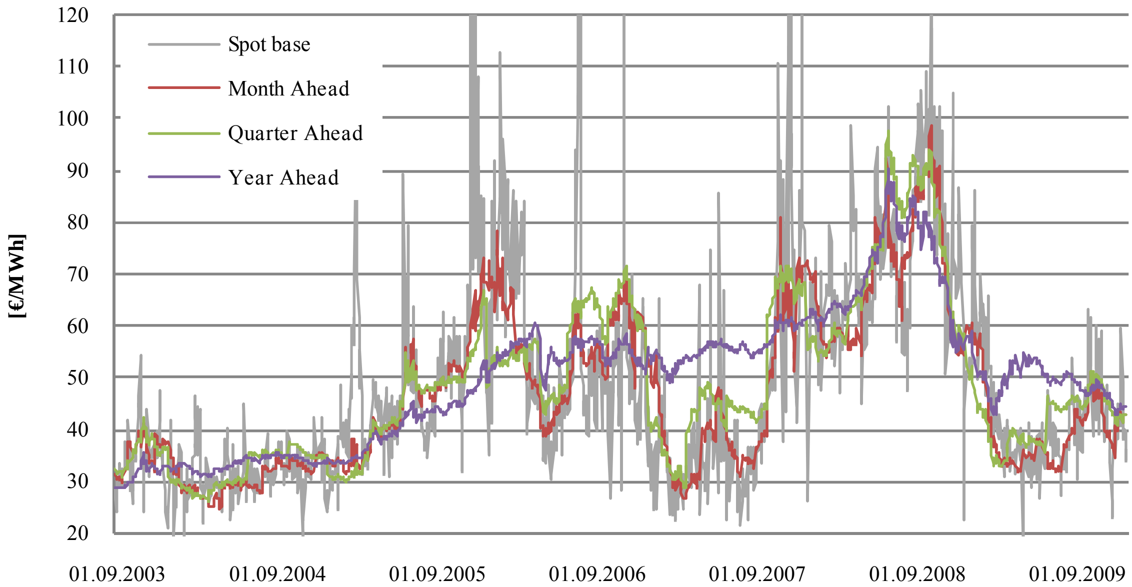

Figure 4.1. Comparison of daily spot prices (grey line) and daily forward settlement prices for the next month, quarter and year (coloured lines). Note that the y-axis is restricted to values ranging from 20 to 120 €/MWh. Source: EEX

Hence, the analyses in the following sub-chapters will address the following questions:

- What are the links between current spot and futures prices (Section 4.1)?
- Are there common (exogenous) drivers of these links (Section 4.2)?
- Which exogenous parameters drive the components of the electricity price system (Section 4.2)?

As will be seen, answers to these questions, in turn, unfold further research questions: What are the consequences of links between spot and forward prices for the (ex-post) forward premium and its link to current prices? And, consequently, are there generalisable patterns in

[44] As mentioned, Shawky et al. (2003) constitutes an exception for electricity. Ng and Pirrong (1996) provide an early analysis for petroleum products.

the forward premium evolution as a function of time to maturity? These questions will be assessed in detail in Chapter 5 and Appendix B.

Several issues have to be considered before judging too quickly on generalisable patterns in the links between spots and forwards. Trading is thin for contracts with maturities more distant in the future. Hence, a model representation including all currently traded products may not touch upon the relevant relations which were governed by actual trading and corresponding “fundamental” market liquidities. A related fact concerns that due to arbitrage prices of several contracts can be determined by the other products on the market which brings about problems of endogeneity. For prices observed in January, for example, the price of the second quarter contract must be the average of the prices for monthly futures for April, May and June updated by transaction cost. Hence, in order to avoid these problems the analysis presented below focuses on spot and one month-, quarter-, and year-ahead prices (see Figure 4.1).

4.1 The link between current spot and futures prices

The finally to be employed empirical methodology depends on the properties of the analysed daily price time series. All time series depicted in Figure 4.1 are non-normally distributed and are highly correlated with correlation coefficients exceeding a minimum value of 0.58 (between current year-ahead and spot prices) and ranging up to 0.92 (between month and quarter-ahead prices).[45] Table 4.1 summarises the correlation coefficients and shows descriptive statistics of the individual distributions. To filter out the relationship only working days are used for the price time series since futures contracts are not traded on weekends and public holidays.

All time series except the spot prices contain a unit root. Hence, an analysis in levels could be performed for the forwards only if the respective time series were cointegrated.[46] Since the analysis comprises stationary spot prices an unrestricted VAR model is tested for the returns (i.e. the logarithmic differences) of the original price series instead. This transformation has to be kept in mind when interpreting the model results. As shown in Figure 4.2 the return series are clearly stationary (which is confirmed by unit root tests). Table 4.2 summarises the correlation coefficients and shows descriptive statistics of the returns data set.

[45] These correlations may appear surprisingly high given a non-storable commodity.

[46] The futures price series are non-stationary when including an intercept as well as a linear trend in the test equation.

Table 4.1. Correlation coefficients between daily EEX spot, month-ahead, quarter-ahead and year-ahead base load prices noted on working days (top panel) from September 2003 to December 2009 and summary statistics (bottom panel).

	S_t	Month-ahead$_{t,T}$	Quarter-ahead$_{t,T}$	Year-ahead$_{t,T}$
S_t	1.00			
Month-ahead$_{t,T}$	0.76	1.00		
Quarter-ahead$_{t,T}$	0.69	0.92	1.00	
Year-ahead$_{t,T}$	0.58	0.79	0.87	1.00
Mean	49.20	46.88	48.55	49.77
Median	43.08	42.32	45.21	51.15
Maximum	301.54	98.41	97.50	90.15
Minimum	17.06	24.85	26.28	28.62
Std. Dev.	21.49	15.42	15.40	12.99
Skewness	2.51	0.81	0.90	0.46
Kurtosis	19.02	2.98	3.35	2.99
Jarque-Bera	18757.27	175.01	225.29	56.77
Observations	1598	1598	1598	1598

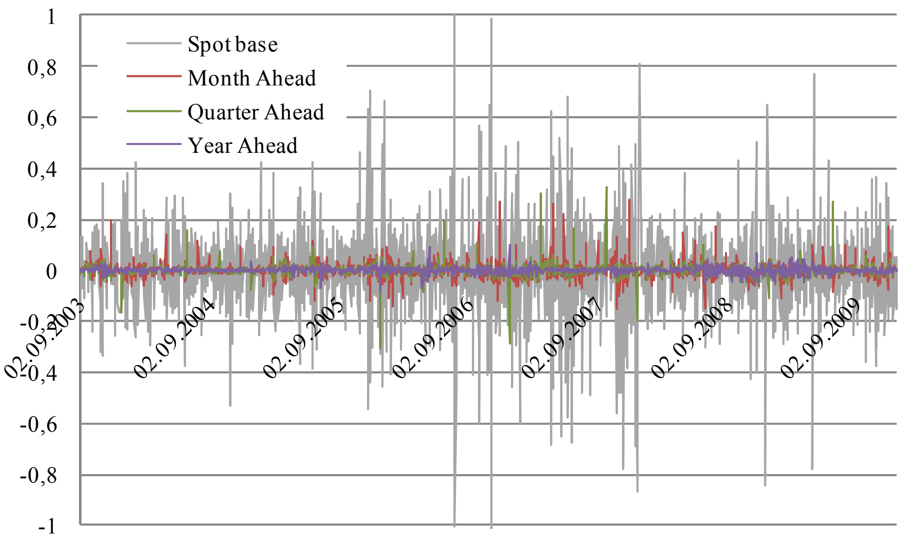

Figure 4.2. Daily spot price and forward price (month, quarter and year-ahead) returns. Source: EEX, own calculations

Table 4.2. Correlation coefficients between daily EEX spot and futures returns (top panel) from September 2003 to December 2009 and summary statistics (bottom panel).

	S_t	$\Delta LogMonthAhead_{t,T}$	$\Delta LogQuarterAhead_{t,T}$	$\Delta LogYearAhead_{t,T}$
$\Delta LogS_t$	1.00			
$\Delta LogMonthAhead_{t,T}$	-0.031	1.00		
$\Delta LogQuarterAhead_{t,T}$	-0.003	0.339	1.00	
$\Delta LogYearAhead_{t,T}$	-0.059	0.386	0.438	1.00
Mean	0.000	0.000	0.000	0.000
Median	0.003	-0.001	0.000	0.000
Maximum	1.096	0.276	0.328	0.102
Minimum	-1.076	-0.150	-0.304	-0.087
Std. Dev.	0.178	0.032	0.026	0.012
Skewness	-0.096	1.953	1.291	-0.008
Kurtosis	8.733	18.747	67.311	11.988
Jarque-Bera	2189.145	17515.330	275653.900	5375.611
Observations	1597	1597	1597	1597

To assess the interrelation between spot and forward prices an unrestricted vector autoregression (VAR) model is estimated:

$$y_t = A_0 + A_1 y_{t-1} + A_2 y_{t-2} + ... + A_p y_{t-p} + \varepsilon_t \tag{4.2}$$

where $y_t = \begin{bmatrix} \Delta Log(S_{t,t+1}) \\ \Delta Log(F_{t,t+1M}) \\ \Delta Log(F_{t,t+1Q}) \\ \Delta Log(F_{t,t+1Y}) \end{bmatrix}$ is a vector of spot and forward price returns, $\underline{A_0}$ is a vector of constants, and $\underline{A_1}$, etc. are the coefficient matrices. $\Delta Log(S_{t,t+1})$ is the daily return in the day-ahead spot market, $\Delta Log(F_{t,t+1M})$, $\Delta Log(F_{t,t+1Q})$, and $\Delta Log(F_{t,t+1Y})$ are the month-, quarter-, and year-ahead futures price returns. Lag length criteria suggest a lag length of 1 (SC), 2 (HQ) and 5 (AIC). Since lag exclusion tests yield significant lags up to the second one, a lag length of two is selected. However, significant autocorrelation is still prevalent in the residuals (most likely due to omitted exogenous variables). Table 4.3 shows the results of the VAR model.

Table 4.3. Results of the unrestricted VAR model (4.2) for daily spot and forward prices of EEX from September 2003 to December 2009 (t-statistics in brackets). *, **, *** denotes significance on the 10%, 5% and 1%-level.

Variable	EEX			
	$\Delta\log(S_{t,t+1})$	$\Delta\log(F_{t,t+1M})$	$\Delta\log(F_{t,t+1Q})$	$\Delta\log(F_{t,t+1Y})$
Constant	0.00 (0.02)	0.00 (0.27)	0.00 (0.25)	0.00 (0.90)
$\Delta\log(S_{t-1})$	-0.36 (-14.38)***	-0.01 (-1.90)*	-0.00 (-0.83)	-0.00 (-3.14)***
$\Delta\log(S_{t-2})$	-0.17 (-6.73)***	-0.00 (-0.86)	-0.00 (-0.28)	-0.00 (-0.90)
$\Delta\log(F_{t-1,t+1M})$	0.13 (0.88)	0.01 (0.26)	0.02 (1.12)	0.01 (0.83)
$\Delta\log(F_{t-2,t+1M})$	-0.09 (-0.61)	-0.06 (-2.10) **	-0.02 (-0.68)	-0.01 (-0.89)
$\Delta\log(F_{t-1,t+1Q})$	-0.11 (-0.61)	0.09 (2.62) **	0.04 (1.51)	0.02 (1.51)
$\Delta\log(F_{t-2,t+1Q})$	-0.14 (-0.75)	0.06 (1.66)	-0.01 (-0.39)	-0.00 (-0.31)
$\Delta\log(F_{t-1,t+1Y})$	0.17 (0.44)	0.05 (0.62)	0.11 (1.79)*	0.06 (2.075) **
$\Delta\log(F_{t-2,t+1Y})$	0.10 (0.27)	-0.15 (-1.95) *	-0.06 (-0.95)	-0.07 (-2.50)**
R^2 (R^2_{corr})	0.12 (0.12)	0.02 (0.01)	0.01 (0.01)	0.02 (0.01)
Observations	1594	1594	1594	1594

Benth et al. (2009) contend that the lacking storability of electricity implies that spot prices are not affected by available information about future price changes (i.e. price changes in the forward contract market). In reverse, futures prices should not be affected by spot price changes. However, the results of model (4.2) suggest the opposite. In fact, the prevalence of behavioural components in the electricity markets' price formation is discernible since different product types (i.e. spots and various forwards) mutually influence each other. The explanatory power of the models is, nevertheless, rather low. However, given the data series constitute daily returns and exogenous variables are excluded this is to be expected. The behavioural component is confirmed by Granger non-causality tests. The null hypothesis that spot prices do not Granger cause forward prices must be rejected for yearly contracts. Similarly, the null hypothesis that quarter-ahead and year-ahead forward prices do not Granger cause month-ahead and quarter-ahead forward prices respectively can be rejected. Therefore, according to the definition of Granger causality, lagged values of the price returns can be used for forecasting the other return series which confirms the interrelatedness of the spot and futures time series.

Table 4.4 and Figure 4.3 summarise these results.

Table 4.4. Results of Granger non-causality tests for daily spot and forward returns of EEX from September 2003 to December 2009.

		EEX		
Variable	H0	Variable	F-statistic	p-value
$\Delta\log(S_{t})$	ǂ	$\Delta\log(F_{t,t+1M})$	1.58	0.21
	ǂ	$\Delta\log(F_{t,t+1Q})$	0.27	0.76
	ǂ	$\Delta\log(F_{t,t+1Y})$	4.25	0.01
$\Delta\log(F_{t,t+1M})$	ǂ	$\Delta\log(S_{t})$	0.73	0.48
	ǂ	$\Delta\log(F_{t,t+1Q})$	1.76	0.17
	ǂ	$\Delta\log(F_{t,t+1Y})$	0.69	0.50
$\Delta\log(F_{t,t+1Q})$	ǂ	$\Delta\log(S_{t})$	0.39	0.67
	ǂ	$\Delta\log(F_{t,t+1M})$	4.68	0.01
	ǂ	$\Delta\log(F_{t,t+1Y})$	1.02	0.36
$\Delta\log(F_{t,t+1Y})$	ǂ	$\Delta\log(S_{t})$	0.18	0.84
	ǂ	$\Delta\log(F_{t,t+1M})$	2.17	0.11
	ǂ	$\Delta\log(F_{t,t+1Q})$	3.03	0.05

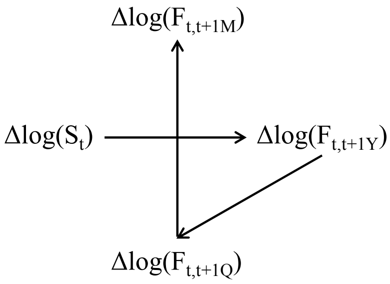

Figure 4.3. Pair wise Granger causality for daily electricity spot and futures price returns at the EEX.

Clearly, this system of (endogenous) electricity prices is not only driven by its interrelation but also by common exogenous parameters. The following section will, therefore, present a model which aims to describe these interactions.

4.2 A VAR model for electricity spot and forward prices

To assess the interrelation between spot and forward prices and exogenous drivers an unrestricted vector autoregression (VAR) model is estimated. The model considers electricity spot and forward prices to be endogenous. These endogenous variables mutually influence each other. Furthermore, exogenous parameters (input prices, electricity demand and wind generation) are included to additionally explain the evolution of the endogenous variables (and their interactions):

$$y_t = A_0 + A_1 y_{t-1} + A_2 y_{t-2} + ... + A_p y_{t-p} + A_x x_t + \varepsilon_t \tag{4.3}$$

where $y_t = \begin{bmatrix} \Delta Log(S_{t,t+1}) \\ \Delta Log(F_{t,t+1M}) \\ \Delta Log(F_{t,t+1Q}) \\ \Delta Log(F_{t,t+1Y}) \end{bmatrix}$ is a vector of spot and forward price returns,

$x_t^T=[\Delta Log(S_{Gas,t,t+1}), \Delta Log(F_{Gas,t,t+1M}), \Delta Log(F_{Gas,t,t+1Q}), \Delta Log(F_{Gas,t,t+1Y}), \Delta Log(S_{CO2,t,t+1}), \Delta Log(F_{CO2,t,t+1Y}), \Delta Log(F_{Coal,t,t+1M}), \Delta Log(F_{Coal,t,t+1Y}), \Delta Log(Demand_{t,t+1}), \Delta Log(Wind_{t,t+1})]$ is a vector of exogenous variables, $\underline{A_0}$ is a vector of constants and $\underline{A_1}$, etc., are the coefficient matrices. $\Delta Log(S_{t,t+1})$ is the daily return in the day-ahead spot market, $\Delta Log(F_{t,t+1M})$, $\Delta Log(F_{t,t+1Q})$, and $\Delta Log(F_{t,t+1Y})$ are the month-, quarter-, and year-ahead futures price returns. Similarly, $\Delta Log(S_{Gas,t,t+1})$, $\Delta Log(F_{Gas,t,t+1M})$, $\Delta Log(F_{Gas,t,t+1Q})$ and $\Delta Log(F_{Gas,t,t+1Y})$ are the daily returns of spot, month-, quarter-, and year-ahead gas prices[47], $\Delta Log(S_{CO2,t,t+1})$ and $\Delta Log(F_{CO2,t,t+1Y})$ are the daily returns of spot and year-ahead CO_2 prices, $\Delta Log(F_{Coal,t,t+1M})$ and $\Delta Log(F_{Coal,t,t+1Y})$ are the daily returns of month- and year-ahead coal prices at the EEX, $\Delta Log(Demand_{t,t+1})$ are German electricity demand returns[48] and $\Delta Log(Wind_{t,t+1})$ are returns of the daily German wind generation. Lag length criteria suggest a lag length of 1 (AIC and HQ). Table 4.5 shows the results of the VAR model (4.3).

As discussed in section 2.1.2 power prices are influenced by electricity demand, fuel costs and carbon prices.[49] Hence, these parameters are treated as exogenous in the model. Demand, however, is influenced by prices. As the elasticity of demand with respect to prices is very low in the short-run, this analysis nevertheless considers system wide demand to be exogenous (Karakatsani and Bunn, 2008). Chapter 5 will discuss this in more detail and present an alternative approach circumventing the endogeneity problem. As regards CO_2 prices, carbon permits in the EU-ETS must be surrendered on an annual basis. For this reason carbon futures are traded with an annual maturity only. Similarly, there exists no coal spot market which explains the absence of coal spot price returns in model (4.3). Finally, wind

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[47] Spot and month-ahead gas prices are from the Zeebrugge hub and quarter- and year-ahead gas prices are taken from EEX.

[48] https://www.entsoe.eu/

[49] The results of Chapter 3 suggested a non-linear effect of CCGT plants' generation costs. It would be reasonable to expect a similar non-linear effect also in a daily representation of the time-series. However, no significant non-linear effect (though regression coefficients were negative as expected) could be detected for gas prices in model (4.3). This might be due to the daily granularity of the data suggesting no immediate short-term effect of rising gas prices on power plant dispatch. Nevertheless, sustained periods of high prices may cause non-linear effects as presented in Chapter 3.

power generation is another exogenous variable in model (4.3). German wind power generation is subject to a support scheme where the transmission system operator has to purchase wind power at a guaranteed feed in tariff. This production is, in turn, sold on the EEX as an unlimited offer and therefore influences the price formation.[50] The demand and wind power time series consist of realised daily values. Given the short forecasting horizon (day-ahead) the quality of the prognosis can be considered very high (e.g. 95% for wind power with respect to the installed capacity, Sperling, 2009) and the inclusion of published forecasts would not have altered the results. Alternatively, the inclusion of lagged demand and wind power series in (4.3) could be interpreted as a test for the adaptive adjustment of market participants. In fact, testing this alternative specification did not affect the results presented in Table 4.5. Given the existence of strong serial correlation in the (daily) demand and wind power time series this appears not surprising.

Table 4.5 Results of the unrestricted VAR model (4.3) for daily electricity spot and forward price returns at the EEX from July 2007 to December 2009 (t-statistics in brackets). *, **, *** denotes significance on the 10%, 5% and 1%-level.

Variable	EEX			
	$\Delta\log(S_{t,t+1})$	$\Delta\log(F_{t,t+1M})$	$\Delta\log(F_{t,t+1Q})$	$\Delta\log(F_{t,t+1Y})$
Constant	0.00 (0.08)	0.00 (0.34)	-0.00 (-0.00)	-0.00 (-0.51)
$\Delta\log(S_{t-1})$	-0.22 (-6.70)***	-0.01 (-1.74)*	0.00 (0.50)	-0.00 (-1.80)*
$\Delta\log(F_{t-1,t+1M})$	0.00 (0.00)	0.04 (1.07)	0.03 (1.18)	0.02 (1.65)*
$\Delta\log(F_{t-1,t+1Q})$	-0.19 (-0.77)	0.09 (1.54)	0.03 (0.80)	0.02 (1.33)
$\Delta\log(F_{t-1,t+1Y})$	0.58 (1.22)	-0.06 (-0.56)	0.02 (0.37)	-0.03 (-0.99)
$\Delta\log(S_{Gas,t,t+1})$	0.21 (2.44)**	0.00 (0.21)	-0.01 (-1.14)	-0.01 (-1.08)
$\Delta\log(F_{Gas,t,t+1M})$	0.19 (1.25)	0.18 (5.29)***	-0.05 (-2.52) **	-0.00 (-0.37)
$\Delta\log(F_{Gas,t,t+1Q})$	0.34 (1.66)*	-0.02 (-0.39)	0.45 (17.22)***	-0.01 (-0.98)
$\Delta\log(F_{Gas,t,t+1Y})$	-0.33 (-0.76)	0.15 (1.49)	-0.41 (-7.31)***	0.20 (8.28)***
$\Delta\log(S_{CO2,t,t+1})$	-0.01 (-0.56)	-0.01 (-1.35)	-0.00 (-0.46)	-0.00 (-0.45)
$\Delta\log(F_{CO2,t,t+1Y})$	0.33 (1.32)	0.14 (2.49)**	0.15 (4.74)***	0.17 (12.41)***
$\Delta\log(F_{Coal,t,t+1M})$	-0.46 (-0.78)	-0.17 (-1.28)	-0.27 (-3.49)***	0.10 (3.05)***
$\Delta\log(F_{Coal,t,t+1Q})$	-0.53 (-0.68)	0.29 (1.66)*	0.32 (3.22)***	0.08 (1.88)*
$\Delta\log(F_{Coal,t,t+1Y})$	0.83 (1.19)	-0.02 (-0.11)	0.32 (3.57)***	0.11 (2.82)***
$\Delta\log(Demand_{t,t+1})$	1.28 (6.78)***	0.02 (0.57)	-0.03 (-1.38)	-0.04 (-3.39)***
$\Delta\log(Wind_{t,t+1})$	-0.11 (-16.02)***	0.00 (0.05)	0.00 (0.12)	0.00 (0.25)
R^2 (R^2_{corr})	0.35 (0.34)	0.14 (0.12)	0.52 (0.51)	0.71 (0.70)
Serial correlation (5 lags)		χ^2_{16DOF} (p-value)	0.725	
Observations		625		

[50] See e.g. Obersteiner (2010) for a detailed analysis.

Electricity spot price returns are significantly negatively influenced by its lagged value which is consistent with mean reversion properties of the stationary spot price series. As expected gas spot price returns (significantly) positively influence electricity spot returns. However, also returns of quarterly gas futures influence electricity spot returns on a 10% significance level. This result might be a consequence of the cost of carry in the storable fuel gas. The fundamental supply and demand variables significantly influence the spot price returns and show the expected signs (i.e. positive for demand and negative for wind power). Interestingly, carbon spot price returns do not affect electricity returns. This seems puzzling. As discussed in Chapter 3 CO_2 certificate prices represent opportunity costs and are therefore part of electricity prices. Moreover, the analysis in section 3.2 has shown that year-ahead futures prices are significantly influenced by carbon returns. Similarly, the results of the fundamental marginal cost model for EEX spot prices presented in section 5.5 (see Figure 5.7) indicate a full pass through of CO_2 allowance prices on a monthly basis. Still, the results of model (4.3) suggest that on a high(er) frequency basis (i.e. daily) carbon spot price returns do not affect the electricity price return system. There is, however, an explanation for this result. Electricity spot returns are positively influenced by carbon futures returns on a (weak) 15% significance level. Apart from the year 2007 (i.e. the last year of the first period of the EU-ETS) carbon spot and futures prices are highly correlated due to the storability of carbon permits.[51] Hence, carbon year-ahead futures returns capture the CO_2-related movement of the electricity price return system for all maturities of the latter (from spot to year-ahead) as will be seen in the following.[52]

Returns of month-ahead futures are negatively influenced by spot price returns on a 10% level whereas lagged values of month-ahead returns do not influence the former. As expected gas month-ahead price returns (significantly) positively influence electricity month-ahead returns. Year-ahead carbon returns do positively affect the month-ahead electricity returns which, at first sight, appears counterintuitive but can be explained by the fact that CO_2 allowances must be surrendered annually and, moreover, the storability of carbon permits implies a strong link between year-ahead prices and those of spot prices (and “virtual” maturities in between). Coal month-ahead futures returns do, interestingly, not influence the corresponding electricity returns whereas coal quarter-ahead returns do. Similar to CO_2, this can be explained by the

[51] Including a dummy variable for the first trading period of the EU-ETS did not alter the results presented in Table 4.5.

[52] Bunn and Fezzi (2008) show that UK and German spot electricity prices are not affected by carbon spot prices. However, they do not consider carbon futures in their model.

storability of coal which implies a high correlation of coal month- and quarter-ahead futures prices.

Returns of quarter-ahead electricity futures are not influenced by the electricity return system which seems to contradict the results of the Granger non-causality tests presented in Table 4.4 indicating Granger causality running from year-ahead to quarter-ahead returns. However, model (4.3) has to rely on a shorter sample size and the movement of the endogenous variables in this model is largely driven by exogenous variables. Gas quarter-ahead price returns (significantly) positively influence electricity quarter-ahead returns whereas there is also a negative effect of gas month- and year-ahead returns.

Returns of year-ahead electricity futures are influenced by electricity spot returns (in accordance with the Granger non-causality tests presented in Table 4.4 indicating Granger causality running from spot to year-ahead returns and the results presented in chapter 3) and month-ahead returns. Gas, coal and carbon year-ahead price returns (significantly) positively influence electricity year-ahead returns which is to be expected whereas returns of coal month- and quarter-ahead futures also positively influence year-ahead electricity returns. There might be an interaction affect between the coal futures returns causing this result. Reinforcing the interpretation of behavioural pricing components, a small negative (but significant) affect of the day-ahead demand returns on the year-ahead electricity futures return can be detected.[53]

In general, a link between electricity spot and futures prices may not only emerge from a behavioural bias. Given storable fuels as production inputs (coal, gas and CO2 permits) a link in electricity may possibly follow from the cost of carry in those inputs. Still, both exogenous variables and endogenous electricity (spot) prices are significant in (4.3). Moreover, the correlation between inputs and spots in (4.3) is low ruling out multicollinearity concerns. This indicates an important influence of the spot price on the futures price itself.[54]

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[53] In terms of behavioural pricing components Chapter 5 will argue that oil market volatility spills over to the price of risk in electricity markets. Accordingly, it might be reasonable to expect a similar effect when assessing the price formation itself. Still, regression coefficients for oil prices turned out insignificant when included in model (4.3). This reinforces the interpretation presented in Chapter 5 that oil markets are relevant for the *risk* assessment of electricity wholesale market participants.

[54] Performed regressions on the electricity basis (the difference between current futures and spot prices) on the basis prevailing in the gas, coal and CO2 markets indeed yielded significant effects. This result implies the spill over of the cost of carry of input fuels to the non-storable commodity electricity. Nevertheless, these regressions also yielded significant influences of lags of the electricity basis (In fact, the regressions are misspecified if only the carrying costs are included). This, again, indicates a behavioural bias. Results are available upon request.

4.3 Conclusions

The analysis in this chapter has disclosed several interesting results. Firstly, Granger-non causality tests have revealed significant interactions among spot price returns and month-, quarter-, and year-ahead futures price returns casting doubt on a clear distinction between short and long term markets. This suggests the existence of behavioural pricing components and rejects claims on a supposedly exogeneity – caused by the non-storability of electricity – of spot prices on the one hand and forward prices on the other.

Secondly, these results are confirmed by VAR regression models. Although the modelled time series are returns (i.e. logarithmic differences) the coefficient of determination R^2 is satisfactorily high (up to 70% for year-ahead returns) in the above presented models. More specifically, the movement of the electricity price system can, to a large extent, be explained by exogenous supply and demand side variables driving the electricity prices. Still, there are strong interactions between the electricity price series confirmed by significant regression coefficients in the VAR models (which accords with Granger non-causality tests).

The results of the regression models additionally suggest the prevalence of behavioural pricing components in the markets which, in turn, casts doubts on the predictive power of forward prices and, in turn, on market efficiency. Additionally, the tie in storable fuels implies the corresponding cost of carry also effecting the non-storable commodity electricity. This complicates the price formation. The risk assessment of market participants might be affected increasing the cost of hedging spot price uncertainty.

What are the implications of this potentially lacking informational function of the forwards? What are the drivers of the corresponding bias? How is the risk assessment of market participants affected? The next chapter will analyse these questions in detail.

5 Components of the forward market premium in electricity [55]

This chapter presents a multifactor empirical analysis of the determinants of the realised premia in forward prices for electricity, when compared to their associated spot prices. Considering a wide-ranging set of factors involving fundamental, behavioural, dynamic, market conduct and shock components, a number of propositions are tested on a long data set from the most liquid of European forward markets, the EEX. It is shown that parts of what is conventionally regarded as the market price of risk in electricity is actually that of its underlying fuel commodity, gas; that market power has a double effect on prices, notwithstanding the theoretical procompetitive properties of forward trading, insofar as it increases spot prices and induces a forward premium; that oil price sentiment spills over and that these premia react in an positive way to scarcity and the higher moments of spot price uncertainty. Finally, it is observed that considerations of the efficiency of the forward premium are at least as important as those of spot market price formation in wholesale power trading.

5.1 Introduction

In fully liberalised wholesale electricity markets, as with most commodities, trading in forwards and futures constitutes a substantially higher volume than physical demand. For example in 2008, churn[56] ratios of about 8 and 7 were reported for the German and Nordic markets, and in Britain, over 90% of the power delivered was via forward contracts with maturities of between a month and two years (Ofgem, 2009). Given the intense scrutiny of wholesale electricity markets by regulatory and competition authorities, questions of the efficiency and determinants of the realised premia in these forward prices, i.e. the systematic difference between the forward price and the associated subsequent spot price(s), are therefore at least as relevant as those regarding the exercise of market power on the spot market itself (European Commission, 2007b, 2008). Whilst forward markets clearly promote market completeness, facilitate the necessary risk management[57], and in theory induce greater competitive behaviour on the spot markets (Bushnell et al., 2008), the transaction costs

[55] A concise version of this analysis has been published in Redl and Bunn (2010).

[56] The ratio of estimated forward traded volume for a particular delivery period to actual physical delivery.

[57] Companies regularly report their forward contracting policy in financial and investor relations reports, e.g. http://rwecom.online-report.eu/2008; www.centrica.com/; www.draxgroup.plc.uk/investor/.

(premia) that emerge may well erode some of these benefits in practice[58]. Thus, in cases where forward and spot market conduct has been investigated by competition authorities, the question of determining fair values for the forward premia as counterfactuals inevitably arise (Christensen et al., 2007).

However, identifying and estimating the components of the premia implied by forward prices has remained, despite an increasing amount of research, a challenging and relatively unresolved area of analysis. Whilst research has been quite widely undertaken documenting the empirical properties of electricity forward premia and proposing stylized equilibrium models, testing the causal factors of the realised premia has not been specified as widely as the complexity and interrelatedness of the price drivers require. From a taxonomy of propositions, therefore, this chapter provides a more complete multi-factor analysis of the empirical determinants of the forward premium and their implications.

The literature on the financial behaviour of energy derivatives and corresponding risk premia is rich and this analysis draws on major results reviewed below. However, since this analysis focuses specifically on derivatives for electricity it is important to point out certain characteristics of electricity that render its forward price formation and analyses of corresponding forward premia rather special.

Firstly, as a product, wholesale electricity is a “flow” rather than a “stock”; it is produced and consumed instantaneously and continuously. This results in a wide range of traded products of different maturities and delivery periods, e.g. for the British market, where the spot market is settled against half-hourly trading periods throughout the day, the APX power exchange[59] offers forward products ranging from blocks of two and four hours for daily maturities to various peak (e.g. 7am to 7pm) and baseload (midnight to midnight) contracts extending over delivery periods ranging from a day, week, month, quarter or a year, for up to three years ahead. This microstructure implies an absence of a 1:1 correspondence between forward and spot products, and, as a consequence, that forward premia evaluations are complicated by the averaging required over more extended delivery periods.

As discussed in detail in section 2.1.3 a more crucial implication of this “flow” aspect is that the nonstorability of power precludes Kaldor’s (1930) cost of carry equilibrium of spot and

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[58] Whilst Bushnell et al. (2008) suggest that forward contracting may have reduced spot prices by over 31% comparing data from California with NE US markets, in the British market, 2001-2005, there was actually a 40% winter month ahead forward premium for peak hours of the day (7am-7pm), though much less for off-peak and summer quarters (Bunn, 2006).

[59] www.apxendex.com.

forwards. Hence, researchers usually consider equilibrium in expectations and risk aversion (Keynes, 1930) amongst agents with heterogeneous needs for hedging spot price uncertainty. As mentioned the forward price is thereby viewed as being determined as the expected spot price plus an ex ante market premium. However, as this ex ante premium is unobservable, empirical analysis looks instead at an ex post (realised) estimate, $F_{t,T}$ - S_T, where $F_{t,T}$ is the forward price quoted at time t, for delivery at time T, whereupon the spot price turns out to be S_T. Thus, expanding equation (2.2),

$$F_{t,T} - S_T = F_{t,T} - E_t(S_T) + E_t(S_T) - S_T = FP_{t,T} + \varepsilon_{t,T} \tag{5.1}$$

and the ex post forward premium clearly equals the ex ante premium $FP_{t,T}$ plus a random error $\varepsilon_{t,T}$ in the (rational) spot price expectation due to price relevant shocks, occurring between t and T. Electricity spot prices are well known to be characterised by high volatility and occasional spikes[60], caused, structurally by the intersection of steeply increasing convex supply curves and, in the short term, price inelastic demand. Supply or demand shocks therefore lead to sudden rises in spot market prices. Hence, the market participants are faced with a forecasting problem and, depending on the spot price distribution and the attitude towards risk, either demand a compensation for contracting, are willing to pay a corresponding premium or to accept a discount to eliminate the risk of uncertain future cash flows. This brings about important policy implications since it is the forward market, due to this economic reasoning, which determines investments and welfare.[61] Hence, it is necessary to understand the components of the risk premium which warrants the attention of policy makers. In turn, understanding the drivers of the forward premium allows a better regulation of electricity markets and improved design of corresponding market rules.

Formal models of asset pricing under risk can be adapted to electricity to associate, under risk neutrality, the emergence of this ex ante forward premium from a market price of risk (Kolos and Ronn, 2008), but it is more usual to invoke concepts of risk aversion between producers and retailers resulting in the forward premium being the net hedging cost in the market (Bessembinder and Lemmon, 2002).

Without appeal to a stylised equilibrium model, in focusing upon the realised (ex post) premium, to the extent that the random error distribution has zero mean, the realised premium

[60] See for example, Lucia and Schwartz (2002), Burger et al. (2004), Huisman et al. (2007), Kanamura and Ohashi (2008), Karakatsani and Bunn (2008), Bowden and Payne (2008), Higgs and Worthington (2008) – and the analysis in Chapter 4.

[61] As mentioned this importance is also reflected in the high share of futures and forward trading compared to the actual electricity consumption.

is a consistent estimator of the ex ante premium. However, it does raise the important question in data analysis of how much of each ex post value reflects the price of risk and how much is error in the rational expectation of the spot price. In a multi-factor analysis, this means that careful consideration needs to be given to variables that influence the forward price formation, known to the market at time *t*, and shocks to the drivers of the spot price that occur between *t* and *T*. In this analysis more consideration is given to this than in previous studies. Specifically, a reduced-form perspective is taken seeking to interpret in detail the significant factors affecting the realised premium, which, since it does not require a theoretical counterfactual, would be taken as the basis of ex post market monitoring.

Another special feature of electricity as a commodity is that it is actually a derived commodity, insofar as in most electricity markets a substantial amount of the technologies use the conversion of gas, coal or oil, and furthermore these technologies tend to set the market price. Forecasts of electricity prices are strongly dependent upon those of the marginal fuels (mainly gas; Bunn, 2004). Indeed, the analyses performed in Chapter 3 and section 4.2 have shown the dependence of electricity futures prices on futures prices of fuels. Hence an important, and as yet unaddressed question, is how much of the market price of risk is due to price formation in the electricity sector as such and how much is simply a supply-chain transmission of the risk premia in the underlying primary fuels.

The industry structure of the electricity sector itself gives rise to another special feature, in that electricity generation is usually a highly concentrated industry and as a consequence oligopoly pricing remains a serious concern (European Commission, 2007b, 2008). Although a substantial amount of theoretical research (following Allaz, 1992) has suggested that forward contracting in a concentrated market may mitigate market power effects in the spot market, we know that market power raises spot prices (Weron, 2006) and it is an open question to what extent market concentration may compound this by inducing additional market power effects in the forward risk premium. This issue is addressed as part of the below multifactor analysis.

Chapter 5 therefore proceeds as follows: The next section summarises related research in forward prices and positions the analysis. Section 5.3 introduces the market setting and quantifies the realised ex post forward premia. Section 5.4 tests a convenient assumption of forward premia determinants. Section 5.5 develops a propositional framework on the forward premia determinants. Section 5.6 presents the results of the econometric model-based analysis. Finally, section 5.7 concludes.

5.2 Research background

5.2.1 Equilibrium models

Two quite different streams of equilibrium modelling in forward markets have been influential for empirically analysing forward premia. One has focussed on the strategic effects of contracts in an oligopolistic risk neutral environment, following Allaz (1992) and Allaz and Vila (1993), and the other on risk aversion in a competitive financial market environment, following the work of Bessembinder and Lemmon (2002).

5.2.1.1 The Allaz and Vila model

Allaz and Vila (1993), using a two stage game, show how Cournot producers can be induced into forward commitments which in turn make them behave more competitively in the spot market. With risk neutral and arbitrage free assumptions, this suggests lower prices than without a forward contracting opportunity. In the following I will use the notation of Bessembinder and Lemmon (2002) to ease comparison of the main model results.

Spot market equilibrium

Taking into account the forward positions $Q_{P1}{}^F$ and $Q_{P2}{}^F$ of the two identical producers the ex post profit function of producer 1 is[62]

$$\pi_{P1}(Q_{P1}, Q_{P2}) = P_F Q_{P1}^F + P_W(Q_{P1} + Q_{P2})(Q_{P1} - Q_{P1}^F) - TC_1(Q_{P1}) \qquad (5.2)^{63}$$

where P_W is the wholesale spot price, Q_{P1} and $Q_{P1}{}^F$ denote the quantities sold by producer *1* in total and on the forward market respectively and TC_1 are the total cost associated with production of producer *1*. As generator *1* has already sold $Q_{P1}{}^F$ on the forward market it can only sell the difference of total production Q_{P1} and $Q_{P1}{}^F$ on the spot market. Total costs are assumed to be linear, $TC_{P1}(Q_{P1}) = bQ_{P1}$, so is the inverse demand function $P_W = a - Q_{P1} - Q_{P2}$. Given these relations the reaction function of the first Cournot producer can be derived:[64]

$$Q_{P1}(Q_{P2}) = \frac{a-b+Q_{P1}^F - Q_{P2}}{2} \qquad (5.3)$$

[62] Due to symmetry of the duopoly game the equations for the second producer are not replicated here.

[63] Clearly, this formulation is equivalent to $\pi_{P1}(Q_{P1}, Q_{P2}) = (P_F - P_W)Q_{P1}^F + P_W Q_{P1} - TC_1(Q_{P1})$. I will later come back to the importance and implication of this formulation.

[64] The first of order condition of the producer *1* is $\frac{\partial \pi_{P1}(Q_{P1},Q_{P2})}{\partial Q_{P1}} = 0 = -2Q_{P1} - Q_{P2} + Q_{P1}^F + a - b$. (5.3) immediately follows.

(5.3) shows the potential pro-competitive effect of forward markets since it is an increasing function in Q_{P1}^F. Solving for the spot market equilibrium by equating the two reaction functions yields

$$Q_{P1} = \frac{a-b+2Q_{P1}^F - Q_{P2}^F}{3} \tag{5.4}$$

$$P_W = \frac{a+2b-Q_{P1}^F - Q_{P2}^F}{3} \tag{5.5}$$

Forward market equilibrium

Under arbitrage free assumptions the forward price converges to the spot price (due to the activity of at least one speculator). Hence, the profit of the first producer reduces to

$$\pi_{P1}(Q_{P1}^F, Q_{P2}^F) = P_W(Q_{P1}^F + Q_{P2}^F)Q_{P1}(Q_{P1}^F, Q_{P2}^F) - TC_1(Q_{P1}(Q_{P1}^F, Q_{P2}^F)) \tag{5.6}$$

Maximising producers' profit therefore yields following equilibrium solutions

$$Q_{P1} = Q_{P2} = \frac{2(a-b)}{5} \tag{5.7}$$

$$Q_{P1}^F = Q_{P2}^F = \frac{a-b}{5} \tag{5.8}$$

$$P_W = P_F = b + \frac{a-b}{5} \tag{5.9}$$

Introducing a forward market in a standard duopoly Cournot market setting increases output, decreases prices and, hence, social welfare increases. Why would the producers enter contracts? Allaz and Vila show, that if only one generator trades forward, acting like a Stackelberg leader, it can increase its profit. Hence, there is a strategic incentive to contract. This, however, leads to a "prisoners dilemma" since this incentive exists for both duopolists. The final outcome will be the Nash equilibrium briefly described above.

Comparison of the standard Cournot game with the Allaz and Vila outcome

For the case of a single spot market the profit of the first duopolist equals

$$\pi_{P1}(Q_{P1}, Q_{P2}) = (a - Q_{P1} - Q_{P2})Q_{P1} - bQ_{P1} \tag{5.10}$$

Maximising (5.10) with respect to Q_{P1} gives the reaction function $Q_{P1}(Q_{P2}) = \frac{a-b-Q_{P2}}{2}$ which, after equating, yields the well-known Cournot outcome:[65]

$$Q_{P1} = Q_{P2} = \frac{a-b}{3} \tag{5.11}$$

$$P_W = \frac{a+2b}{3} \tag{5.12}$$

The comparison of (5.7) with (5.11) shows that output increases by 20% if a forward market is introduced in the Cournot duopoly setting. Figure 5.1 qualitatively depicts the price decrease effect of the introduction of a forward market in a non-competitive market environment. Strategic producers maximise revenues by equating marginal costs *MC* and marginal revenues *MR*. Hence, they act as a monopolist on their residual demand (Holmberg, 2011). That is, the remainder of demand not supplied by the second duopolist. This yields the Cournot price P_Q and the associated quantity produced Q_Q. If, however, a certain quantity Q_F is already contracted beforehand the new equilibrium price P_{QF} emerges and the total quantity produced equals Q_{Q_F}. In sum, the price decreases by ΔP and quantities produces increase by ΔQ. Allaz and Vila show that if the forward trades can take place in several periods before the spot period ($T<\infty$), the spot price converges to the competitive outcome.

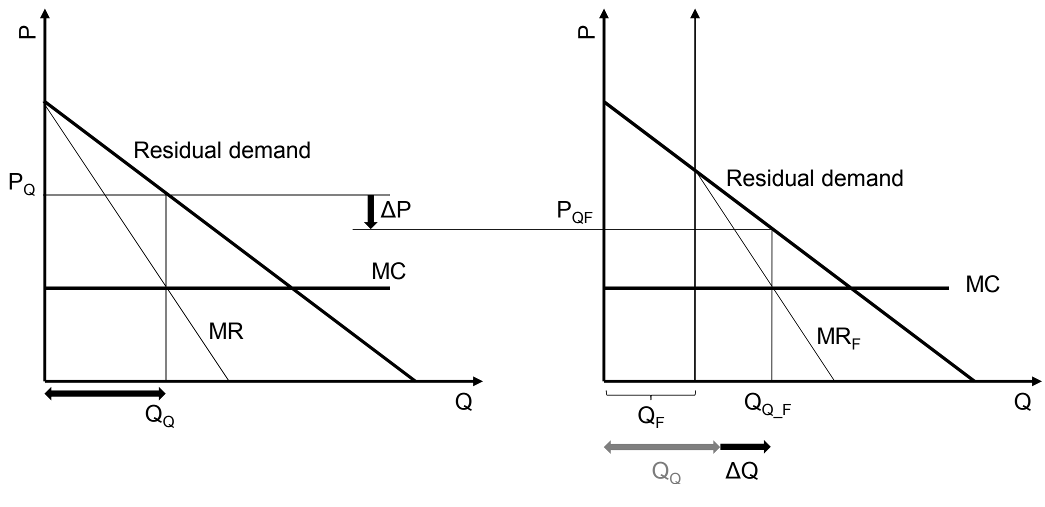

Figure 5.1. Effects of introducing a forward market in a Cournot type market. Left: Market without contracts. Right: Market where Q_F was sold beforehand on the forward market. Source: Based on Willems (2004)

[65] See Appendix D for a derivation of the standard Cournot spot market equilibrium.

Although this pro-competitive view of forward markets continues to be endorsed (Bushnell, 2007, et al., 2008), the theory has been challenged by several authors (e.g. Mahenc and Salanie, 2004), when the simple two stage view of contracting is relaxed.

5.2.1.2 The Bessembinder and Lemmon model

From the other perspective, Bessembinder and Lemmon (2002), using a Taylor series expansion of expected utility, suggest that the forward premium is a function of the variance (negative influence) and skewness (positive influence) of spot prices. In their model N_P non-strategic symmetric generators interact with N_R retailers. Demand is constant updated by a random noise. Both producers and retailers are equally risk averse. The retail price P_R is fixed. Total costs of producer i, TC_i, to produce quantity Q_{Pi} are modelled as:

$$TC_i = FC + \frac{a}{c}(Q_{Pi})^c \tag{5.13}$$

where FC are fixed costs and a and c are constants.

Spot market equilibrium

When the spot market clears demand is known with certainty. Producers sell to retailers who, in turn, sell to final consumers. Taking into account the previously agreed forward positions the ex post profit π_{Pi} of producer i equals

$$\pi_{Pi} = P_W Q_{Pi}^W + P_F Q_{Pi}^F - TC_i \tag{5.14}$$

where P_W is the wholesale spot price, $Q_{Pi}{}^W$ and $Q_{Pi}{}^F$ denote the quantities sold by producer i on the spot and forward market respectively and P_F is the forward price. Clearly, generator i's total physical production Q_{Pi} is the sum of $Q_{Pi}{}^W$ and $Q_{Pi}{}^F$.

Retailers buy the difference between their forward purchases and the realised demand on the spot market. Retailer's j ex post profit π_{Ri} therefore equals

$$\pi_{Rj} = P_R Q_{Rj} + P_F Q_{Rj}^F - P_W\left(Q_{Rj} + Q_{Rj}^F\right) \tag{5.15}$$

where $Q_{Rj}{}^F$ is the quantity sold forward (if purchased than negative) and Q_{Rj} is the sold retail quantity of retailer j.

The profit maximising quantity sold by producer i in the spot market is

$$Q_{Pi}^W = \left(\frac{P_W}{a}\right)^{\frac{1}{c-1}} - Q_{Pi}^F \tag{5.16}$$

Given that total physical production $\sum_{i=1}^{N_P} Q_{Pi}$ must equal total retail demand $\sum_{j=1}^{N_R} Q_{Rj} \equiv Q_D$ and considering that forward contracts are net zero supply $\sum Q^F = 0 = \sum_{j=1}^{N_R} Q_{Rj}^F + \sum_{i=1}^{N_P} Q_{Pi}^F$ yields the equilibrium spot market price

$$P_W = a\left(\frac{Q^D}{N_P}\right)^{c-1} \tag{5.17}$$

Inserting (5.17) into (5.16) yields the spot market sales of producer *i*:

$$Q_{Pi}^W = \frac{Q^D}{N_P} - Q_{Pi}^F \tag{5.18}$$

Forward market equilibrium

Bessembinder and Lemmon show, using the result of Hirshleifer and Subramanyam (1993), that the optimal forward position of producer *i* is

$$Q_{Pi}^F = \frac{P_F - E(P_W)}{AVar(P_W)} + \frac{Cov[P_W\left(\frac{Q^D}{N_P}\right) - F - \frac{a}{c}\left(\frac{Q^D}{N_P}\right)^c, P_W]}{Var(P_W)} \tag{5.19}$$

and of retailer *j* is:

$$Q_{Rj}^F = \frac{P_F - E(P_W)}{AVar(P_W)} + \frac{Cov[P_R Q_{Rj} - P_W Q_{Rj}, P_W]}{Var(P_W)} \tag{5.20}$$

where *A* is the coefficient of absolute risk aversion to the variance of profits in the objective function. Positive values of *A* indicate that volatility risk is perceived negative.

The optimal forward position consists of two components. The first term on the right hand side of (5.19) and (5.20) respectively is the response to the difference between the forward price and the expected spot price (i.e. the forward premium). The second term is the quantity sold forward to minimise the profit variance. The first term can be denoted as a speculative position whereas the second one stems from the "pure" hedging motive (Anderson and Danthine, 1981). Since forward contracts are net zero supply $\sum Q^F = 0$ the equilibrium forward price is

$$P_F = E(P_W) - \frac{N_P}{Nca^x}[cP_R Cov(P_W^x, P_W) - Cov(P_W^{x+1}, P_W)] \tag{5.21}$$

where $N = \frac{N_R + N_P}{A}$ and $x = \frac{1}{c-1}$. Bessembinder and Lemmon (2002) show that when P_W^x and P_W^{x+1} are approximated by a second order Taylor series expansion (5.21) can be stated as:

$$P_F = E(P_W) + \alpha Var(P_W) + \beta Skew(P_W) \tag{5.22}$$

Since $\alpha < 0$ and $\beta > 0$ the forward premium P_F-$E(P_W)$ is a negative function of the variance of spot prices and a positive function of skewness of spot prices. Finally, the optimal forward positions for producers and retailers can be expressed, to a second order Taylor series expansion, as

$$Q_{Pi}^{F} = \frac{E(Q^{D})}{N_P} + \frac{P_F - E(P_W)}{AVar(P_W)} + \left(\frac{x[E(P_W)]^{x-1}}{2a^{x}}\right)\left(\frac{Skew(P_W)}{Var(P_W)}\right) \quad (5.23)$$

and

$$Q_{Rj}^{F} = -E(Q_{Rj}) + \frac{P_F - E(P_W)}{AVar(P_W)} + \left(\frac{\beta_j}{a^{x}}\right)\left(\frac{N_P}{N_R}\right)\left(Z + Y\left[\frac{Skew(P_W)}{Var(P_W)}\right]\right) \quad (5.24)$$

Empirical confirmations of the significance of variance and skewness in the risk premia have been mixed, however. Douglas and Popova (2008) confirm these results for the PJM day-ahead forward market. Moreover, they propose an augmented model including, among others, gas storage inventories. In fact, increasing gas storage inventories decrease the forward premium as the likelihood of price spikes in the real-time spot market decreases. This analysis is, however, not readily applicable to the European wholesale electricity markets. First, liberalisation of the European gas sector is lacking. Gas supply in Continental Europe is still characterised by long-term "Take or pay" contracts (Maisonnier, 2006). As possibilities to resell gas from these long-term contracts at spot markets are limited liquidity is low and storage facilities are of minor importance in gas trading. Second, as the huge majority of electricity is traded forward (i.e. month-, quarter-, and year(s)-ahead) physical storage quantities are small compared to traded electricity quantities. Whilst Douglas and Popova (2008) confirm Bessembinder and Lemmon, others including Lucia and Torro (2008), Botterud et al. (2009) for weekly contracts at the Nord Pool, Redl et al. (2009) for monthly contracts at the EEX and Nord Pool, and Furio and Meneu (2010) for monthly contracts in the Spanish electricity market find at best only partial support (Redl et al., 2009).

5.2.2 Empirical analysis

Following Keynes (1930) futures prices are related to expected spot prices. This forward pricing theory has extended to a broad stream of empirical literature. In general, descriptive research on forward premia show significant values, although signs vary by time of day and season. Longstaff and Wang (2004), Hadsell and Shawky (2006), Diko et al. (2006), and Gjolberg and Johnsen (2001), Weron (2008) as well as Daskalakis and Markellos (2009) find significant premia in the PJM, NYISO, APX, Powernext and Nord Pool long-term electricity markets respectively.

The analysis in this chapter focuses upon the EEX based in Leipzig, Germany, which has the most liquid futures/forward market in Europe (European Commission, 2007b). Previous studies which have analysed EEX forward premia include Diko et al. (2006), Bierbauer et al. (2007), Kolos and Ronn (2008), Benth et al. (2008), Daskalakis and Markellos (2009) and Redl et al. (2009). Most of these studies employ stochastic models to determine the magnitude of inherent market risk. Kolos and Ronn (2008) find, in contrast to this study, a negative forward premium for monthly, quarterly and yearly contracts at the EEX. However, their sample size is smaller and covers only forward trading in 2002 and 2003. Diko et al. (2006) find that the forward premium decreases as time to maturity for EEX peak load contracts decreases, whilst Benth et al. (2008) relate the term structure of the forward premium to the net hedging demand of consumers and producers (which they term as market power). Their model yields decreasing absolute values of forward premia (eventually getting negative) and market power estimates when time to maturity or delivery period length increase. These EEX price studies take the risk considerations of market participants as the source of the forward premium (implicitly assuming efficient spot price forecasts). Nevertheless, not only risk considerations but also misjudgements of future fundamental generation and demand conditions have to be considered. This is confirmed by Bunn and Karakatsani (2003) who state that the arguments for absence of price convergence between day-ahead and real-time markets "still underestimates the fact that different timing of the two markets implies different information uncertainties and plant flexibility requirements, which are converted to costs." Hence, extending this, Redl et al. (2009) show that additionally supply and demand shocks can contribute to the explanation of the futures-spot difference as well as the conventional stochastic risk measures (variance and skewness of spot prices).

For completeness, additional empirical forward premium analyses on other electricity markets are summarised as well. Although supply and demand conditions differ fundamentally between the markets, in general, similar results with respect to the risk assessment of market participants apply. Gjolberg and Johnsen (2001) identify positive premia in the Nord Pool market. Gjolberg and Johnsen (2001) argue that due to the identified size, differences cannot be explained by risk premia only but would indicate informational inefficiencies or the exercise of market power because of the high concentration of suppliers. Weron (2008) determines the market price of risk in the Nord Pool futures market using stochastic models. He finds increasing risk premia with decreasing time to maturity (which is equivalent to decreasing forward premia over time). Bunn (2006) identifies positive premia for peak hours when comparing the UK day ahead and prompt market and the week ahead and day ahead market which is explained by a higher willingness to pay day ahead of the demand side in order to avoid the intra-day market volatility (and vice versa for the off peak hours). Similarly, Longstaff and Wang (2004), Hadsell and Shawky (2006), Diko et al. (2006), and Daskalakis and Markellos (2009) find significant risk premia in the PJM, NYISO, APX, Powernext and Nord Pool long-term electricity markets respectively.

5.3 Market setting and Initial Data Analysis

This analysis focuses on month-ahead futures prices for several reasons. Firstly, this is the most liquid contract and most price data is available for futures with monthly delivery periods. Secondly, due to the near-term delivery period, the forecast errors of market participants should, on average, be low for up to one month ahead.[66] More specifically, prices on the last trading day before the delivery month are considered only due to the limited availability of fundamental data (e.g. supply and demand data).

Futures at the EEX are settled financially. For baseload the underlying is the mean of all hourly spot prices during the delivery period. For peak load the underlying is the Phelix peak load index, which is the mean of the peak hours from 8:00am to 8:00 pm from Monday to Friday during the delivery period.[67]

As discussed in Chapter 3 the European electricity market is still characterised by several (regional or national) wholesale price areas. As the Central/Western European power market is, however, formed by several countries fundamental supply and demand conditions in all of these countries have to be considered even if the EEX is the leading exchange in this extended region. Figure 5.2 shows the evolution of monthly averages of spot peak load prices as well as month-ahead peak load prices, as reported on the last trading day for delivery during the plotted month, at the EEX from October 2003 to January 2010.[68] Spot and forward prices were rising continuously until early 2006. Since fossil fuelled power plants constitute the price setting technologies in the EEX market, increasing power prices mainly reflected rising

[66] Still, a spot price forecast covering an entire month may yield significant errors. I will deal with this issue in the following sections.

[67] http://www.eex.com/en

[68] In Figure 5.2 the depicted forward price at, e.g. October 2003, was the settlement price of the month-ahead peak load futures on 30 September 2003 for a delivery during peak hours in October 2003.

primary energy prices. The increase observed during 2005 was partly due to the commencement of carbon trading through the EU-ETS.

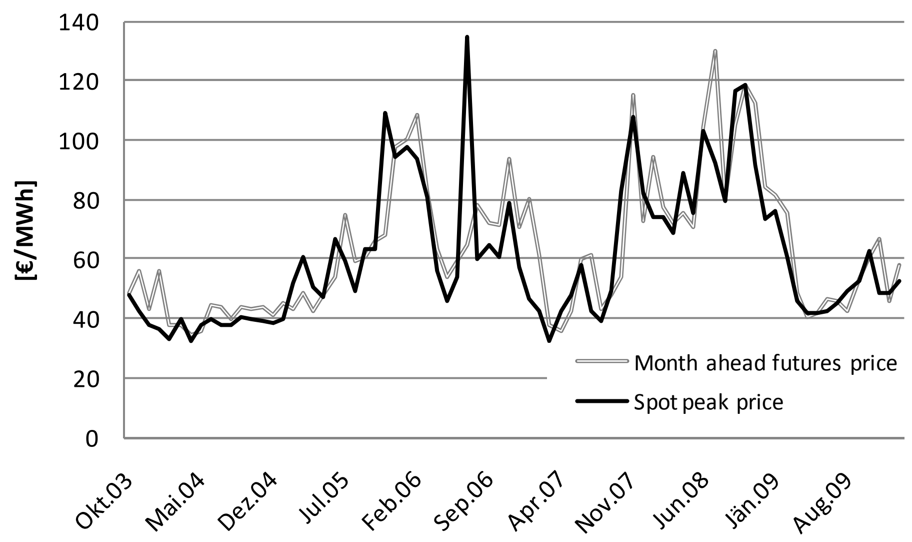

Figure 5.2. Evolution of monthly averages of peak load spot prices (black) and peak load month-ahead futures prices on the last trading day (grey) at the EEX from October 2003 to January 2010. Source: EEX

Figure 5.3 presents descriptive statistics for daily EEX base and peak load spot prices from October 2003 to January 2010. The price series are non-normal, positively skewed and show a high kurtosis. As expected, the peak load price series is more volatile than the baseload series (in terms of both the standard deviation and the coefficient of variation). It is this distribution which faces the market participants with a forecasting problem of future spot prices. Moreover, risk-averse agents have an incentive to reduce their risk exposure by trading on the forward market. As will be shown in the following, the willingness to pay in order to reduce this risk exposure is significant.

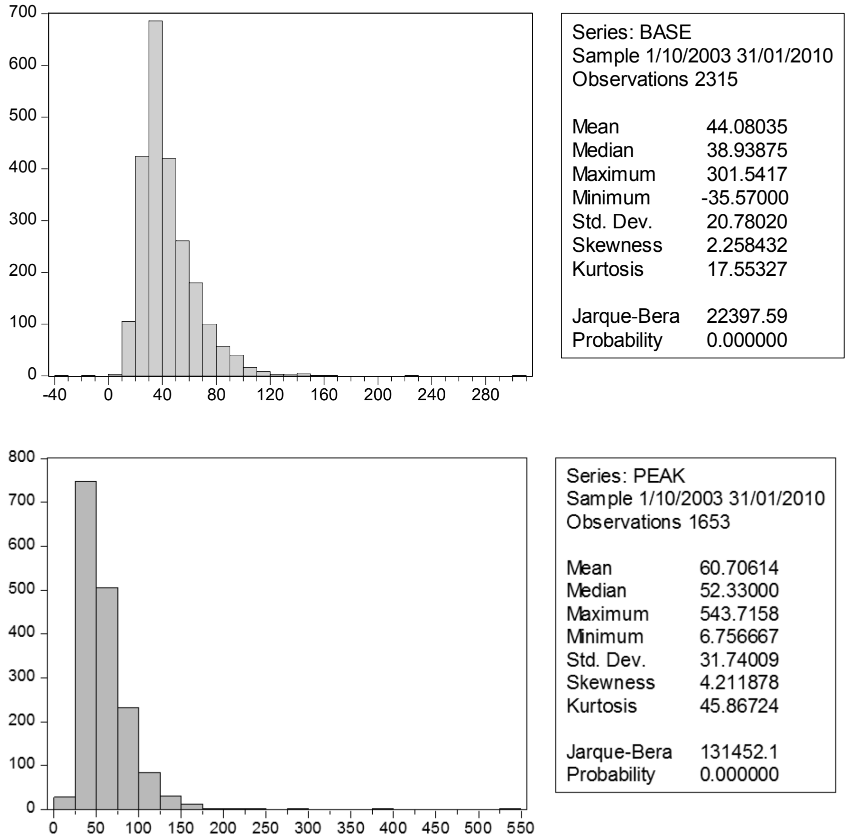

Figure 5.3 Descriptive statistics and histogram of daily base (top) and peak load spot prices (bottom) at the EEX from October 2003 to January 2010. Daily baseload prices are the averages of all 24 hourly prices each day. Daily peak load prices are calculated Monday's to Friday's as the average of the hourly prices from 8:00am to 8:00pm.

For each monthly contract the relative ex-post difference between the forward price in the trading period and spot price in the delivery period is expressed as a ratio:

$$\Delta_T = \frac{F_{t,T} - S_T}{S_T} \qquad (5.25)$$

where Δ_T is the relative difference between the forward and spot price, $F_{t,T}$ is either the average futures price in month t for delivery in T or the settlement price on the last trading day in month t for delivery in T and S_T is the spot price average in month T. The differences between forward and corresponding spot prices are significant (see Figure 5.4). Table 5.1 summarises some additional statistics. On a monthly average, base load contracts were traded 9% above actual spot prices in the delivery periods of the futures at EEX. Month-ahead peak load futures were traded at 12% above spot prices in the delivery period. The identified differences are significantly different from zero for a double-sided test. Moreover, errors for base load and peak load are significantly larger than zero. If one looks at each contract separately, the absolute value of the relative difference Δ_T for peak load is greater than for base load for almost every contract.[69] Due to a higher slope of the supply curve when approaching system capacity misconceptions of future generation and demand conditions induce greater price differences between forward and spot prices in peak load which is confirmed by the results in Table 5.1. Figure 5.5 depicts this effect of the convexity of the supply curve graphically.

Using futures prices on the last trading day instead of monthly averages for determination of the relative differences Δ_T still yields significant positive errors although the magnitude is lower. This indicates the important role of information – and its link with expectations. The shorter the remaining time to delivery, the more information about conditions during the delivery period available and, hence, the lower the forecast error. In fact, on the last trading day base load contracts were traded 5% above actual spot prices in the delivery periods. Peak load futures were traded on the last trading day 7% above spot prices in the delivery period.

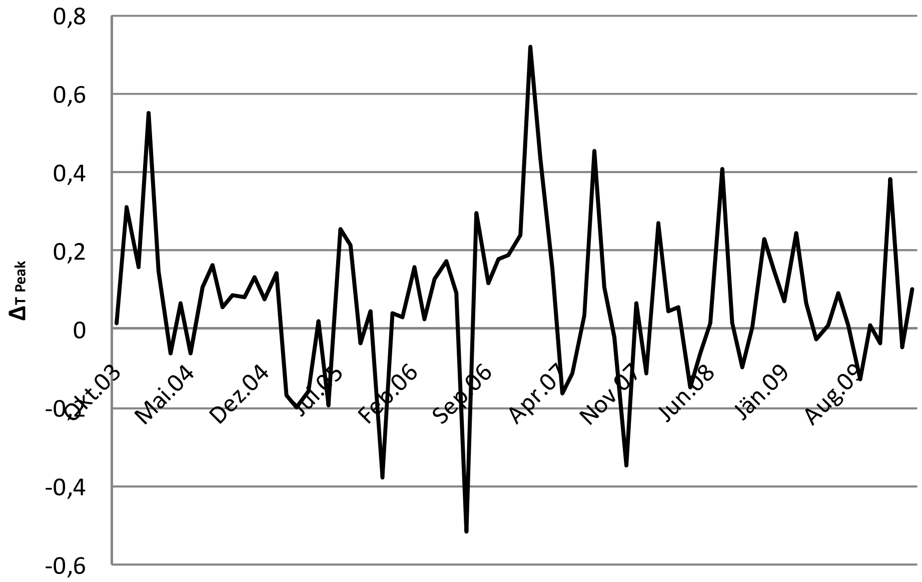

Figure 5.4. Relative differences of month-ahead peak load futures prices (noted on the last trading day) with respect to the actual spot price during the delivery period at the EEX from October 2003 to January 2010. Source: EEX, own calculations

[69] Since peak load futures comprise only weekday hours, spot prices for weekend hours, which are an additional source for forecast errors, are not part of the bias of peak load futures.

Table 5.1. Summary statistics of the relative differences of monthly averages and prices on the last trading day of EEX month-ahead futures (with delivery from October 2003 to January 2010) and average spot prices in the respective delivery period.

	EEX			
	Base load		Peak load	
	Monthly average	Last trading day	Monthly average	Last trading day
Mean	9%	5%	12%	7%
Standard dev.	21%	15%	26%	20%
Minimum	-38%	-38%	-50%	-50%
Maximum	87%	65%	98%	72%
Skewness	0.79	0.47	0.58	0.24
Kurtosis	4.88	5.47	3.98	4.80
t-statistic	3.66*	2.96*	4.04*	3.16*

* denotes significance for the double- and one-sided test

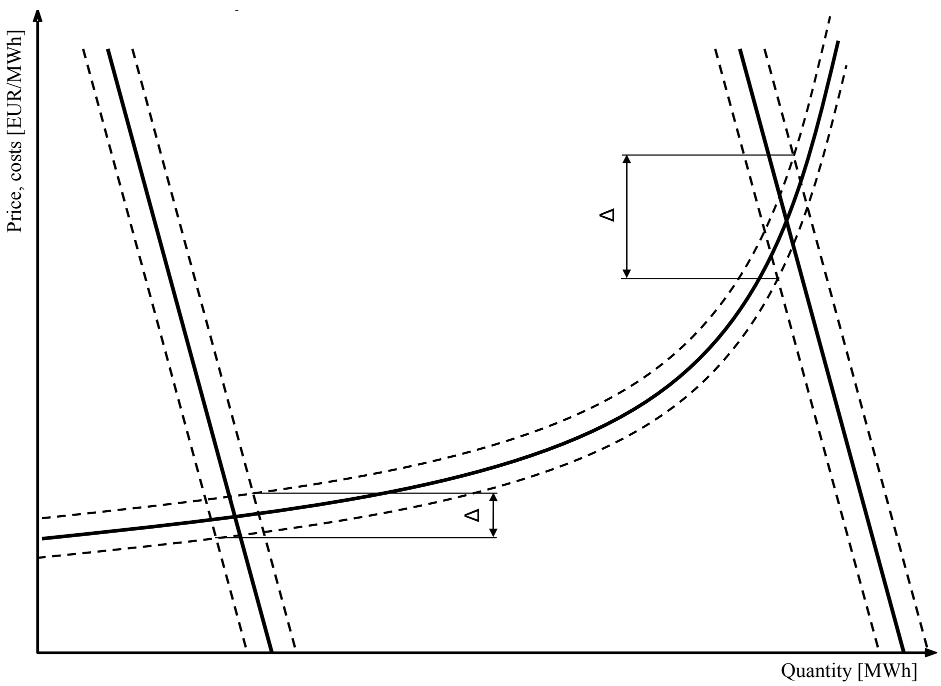

Figure 5.5. Effects of the convexity of the supply curve on price changes due to similar deviations of the supply and demand curves in base load (off-peak) versus peak load.

The above analysis does not consider seasonalities in the (relative and absolute) forward premium. Figure 5.6 shows a seasonal graph of the relative differences for peak load. Noting from visual inspection a seasonal pattern in the forward premium seems to exist, being highest in January and lowest in the mid seasons April and September. However, the autocorrelation functions and hence seasonal effects of the ex post forward premia are not significant for the data set – both for absolute and percentage premia. Hence, (annual) seasonality will not be elaborated further in the empirical models below.

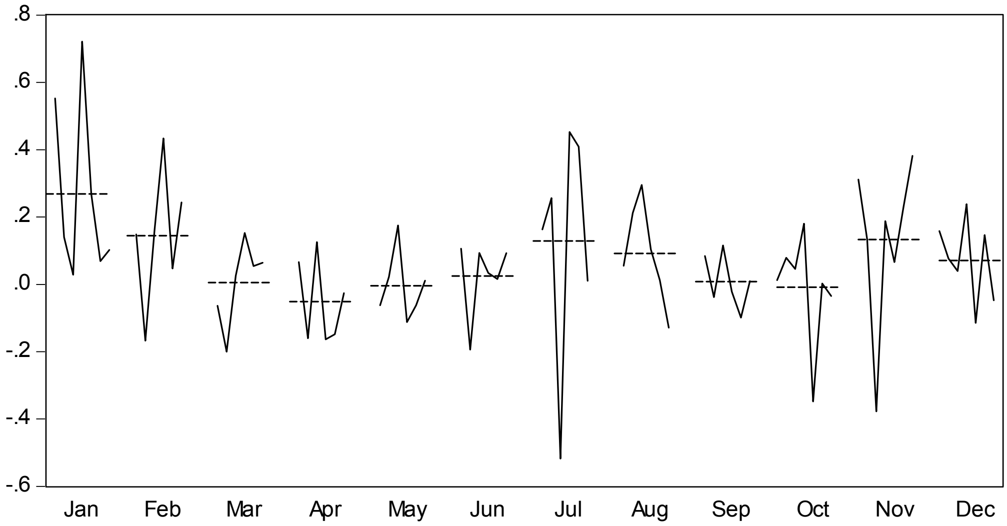

Figure 5.6. Seasonal graph of realised monthly percentage peak load forward premia at the EEX.

Considering perfect foresight, clearly a very strong assumption, the identified differences in spot and forward prices would indicate the existence of pronounced risk premiums in the forward markets. However, because of the correlation between futures and spot prices positive premia should be expected due to associated systematic risk (Kristiansen, 2004). Additionally, the analysis in this chapter also proves the prominent role of a simple misjudgement of future fundamental generation and demand conditions by market actors since the sign of the relative differences changes over time which cannot be explained by risk considerations only (see Figure 5.4). This deviation between expected and actual conditions arises from shocks between futures and spot trades (e.g. unexpected cold or warm weather, high or low CO_2 prices, high or low hydro availability, etc. in the delivery period). Still, analyses of the forward premium as a single function of the spot price stochastics are common (see references in section 5.2.2). The next section will discuss whether this convenient approach is justifiable. As an empirical example both the EEX and the Nord Pool markets are assessed to control for the effect of the supply structure.

5.4 Excursus: Is the forward premium explained well by stochastic properties of spot prices?

5.4.1 Testing the Bessembinder and Lemmon model [70]

The following equation is estimated by OLS to test the predictions of the model of Bessembinder and Lemmon (2002):[71]

$$F_{t,T} - S_T = b_1 + b_2 Var(S_t) + b_3 Skew(S_t) + \varepsilon_t \qquad (5.26)$$

where $F_{t,T}$-S_T is the ex post forward premium, $F_{t,T}$ is the futures price in t for delivery in month T, S_T is the spot price average in month T, $Var(S_t)$ is the variance of daily spot prices in month t and $Skew(S_t)$ is the skewness of daily spot prices in month t.

For monthly averages of futures prices strong serial correlation in the residuals is noticed from diagnostic checks which could be constituted to the fact that the data represent monthly averages. Therefore, this regression is tested with the definition of the forward price on the last trading day. Results for corresponding forward premia are shown in Table 5.2. As can be seen, serial correlation is no longer present in the residuals.

At the EEX the (positive) influence of the variance of baseload spot prices in the trading period of the futures contracts on forward premia is significant on a 10% level. The skewness of spot prices is not significant. For EEX peak load premia, similarly, a significant variance coefficient is obtained which points to its relevance but does not correspond to the interpretation in the Bessembinder and Lemmon (2002) model. The regression coefficient of the skewness of spot prices is positive for peak load but not significant. The models can only explain 7% (baseload model) and 4% (peak load model) of the variance of the forward premium. However, as peak load prices are very sensitive to changes in a variety of parameters – many not considered in model (5.26) – a lower performance of the peak load model is to be expected. Due to the asymmetry of spot prices and occasional spikes the hypothesis of normally distributed error terms has to be rejected although other diagnostic test statistics of the residuals are not significant.

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[70] Based on Redl et al. (2009).

[71] Using the spot price distributions for month *t* (the trading month) is an intentional choice. The analytical result of Bessembinder and Lemmon is that the premium depends on the spot price distribution in month *T*. Hence, the model of BL assumes rational expectations. The analysis in this thesis is based on testing an adaptive expectation formation instead. Hence month *t* values are used. All variables in the empirical model are therefore observable for the market participants. Douglas and Popova (2008) use a similar "adaptive" model. Moreover, estimating (5.26) with month *T* values would bring about the problem of overlapping observations. Running (5.26) nevertheless with month *T* values does not conform to the results of BL as well.

Table 5.2. Results of regression analysis (5.26) for ex post forward premia of month-ahead baseload and peak load futures at EEX and Nord Pool with monthly delivery periods from November 2003 to January 2010 (t-statistics in brackets). All tests are based on heteroscedasticity consistent standard errors. Results are shown for premia determined by futures prices on the last trading day.

Coefficient	Variable	EEX		Nord Pool
		Base load	Peak load	Base load
b_1	Constant	1.34 (1.47)	1.81 (0.98)	1.25 (1.97)
b_2	Variance spot price t	0.0027 (1.83)	0.001 (2.87)	-0.012 (-0.40)
b_3	Skewness spot price t	1.04 (1.23)	1.42 (1.07)	-0.38 (-0.60)
R^2 (R^2_{corr})		0.07 (0.04)	0.04 (0.01)	0.01 (-0.01)
DW		1.71	1.78	1.36
Serial correlation	χ^2_{12} (p-value)	0.478	0.370	0.348
Functional form	χ^2_1 (p-value)	0.292	0.486	0.104
Normality	χ^2_2 (p-value)	0.000	0.000	0.845
Heteroscedasticity	χ^2_1 (p-value)	0.630	0.572	0.155
Observations		75	75	75

At the Nordic market all regression coefficients are insignificant. Moreover, the sign of the skewness coefficient do not show the sign determined by Bessembinder and Lemmon (2002). Most likely, this is caused because of the characteristics of the Nordic power market (e.g. high amount of flexible storage hydro capacity). The resulting distribution of Nordic spot prices yields less skewed prices which cause the insignificance of coefficient b_3 in model (5.26).

In summary, the empirical performance of the Bessembinder Lemmon model is weak. Both statistical significance and explanatory power are far from satisfying. Hence, in the following a categorisation of forward premia determinants is proposed which shall mirror the risk and market assessment of the market participants and, moreover, comprehensively describe the structural supply and demand characteristics and its effects on the market outcome. Within each category several explanatory variables are described which give further insights on the propositions on the electricity forward premium.

5.5 A multifactor propositional framework

The realisation of the forward premium is affected by the participants' understanding of the market and their corresponding risk behaviour. The literature addresses some relevant aspects whereas this chapter proposes a more comprehensive approach. Clearly, risk aversion arises from the stochastics of the spot price process (and can be broken down with the help of utility functions to aversion to higher moments of the price distribution). But also fundamentals are expected to cause variations in the market price of risk. The margin, for example, constitutes a well known property of the spot price. Hence, the margin is expected to be a part of the risk assessment. Similarly, input fuel prices should affect the price of risk. Furthermore, the participants' perception of commodity markets in general can influence their assessment of the commodity electricity as well as behavioural biases (e.g. caused by employing heuristics or anchoring decisions to past events).[72]

This chapter therefore seeks to embed and extend the various factors introduced in previous work into a more comprehensive analysis. In doing this the forward premium components are organised into a taxonomy of fundamental influences, behavioural effects, market conduct, dynamic effects and shock effects. Specifically the following propositions are addressed:

Fundamental influences

The fundamental drivers (Bunn, 2004, Weron, 2006) of power prices are demand, marginal costs (fuel and carbon prices), and scarcity (margin). Demand presents a particular problem. Because of endogeniety concerns and the difficulty of specifying demand for a market with a high degree of interconnection to neighbours, such as EEX, an average central European temperature was taken as a proxy. This proved not to be significant, however. An analysis of the effect of temperature surprises (actual monthly average in the delivery month minus long term ex ante monthly average) did turn out to be significant. Nevertheless, the series on temperature data has several shortcomings. Hence, demand measured by its proxy temperature is not considered in the model below. The robustness analysis in section 5.6.3.1 will elaborate on this issue. Daskalakis and Markellos (2009) find that EEX forward premia can be partly explained by the volatility of CO_2 spot price returns. This analysis does not consider CO_2 prices, since the volatility of electricity spot prices, which, in turn, are influenced by carbon prices, is included.[73] For specific propositions, therefore only fuels and scarcity are considered.

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[72] See Ricciardi (2008) for a review of behavioural decision theory.

[73] Reassuringly, the inclusion of carbon price volatility resulted in an insignificant regression coefficient. Apart from the volatility of CO_2 prices affecting the electricity forward premium the latter could also be influenced by the premium in the CO_2 market. However, there are no month-ahead CO_2 contracts traded.

- Fuels and their risk premia: *Proposition: An increase in the gas forward premium is expected to increase the electricity forward premium, whereas the effect is anticipated to be more pronounced in peak load compared to base load.*
  Given the high importance of fossil fuelled generation technologies in the EEX market, the premium prevailing in the electricity contract market should be directly influenced by the premium in the gas market.[74] This influence can be motivated by either risk management considerations, since – assuming gas fired price setting technologies – the realised spark spread constitutes the risk exposure of a generator having contracted gas, or the forecast errors of the respective market participant.
- Scarcity: *Proposition: A negative relationship between the observed reserve margin and the forward premium is expected*[75].
  A reduction in the reserve margin indicates relative scarcity and one would expect that this leads to a higher propensity for shocks to induce greater price volatility and spikes. Given an adaptive expectations adjustment by market participants, a perceived decreasing margin in the spot market may cause expected spot prices and therefore forward prices and, correspondingly, premia to increase.[76]

Behavioural effects

Adaptive expectation formation with respect to the risk assessment of the market participants is postulated, as motivated by high correlations between current spot and forward electricity prices and the adaptive heuristics that research in behavioural finance indicates is likely to prevail (e.g., Ricciardi, 2008). It is plausible that spot market realisations in the trading month of the forward contract will be used by agents as proxies for the anticipated realisations in the delivery month as spot price forecasts for a delivery period comprising one month ahead prove to be elusive (for research aiming to model expectation behaviour and market participants alike). Hence, a link between current long and short term prices appears not surprising. Similarly, the risk assessment of market participants considers current market

[74] The price setting technologies in the peak load segment are gas fired. For base load, the coal market could similarly influence the electricity market. Still, there exists no coal spot market in the EEX region which precludes the calculation of corresponding forward premia. Moreover, with the introduction of carbon trading, gas fired power plants have gained increased importance also in the base load segment.

[75] The reserve margin as ratio of generation and demand constitutes a measurement for scarcity in the electricity supply system.

[76] It would be reasonable to suggest a nonlinear effect of the reserve margin given the convexity of the supply curve. However, the results did not differ when linear margin terms are replaced by quadratic ones.

developments. Thus, in the following models the realisations of the relevant assessment parameters in the spot market in the trading month of the forward contract are used as proxies for the anticipated spot distribution realisations in the delivery month.[77]

- Higher moments: *Proposition: Higher central moments of the spot price distribution (variance, skewness and kurtosis) are of importance for the risk assessment of market actors.*

  The capital asset pricing model and, correspondingly, the mean-variance utility assumption, are widely used for the assessment of securities markets (Newbery, 1988). This popular approach has spilled over to plenty of analyses in the field of electricity forward markets and, especially, electricity forward premia. The influential work of Bessembinder and Lemmon (2002) considers agents to be non-strategic, risk averse utility maximisers, but their main result neglects higher moments beyond variance and skewness in the Taylor series expansion. Given the increasing interest in fat tails and aversion to extreme outcomes, it is plausible that a positive influence of the kurtosis of spot prices on the premium could be expected.

  Positively skewed spot prices increase the hedging demand of retailers given fixed retail prices. On the other hand, spot price spikes represent opportunity costs of generators having sold forward. Both factors contribute to a positive forward premium. Hence the regression coefficient associated with the skewness should show a positive sign. The influence of the variance of spot prices on the forward premium is, however, not clear cut. Bessembinder and Lemmon (2002) predict a negative effect. It could be argued however, that, due to the convexity of the supply curve, shocks that create high skewness and volatility are very similar and therefore in the risk premia regressions, these two moments should have similar signs.
- Spikes: *Proposition: The forward premium increases due to the occurrence of spikes in the spot market.*

  It is plausible that recent spike episodes may induce greater risk aversion. Dummy variables which account for the occurrence of spikes may allow a more subtle representation of this compared to the skewness and kurtosis measures. Different degrees of spikiness respectively thresholds can be defined (mean plus one, 1.5, two, 2.5 and three standard deviations, Weron, 2006). The relevant spot price aggregation

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[77] In the light of adaptive expectations a further natural risk assessment parameter would be the corresponding realisation in the spot market of the same delivery month a year ago. Still, all 12-month lagged variables turned out to be statistically insignificant in the models.

level for estimating spikes at the EEX is the daily base or peak load spot price average (Phelix Base, Phelix Peak), since the underlying of monthly futures contracts is the monthly average of the Phelix day indices. Given positively skewed spot prices a positive influence of the spike count variable on the premium is expected.

- Oil market volatility: *Proposition: Increased volatility in the oil market increases the electricity forward premium.*

  Due to the dominance of oil prices in the energy commodity bundle and its sentiment effect for energy commodities in general, it is plausible that electricity market agents are influenced by activity in the oil market.[78] Hence, a regression coefficient associated with oil market volatility would be expected to show a positive sign.

Market conduct

- Market power: *Proposition: The exercise of market power in the spot market positively influences the forward premium.*

  Theory is mixed on the interaction of market power and forward contracting. I have already referred to the work of Allaz and Vila (1993), which suggests that forward contracting mitigates the exercise of market power in the spot market. On the other hand, the model of Robinson and Baniak (2002) including oligopolistic risk neutral generators and risk averse retailers suggests that the generators increase the spot market volatility in order to increase the forward premium in contracts. Furthermore, it is plausible to argue, similarly to Anderson and Hu (2008), that producers who can increase spot market prices demand a higher premium to contract forward and that buyers see generator market power as an additional risk factor which increases their willingness to pay forward premia.

  The estimation of reliable forward market concentration proxy variables, which would allow empirical insights into market power, is, however, quite elusive in the absence of detailed contract data. On the other hand, estimated base load and peak load price mark ups above marginal cost estimates for the spot market can be included in the analysis. Figure 5.7 below depicts the evolution of EEX spot prices and estimated monthly averages of marginal costs in the regional EU4 market from 2003-2009. The corresponding mark up variable, defined as the ratio of the price-cost-difference to the

[78] Even though oil fired power plants are very rarely dispatched.

cost estimate, especially its relative pattern compared to observed spot prices, can be an indicator of the exercise of market power of the dominant producers.[79]

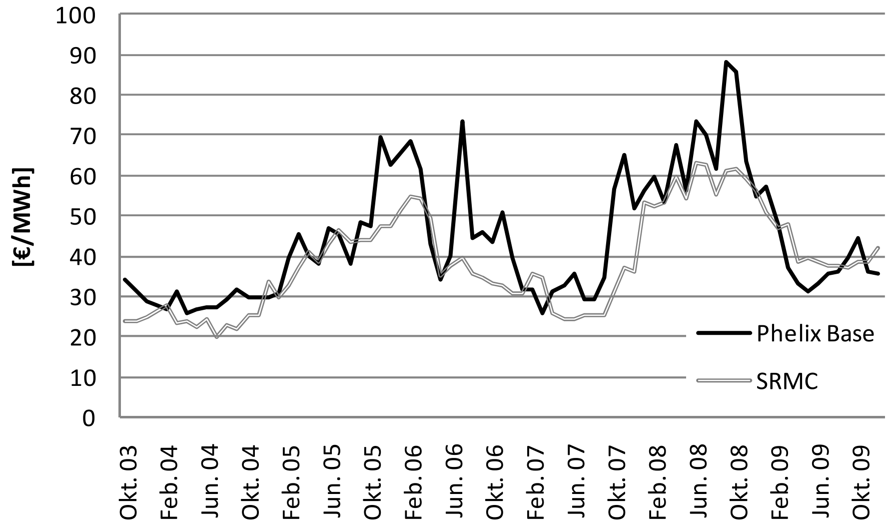

Figure 5.7. Evolution of electricity prices (average baseload price at the EEX) and system marginal costs in the regional EU-4-market from October 2003 to December 2009. Source: EEX, BAFA, UCTE, own calculations

Dynamic effects

- Basis: *Proposition: An increasing basis causes the forward premium to increase.*

  Basis is defined as the forward price (from the last trading day of the month) minus the average spot price in the trading month up to that day. Since current month-ahead forward prices are, given the nonstorability of electricity, characterised by a surprisingly (in view of nonstorability) high correlation with current spot prices, market actors faced with the challenge of forming month-ahead spot price forecasts, may adapt expectations to the recent average.[80] This analysis deliberately considers forward price on the last trading day only, as some of the fundamental market data is publicly available on a monthly basis only. Thus, the definition of the forward premium on the last trading day is particularly attractive from a modelling point of view. Nevertheless, consequences of the market dynamics and their interaction are

[79] The marginal cost estimate is an average monthly value, which is compared to the average base or peak load price index. Start up costs or other opportunity cost considerations are, hence, not part of the monthly average cost estimate. On the other hand, brief downward excursions in the day ahead price (e.g. negative daily prices on certain days in 2009) can cause average monthly prices to decrease, which, however, is not reflected in the average SRMC estimate. Therefore, observed market prices can, at certain months, also be below the SRMC estimate.

[80] For comparison, Chapter 4 showed significant influences of current spot prices on year-ahead forward prices at the EEX and the Nord Pool.

considered in this analysis. Specifically, the tie between spot and forward prices is also reflected in the basis. A significant influence of the basis therefore gives further insight into the expectation formation of the market participants. An increasing basis is expected to increase the forward premium.

- Seasonality: Seasonal effects, above those which can be fundamentally modelled (e.g. the system margin), have been observed in other studies (Weron, 2008) of the forward premium. However, due to the statistical insignificance reported in section 5.3, (annual) seasonality will not be considered in the empirical analysis below.

Shocks

Proposition: Margin shocks positively influence the forward premium.

To be able to account for supply and demand shocks between forward trades and future spot trades a margin shock variable is introduced. Specifically, the margin shock variable captures the ratio between total generation and actual electricity consumption in the relevant regional market. This combined approach has been chosen to avoid long-term trend effects of a separate consumption and generation representation. If, ceteris paribus, consumption is unexpectedly high in the delivery month spot prices should exceed forward prices due to a decreasing margin. On the other hand, if, ceteris paribus, total generation rises unexpectedly spot prices should fall below forward prices since the supply curve is shifted to the right. Hence, the regression coefficient associated with the realised margin is expected to show a positive sign.

Summary of propositions

Table 5.3 summarises the above propositions on the effects of forward premia components and respective proxy variables. Apart from the margin shock, all variables are observable for the market participants on the forward trading day.

Table 5.3. Summary of forward premia determinants. * denotes that the respective variables are observable for market participants on the forward trading day.

	Effect on forward premium	Proxy variable
*Fundamentals**		
Premia in fuels	+	Month ahead gas forward premium
Scarcity	-	Reserve margin: Ratio generation/consumption in the regional market
*Behavioural effects**		
Variance	+	Coefficient of variation of spot price
Skewness	+	Skewness of spot price
Kurtosis	+	Kurtosis of spot price
Spikes	+	Count spikes outside 1, 1.5, 2, 2.5, 3 standard deviations of mean spot
Oil volatility	+	Coefficient of variation of Brent oil spot price
*Conduct**		
Spot market power	+	Fundamental cost mark up estimate for regional spot market
*Dynamics**		
Basis	+	Difference of forward price and spot price average in trading month
Shocks		
Margin shocks	+	Change in supply margin during delivery month

In the following reduced form models aiming to give insights on the above propositions are presented.

5.6 A model of the ex post forward premium

This section develops reduced form models to give insights on the above propositions. Furthermore, the analysis assumes myopic expectations in the sense that the market participants are influenced by current and historic events on the spot market. These events, in turn, contribute to the risk and market assessment of the agents and, hence, to the forward premium. All parameters except the margin shock are observable for the market participants on the last trading day of month t.[81]

5.6.1 Base load premium model

Sequentially minimising the AIC criterion, pursuing a general-to-specific model identification characterised by all variables discussed in section 5.5, yields the following equation for the ex post baseload forward premium:

[81] For comparison, Douglas and Popova (2008) also partly assume adaptive expectations in their model – represented in particular by one period lagged values of variance and skewness of spot prices and gas storage levels.

$$F_{t,T} - S_T = b_1 + b_2 c_v(S_t) + b_3 c_v(Brent_t) + b_4 FP_{Gas\ t-1,t} + b_5 Margin_t + b_6 Basis_t + b7MarginT+\varepsilon t,T \quad (5.27)$$

where $F_{t,T}$-S_T is the ex post forward premium, $F_{t,T}$ is the futures price on the last trading day in month t for delivery in month T, S_T is the spot price average in month T, $c_v(S_t)$ is the coefficient of variation of daily spot prices in month t, $c_v(Brent_t)$ is the coefficient of variation of daily Brent spot prices in month t, $FP_{Gas\ t-1,t}$ is the realised gas forward premium of a month ahead futures for month t, $Margin_t$ is the realised ratio of generation and consumption in month t, $Basis_t$ is the difference between the futures price on the last trading day in month t for delivery in month T ($F_{t,T}$) and the spot price average in month t (S_t), and $Margin_T$ is the margin shock in month T. Results for the corresponding model are shown in Table 5.4.

The significant positive influence of volatility in the oil market confirms the "sentimental" importance of the oil market for energy commodities in general. Interestingly, its influence is as important as the influence of the volatility on the electricity market itself (in terms of statistical significance). Similarly, the economic responsiveness is very high with an average elasticity of 2.4.[82] Hence, a one percentage increase of the oil market volatility causes a 2.4% change of the electricity forward premium. The volatility of electricity spot prices positively influences the futures price and, hence, the forward premium. The influence of the spot price volatility on the forward premium is in general agreement with the empirical literature cited in section 5.2 but in previous research the sign of this measure seems to be indeterminate. In the present case the sign is positive which is opposite to Bessembinder and Lemmon (2002) but conforms to the above presented proposition.[83] The forward premium responds highly elastic to a change in the electricity market volatility with an average elasticity of 4.

[82] The models in this chapter contain the levels of the variables. Hence they cannot be interpreted as elasticities. Instead, an average elasticity is calculated by multiplying the regression coefficient by the ratio of the average of the explanatory variable to the average of the endogenous variable.

[83] Note that in this analysis volatility is measured via the coefficient of variation – and not via variance. Among others, this is motivated by allowing a better comparison between different "informational sources" of volatility for market actors (i.e. oil and power market volatility).

Table 5.4. Results of regression analysis (5.27) for ex post forward premia of month-ahead baseload futures at EEX for monthly delivery periods (t-statistics in brackets). All tests are based on heteroscedasticity consistent standard errors. Results are shown for premia determined by futures prices on the last trading day. *, **, *** denotes significance on the 10%, 5% and 1%-level.[84]

Coefficient	Variable	Baseload
b_1	Constant	9.06 (.18)
b_2	Coeff. of var. ($Spot_t$)	26.77 (5.00)***
b_3	Coeff. of var. ($Brent_t$)	97.47 (3.54)***
b_4	Forward premium gas t	0.26 (1.51)
b_5	Margin t	-238.73 (-2.60)**
b_6	Basis t	0.39 (2.77)***
b_7	Margin T	220.92 (2.89)***
R^2 (R^2_{corr})		0.30 (0.23)
DW		1.99
F-statistic		4.73
Serial correlation	χ^2_{12} (p-value)	0.231
Functional form	χ^2_1 (p-value)	0.691
Normality	JB (p-value)	0.000
Heteroscedasticity	χ^2_6 (p-value)	0.361
Observations		74; 11/03-12/09

Realised premia in the gas market influence the electricity premia although at a weak 14% significance level only. Still, given the expected sign, this variable is an interesting indication of the increasing importance of gas fired power plants in EEX baseload.[85] On scarcity, if market participants perceive a decreasing reserve margin in the spot market, measured as the ratio of available generation to consumption, the forward premium increases, as expected. The significant positive influence of the basis (i.e. the current forward-spot difference) gives further insight into the adaption expectation formation of the market participants. Upward trends in the, to a certain extent, tied spot and forward price series yield an increasing basis. This, in turn, results in an increasing forward premium. Hence, the dynamics of the spot market are reflected in the forward premium. Compared to the other parameters the economic impact of basis is, nevertheless, relatively small since the average elasticity of the premium to a percentage change in the basis is 0.4. Finally, the margin shock coefficient gives the expected sign and is statistically significant. Therefore, this variable can assess

[84] Tests on ARCH-effects were not significant.

[85] For comparison, Chapter 3 has shown that generation costs of gas fired power plants influence year-ahead baseload futures prices at the EEX significantly.

misjudgements of future supply and demand conditions and captures some of the forecast error part of the forward premium defined by equation (5.1).[86]

5.6.2 Peak load premium model

A similar procedure to the above described one yields the following equation for the ex post peak load forward premium:

$$F_{t,T} - S_T = b_1 + b_2 Skew(S_t) + b_3 Spike_{2sd\,t} + b_4 FP_{Gas\,t-1,t} + b_5 Market\ power_t + b_6 Margin_t + b_7 Basis_t + b_8 Margin_T + \varepsilon_{t,T} \quad (5.28)$$

where $F_{t,T}$-S_T is the ex post forward premium, $F_{t,T}$ is the peak load futures price on the last trading day in month *t* for delivery during peak hours in month *T*, S_T is the peak load spot price average in month *T*, $Skew(S_t)$ is the skewness of daily spot prices in month *t*, $Spike_{2sd\,t}$ is the count of spikes outside of 2 standard deviations of the mean spot price in month *t*, $FP_{Gas\ t-1,t}$ is the realised gas forward premium of a month ahead futures for month *t*, *Spot market power*$_t$ is the ratio of the spot price in month *t* and the fundamental marginal cost estimate for month *t*, $Margin_t$ is the ratio of regional generation and demand in month *t*, $Basis_t$ is the difference between the futures price on the last trading day in month *t* for delivery in month *T* ($F_{t,T}$) and the spot price average in month *t* (S_t), and $Margin_T$ is the margin shock in month *T*. Results for the corresponding model are shown in Table 5.5.

Realised premia in the gas market, as expected, have a significantly positive effect on the electricity peak load premia. The price setting technologies in peak load hours are, in fact, gas fired power plants. The significant positive influence gas market confirms the importance of these generation technologies although the electricity premium reacts in economic terms inelastically to changes in the gas premium with an elasticity of 0.15. The skewness of spot prices positively influences forward premia for peak load. If the observed spot price skewness increases by one percentage point the forward premium increases by 0.4%. Positively skewed spot prices increase the hedging demand of retailers given fixed retail prices. On the other hand, they represent opportunity costs of generators having sold forward. Both factors contribute to a positive forward premium, as suggested by Bessembinder and Lemmon (2002). However, we observe a negative influence of price spikes occurring in the spot market which appears counterintuitive. There is possibly an interaction effect with skewness, since the skewness measure, which computes cubic difference terms, may put too much weight on

[86] Margin constitutes an autoregressive process. Since in our models also lagged values of margin are included the economic interpretation in terms of elasticity is meaningless. Hence, elasticities are not reported for margin.

extremes (i.e. spikes) which perhaps becomes trimmed by a negative influence of the spike dummy variable. In this sense, skewness would be a too sensitive risk assessment parameter.

Table 5.5. Results of regression analysis (5.28) for ex post forward premia of month-ahead peak load futures at EEX for monthly delivery periods (t-statistics in brackets). All tests are based on heteroscedasticity consistent standard errors. Results are shown for premia determined by futures prices on the last trading day. *, **, *** denotes significance on the 10%, 5% and 1%-level.[87]

Coefficient	Variable	Peak load
b_1	Constant	86.00 (0.44)
b_2	Skew spot t	2.84 (2.11)**
b_3	Spike spot 2sd t	-4.98 (-2.06)**
b_4	Forward premium gas t	1.18 (3.02)***
b_5	Market power spot t	20.99 (3.86)***
b_6	Margin t	-459.33 (-2.62)**
b_7	Basis t	0.39 (2.87)***
b_8	Margin T	379.38 (2.89)***
R^2 (R^2_{corr})		0.25 (0.17)
DW		1.96
F-statistic		3.18
Serial correlation	χ^2_{12} (p-value)	0.483
Functional form	χ^2_1 (p-value)	0.285
Normality	JB (p-value)	0.000
Heteroscedasticity	χ^2_7 (p-value)	0.668
Observations		74; 11/03-12/09

On scarcity, if market participants perceive a decreasing margin in the spot market, measured as the ratio of available generation to consumption, the forward premium increases. A decreasing margin is related to the increased likelihood of spikes occurring in the spot market and, due to the convex supply curve, an increased skewness of spot prices. It is also this close interrelation between the fundamental state of the system (margin) and higher moments and parameters characterising the spot price distribution (skewness, price spikes) which make functional form specification and interpretation delicate. Interestingly, the forward premium is positively influenced by the market power estimate. In fact, spot price mark ups yield increases in the forward premium. This can be caused by a higher willingness to pay of the buyers, which price generator market power as a risk factor, and compensation demanded by dominant producers to be willing to sell forward (Anderson and Hu, 2008). This result suggests that any (positive) procompetitive effect of forward markets is, in fact, counteracted

[87] Tests on ARCH-effects were not significant.

by an increased risk premium. The economic importance of this result is reinforced by a responsiveness of the premium close to unit elasticity. If the mark up above marginal costs in the spot market increases by 1% the forward premium increases by 0.9%. Upward trends in the, to a certain extent, tied spot and forward price series yield an increasing basis. This, in turn, results in an increasing forward premium which is reflected in a significant regression coefficient. The economic impact of basis is somewhat smaller as the average elasticity of the premium to a percentage change in the basis is 0.3. Finally, the scarcity shock coefficient shows the expected sign and is statistically significant. This variable captures as in the baseload case, the forecast error part of the forward premium.

5.6.3 Robustness of model results

One might be inclined to interpret the results on the forward premium components presented in Table 5.4 and Table 5.5 with care due to the clear rejection of the normality hypothesis of the residuals $\varepsilon_{t,T}$ of the individual regressions. In fact, the results might be distorted owing to few outliers which could smear the true effect of premia determinants. Hence, in order to determine the robustness of the regression results presented in Table 5.4 and Table 5.5 – where coefficient estimates of the exogenous variables are assumed constant over time – recursive estimates are computed.[88]

Figure 5.8 depicts the results of the cumulative sums of the recursive residuals (CUSUM test) and the cumulative sum of squared residuals (CUSUM of Squares test) for the baseload and peak load models presented above. Both tests clearly show stability of the regression parameters during the sample period for the 5% significance level.

[88] See Chapter 4 for an explanation of the recursive estimation technique.

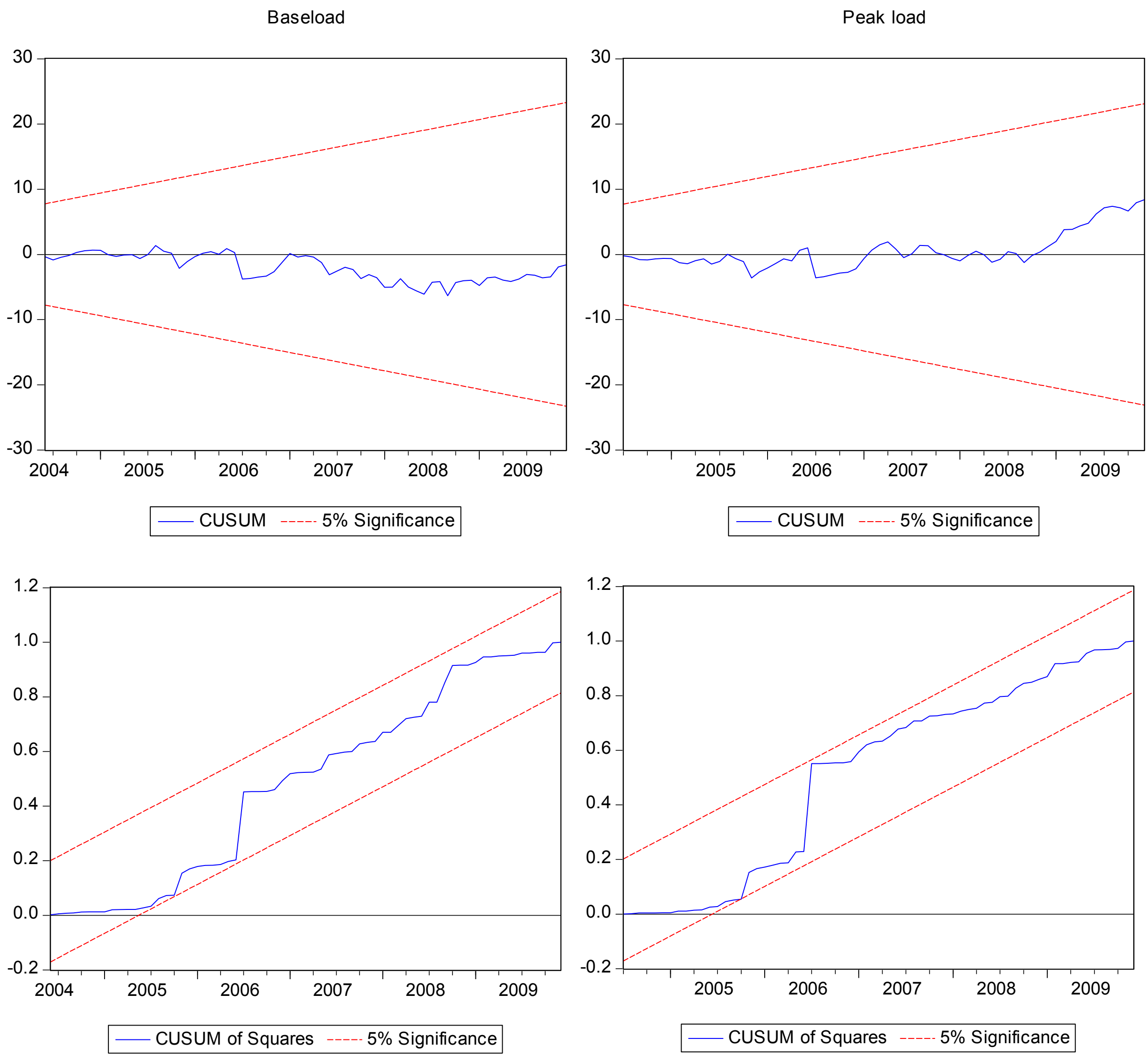

Figure 5.8. CUSUM and CUSUM of squares test for regression models (5.27) (baseload model, left) and (5.28) (peak load model, right) applied to EEX month-ahead forward premia

Still, assessment of the residuals of the recursive estimation of (5.27) and (5.28) suggests slight instability in the parameters as the residuals hit the significance line for November 2005 and July 2006 (see Figure 5.9). Indeed, re-estimation of (5.27) and (5.28) including dummy variables for these dates yield significant coefficients for the dummies. However, the inclusion of the dummies did not significantly affect the coefficient estimations of the original models (5.27) and (5.28). Hence, the robustness analysis in the following does not consider dummy variables for November 2005 and July 2006. Model results including dummies can be found in Appendix A.

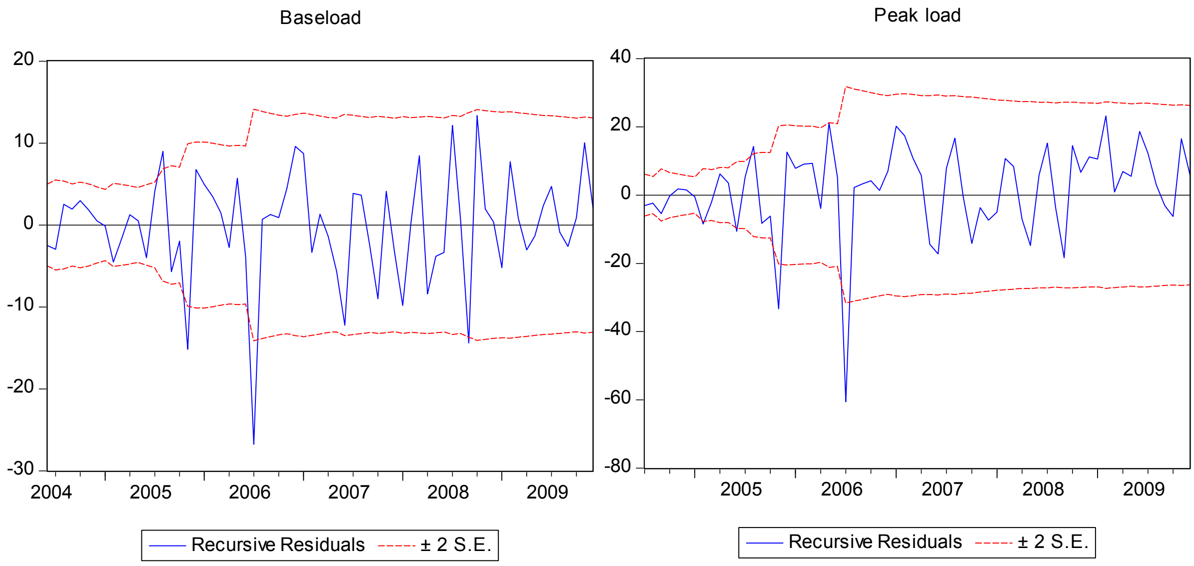

Figure 5.9. Recursive residuals for regression models (6.26 – baseload model, left) and (6.27 – peak load model, right) applied to EEX month-ahead forward premia

Figure 5.10 presents graphs of the recursively estimated regression coefficients for the baseload model (5.27). Clearly the parameters behave rather unstable at the beginning of the sample period since the degrees of freedom of the model are low. However, as the sample size increases, the estimates of the coefficients show a low variation which is an indicator of parameter stability. Also the significance of the coefficients shows the expected trend behaviour. Interestingly, the coefficient on the volatility in the oil market gets significant only as of the year 2008. In fact, in this year the highest increases in the oil market history could be observed – followed by a pronounced decrease. This, most likely, has caused the increased awareness of market actors in the energy field to activities in the oil market and, in turn, the increased importance of the oil market for the electricity market. Overall, the analysis of recursive estimates for the baseload premium model has confirmed the robustness of the results presented in Table 5.4.

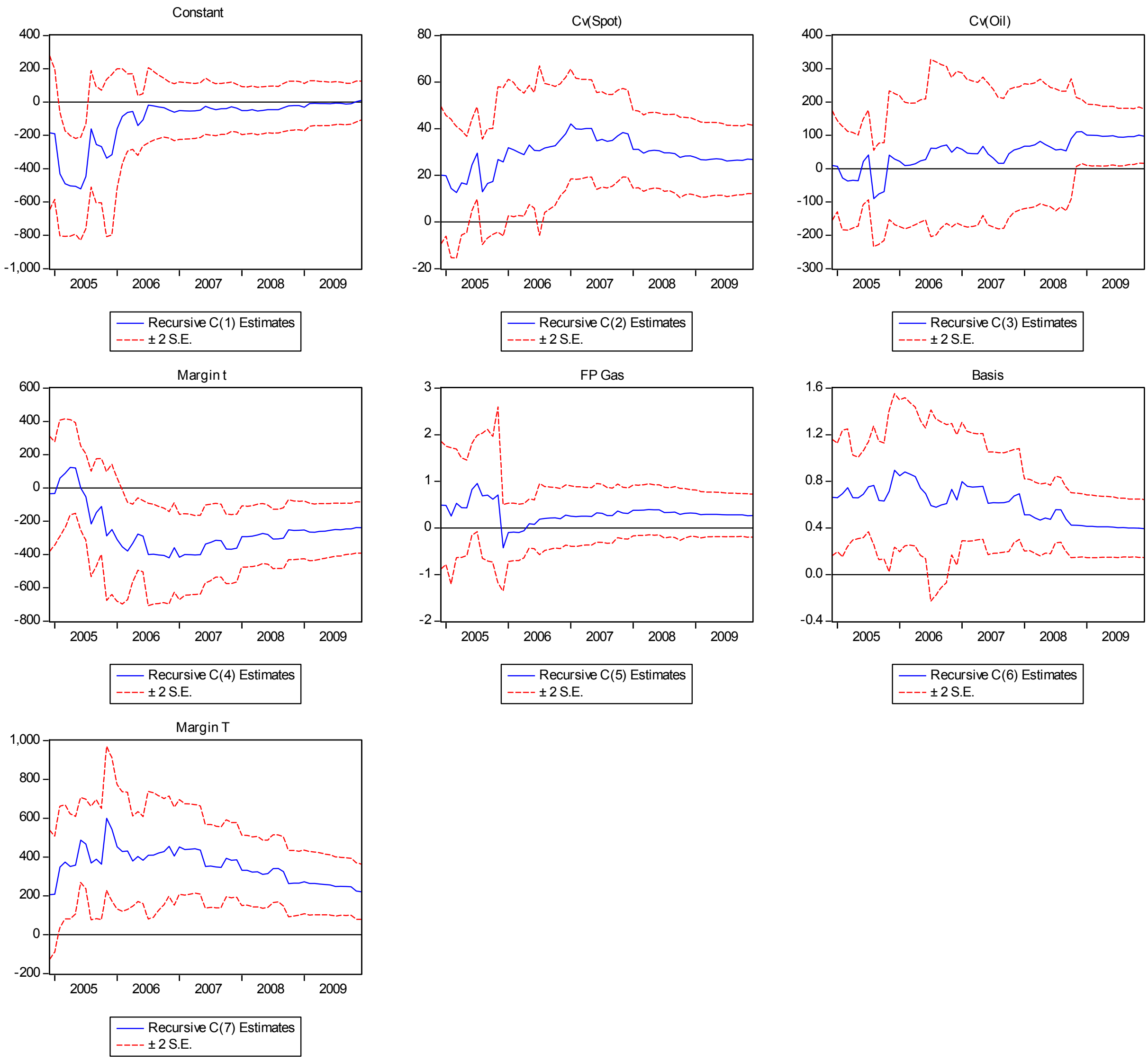

Figure 5.10. Recursive estimates of the coefficients of model (5.27) for baseload forward premia at the EEX

Similarly, Figure 5.11 presents graphs of the recursively estimated regression coefficients for the peak load model (5.28). Clearly the parameters behave rather unstable at the beginning of the sample period since the degrees of freedom of the model are low. However, as the sample size increases, the estimates of the coefficients show a low variation which is an indicator of parameter stability. Also the significance of the coefficients shows the expected trend behaviour. Overall, the analysis of recursive estimates for the peak load premium model has confirmed the robustness of the results presented in Table 5.5.

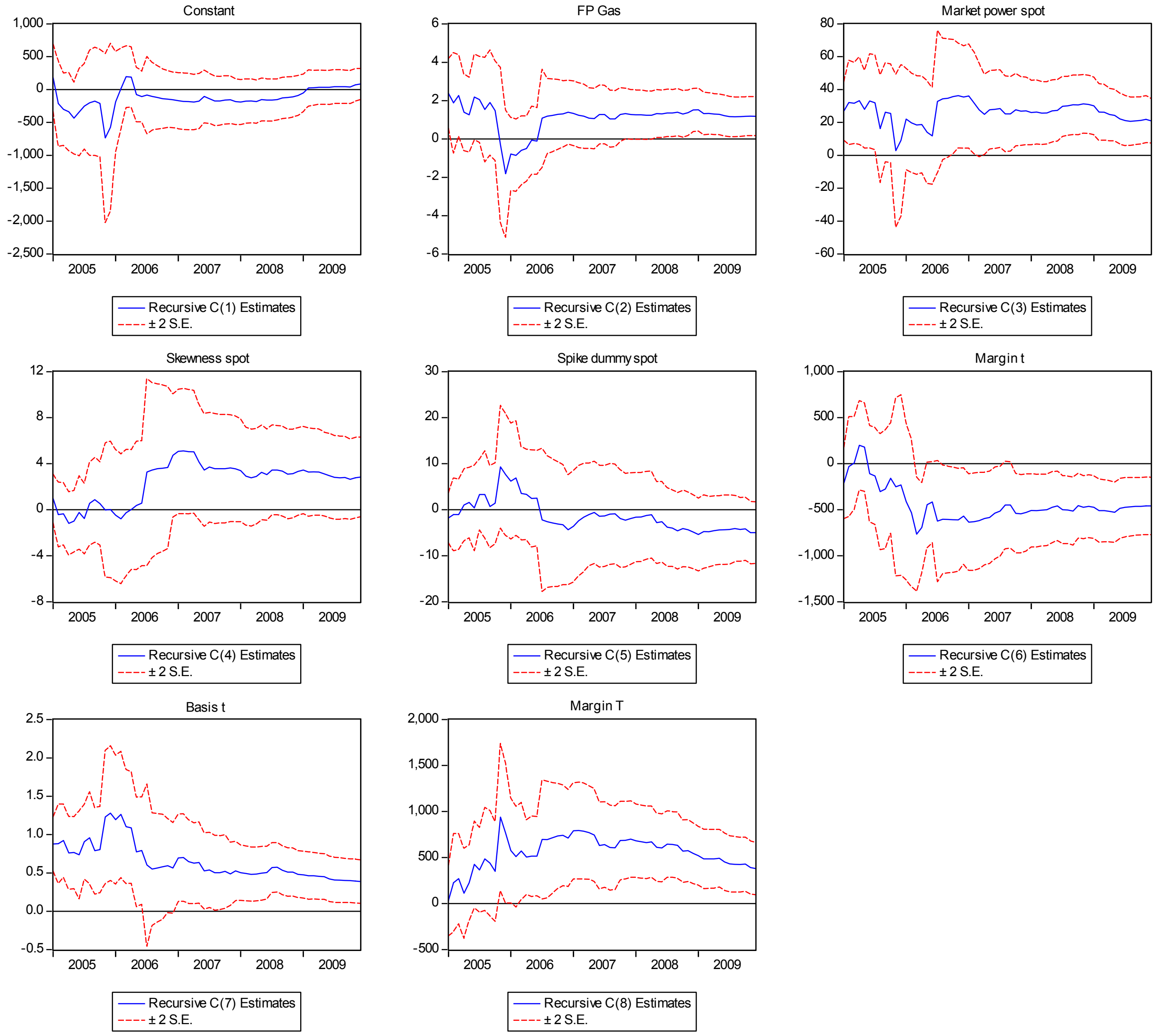

Figure 5.11. Recursive estimates of the coefficients of model (5.28) for peak load forward premia at the EEX

The robustness of models (5.27) and (5.28) is additionally confirmed by insignificant effects on the models' overall performance when dummy variables accounting for various outliers of the forward premium are included (see Appendix A for a detailed analysis). Clearly, the in- or preclusion of potential variables of interest can strongly affect the model results. The following section will demonstrate these effects and, more importantly, the consequences for the interpretation of the results – and potential drawbacks.

5.6.3.1 A note on variable selection: The influence of temperature surprise series on the explanation of the forward premium

This section discusses effects of different representations of variables for supply and demand surprises in the EEX forward premium model. In the original models (5.27) and (5.28) supply and demand shocks are captured by one common margin shock variable in order to avoid long-term trend effects of a separate consumption and generation representation. The aim of this section is to point out the importance of a careful parameter selection in an empirical model and to show consequences for the results of different model specifications – in terms of both statistical as well as fundamental properties.

Demand surprises

By using average daily temperature data from the University of Dayton (http://www.engr.udayton.edu/weather/), available from January 1995, it is possible to construct monthly temperature time series for several cities (mainly the capitals) in the relevant regional electricity market. The monthly temperature series are highly correlated (correlation coefficient > 0.96). Hence, the core regional Western European market (Austria, France, Germany, and Switzerland) and corresponding average temperature series are used for the demand surprise analysis.

Using monthly temperature series allows the calculation of a surprise variable which measures the difference between the actual average temperature in the delivery month of the futures contract and the historic average in the specific month. Figure 5.12 shows the temperature surprises from October 2003 to January 2010.

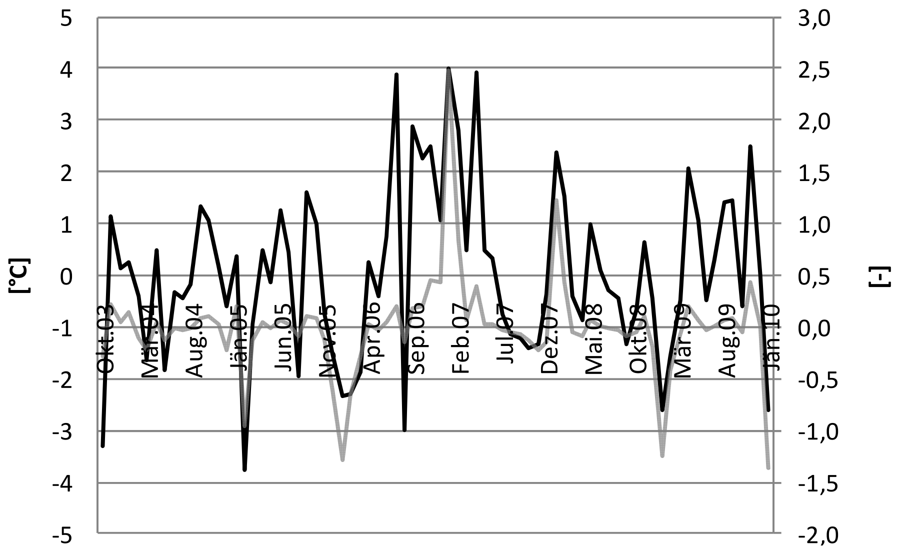

Figure 5.12. Temperature surprises (absolute values: black line and left scale; relative values: grey line and right scale) in the delivery months of the forward contracts computed as differences to the historic long term values. Source: http://www.engr.udayton.edu/weather/, own calculations

When using temperature surprise variables it is important to consider seasonality effects since temperature has a nonlinear effect (Bunn and Fezzi, 2008). In an empirical model therefore the temperature surprises need to be split up in at least two different surprise variable series (one for winter months and one for summer months). Table 5.6 depicts this nonlinear effect for a separation of temperature surprises in surprises during summer months and surprises during winter months assuming a positive ex-ante forward premium. If in summer months the realised temperature is lower than the expected temperature realised spot prices are lower than expected ones' due to lower cooling energy demand. This causes the realised forward premium to increase compared to the ex ante premium. On the other hand, if in winter months the realised temperature is lower than the expected temperature realised spot prices are higher than expected ones' due to higher heating energy demand. This causes the realised forward premium to decrease compared to the ex ante premium. Similar nonlinear effects pertain if the realised temperature is higher than the expected temperature.

Table 5.6. Effect of temperature surprises on the realised ex post forward premium for winter and summer months.

	$E(T_T) < T_T$	$E(T_T) > T_T$
Summer	$S_T > E(S_T)$: $F_{t,T}-S_T < E(F_{t,T}-S_T)$	$S_T < E(S_T)$: $F_{t,T}-S_T > E(F_{t,T}-S_T)$
Winter	$S_T < E(S_T)$: $F_{t,T}-S_T > E(F_{t,T}-S_T)$	$S_T > E(S_T)$: $F_{t,T}-S_T < E(F_{t,T}-S_T)$

Supply surprises

Clearly, the splitting up of the demand component (proxy: temperature) from the margin shock necessitates the creation of a separate supply surprise variable to yield a model with similar properties. Hence, this analysis considers the generation shock of inframarginal hydro and nuclear generation. Specifically, this variable calculates the difference between actual hydro and nuclear generation in the delivery month and the corresponding historic long term average. The historic data is available as of January 1991. Figure 5.13 shows the generation surprises from October 2003 to January 2010.

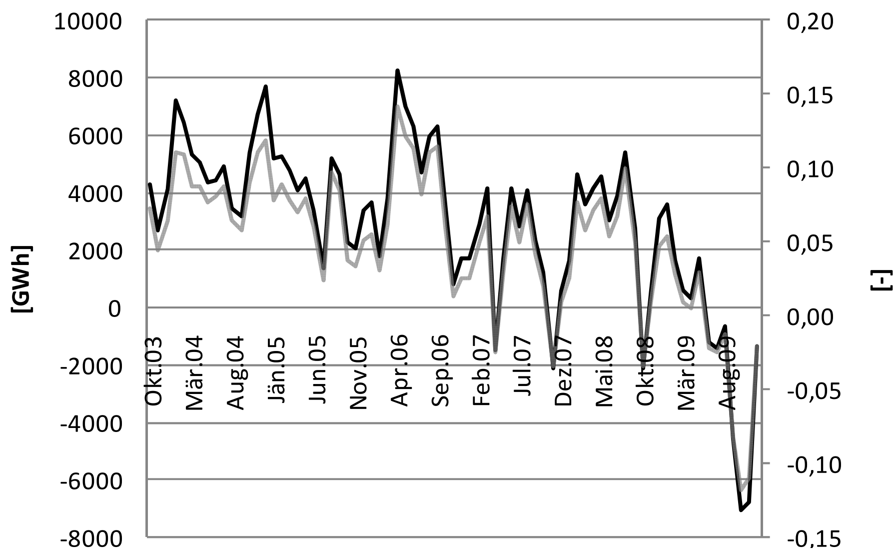

Figure 5.13. Inframarginal generation surprises (absolute values: black line and left scale; relative values: grey line and right scale) in the delivery months of the forward contracts computed as differences to the historic long term values. Source: ENTSOE, own calculations

Forward premium models including surprise variables

This model splits up the temperature surprises into two different surprise variable series (one for winter months and one for summer months).

Baseload case

The following model is estimated by OLS for the ex post baseload forward premium:

$$F_{t,T} - S_T = b_1 + b_2 c_v(S_t) + b_3 c_v(Brent_t) + b_4 Margin_t + b_5 Basis_t + b_6 SurT_T^S + b_7 SurT_T^W + b_8 SurGen_T + \varepsilon_{t,T} \qquad (5.29)$$

where $F_{t,T}$-S_T is the ex post forward premium, $F_{t,T}$ is the futures price on the last trading day in month t for delivery in month T, S_T is the spot price average in month T, $c_v(S_t)$ is the coefficient of variation of daily spot prices in month t, $c_v(Brent_t)$ is the coefficient of variation of daily Brent spot prices in month t, $Margin_t$ is the realised ratio of generation and consumption in month t, $Basis_t$ is the difference between the futures price on the last trading day in month t for delivery in month T ($F_{t,T}$) and the spot price average in month t (S_t), $SurT_T^S$ is the vector of unexpected summer month temperature surprises for month T (where T comprises the months April to September and the vector is set to zero in the winter months), $SurT_T^W$ is the vector of unexpected winter month temperature surprises for month T (where T comprises the months October to March and the vector is set to zero in the summer months), and $SurGen_T$ is the supply shock in month T. Results for the corresponding model are shown in Table 5.7.

Table 5.7. Results of regression analysis (5.29) for ex post forward premia of month-ahead baseload futures at EEX for monthly delivery periods (t-statistics in brackets). All tests are based on heteroscedasticity consistent standard errors. Results are shown for premia determined by futures prices on the last trading day. *, **, *** denotes significance on the 10%, 5% and 1%-level

Coefficient	Variable	Base load
b_1	Constant	141.41 (2.39) **
b_2	Coeff of var. (spot t)	15.23 (2.92)***
b_3	Coeff of var. (brent t)	90.27 (4.58)***
b_4	Margin t	-140.14 (-2.50)**
b_5	Basis t	0.22 (1.94)*
b_6	$SurT_T^S$	-2.13 (1.61)
b_7	$SurT_T^W$	2.93 (5.81)***
b_8	$SurGen_T$	0.00 (1.06)
R^2 (R^2_{corr})		0.45 (0.40)
DW		2.11
F-statistic		4.73
Serial correlation	χ^2_8 (p-value)	0.049
Functional form	χ^2_1 (p-value)	0.18
Normality	JB (p-value)	0.000
Heteroscedasticity	χ^2_7 (p-value)	0.034
Observations		74; 11/03-12/09

In general, the base load model does not improve compared to the original model presented in Table 5.4 in terms of its overall performance. The winter temperature surprise variable is significant on a 1% significance level whereas the summer temperature surprise is not significant. This is caused by an – on average – larger absolute value of the premium for winter months. Both variables show the expected signs – positive for the winter months and negative for the summer months. The AIC-criterion and the goodness of fit measured by measured by the coefficient of determination R^2 perform better in the model with temperature surprises which reduces to the poor forecasting power of the forward price. This, of course, brings about difficulties when assessing the ex ante risk assessment in an ex post analysis. As noted by the literature random shocks are large compared to any ex ante premium. Model (5.29) shows auto-correlated residuals for higher lag orders equal to 8. This, however, is an indication of a mis-specified model.

Peak load case

The following model is estimated by OLS for the ex post peak load forward premium:

$$F_{t,T} - S_T = b_1 + b_2 Skew(S_t) + b_3 Spike_{2.5sd\,t} + b_4 FP_{Gas\,t-1,t} + b_5 Market\ power_t + b_6 Margin_t + b_7 Basis_t + b_8 SurT_T^S + b_9 SurT_T^W + b_{10} Margin_T + \varepsilon_{t,T} \quad (5.30)$$

where $F_{t,T}$-S_T is the ex post forward premium, $F_{t,T}$ is the peak load futures price on the last trading day in month t for delivery during peak hours in month T, S_T is the peak load spot price average in month T, $Skew(S_t)$ is the skewness of daily spot prices in month t, $Spike_{2.5sd\,t}$ is the count of spikes outside of 2.5 standard deviations of the mean spot price in month t, $FP_{Gas\ t\text{-}1,t}$ is the realised gas forward premium of a month ahead futures for month t, *Spot market power*$_t$ is the ratio of the spot price in month t and the fundamental marginal cost estimate for month t, $Margin_t$ is the ratio of regional generation and demand in month t, $Basis_t$ is the difference between the futures price on the last trading day in month t for delivery in month T ($F_{t,T}$) and the spot price average in month t (S_t), $SurT_T{}^S$ is the vector of unexpected summer month temperature surprises for month T (where T comprises the months April to September and the vector is set to zero in the winter months), $SurT_T{}^W$ is the vector of unexpected winter month temperature surprises for month T (where T comprises the months October to March and the vector is set to zero in the summer months), and $Margin_T$ is the margin shock in month T. Results for the corresponding model are shown in Table 5.8.

In general, the peak load model improves compared to the original model presented in Table 5.5 in terms of its overall performance. The winter temperature surprise variable is significant on a 1% significance level whereas the summer temperature surprise is not significant. This is caused by an – on average – larger absolute value of the premium for winter months. Both variables show the expected signs – positive for the winter months and negative for the summer months. The supply side surprise variable is not statistically significant. The goodness of fit measured by the coefficient of determination R^2 and the AIC-criterion improve which reduces to the poor forecasting power of the forward price. Still, the performance of the model (5.30) is not conclusive. Much of the variation in the forward premium is captured by a significant constant term. This, however, is not a satisfying result when analysing the time-varying properties of the forward premium.

Table 5.8. Results of regression analysis (5.30) for ex post forward premia of month-ahead peak load futures at EEX for monthly delivery periods (t-statistics in brackets). All tests are based on heteroscedasticity consistent standard errors. Results are shown for premia determined by futures prices on the last trading day. *, **, *** denotes significance on the 10%, 5% and 1%-level

Coefficient	Variable	Peak load
b_1	Constant	295.65 (2.39)**
b_2	Skew spot t	2.94 (1.72)*
b_3	Spike spot 2.5sd t	-3.92 (-1.23)
b_4	Forward premium gas t	0.48 (1.50)
b_5	Market power spot t	6.67 (1.28)
b_6	Margin t	-279.89 (-2.37)**
b_7	Basis t	0.28 (2.44)**
b_8	$SurT_T^S$	-5.04 (-1.60)
b_9	$SurT_T^W$	4.88 (5.69)***
b_{10}	$SurGen_T$	0.00 (1.54)
R^2 (R^2_{corr})		0.41 (0.32)
DW		1.97
F-statistic		4.84
Serial correlation	χ^2_{12} (p-value)	0.251
Functional form	χ^2_1 (p-value)	0.217
Normality	JB (p-value)	0.000
Heteroscedasticity	χ^2_9 (p-value)	0.09
Observations		74; 11/03-12/09

Comparing the original models (5.27) and (5.28) where combined supply and demand shock proxies were used to capture the forecast error part of the forward premium and models (5.29) and (5.30) where the representation of surprises is split up among the demand side (temperature) and the supply side (inframarginal hydro and nuclear generation) yields different results. Generally, the use of more detailed surprise variables increases the goodness of fit of the regression models. This would favour the latter type of models. However, the results should be interpreted with due care. First, temperature data series are available only for selected cities in the relevant regional market. Instead, the use of a common margin shock variable which captures the total generation and demand in the regional market is better suited to characterise a regional market.

Although the temperature surprises can capture significant parts of the forecast error part of the forward premium, which, of course, affects the performance of the ex ante risk assessment variables, lacking completeness of the temperature data casts doubt on the usefulness of this data source and brings about the problem of spurious regression results. Still, the analysis has shown that shocks – due to their magnitude – make statistical inference regarding risk assessment delicate. However, due to the nature of the temperature data, this result may be the cause of a pretended accuracy of the temperature data. The fundamental (aggregated) margin variable presents itself to be a more precise representation of shocks occurring in the regional market.

5.7 Conclusions

This chapter has introduced a multifactor analysis of electricity forward premia determinants to give insights into some important propositions on the electricity forward premium. In general several significant new effects have been shown:

- The ex post nature of the analysis was controlled for by including a margin shock variable in the regressions, and this was indeed significant in both the peak and baseload monthly ex post risk premia.
- As a derived commodity, electricity translates a substantial amount of the underlying fuel's market price of risk (i.e. the peak forward premium is in fact determined partly due to the gas market).
- As part of the energy commodity trading bundle, oil market sentiment spills over, in that increased oil price volatility increases the forward premium.
- Market concentration appears to have a double influence on power prices – in addition to its potential effect on spot prices, it increases the forward premium. It seems therefore that whilst the theoretical effect of forward contracting may be to make the spot market more competitive, generators are able to compensate for this through a higher forward premium.[89]
- The effects of scarcity (reserve margin), spot volatility and skewness were significant and consistent with propositions on the positive effects of market risk aversion.

Overall, the forward premium in electricity is a rather complex function of fundamental, behavioural, dynamic, market conduct and shock components. It is clearly an oversimplification in practice to analyse it only in terms of the stochastic properties of the

[89] The theoretical model of Allaz and Vila (1993) indicated an increase in physical supply of 20% compared to the no contract case, and in a similar way Green (1999) estimates, in a numerical example, price decreases of 25% when comparing fully contracted to uncontracted firms. The extensive analyses by Bushnell (2007, et. al., 2008) suggests price decreases of around 50% when firms' contract positions are considered against a theoretical counterfactual. This contrasts with actual empirical studies reporting significant positive forward premia: Longstaff and Wang (2004) show for the PJM day ahead market premia up to 14%. Botterud et al. (2009) report for the Nord Pool market baseload premia from 1.3 to 4.4% for one week to six weeks ahead. Similarly, Redl et al. (2009) determine Nord Pool baseload premia of 8% for month-ahead contracts and EEX month-ahead premia of 9% for baseload and 13% for peak load.

spot prices (variance and skewness). Only part of the risk can be attributed to the electricity sector per se, but in that, risk aversion to scarcity, volatility and extreme events, as well as behavioural adaptation and oil sentiment spillovers characterises agent behaviour. Furthermore, market concentration appears to translate market power effects into the risk premium, which may have important market monitoring implications since forward markets have, so far, been considered to be procompetitive.[90] Policy makers and regulators seek to increase consumer welfare. In the context of electricity markets this is associated with measures aiming to reduce the forward premium. The reserve margin plays therefore a crucial role since increased scarcity increases spot prices (which is amplified in the case of concentrated markets) and, moreover, also the forward premium. Hence, consumers take a "double hit" if the margin reduces, and if this is due to strategic withholding, then it is an important anti-trust concern. In general, some of the insights presented here suggest that forward premia should be considered key elements of a transaction cost view of market efficiency in power trading.

Finally, the analysis purposely relied on variables which are observable for the market actors on the forward trading day. As some of the fundamental market data is publicly available only on a monthly basis, the definition of the forward premium on the last trading day is particularly attractive for analysis. A more thorough investigation of the dynamic interrelations between current spot and forward prices (and premia) would, however, benefit from the higher granularity of daily representations or even higher frequency impact studies of news on forward prices.

[90] See Anderson and Hu (2008) for a similar argument arising from a theoretical equilibrium model.

6 Conclusions and Outlook

This thesis contributed to the literature analysing the functioning of deregulated wholesale electricity markets. Specifically, it focused on the empirical assessment of major European long-term futures and forward markets. Wholesale market participants are faced with a multitude of uncertainties and risks. Long-term markets are particularly attractive from a risk management point of view as they allow for hedging price risks. High trading volumes on these markets, eventually exceeding actual physical demand, reflect their importance.

High trading volumes and, correspondingly, high market liquidity are generally considered as indications of mature and well-functioning markets. Yet it is crucial to gain deeper insight into the price formation process – not at least because of the special characteristics of the physical commodity electricity, associated consequences for the market structure, and its importance for the overall economy. These insights enable an efficient and effective design of the markets and its regulatory and legislative provisions.

The analyses carried out contribute to an assessment of the deregulation exercise of the European power sector. Firstly, the main drivers of year-ahead futures prices at the two analysed major European power markets (the EEX and Nord Pool power exchanges) were analysed. It was followed by a high-frequency analysis of the interaction between spot and forward prices of different maturities and their drivers. Finally, the price of risk inherent in the long-term markets was studied by a multifactor analysis of month-ahead forward premia and their corresponding determinants. These analyses have revealed several new effects:

Year-ahead futures prices are both influenced by expectations of generation costs of price setting power plant technologies and current spot market prices. This pricing mechanism could be revealed for both of the two analysed markets. In fact, the results suggest that the pricing of futures is a complex function of rational[91] and behavioural components.

The results of the high-frequency analysis of the daily electricity price system support this finding. The price system consists of daily spot and forward prices of various maturities. First, fundamental supply and demand variables effect the system of electricity prices. Second, electricity spot prices influence electricity futures prices and vice versa. These results appear particularly surprising given the non-storability of electricity and are counter to the implications of a rational pricing model of non-storable commodities. In turn, they cast doubt

[91] In the neo-classical sense.

on the predictive power of forward prices and on market efficiency. Additionally, the tie in storable fuels implies the corresponding cost of carry also effecting the non-storable commodity electricity. Consequently, this complicates the price formation. Furthermore, the risk assessment of market participants gets affected increasing the cost of hedging spot price uncertainty.

Specifically, the effects of compound forward pricing on the futures prices' inherent price of risk were revealed by a multifactor analysis of realised month-ahead forward premia. The premia are a complex function of fundamental, behavioural, market structure, dynamic and external shock components. These premia determinants are partly in line with theories of risk aversion of rational market participants. The action of spill over and market power effects, however, reveals unexpected significant transaction costs associated with power trading.

What are the implications for the performance of electricity wholesale markets? Firstly, the conducted analyses give insights into the structure of the market participants. For example, as of January 2011 about 150 organisations, including all major (investment) banks, were registered for trading in the EEX's power derivatives market[92]. On average a subset of about 50 are actively participating.[93] The performed analyses suggest that futures market results are largely determined by market actors with a physical position (i.e. generators, retailers and large consumers). This is indicated by the magnitude of realised forward premia in the order of 10% on a monthly basis. The premium would represent the willingness to pay for risk reduction if systematic forecast errors were neglected (i.e. market participants forming rational expectations). Forward premia are also affected by external shocks. Still, it is possible to contend that premia on the short-end of the forward curve are largely determined by risk averse buyers because there are significant trend effects in the time to maturity behaviour of the premia.

Sufficient short selling of futures contracts of "outside" speculators, that is, market actors without a physical position, would bring down these premia to a level determined by transaction costs.[94] Yet increased trading activities in markets can cause price volatility to

[92] http://www.eex.com/en/EEX/Participants

[93] http://www.eex.com/en/Transparency

[94] Speculative positions in derivative markets are taken in response to price differences between futures and consecutive spot prices. "Speculators" acting in financial markets do not have delivery obligations in physical markets. It is worthwhile to point out that every trade in financial contracts markets, i.e. also risk management activities of participants with physical positions, is partly determined by a speculative position. See chapter 2.3.2 for details.

increase.[95] Forward premia should decrease in absolute terms if the number of speculative trades grows. It might, however, have implications for the price of risk due to an increased short-term volatility. These implications are not clear cut in an electricity price system characterised by repercussions among the price series. They suggest further investigation.

Speculative trading activities in energy commodity markets have caused a lively public debate about its effects on price levels, especially since prices in the crude oil market rose to unprecedented highs in 2008. Sole speculative trading can be ruled out to be responsible for the electricity futures price formation for reasons outlined above. Still, prices on long-term markets are driven by expectations and corresponding trades bring about an equilibrium market price. In essence, these trades on derivative markets are zero sum games.[96] Hence, if markets "don't get it right" it is also an issue of market participants' expectations.

The analysis in this thesis has revealed that the futures price formation and, correspondingly, the expectation formation of the market participants are a compound mix of rational and several behavioural components. As market equilibrium is linked to equilibrium in expectations the existence of behavioural effects applies for all groups of market participants. Future research could build a formal model of different groups of market actors detailing psychological biases. This could shed light on the specific short and long positions taken in the forward markets. Moreover, this would allow testing for expectations induced trend (herding) effects.

Futures prices are affected by behavioural pricing components and a – due to changing degrees of risk aversion – time-varying market price of risk. In combination with shock (i.e. uncertainty) induced errors these influences yield, in terms of forecasting power, a biased futures price. On the month-ahead level this adds up to forward prices being on average in the order of 10% above subsequent spot prices. This unfolds market monitoring issues. The analyses suggest that market power effects of concentrated supply structures spill over to forward premia due to a risk averse demand. Lacking transparency on the positions entered by market actors not only makes empirical analysis an elusive task but also determines

[95] In fact, there is theoretical and empirical evidence that derivative markets in particular are characterised by a positive correlation between traded volume (being a proxy for new information) and price volatility. For details see Fontana et al. (2007) and the references therein.

[96] More specifically, each trade is a zero sum game on a microeconomic level. Clearly, well functioning forward markets have a positive value on a macroeconomic level. See chapter 2.2 for details.

information asymmetries.[97] Information asymmetry though renders an inefficient resource allocation on markets (Stiglitz, 2001).

The spill over of market power effects into the forward premium, in turn, has essential monitoring implications since forward markets have, so far, been considered to be procompetitive. Analyses concerning market power effects in electricity markets focus typically on spot markets only. Whereas these studies do confirm the crucial role of excess supply capacities and of strategic withholding on spot market results the impact of margin and mark ups on risk aversion is not considered.

Publications of the USA based Commodity Futures Trading Commission (CFTC) list long and short open interests of different types of traders.[98] If such market transparency programmes were implemented in the European electricity futures markets this would decrease asymmetries and increase the data base for new descriptive analysis and new theories on decision making of market participants.[99] In fact, publication on aggregated trader category levels would take into account the trade-off between reducing asymmetries and releasing sensitive business related information.

The analyses in this thesis have relied on aggregated market data – basically settlement prices of different commodities and fundamental supply and demand quantities. The insights could be enlarged by the inclusion of data related to the positions taken, at least on aggregate, by hedgers and speculators and market concentrations. The robustness of the results could be increased by assessing additional forward contract maturities and taking into account higher granularities of daily or intra-daily price time series. Still, this would necessitate far higher transparency levels.

New empirical insights can frame new theories of decision making under risk. This thesis provided empirical insights into the price formation in electricity futures markets. They suggest expanding existing equilibrium models considering oligopolistic market environments, psychologically based behavioural concepts and different information levels.

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[97] This applies both for organised marketplaces (i.e. power exchanges) and bilateral OTC trades.

[98] Commitment of Traders reports available at http://www.cftc.gov/MarketReports/CommitmentsofTraders/index.htm

[99] Indeed, European Commission (2010) proposes draft rules on regulative oversight of trading in wholesale power markets. This proposal includes data collection on transactions and corresponding orders.

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Appendix A – Modelling the ex post forward premium including dummy variables

The residuals of the recursive estimation of (5.27) and (5.28) suggest a potential instability in the parameters as the residuals hit the significance line for November 2005 and July 2006 (see Figure 5.9). To test for this effect the models are re-estimated including dummy variables for these dates. The following equation for the ex post baseload forward premium is tested:

$$F_{t,T} - S_T = b_1 + b_2 c_v(S_t) + b_3 c_v(Brent_t) + b_4 FP_{Gas\,t-1,t} + b_5 Margin_t + b_6 Basis_t + b7MarginT + b8DummyNov'05 + b9DummyJul'06 + \varepsilon t,T \qquad \text{(A.1)}$$

where $F_{t,T}$-S_T is the ex post forward premium, $F_{t,T}$ is the futures price on the last trading day in month t for delivery in month T, S_T is the spot price average in month T, $c_v(S_t)$ is the coefficient of variation of daily spot prices in month t, $c_v(Brent_t)$ is the coefficient of variation of daily Brent spot prices in month t, $FP_{Gas\ t-1,t}$ is the realised gas forward premium of a month ahead futures for month t, $Margin_t$ is the realised ratio of generation and consumption in month t, $Basis_t$ is the difference between the futures price on the last trading day in month t for delivery in month T ($F_{t,T}$) and the spot price average in month t (S_t), $Margin_T$ is the margin shock in month T, and $Dummy_{Nov'05}$ and $Dummy_{Jul'06}$ are dummy variables representing the outlier of the forward premium in November 2005 and July 2006 respectively. Results for the corresponding model are shown in Table A 1.

Table A 1. Results of regression analysis (A.1) for ex post forward premia of month-ahead baseload futures at EEX for monthly delivery periods (t-statistics in brackets). All tests are based on heteroscedasticity consistent standard errors. Results are shown for premia determined by futures prices on the last trading day. *, **, *** denotes significance on the 10%, 5% and 1%-level.

Coefficient	Variable	Base load
b_1	Constant	-17.36 (-0.44)
b_2	Coeff of var. (spot t)	24.21 (5.31)***
b_3	Coeff of var. (brent t)	80.97 (2.84)***
b_4	Forward premium gas t	0.25 (1.49)
b_5	Margin t	-165.739(-2.16)**
b_6	Basis t	0.36 (2.61)**
b_7	Margin T	174.89 (2.45)**
b_8	Dummy Nov '05	-16.11 (-11.44)***
b_9	Dummy Jul '06	-28.84 (-20.81)***
R^2 (R^2_{corr})		0.54 (0.49)
DW		1.87
F-statistic		9.73
Serial correlation	χ^2_{12} (p-value)	0.478
Functional form	χ^2_1 (p-value)	0.874
Normality	JB (p-value)	0.105
Heteroscedasticity	χ^2_8 (p-value)	0.199
Observations		74; 11/03-12/09

Similarly, the following equation for the ex post peak load forward premium is tested:

$$F_{t,T} - S_T = b_1 + b_2 Skew(S_t) + b_3 Spike_{2sd\,t} + b_4 FP_{Gas\,t-1,t} + b_5 Market\ power_t + b_6 Margin_t + b_7 Basis_t + b_8 Margin_T + b_9 Dummy_{Nov'05} + b_{10} Dummy_{Jul'06} + \varepsilon_{t,T} \quad \text{(A.2)}$$

where $F_{t,T}$-S_T is the ex post forward premium, $F_{t,T}$ is the peak load futures price on the last trading day in month t for delivery during peak hours in month T, S_T is the peak load spot price average in month T, $Skew(S_t)$ is the skewness of daily spot prices in month t, $Spike_{2sd\,t}$ is the count of spikes outside of 2 standard deviations of the mean spot price in month t, $FP_{Gas\ t-1,t}$ is the realised gas forward premium of a month ahead futures for month t, *Spot market power$_t$* is the ratio of the spot price in month t and the fundamental marginal cost estimate for month t, $Margin_t$ is the ratio of regional generation and demand in month t, $Basis_t$ is the difference between the futures price on the last trading day in month t for delivery in month T ($F_{t,T}$) and the spot price average in month t (S_t), $Margin_T$ is the margin shock in month T, and $Dummy_{Nov'05}$ and $Dummy_{Jul'06}$ are dummy variables representing the outlier of the forward premium in November 2005 and July 2006 respectively. Results for the corresponding model are shown in Table A 2.

Table A 2. Results of regression analysis (A.2) for ex post forward premia of month-ahead peak load futures at EEX for monthly delivery periods (t-statistics in brackets). All tests are based on heteroscedasticity consistent standard errors. Results are shown for premia determined by futures prices on the last trading day. *, **, *** denotes significance on the 10%, 5% and 1%-level.

Coefficient	Variable	Peak load
b_1	Constant	36.26 (0.43)
b_2	Skew spot t	1.98 (1.92)*
b_3	Spike spot 2sd t	-5.99 (-3.07)***
b_4	Forward premium gas t	1.15 (3.46)***
b_5	Market power spot t	20.55 (4.68)***
b_6	Margin t	-293.03 (-2.32)**
b_7	Basis t	0.33 (2.61)**
b_8	Margin T	262.87 (2.61)**
b_9	Dummy Nov '05	-46.38 (-24.61)***
b_{10}	Dummy Jul '06	-68.91 (-30.00)***
R^2 (R^2_{corr})		0.66 (0.62)
DW		1.63
F-statistic		14.03
Serial correlation	χ^2_{12} (p-value)	0.087
Functional form	χ^2_1 (p-value)	0.063
Normality	JB (p-value)	0.810
Heteroscedasticity	χ^2_9 (p-value)	0.82
Observations		74; 11/03-12/09

Not surprisingly, the coefficients of determination R^2 rise sharply for both base and peak load when the dummy variables are included since they can capture the two outliers of the forward premium in November 2005 and July 2006 which the “regular” explanatory variables cannot. Overall, the inclusion of the dummies, however, does not significantly affect the coefficient estimations of the original models (5.27) and (5.28). This reinforces the robustness of those models.

Appendix B – Time trend effects in the ex post forward premium

Chapter 4 has revealed strong interactions between current spot and forward prices. Accordingly, the analysis performed in Chapter 5 has shown that the higher moments of spot price uncertainty affect realised forward premia. What are the consequences of these interactions for the dynamics in the EEX forward premium? Are there generalisable patterns in the premia evolutions as a function of time to maturity? The analysis introduced in this Appendix aims to answer these questions.

Methodologically, the daily ex post forward premia of all monthly futures contracts in the sample are averaged according to their remaining time to maturity and a simple OLS regression is run.[100] For these monthly contracts 76 contracts are averaged.[101] For each monthly contract the relative ex-post difference between the forward price in the trading period and spot price in the delivery period is expressed as a ratio on a daily basis:

$$\Delta_{t,T} = \frac{F_{t,T} - S_T}{S_T} \qquad \text{(B.1)}$$

where $\Delta_{t,T}$ is the relative difference between the forward and spot price, $F_{t,T}$ is the daily futures price in on trading day t for delivery in T and S_T is the spot price average during the delivery period (i.e. month) T.

As shown in Figure B 1, the ex post determined relative forward premium of monthly contracts is on average positive and an increasing function of the remaining time to maturity. The premium stays fairly constant over the first half of the contracts' trading period and starts to decline presumably as new information is available for market participants. Given the fact that trading is very thin in the first half of the trading period this analysis focuses on the premium evolution over the last 75 days of trading.[102,103]

Without formal modelling of the first half of the trading period the visual inspection of Figure B 1 might indicate another interesting behavioural component. In fact, the ex post

[100] The forward premia are averaged on a daily basis for the first trading day of all contracts up to the last day of trading before the delivery period.

[101] See Shawky et al. (2003) for a similar analysis.

[102] Monthly futures contracts at the EEX are typically available for trading 120 to 130 days before delivery.

[103] Interestingly, the average relative forward premium of quarter-ahead futures follows a very similar time-to-maturity function for the last 150 days of trading – except for higher values of the premium when the contracts are about to mature.

premium stays fairly constant before it starts decreasing almost linearly as the delivery period comes closer. This could be a consequence of hyperbolic discounting resulting in a time inconsistency where discount rates decrease hyperbolically for future payoffs. It is, however, beyond the scope of this chapter to study this issue in depth. For further details on hyperbolic discounting see e.g. Thaler (1981).

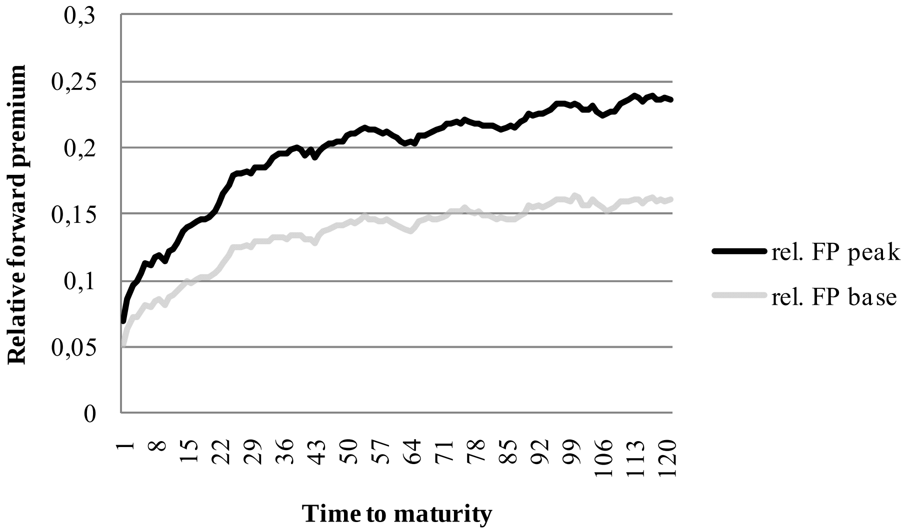

Figure B 1. Average relative ex post forward premium for EEX base and peak load futures with a monthly delivery period as a function of time to maturity. Source: EEX, own calculations

Augmented Dickey-Fuller tests provide somewhat mixed evidence on the type of stationarity of the average premia evolution. *P*-values amount to 0.00 (0.00 for peak load) when an intercept is included and 0.04 (0.07 for peak load) when both an intercept and a trend are included in the test equation. Given the objective of this analysis I will consider all variables to be trend stationary.

To filter out the potential time trend effects a simple econometric model is tested. The model explains the average relative forward premium on a daily basis as a function of a constant term and linear time trend:

$$\Delta_{t,T} = b_0 + b_1 t + \varepsilon_t \tag{B.2}$$

where $\Delta_{t,T}$ is the daily ex post relative forward premium according to equation (B.1), T is the maturity date (i.e. zero) of the contract and t is the trading day. The higher t the longer is the remaining time to maturity (compare Figure B 1). Table B 1 summarises the results of model (B.2).

As can be seen the relative forward premia follow a linear time trend and increase by 0.11% for baseload and 0.16% for peak load as time to maturity increases. Put differently, the premia decrease by approximately 0.11% and 0.16% respectively per day as the delivery period approaches. As more information about fundamentals during the delivery period becomes available as maturity approaches this trending behaviour seems straight forward. However, as the analysis in Chapter 5 has shown, premia on the last trading day are strongly affected by numerous behavioural factors. This analysis, therefore, indicates that the longer the remaining trading period of the futures contracts, the higher the impacts of these behavioural factors. Some econometric problems are associated with equation (B.2). The residuals are serially correlated, which, nevertheless, is to be expected due to overlapping observations which imply autocorrelation (Working, 1960). Using Newey-West heteroscedasticity consistent standard errors which are consistent in the presence of serial correlation does not, however, alter the results presented in Table B 1.[104]

Table B 1. Results of regression analysis (B.2) for average daily ex post forward premia of month-ahead baseload and peak load futures at EEX with monthly delivery periods from October 2003 to January 2010 (t-statistics in brackets). All tests are based on White heteroscedasticity consistent standard errors. *, **, *** denotes significance on the 10%, 5% and 1%-level.

Coefficient	Variable	Base load	Peak load
b_1	Constant	0.08 (29.39)***	0.12 (26.09)***
b_2	Time trend	0.001 (17.10)***	0.002 (16.36)***
R^2 (R^2_{corr})		0.85 (0.84)	0.84 (0.83)
DW		0.07	0.05
F-statistic		400.09	369.56
Serial correlation	χ^2_5 (p-value)	0.000	0.000
Functional form	χ^2_1 (p-value)	0.000	0.000
Normality	JB (p-value)	0.301	0.217
Heteroscedasticity	χ^2_1 (p-value)	0.057	0.097
Observations		75	75

[104] In order to filter out potential seasonalities in the dynamics of the forward premium the daily time series was spilt up into a summer and winter series and equation (B.2) was tested separately for the winter and the summer series. However, this seasonal analysis also yielded a significant linear time trend for both the summer and winter daily forward premium.

Appendix C – Derivation of the forward market equilibrium

This Appendix derives the forward market equilibrium of section 2.3.2. The mean variance utility function can be expanded to:

$$U(\pi_{i,j}) = E(\pi_{i,j}) - \frac{A}{2}Var(\pi_{i,j}) = E(\pi_{i,j}) - \frac{A}{2}[E(\pi_{i,j}^2) - E^2(\pi_{i,j})] \quad \text{(C.1)}$$

Using (2.5) the ex-post profit of producer *i* expands to:

$$\pi_{Pi} = \frac{1}{a}P_W^2 - P_W Q_{Pi}^F + P_F Q_{Pi}^F - FC - \frac{1}{2a}P_W^2 \quad \text{(C.2)}$$

Now the components of (C.1) can be calculated:

$$E(\pi_{Pi}) = \frac{1}{2a}E(P_W^2) - E(P_W)Q_{Pi}^F + P_F Q_{Pi}^F - FC \quad \text{(C.3)}$$

$$E(\pi_{Pi}^2) = \frac{1}{4a^2}E(P_W^4) - \frac{1}{a}E(P_W^3)Q_{Pi}^F + \frac{1}{a}P_F Q_{Pi}^F E(P_W^2) - \frac{FC}{a}E(P_W^2) + Q_{Pi}^{F^2}E(P_W^2) - 2P_F Q_{P1}^{F^2}E(P_W) + 2FCQ_{Pi}^F E(P_W) + P_F^2 Q_{Pi}^{F^2} - 2FCP_F Q_{Pi}^F + FC^2 \quad \text{(C.4)}$$

$$E^2(\pi_{Pi}) = \frac{1}{4a^2}E^2(P_W^2) - \frac{1}{a}E(P_W^2)E(P_W)Q_{Pi}^F + \frac{1}{a}P_F Q_{Pi}^F E(P_W^2) - \frac{FC}{a}E(P_W^2) + Q_{Pi}^{F^2}E^2(P_W) - 2P_F Q_{Pi}^{F^2}E(P_W) + 2FCQ_{Pi}^F E(P_W) + P_F^2 Q_{Pi}^{F^2} - 2FCP_F Q_{Pi}^F + FC^2 \quad \text{(C.5)}$$

(C.4) and (C.5) yield

$$Var(\pi_{Pi}) = (\frac{1}{4a^2} + Q_{Pi}^{F^2})Var(P_W) - \frac{1}{a}Q_{Pi}^F Cov(P_W^2, P_W) \quad \text{(C.6)}$$

Hence,

$$U(\pi_{Pi}) = \frac{1}{2a}E(P_W^2) - E(P_W)Q_{Pi}^F + P_F Q_{Pi}^F - FC - \frac{A^2}{8a^2}Var(P_W) - \frac{A}{2}Q_{Pi}{}^{F^2}Var(P_W) + \frac{A}{2a}Q_{Pi}^F Cov(P_W^2, P) \quad \text{(C.7)}$$

which is text equation (2.8). The first order conditions give the profit maximising quantity sold (or bought) in the forward market:

$$\frac{\partial U(\pi_{Pi})}{\partial Q_{Pi}^F} = 0 = -E(P_W) + P_F - AQ_{Pi}^F Var(P_W) + \frac{A}{2a}Cov(P_W^2, P_W) \quad \text{(C.8)}$$

$$Q_{Pi}^F = \frac{P_F - E(P_W)}{AVar(P_W)} + \frac{1}{2a}\frac{Cov(P_W^2, P_W)}{Var(P_W)} \quad \text{(C.9)}$$

which is text equation (2.10).

Speculator *j* maximises the following profit equation:

$$\pi_{Sj} = (P_F - P_W)Q_{Sj}^F \quad \text{(C.10)}$$

Hence, similar to producer i, the components of (C.1) for solving the speculators' optimisation are:

$$E(\pi_{Sj}^2) = E(P_W^2)Q_{Sj}^{F^2} - 2E(P_W)P_F Q_{Sj}^{F^2} + P_F^2 Q_S^2 \tag{C.11}$$

$$E^2(\pi_{Sj}) = E^2(P_W)Q_{Sj}^{F^2} - 2E(P_W)P_F Q_{Sj}^{F^2} + P_F^2 Q_S^2 \tag{C.12}$$

$$Var(\pi_{Sj}) = Q_{Sj}^{F^2} Var(P_W) \tag{C.13}$$

This yields

$$U(\pi_{Sj}) = -E(P_W)Q_{Sj}^F + P_F Q_{Sj}^F - \frac{A}{2} {Q_{Sj}}^{F^2} Var(P_W) \tag{C.14}$$

which is text equation (2.9).

The first order conditions give the profit maximising quantity sold (or bought) in the forward market:

$$\frac{\partial U(\pi_{Sj})}{\partial Q_{Sj}^F} = 0 = -E(P_W) + P_F - AQ_{Sj}^F Var(P_W) \tag{C.15}$$

$$Q_{Sj}^F = \frac{P_F - E(P_W)}{AVar(P_W)} \tag{C.16}$$

which is text equation (2.11). Since forward markets are in sum zero net[105] supply the market clearing forward price can, finally, be calculated:

$$P_F = E(P_W) - \frac{AN_P}{2a(N_P + N_S)} Cov(P_W^2, P_W) \tag{C.17}$$

Inserting (C.17) in (C.15) and (C.16) yields text equations (2.13) and (2.14).

[105] $\sum_{i=1}^{N_P} Q_{Pi}^F + \sum_{j=1}^{N_S} Q_{Sj}^F = 0$

Appendix D – Cournot duopoly equilibrium

This Appendix summarises the derivation of the standard Cournot duopoly solution referred to in section 5.2.1.1. For further details see e.g. Henderson and Quandt (1980). For the case of a single spot market the profit of the first duopolist equals

$$\pi_{P1}(Q_{P1}, Q_{P2}) = P_W(Q_{P1}, Q_{P2})Q_{P1} - TC_{P1}(Q_{P1}) = (a - Q_{P1} - Q_{P2})Q_{P1} - bQ_{P1} \quad \text{(D.1)}$$

where P_W is the wholesale price, Q_{P1} denotes the quantity sold by producer *1* and TC_1 are the total cost associated with production of producer *1*. Total costs are assumed to be linear, $TC_{P1}(Q_{P1}) = bQ_{P1}$, so is the inverse demand function $P_W = a - Q_{P1} - Q_{P2}$. Given these relations the reaction function of the Cournot producers can be derived:

$$\frac{\partial \pi_{P1}(Q_{P1}, Q_{P2})}{\partial Q_{P1}} = 0 = -2Q_{P1} - Q_{P2} + a - b \quad \text{(D.2)}$$

$$Q_{P1}(Q_{P2}) = \frac{a - b - Q_{P2}}{2} \quad \text{(D.3)}$$

$$Q_{P2}(Q_{P1}) = \frac{a - b - Q_{P1}}{2} \quad \text{(D.4)}$$

Solving for the spot market equilibrium by inserting (D.4) in (D.3) yields the well-known Cournot duopoly solution:

$$Q_{P1} = \frac{a - b}{3} = Q_{P2} \quad \text{(D.5)}$$

$$P_W = \frac{a + 2b}{3} \quad \text{(D.6)}$$

which are text equations (5.11) and (5.12).

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