Intra-Day Risk Premia in European Electricity Forward Markets

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Abstract

Using a detailed data set of electricity forward prices in Central Europe, we compute the intra-day market price of risk for the two electricity exchanges European Energy Exchange (EEX) and Energy Exchange Austria (EXAA). Given the significant volatility and jump risk of electricity prices, these closely-linked markets offer an opportunity to study whether market participants are willing to pay a premium to secure day-ahead delivery prices earlier in a trading day. Generally, we find such a positive risk premium, leading to a statistically significant negative market price of risk and the implication that forward prices are upward-biased predictors of expected electricity spot prices.

JEL classification: G13; Q40.

Keywords: Electricity Forwards; Intra-Day Prices; Risk Premium; Market Price of Risk.

1 Introduction

The question whether forward prices are upward- or downward biased predictors of future spot prices has attracted substantial theoretical and empirical research. To determine the prevailing relation for an asset, the risk premium, defined as the difference between the forward price and the expected spot price,[1] and the corresponding market price of risk (MPR) are in general investigated. For a costless-to-enter forward contract the market price of risk is the expected rate-of-return compensation per unit standard deviation of returns, i.e., the risk associated with holding the asset. A negative market price of risk translates into a positive risk premium normalized by volatility. Both quantities have been examined for various financial and commodity markets. In financial markets the risk premium (market price of risk) is assumed negative (positive), whereas in commodity markets they could be of opposite sign depending on the time horizon considered. Benth, Cartea and Kiesel (2007) provide a framework that explains the risk premium across different forward maturities with risk preferences and related hedging demand of market participants. They associate a positive short-term (negative long-term) risk premium with hedging demand from consumers larger (smaller) than from producers.

Knowledge of the sign and magnitude of both the risk premium and market price of risk in electricity prices is relevant not only for understanding electricity markets and their relationship to other physical and financial markets, but also more practically for informed hedging decisions by market participants. In electricity markets where prices exhibit high volatility and occasional sharp upward jumps, this is especially important. In this study we examine the risk premium and market price of risk in day-ahead electricity forward markets at the German European Energy Exchange (EEX) and the Energy Exchange Austria (EXAA).

The German electricity market is the single largest electricity market in Europe in terms of both electricity production and consumption. Due the geographic position in Central Europe it represents, together with the Austrian and Swiss markets, the hub for the physical exchange of electricity across national borders in Europe. Although cross-border flows have modestly increased since the European Commission started the liberalization of the European electricity markets in 1996, cross-border transmission capacities remain insufficient, and con-

1 This risk premium, also termed forward (risk) premium or forward bias, is not defined consistently in the studies for electricity markets, which has caused mixed evidence on the risk premium to some extent. See Weron (2008), p. 1104 for a discussion.

gestion occurs frequently. As a consequence, price differences across these markets continue to exist. For the transmission grid between the German and Austrian electricity market, however, the picture is different. As noted by the German Federal Network Agency in its 2007 Monitoring Report (p. 9), "there is congestion at all German borders, with the exception of the Austrian border." This offers a rare case of two largely integrated electricity markets where unrestricted delivery can take place in each other's grid network thus enabling the full alignment of prices. Such price alignment does not rely on perfect competition in electricity generation, but rather on a sufficient number of competitive market participants able to exploit any price differences in the OTC market or exchange trading.[2] The high concentration in generation, observed in most European electricity markets including Germany and Austria, is no suitable measure for the market power potential in day-ahead markets as only capacity available in these markets is relevant and major generators typically sell most of their production in the forward market well in advance of delivery.[3] Given the relatively large number of active market participants and the much lower concentration in trading activity compared to generation, the German and Austrian day-ahead markets can be regarded as sufficiently competitive.[4]

At the EEX and EXAA, day-ahead markets exist, where contracts for the physical delivery of electricity during specific time intervals at the next day(s) are available. These markets are often termed spot markets, but basically offer forward contracts with a time-to-maturity of one to three calendar days. The EEX operates two separate market segments for these forwards. On each trading day from 8:00 to 12:00 am (CET) specified block contracts (baseload, peakload and weekend baseload) trade in a continuous market. In addition, shortly after the continuous trading 24 auctions take place where the prices for the single hours of a delivery day are jointly established. Note that the continuously traded block contracts can be replicated with corresponding hourly day-ahead forwards. At the EXAA the auctions for single hours commence at 10:15 am, two hours before the EEX and also well before other exchanges. The early EXAA auctions thus provide a first price signal to participants in the European electricity market. This is especially relevant for the single hours, which are typically not actively traded in the OTC market.

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2 See Borenstein et al. (2006), p. 8.

3 See Ockenfels (2007), p. 14.

4 For detailed daily information on the concentration in trading activity at the EEX see the EEX website, www.eex.com. Similar information is provided by the EXAA in its annual trader group meeting.

The delivery of EEX and EXAA day-ahead forwards takes place in the grid zones of both the German and Austrian transmission system operators (TSOs). Although the permissible zones are different, they largely overlap and more important transmission constraints between any of them do not occur. All further product specifications are the same.[5] Therefore we have identical contracts traded on two exchanges at different times of a trading day. The transaction costs for these contracts are virtually the same at the EEX and EXAA. Given the closely-linked physical electricity markets and the special institutional structure of the day-ahead forward markets, this set up offers a unique opportunity to study whether market participants are willing to pay a premium to secure day-ahead delivery earlier in a trading day.[6]

Generally, we find market participants are indeed willing to pay a positive risk premium. In particular the risk premia for those day-ahead forwards with the longest time-to-maturity, i.e., delivery on Mondays, are well-pronounced and statistically significant. Consistent with the positive risk premium a statistically significant negative market price of risk is observed. Thus, in these markets forward prices represent upward-biased predictors of expected spot prices.

The only study similar to ours is Diko, Lawford and Limpens (2006). They investigate risk premia for day-ahead electricity forwards at three continental European exchanges, including the EEX auction market, and corresponding contracts traded earlier on the same day in the OTC markets. This set up is comparable to our analysis of the EEX continuous trading and auction segments. For peakload contracts they also find a statistically significant positive risk premium, whereas for the off-peak hours the premium is significantly negative.

The remainder of this paper is organized as follows. In the following Section 2, we describe the EEX and EXAA markets for day-ahead electricity forwards and define our data base. The calculation of the intra-day risk premium and the empirical results are discussed in Section 3. In addition, the Bessembinder and Lemmon (2002) model is utilized to explore two potential determinants of the risk premium. Section 4 examines the intra-day market price of risk based on four different estimators to ensure robustness of results. The final Section 5 concludes.

5 A potential difference in the counterparty risk of the EEX and EXAA, which serve as central counterparty for all transactions in the respective day-ahead forwards, is negligible.

6 Note that roughly 90% of the EXAA electricity market participants are admitted to the EEX as well. The number of participants at the EEX day-ahead electricity market, however, is substantially higher.

2 Day-Ahead Electricity Forwards at the EEX and EXAA

The EEX, founded in 1999 and merged with the Leipzig Power Exchange (LPX) in 2001, has operated a market for day-ahead electricity forwards with physical delivery since June 2000.[7] Trading takes place in auctions and during the continuous block trading on the exchange trading day preceding the delivery day(s). At the auction segment, the 24 hours of the next delivery day trade in a single auction each from 12:00 to 12:15 am (CET). Auctions for the single hours of further tradable delivery days, for example, Sunday delivery on a Friday trading day, follow at intervals of 30 minutes. In addition to single hour bids, a set of hours can be combined freely to a block bid, which is executed as a whole or not. These block bids, however, do not form separate products and their prices are based on the arithmetic average of the respective single hours. The continuous block trading lasts from 8:00 to 12:00 am and orders are executed continuously in accordance with price-time priority.[8] Products at this segment comprise the predetermined hourly blocks baseload (0:00-24:00) for the next calendar day(s), peakload (8:00-20:00) for the next working day and on Fridays also weekend baseload (Saturday 0:00 to Sunday 24:00).[9] Actual trading of these products, however, is infrequent and their overall volumes are typically only a fraction of those for the corresponding single hours from the auctions. For the physical delivery of all EEX day-ahead electricity forwards market participants have to specify a permissible TSO zone with each bid. At the EEX the four German TSO zones (EnBW, E.ON, RWE, Vattenfall), and since April 2005 the largest Austrian zone (APG), are available.

Founded in 2001, the EXAA offers an auction market for day-ahead electricity forwards with physical delivery since March 2002. Similar to the EEX, the 24 hours of the next delivery day(s) trade in a single auction each and a set of hours can be combined to certain block bids. The auctions for all tradable delivery days take place from 10:12 to 10:15 am, well before the EEX auctions and other European electricity exchanges. Immediately after the auctions a post-trading period of 3 minutes takes place where market participants can buy or sell surplus volumes from the auctions for the next delivery day at the calculated market clearing price. The post-trading of further delivery days starts sequently. Transactions in the post-

7 The continuous block trading segment for day-ahead electricity forwards has existed since August 2000.

8 Note that the continuous block trading begins with an opening auction and ends with a closing auction, which is finished before the auctions for the single hours start. According to information from the EEX, there is typically no volume in these opening and closing auctions.

9 The weekend baseload block was not introduced until November 2002. It can be replicated with the baseload blocks for Saturday and Sunday.

trading period increase the daily trading volume of EXAA day-ahead electricity forwards on average between 5% and 10% according to information from the EXAA. As the post-trading does not directly influence EXAA prices and its relatively low volumes are published only in combination with the original auctions results, we do not further consider it. The delivery zones at the EXAA are the three Austrian TSO zones (APG, TIWAG, VKW) and since June 2004 and May 2005 respectively two German zones (E.ON, RWE). **Figure 1** gives an overview of the trading process at the EEX and EXAA.[10]

10 See EEX (2008) and EXAA (2008) for the introduction to the exchange trading at the EEX and EXAA.

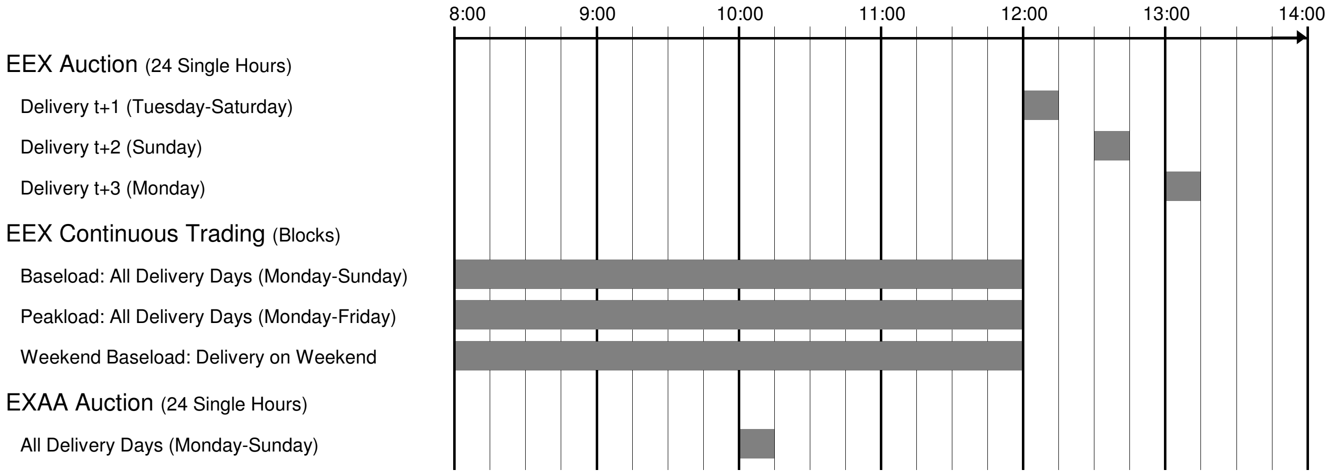

Figure 1
Trading of Day-Ahead Forwards at the EEX and EXAA

Trading hours of day-ahead electricity forwards at the EEX and EXAA are presented. The trading takes place in auctions or during the continuous trading on the exchange trading day preceeding the delivery day(s). In the EEX and EXAA auctions a set of single hours can be combined to a block bid, which is executed as a whole or not. These block bids, however, do not form separate products and their prices are based on the respective single hours.

With an annual trading volume of 85.7 TWh in 2005 the EEX market for day-ahead electricity forwards is roughly 55 times larger than the EXAA market. Furthermore, it is by far the second largest exchange in Europe for day-ahead electricity forwards and surpassed only by the Scandinavian Nord Pool. The physical German electricity market, however, is only about 10 times the Austrian one. Consequently the EEX trading volume represents 17% of the national final electricity consumption in 2005, whereas the corresponding figure for the EXAA is a rather low 3%. Two market makers ensure a minimum liquidity at the EXAA auctions.[11]

Our data set consists of hourly and block day-ahead electricity forward prices from the EEX for the period from August 1, 2002 to September 30, 2007 and hourly day-ahead electricity forward prices from the EXAA for the period from June 1, 2004 to September 30, 2007. Although these products were launched earlier, our study is restricted to these time series, since after its merger the EEX switched to a common trading system in August 2002 and the EXAA introduced their first German delivery zone in June 2004. Moreover, the German and Austrian TSOs, amongst others, abandoned their fee on (cross-border) electricity exports at the beginning of 2004.[12] In addition, we employ only base- and peakload prices when comparing EEX and EXAA auction prices, because block bids are typically dominant and base- and peakload are the most important ones. The prices of the single hours from 0:00 to 24:00 and 8:00 to 20:00 respectively are thus aggregated to base- and peakload indices for all calendar days within a year by taking their arithmetic average. For day-ahead forwards from the EEX continuous block trading three indices, based on the volume-weighted average price of the respective block transactions, are available to us for each delivery day with at least one transaction each. All data are obtained directly from the EEX and EXAA.

Table 1 presents descriptive statistics for the indices of EEX and EXAA day-ahead electricity forward prices, broken down by working and non-working delivery days. This break down is chosen to reflect the different electricity demand patterns on working and non-working days and resulting different electricity price characteristics. Furthermore, it accounts for the various maturities of the day-ahead forwards. In Panel A statistics for the base- and peakload prices from the auctions and continuous block trading at the EEX between August 2002 and September 2007 are shown, whereas Panel B provides the figures for the EEX segments and EXAA auctions over the period June 2004 to September 2007. For all different samples the prices for peakload are on average higher and more volatile than for baseload and exhibit stronger right-skewed and leptokurtic distributions. These statistics are also higher for work-

11 See EEX (2006) and EXAA (2006), p. 22 for the figures on trading volume.

12 See ETSO (2004).

ing than non-working days. The rather high kurtosis and positive skewness of the working days price distributions reflect the occasional price spikes or jumps that are characteristic of electricity markets. In addition, market participants pay slightly more on average for the same product in the EXAA auctions than in the subsequent EEX auctions. The figures for the two EEX segments, shown in Panel A and B, are, however, not directly comparable, since the continuous block trading is less frequent than the auctions and the block trading activity is not evenly distributed over the sample period.[13]

13 Block contracts with delivery on the working days from Tuesday to Friday exhibit relatively fewer zero transaction days compared to the contracts with delivery on Mondays and weekend days in particular. Other systematic patterns in the occurrence of zero transaction days over time are not evident in the data.

Table 1
Descriptive Statistics for Day-Ahead Forward Prices

Statistics for the prices of day-ahead delivery of electricity baseload (0:00-24:00), peakload (8:00-20:00) and weekend baseload are presented, with prices in EUR/MWh. Panel A covers the continuous block trading (8:00-12:00) and the following auctions (12:15, etc.) at the EEX. Panel B in addition covers the EXAA auctions (10:15). The prices of both exchanges are aggregated to daily base- and peakload indices based on the average of the respective single hours (auctions) or volume-weighted average of the block transactions. Figures for continuously traded peakload blocks on non-working days are not shown, because these contracts do not exist for weekends and thus the number of observations are too low. For days without volume no indices are calculated. The number of observations for EEX and EXAA prices diverge also due to different trading holidays.

A. EEX Indices from August 2002 to September 2007*

Working Days	N	Mean	Min.	Max.	Std.dev.	Skewn.	Kurtosis
EEX Auction Base	1,304	41.17	12.40	301.54	19.24	4.19	36.65
EEX Auction Peak	1,304	52.12	15.86	543.72	30.15	6.31	73.71
EEX Continuous Base	801	42.08	12.00	179.33	20.10	2.55	10.29
EEX Continuous Peak	883	54.69	16.67	288.42	28.82	3.23	16.67

Non-Working Days							
EEX Auction Base	583	25.56	3.12	66.77	10.20	0.95	1.40
EEX Auction Peak	583	28.91	0.80	79.55	11.50	1.06	1.97
EEX Continuous Base	183	22.49	5.25	62.00	9.33	1.21	2.34
EEX Continuous Weekend Base*	127	25.38	10.68	56.25	9.97	1.45	1.61

B. EEX and EXAA Indices from June 2004 to September 2007

Working Days	N	Mean	Min.	Max.	Std.dev.	Skewn.	Kurtosis
EEX Auction Base	847	46.24	19.22	301.54	20.86	4.18	35.18
EEX Auction Peak	847	58.49	23.93	543.72	33.38	6.20	68.02
EEX Continuous Base	412	50.53	22.75	179.33	21.84	2.03	6.92
EEX Continuous Peak	488	63.66	27.00	288.42	30.66	2.87	14.08
EXAA Auction Base	831	46.69	22.70	177.85	18.53	2.36	9.14
EXAA Auction Peak	831	59.07	27.25	299.99	27.72	3.29	18.02

Non-Working Days							
EEX Auction Base	370	29.63	5.80	66.77	9.99	0.90	1.16
EEX Auction Peak	370	33.44	6.76	79.55	11.33	1.07	1.74
EEX Continuous Base	73	29.58	14.50	62.00	9.56	1.07	1.31
EEX Continuous Weekend Base	68	30.70	16.66	56.25	10.65	0.98	-0.23
EXAA Auction Base	384	30.28	11.50	76.27	10.13	1.03	1.41
EXAA Auction Peak	385	34.38	13.36	102.00	11.81	1.36	3.23

* The time series for EEX Continuous Weekend Base starts in November 2002.

3 The Intra-Day Risk Premium

The well-known risk premium model for pricing forward contracts defines the forward price as the sum of the expected spot price of the underlying at maturity and a risk premium.[14] This risk premium reflects the compensation to investors for bearing the risk of holding the asset. For empirical research on the risk premium two basic approaches exist. The first approach estimates the *ex ante* or expected risk premium as the difference of the forward price and the (unobservable) expected spot price at maturity. Obtaining a reliable direct estimate for the expected spot price, however, is rather difficult. Karakatsani and Bunn (2005), for example, follow this approach to examine risk premia in day-ahead forwards in the British electricity market and note the sensitivity of their results to the assumptions on the agent's spot price model, information set and learning scheme. The second approach avoids these difficulties and estimates the *ex post* or realized risk premium. Under the assumption of rational expectations, the *ex post* risk premium equals the *ex ante* premium plus random noise, i.e., the forecasting error is zero on average and uncorrelated with the information set at the time of the forecast.[15]

In this study the second approach is employed. In order to investigate the existence of ex post intra-day risk premia in day-ahead electricity forward prices at the EEX and EXAA, we follow Longstaff and Wang (2004). The risk premium between the prices of two electricity forwards with the same delivery period i, delivery day and other contract specifications but different trading times t_1 and t_2 on day t, can be defined as

$$RP_{it} = E_t\left(F_{i,t_1} - F_{i,t_2}\right), \tag{1}$$

whereas $t_1 < t_2$. Thus, the day-ahead price at t_1 serves as the "forward" price for the subsequently realized day-ahead price at t_2. The trading of these forwards might take place either at the two different EEX segments, or across the EEX and EXAA markets. To estimate the risk premia, we take the sample mean of the differences in day-ahead electricity forward prices and test whether the means are significantly different from zero

14 For the pricing of forwards there is also the standard no-arbitrage or cost-of-carry model, where the forward price is linked to the current spot price via interest rates, storage costs and convenience yield. As electricity storage costs are very large (almost infinite) such that electricity is essentially non-storable, this approach is not applicable to electricity forwards.

15 See Lucia and Torro (2007), pp. 4-6.

$$E\left(RP_{it}\right)=\frac{1}{T}\sum_{t=1}^{T}\left(F_{i,t_1}-F_{i,t_2}\right), \tag{2}$$

where the expectation is unconditional. In order to test the statistical significance of the risk premia, we employ a t-statistic based on autocorrelation and heteroskedasticity consistent estimates of the variances according to Newey-West. This approach is adopted given the findings of Routledge, Seppi and Spatt (2001) that electricity prices should exhibit conditional heteroskedasticity. The estimated risk premia and respective t-statistics are reported separately for the different working and non-working days.

Descriptive statistics for the risk premia in our samples are reported in **Table 2**. As shown in Panel A, the intra-market risk premia for delivery on working days exhibit high variability, but are clearly positive and highly significant for Mondays. The mean risk premia for baseload and peakload on Mondays are 1.98 EUR/MWh and 3.51 EUR/MWh respectively, substantially higher as those for the corresponding other working days. This is intuitively plausible, since peakload contracts typically display more variable and extreme prices than those for baseload. In addition, day-ahead forwards for delivery on Mondays are traded on Fridays and thus have a longer time-to-maturity and greater price uncertainty than do other day-ahead forwards.[16] These figures are also noteworthy, since, in terms of average block trading prices, they represent percentage risk premia of 4.94% and 6.36% respectively. These are quite substantial premia for a time period as short as at maximum five hours and fifteen minutes. Whether this high level is also a result of the infrequent continuous block trading, different calculation methods for the EEX indices, different minimum contract sizes or the aggregation of single hour and block bids in the auctions deserves further research. For forwards with delivery on non-working days risk premia are negligible, on average.

The statistics for the risk premia between forwards traded in the EEX and EXAA auctions are provided in Panel B.[17] As noted by the EXAA in their 2005 annual report (p. 20): "In comparison with EEX, 2005 prices on EXAA were on average slightly higher than on EEX. These differences are, however, not statistically significant, which is to be expected given the absence of restrictions between the Austrian and German electricity markets." The results for our sample partially support this view, although we find significant premia of 1.00 EUR/ MWh for baseload on Mondays and 0.44 (0.77) EUR/MWh for baseload (peakload) on Sun-

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16 Shawky, Marathe and Barrett (2003) document that the forward premium for monthly electricity futures delivered at the California-Oregon border (COB) is an increasing function of time-to-maturity.

17 In October 2003 the EXAA launched eSpreads, financial products on the difference between the EXAA and EEX auction prices for day-ahead delivery of base- or peakload. After some initial trading activity, eSpreads were discontinued at the end of 2005 due to disappointing trading volume.

days. In terms of average EXAA auction prices, this presents percentage premia of 2.14%, 1.64% and 2.57%. Panel C shows the statistics for the price differences between the EEX continuous trading and EXAA auction. In contrast to Panel A and B, the premia for baseload on working days are, on average, negative, with a significant mean premium of -0.20 EUR/MWh (-0.40%) on the working days from Tuesday to Friday. The range and variability of the premia for all contracts are comparably low. Given that we do not have definite information whether the majority of activity in the EEX continuous trading, both in terms of number of transactions and volume, takes place before or after the EXAA auctions, the results in panel C should be interpreted with caution.

Table 2
Descriptive Statistics for Risk Premia between Day-Ahead Forward Prices

Statistics for the risk premia of day-ahead delivery of electricity baseload (0:00-24:00), peakload (8:00-20:00) and weekend baseload are presented, with risk premia in EUR/MWh. Panel A provides the premia between the indices of the continuous block trading (8:00-12:00) and the following auctions (12:15, etc.) at the EEX. Panel B provides the premia between the indices of the EXAA auctions (10:15) and EEX auctions. Panel C provides the premia between the indices of the EEX continuous block trading and the EXAA auctions. The EXAA and EEX Auction baseload index for the whole weekend are calculated as average of the respective prices for Saturday and Sunday. Figures for some risk premia series on non-working days are not shown, because the number of observations are too low. Observations for dates with different holiday classifications at the EEX and EXAA are excluded from the dataset. $^{+++}$ ($^{++}$, $^{+}$) indicates significance at the 1% (5%, 10%) level according to t-statistics based on autocorrelation and heteroskedasticity consistent estimates of the variances.

A. Risk Premia between EEX Forward Prices from August 2002 to September 2007*

Working Days	N	Mean	Min.	Max.	Std.dev.	Skewn.	Kurtosis
EEX (Continuous - Auction) Base	801	0.65 $^{+}$	-131.54	128.94	11.58	-2.27	70.92
Monday	127	1.98 $^{+++}$	-34.26	36.01	6.36	0.25	14.43
Tuesday - Friday	674	0.40	-131.54	128.94	12.30	-2.21	65.58
EEX (Continuous - Auction) Peak	883	1.27 $^{+}$	-255.30	190.45	20.75	-4.41	74.45
Monday	142	3.51 $^{+++}$	-56.69	69.24	12.26	0.82	11.53
Tuesday - Friday	741	0.84	-255.30	190.45	21.99	-4.41	69.71
Non-Working Days							
EEX (Continuous - Auction) Base	183	0.06	-6.56	8.37	2.69	0.31	0.13
Saturday	83	-0.15	-6.56	8.37	2.96	0.38	0.06
Sunday	80	-0.05	-5.56	5.84	2.15	0.04	0.24
EEX (Continuous Weekend - Auction) Base*	127	-0.01	-7.06	9.25	2.65	0.42	1.11

B. Risk Premia between EEX and EXAA Auction Forward Prices from June 2004 to September 2007

Working Days	N	Mean	Min.	Max.	Std.dev.	Skewn.	Kurtosis
(EXAA - EEX) Auction Base	829	0.24	-123.69	69.26	9.40	-5.61	75.78
Monday	160	1.00 $^{+}$	-27.34	39.32	6.55	1.63	13.18
Tuesday - Friday	669	0.06	-123.69	69.26	9.96	-5.93	73.53
(EXAA - EEX) Auction Peak	829	0.28	-243.73	137.52	17.67	-6.46	92.77
Monday	160	1.20	-52.93	66.37	11.50	1.20	14.18
Tuesday - Friday	669	0.06	-243.73	137.52	18.85	-6.64	87.96
Non-Working Days							
(EXAA - EEX) Auction Base	366	0.29	-10.93	9.83	2.95	0.16	0.57
Saturday	174	0.02	-10.93	9.83	3.32	0.11	0.42
Sunday	172	0.44 $^{++}$	-5.10	7.39	2.41	0.37	0.11
(EXAA - EEX) Auction Peak	367	0.40 $^{+}$	-14.22	12.64	3.45	0.20	1.70
Saturday	174	-0.11	-14.22	12.64	4.00	0.20	1.42
Sunday	173	0.77 $^{+++}$	-5.13	9.24	2.66	0.74	0.47

C. Risk Premia between EEX Continuous and EXAA Auction Forward Prices from June 2004 to September 2007

Working Days	N	Mean	Min.	Max.	Std.dev.	Skewn.	Kurtosis
(EEX Continuous - EXAA Auction) Base	406	-0.22 $^{++}$	-18.87	26.03	2.13	2.35	73.04
Monday	53	-0.33	-6.92	3.72	1.64	-2.05	7.27
Tuesday - Friday	353	-0.20 $^{++}$	-18.87	26.03	2.19	2.59	74.22
(EEX Continuous - EXAA Auction) Peak	480	0.08	-26.46	32.86	3.00	2.50	56.41
Monday	68	-0.14	-26.46	8.50	4.05	-4.09	26.80
Tuesday - Friday	412	0.11	-14.81	32.86	2.80	5.61	68.30
Non-Working Days							
(EEX Continuous - EXAA Auction) Base	73	0.03	-1.30	1.66	0.58	0.11	0.72
(EEX Continuous Weekend - EXAA Auction) Base	68	-0.01	-1.44	1.59	0.59	0.35	0.26

* The time series for risk premia including EEX Continuous Weekend Base starts in November 2002.

Our results are in general consistent with existing studies for other electricity markets that substantially find significant positive risk premia for day-ahead forwards or short-term futures.[18] These studies are focused on the US and Scandinavia due to the early liberalization of these electricity markets and the corresponding availability of sufficient price time series. For day-ahead forwards at the US Pennsylvania–New Jersey–Maryland (PJM) market, for example, Geman and Vasicek (2001) and Pirrong and Jermakyan (2005) find a positive mean risk premium. Longstaff and Wang (2004) also identify significant risk premia. Though positive on average, the risk premia vary in sign and magnitude across hours. The average percentage premium for all hours is 1.8%, but for certain peak hours goes up to quite substantial 14%. Large risk premia in day-ahead forwards with delivery during the volatile peak hours are consistent with the theoretical model of Bessembinder and Lemmon (2002). The different spot price volatilities across seasons are also reflected in the risk premium. For one-month PJM forwards with delivery during the summer, Bessembinder and Lemmon (2002) obtain risk premia substantially above those for delivery in winter. The empirical findings on risk premia for short-term futures are similar to those for day-ahead forward markets. For weekly electricity futures traded at Nord Pool, for example, Bühler and Müller-Merbach (2007) and Lucia and Torro (2007) find statistically significant positive risk premia. In general, these risk premia increase with time-to-maturity. The analysis of Botterud, Bhattacharyya and Ilic (2002) confirms these results for futures contracts with up to one year to maturity.

The risk premia for baseload day-ahead forwards and monthly futures at the EEX are investigated by Daskalakis and Markellos (2008). For the forwards they find a significant negative mean premium of -23.5% compared to the prices from the real-time segment, where single hours trade continuously until 75 minutes prior to each delivery. This result, however, has to be treated as preliminary, because the period under observation covers only the first year of operation of the EEX real-time segment. The evidence for the futures over an extended period is mixed, with significant positive premia for most contracts. Based on three different spot price models, Bierbrauer et al. (2007) estimate *ex ante* risk premia for all monthly and quarterly EEX futures quoted on a single day and find positive short-term und negative medium-term risk premia. Their set up, however, does not allow them to draw conclusions about the significance of these results.

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18 The realized spot prices used to calculate the ex post risk premia of day-ahead forwards and short-term futures in these studies are the real-time and day-ahead electricity prices respectively. Note that some studies use different risk premium definitions. We adapt the results presented below to make them comparable to our findings.

Diko, Lawford and Limpens (2006) examine the risk premia for day-ahead forwards at the three continental European electricity exchanges APX (Netherlands), Powernext (France) and EEX. Prices for day-ahead electricity forwards from the exchange auctions around noon and the earlier OTC trading, which typically closes before the auctions, are utilized. Therefore, their set up is comparable to our intra-market analysis for the two EEX segments. Their results reveal statistically significant positive risk premia for peakload at all three markets. A risk premium for the French market of about half the size of those for the other markets reflects the special generation structure in France, where roughly 80% of generated electricity comes from nuclear plants and a substantial part is provided by hydro power. For the off-peak hours, not analyzed in our study, a statistically significant negative risk premium is obtained for the EEX. Its magnitude is clearly lower than the risk premium for peakload.

Besides information on the sign and magnitude of risk premia, an understanding of their determinants is essential for risk management. To explore potential determinants we build on the static equilibrium model for electricity forward prices by Bessembinder and Lemmon (2002). They show that *ex ante* electricity forward premia are negatively related to the variance and positively related to the skewness of expected electricity spot prices in a linear way. The approach by Longstaff and Wang (2004) allows us to carry out a simple test of these implications. Specifically, we regress the 24 *ex post* mean risk premia between the hourly day-ahead forwards from the EEX and EXAA auctions on the sample variance and unstandardized skewness of the corresponding hourly forward prices at the EEX auction. For a more detailed view not taken in other studies, the cross-section regression is also performed for the different working and non-working days:

$$\mathrm{AveRP}_i = a + b\,\mathrm{Var}_i + c\,\mathrm{Skew}_i + \varepsilon_i \,. \tag{3}$$

We refrain from reporting detailed figures here, since statistically significant results for the two determinants are obtained only for risk premia on Sundays at the 5%-level. This may reflect that we find statistically significant risk premia for both base- and peakload prices only for Sundays as well, as shown in Panel B of Table 2. The insignificant results for all calendar days are in contrast to Longstaff and Wang (2004), who analyze the forward premia of day-ahead electricity forwards at the PJM market and find support for both model implications. Ullrich (2007), however, shows that over an extended period both implications hold for PJM contracts only for relatively low spot price levels. Lucia and Torro (2007) investigate the premia of weekly electricity futures at Nord Pool and receive mixed results, depending on the period chosen. Based on a GARCH approach Hadsell and Shawky (2006) demonstrate the importance of spot price volatility in determining premia of day-ahead electricity forwards for peakload at the NYISO market.

4 The Intra-Day Electricity Market Price of Risk

Following earlier work by Dincerler and Ronn (2001) and Kolos and Ronn (2008), we estimate the intra-day market price of risk for day-ahead electricity forwards.[19] For a costless-to-enter forward contract the market price of risk is defined as the expected rate-of-return compensation per unit standard deviation of returns. Daily returns are calculated as natural logarithm of the day-ahead forward price at t_2 divided by the one at t_1 on the same day. Note that the price at the EEX continuous trading is assumed mid-morning. To account for the different time intervals between t_2 and t_1 across forwards, we standardize the returns to a one-hour log return by multiplying with $1/\Delta t$, where Δt denotes the length of the time interval in hours. Since the sequence and exact time interval between transactions at the EEX continuous trading and EXAA auctions are not available, we exclude this object of investigation from the further analyses. Moreover, weekend baseload at the two EEX segments is not considered, because of the different time of the auctions for Saturday and Sunday delivery.

To make our results somewhat robust against certain assumptions on the return distribution, we estimate the market price of risk λ in four different ways:

A) *Parametric estimator (MPR_A)*: For the parametric estimator of the market price of risk and its estimation using maximum likelihood we follow Kolos and Ronn (2008). Assuming a constant market price of risk,[20] the evolution of forward prices subject to a term structure of volatility (TSOV) is described by the stochastic differential equation

$$dF = \mu_t F dt + \sigma_t F dz = \lambda \sigma_t F dt + \sigma_t F dz, \tag{4}$$

where dz denotes the increment of a standard Brownian motion and the volatility σ_t in-

19 In principle, the market price of risk could also be inferred from futures and option prices. The design of these contracts at the EEX, however, does not allow us to obtain estimates of the market price of risk for daily electricity prices. At the EXAA, there are no electricity products in addition to day-ahead forwards.

20 This is deemed reasonable as the time variability of the market price of risk is much smaller compared to the drift and volatility of the price processes. It also reflects the behavioral attribute of a constant compensation per unit standard deviation. See Kolos and Ronn (2008), p. 625.

creases with declining time-to-maturity. In our case, no TSOV exists as the prices of the day-ahead forwards are observed at t_1 and t_2 on the same trading day. Therefore discretizing equation (4) gives

$$\ln\frac{F_{t_2}}{F_{t_1}} = \left(\lambda\sigma_T - \frac{\sigma_T^2}{2}\right)\Delta t + \sigma_T\sqrt{\Delta t}\,\varepsilon_T\,. \tag{5}$$

The intra-day volatility σ_T might change by season. Under the assumption of a constant σ_T within a given season and no TSOV the maximum likelihood estimator of the market price of risk derived by Kolos and Ronn (2008) reduces to

$$\lambda = \frac{\mathrm{Ave}\left(\ln\frac{F_{t_2}}{F_{t_1}}\right)}{\Delta t\,\sigma} + \frac{\sigma}{2}\,, \tag{6}$$

with

$$\sigma = \sqrt{\frac{\mathrm{Var}\left(\ln\frac{F_{t_2}}{F_{t_1}}\right)}{\Delta t}} \tag{7}$$

and $\Delta t = 1/(24 * 365) = 0.000114$ to receive an annualized estimate of the market price of risk. Note the addendum of $\sigma/2$ in equation (6), which is due to the effect of Ito's Lemma. In our case of no TSOV, σ sigma plays the dual role of the standard deviation of returns as well as the standard deviation of λ. Thus, the computation of a t-statistic in order to test the statistical significance of this market price of risk estimate is straightforward.

B) *Non-parametric estimator (MPR_B)*: In case of non-normally distributed returns, for example, heavy-tailed ones, a good estimator of the market price of risk is the sample mean divided by the sample standard deviation. Although this might not represent the best estimator for such non-normal cases, it constitutes a consistent estimator.

C) *Non-parametric estimator (MPR_C)*: A less volatile measure for non-normally distributed returns is

$$\lambda = \frac{1.34898 \cdot \mathrm{median}}{Q3 - Q1}\,, \tag{8}$$

where Q3-Q1 is the sample interquartile range, and the factor 1.34898 makes the measure equal to the first non-parametric estimator when the return distribution is in fact normal.

In order to annualize the estimates of the market price of risk based on these two non-parametric estimators, we multiply with $1/\sqrt{\Delta t}$, where $\Delta t = 1/(24*365) = 0.000114$. For inference on the statistical significance of these two non-parametric estimators the t-statistics is not appropriate in the absence of a normality assumption. We thus apply non-parametric bootstrapping. Following Efron and Tibshirani (1993, p. 162), the bootstrap is run with 1000 replications.

D) *Non-parametric estimator (MPR_D)*: To account for the occasional price spikes in electricity markets and corresponding heavy-tailed return distribution, we estimate a jump-diffusion model using maximum likelihood methods. From the jump-diffusion process

$$d\ln F = \mu\, dt + \sigma\, dz + J\, dq \tag{9}$$

where the jump size J is characterized by a normal distribution with mean α and variance γ^2, we get conditional on no-jump

$$E\left(\ln F_{t_2} - \ln F_{t_1}\right) = \mu\,\Delta t \tag{10}$$

$$E\left(\ln F_{t_2} - \ln F_{t_1}\right) = \sigma^2 \Delta t \tag{11}$$

and further, conditional on a jump event occurring

$$E\left(\ln F_{t_2} - \ln F_{t_1}\right) = \mu\,\Delta t + \alpha \tag{12}$$

$$E\left(\ln F_{t_2} - \ln F_{t_1}\right) = \sigma^2 \Delta t + \gamma^2 . \tag{13}$$

The Poisson distributed probability q of a jump event occurring is $\kappa\,\Delta t$, and the complementary probability of no-jump is $1-\kappa\,\Delta t$. Maximization of the objective function reduces to choosing the set of parameters of the jump-diffusion process to make the particular time series most likely to have been observed – technically, "maximizes the log-likelihood function"

$$\sum_t \ln x_t \ , \tag{14}$$

where

$$x_t \equiv \left(1-\kappa\,\Delta t\right) n\left[\ln\frac{F_{t_2}}{F_{t_1}}, \mu\,\Delta t, \sigma^2 \Delta t\right] + \left(\kappa\,\Delta t\right) n\left[\ln\frac{F_{t_2}}{F_{t_1}}, \mu\,\Delta t + \alpha, \gamma + \sigma^2 \Delta t\right] \tag{15}$$

and the three inputs into the normal density $n[\cdot,\cdot,\cdot]$ are

$$n\left(a_t, b_t, c\right) = \frac{1}{\sqrt{2\pi c}} \exp\left\{-\frac{\left(a_t - b_t\right)^2}{2c^2}\right\}. \tag{16}$$

The estimate of the market price of risk, where we ignore elements of order $\left(\Delta t\right)^2$, is given by

$$\begin{aligned}\lambda = \frac{\text{Expected Rate of Return}}{\text{Standard Deviation}} &= \frac{\left(1-\kappa\,\Delta t\right)\mu\Delta t + \kappa\Delta t\left(\mu\Delta t + \alpha\right)}{\sqrt{\sigma^2\Delta t + \gamma^2}} \\ &\cong \Delta t \frac{\mu + \kappa\alpha}{\sqrt{\sigma^2\Delta t + \gamma^2}}\end{aligned} \tag{17}$$

and thus the annualized instantaneous market price risk based on one-hour log-returns is

$$\lambda = \frac{\mu + \kappa\alpha}{\sqrt{\sigma^2 + \gamma^2}}. \tag{18}$$

For computing standard errors we adapt the approach set forth by Ball and Torous (1983, 1985).

The annualized estimates of the intra-day market price of risk are presented in **Table 3**. Results for the intra-market analysis between the EEX segments are shown in Panel A. As can be seen, the significantly negative mean daily returns on working days yield to substantial negative MPRs. The MPRs are more pronounced for peakload than for baseload and also higher for Mondays as for the other working days. These findings are independent of the estimation method chosen. For forwards with delivery on non-working days no significant results are obtained. The findings for working days in the inter-market analysis between the EEX and EXAA auctions, displayed in Panel B, are less distinct. Mean returns and their variability have a lower magnitude and returns for baseload and peakload on Saturdays are not significant. Still MPR estimates are predominantly negative, with MPRs for working days except Mondays higher for peak- than for baseload.

Though the results, especially for working days, form an overall consistent picture, the above findings have to be treated as preliminary since further investigations into the significance and robustness of the MPR estimates are required.

Table 3
Estimates of the Intra-Day Market Price of Risk for Electricity Forward Prices

Estimates of the intra-day market price of risk (MPR) for day-ahead electricity forward prices, based on one parametric (A) and three non-parametric (B, C, D) estimation methods, are presented. All MPR figures constitute annualized estimates. Panel A provides the results for the one-hour ln returns (r) of the EEX auction on the EEX continuous trading prices. Figures for the returns of baseload (Mo-Fri) and peakload on non-working days are not shown, because the number of observations are too low. Panel B provides the results for the one-hour ln returns of the EEX auction on the EXAA auction prices. The figures for the returns of base- and peakload on non-working days (Mo-Fri) are not shown, because the number of observations are too low. Observations for dates with different holiday classifications at the EEX and EXAA are excluded from the dataset. $^{+++}$ ($^{++}$, $^{+}$) indicates significance of the one-hour ln returns and MPR_A at the 1% (5%, 10%) level according to classic t-statistics.

A. Market Price of Risk - EEX Indices from August 2002 to September 2007

Working Days	r_{Mean}	$r_{Std.dev.}$	MPR_A	MPR_B	MPR_C	MPR_D
EEX (ln Auction - ln Continuous) Base	-0.009 $^{+++}$	0.065	-9.457	-12.490	-17.168	-
Monday	-0.016 $^{+++}$	0.038	-38.016 $^{+++}$	-39.797	-38.901	-
Tuesday - Friday	-0.007 $^{+++}$	0.069	-6.648	-9.859	-13.230	-
EEX (ln Auction - ln Continuous) Peak	-0.015 $^{+++}$	0.078	-14.475 $^{++}$	-18.110	-29.848	-
Monday	-0.020 $^{+++}$	0.045	-39.282 $^{+++}$	-41.407	-40.639	-
Tuesday - Friday	-0.014 $^{+++}$	0.082	-12.110	-15.967	-27.250	-
Non-Working Days						
EEX (ln Auction - ln Continuous) Base	-0.006	0.075	-3.814	-7.344	6.935	-
Saturday	0.000	0.053	2.896	0.430	17.921	-
Sunday	0.003	0.054	8.078	5.552	4.771	-

B. Market Price of Risk - EEX and EXAA Auction Indices from June 2004 to September 2007

Working Days	r_{Mean}	$r_{Std.dev.}$	MPR_A	MPR_B	MPR_C	MPR_D
(ln EEX - ln EXAA) Auction Base	-0.005 $^{+++}$	0.054	-6.906	-9.434	-17.269	-
Monday	-0.007 $^{++}$	0.032	-17.658 $^{+++}$	-19.173	-14.321	-
Tuesday - Friday	-0.005 $^{++}$	0.058	-5.609	-8.324	-18.263	-
(ln EEX - ln EXAA) Auction Peak	-0.008 $^{+++}$	0.066	-8.038	-11.116	-22.309	-
Monday	-0.006 $^{+}$	0.039	-12.398 $^{+++}$	-14.229	-17.948	-
Tuesday - Friday	-0.008 $^{+++}$	0.071	-7.625	-10.933	-26.030	-
Non-Working Days						
(ln EEX - ln EXAA) Auction Base	-0.006 $^{++}$	0.051	-7.882 $^{+}$	-10.276	-4.945	-
Saturday	-0.001	0.054	0.988	-1.517	9.884	-
Sunday	-0.007 $^{++}$	0.041	-14.300 $^{+++}$	-16.210	-13.190	-
(ln EEX - ln EXAA) Auction Peak	-0.006 $^{++}$	0.049	-9.732 $^{++}$	-12.032	-5.831	-
Saturday	0.001	0.052	5.000	2.586	12.391	-
Sunday	-0.010 $^{+++}$	0.038	-23.371 $^{+++}$	-25.157	-13.956	-

Our result of a negative intra-day market price of risk for day-ahead electricity forwards is in general in-line with the studies for other markets, although only a few studies directly address the MPR in electricity markets. For day-ahead forwards at the PJM market Kolos and Ronn (2008) find a significant negative MPR. The short-term MPR for Cinergy and PJM electricity forwards with longer maturities, estimated based on a two-factor model, are negative as well, but not statistically significant. The short-term MPR for EEX futures over the trading period July 2002 to October 2003, however, is significantly positive, which is attributed to the market design, structure of the contracts or early participation of outside industry investors. But given that EEX futures were introduced in July 2002, the positive MPR might actually result from the early stage of the market. Dincerler and Ronn (2001) investigate the MPR for PJM electricity futures with monthly delivery periods traded at the New York Mercantile Exchange (NYMEX) and obtain a significant negative MPR. Note that both studies assume a constant market price of risk across maturities, but allow for its seasonal variation. Ollmar (2001), who investigates the MPR in the Scandinavian electricity market by utilizing electricity futures and forwards at Nord Pool, relaxes this constancy assumption. The estimated MPR is negative for all maturity dates and increases in absolute terms near to maturity. In addition, a clear seasonal pattern is documented. Weron (2008) further analyzes the MPR in the Nord Pool market based on Asian-style electricity options and futures. For most of the time he also detects a negative MPR, which is, however, declining in absolute terms with decreasing time-to-maturity.

5 Conclusion and Outlook

In this paper, we have computed the risk premia and market price of risk for day-ahead electricity forwards at the German European Energy Exchange (EEX) and Energy Exchange Austria (EXAA). Given the richness and unique institutional structure afforded by these closely-linked markets, with inter-market deliverability of electricity, this market offers a special opportunity to study whether market participants are willing to pay a premium to secure early delivery during a trading day. Generally, we find market participants are willing to pay such a premium, leading to a statistically significant negative market price of risk and the implication that prices of short-term electricity forwards are upward-biased predictors of expected spot prices.

Future research might usefully extend our analyses by including the EEX real-time electricity market, introduced in September 2006, when a sufficiently long time series of competitive prices becomes available. In order to explore the risk premia and market price of risk for contracts with longer maturities and delivery periods, the electricity futures at the EEX should be considered. Moreover, an investigation of seasonal variation of the risk premia and market price of risk in the EEX and EXAA markets could yield further valuable insights.

References

Ball, Clifford A. and Walter N. Torous, "A Simplified Jump Process for Common Stock Returns," *Journal of Financial and Quantitative Analysis*, Vol. 18, 1983, pp. 53-65.

Ball, Clifford A. and Walter N. Torous, "On Jumps in Common Stock Prices and Their Impact on Call Option Pricing," *Journal of Finance*, Vol. 40, 1985, pp. 155-173.

Benth, Fred Espen, Alvaro Cartea and Rüdiger Kiesel, "Pricing Forward Contracts in Power Markets by the Certainty Equivalence Principle: Explaining the Sign of the Market Risk Premium," forthcoming *Journal of Banking and Finance*, 2007.

Bessembinder, Hendrik and Michael L. Lemmon, "Equilibrium Pricing and Optimal Hedging in Electricity Forward Markets," *Journal of Finance*, Vol. 57, 2002, pp. 1347-1382.

Bierbrauer, Michael, Christian Menn, Svetlozar T. Rachev and Stefan Trück, "Spot and Derivative Pricing in the EEX Power Market," *Journal of Banking and Finance*, Vol. 31, 2007, pp. 3462-3485.

Borenstein, Severin, James Bushnell, Christopher R. Knittel and Catherine Wolfram, "Inefficiencies and Market Power in Financial Arbitrage: A Study of California's Electricity Markets," forthcoming *Journal of Industrial Economics*, 2006.

Botterud, Audun, Arnob K. Bhattacharyya and Marija Ilic, "Futures and Spot Prices: An Analysis of the Scandinavian Electricity Market," *Proceedings of the 34th North American Power Symposium 2002*.

Bühler, Wolfgang and Jens Müller-Merbach, "Valuation of Electricity Futures: Reduced-Form vs. Dynamic Equilibrium Models," Working Paper, University of Mannheim, April 2007.

Cartea, Alvaro and Marcelo G. Figueroa, "Pricing in Electricity Markets: A Mean Reverting Jump Diffusion Model with Seasonality," *Applied Mathematical Finance*, Vol. 12, 2005, pp. 313-335.

Daskalakis, George and Raphael N. Markellos, "Are Electricity Risk Premia affected by Emission Allowance Prices? Evidence form the EEX," Working Paper, Athens University of Economics and Business, January 2008.

Diko, Pavel, Steve Lawford and Valerie Limpens, "Risk Premia in Electricity Forward Prices," *Studies in Nonlinear Dynamics and Econometrics*, Vol. 10 (3), 2006.

Dincerler, Cantekin and Ehud I. Ronn, "Risk Premia and Price Dynamics in Electric Power Markets," Working Paper, University of Texas at Austin, June 2001.

Efron, Bradley and Robert J. Tibshirani, *An Introduction to the Bootstrap*, Chapman & Hall, 1993.

ETSO, "ETSO 2004 Cross-Border Trade Mechanism," January 2004.

EEX, "2005 Best Year of Trading since Establishment," Press Release, January 12, 2006.

EEX, "Introduction to Exchange Trading at EEX," January 2008.

EXAA, "Annual Report 2005," March 2006.

EXAA, "Information Brochure Power and Carbon EXAA," February 2008.

Federal Network Agency, "2007 Report by the Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway to the European Commission on the German Electricity and Gas Market" (Summary), November 2007.

Geman, Helyette and Oldrich Vasicek, "Forward and Future Contracts on Non-Storable Commodities: The Case of Electricity," *Risk*, Vol. 14(8), 2001, pp. 93-97.

Hadsell, Lester and Hany A. Shawky, "Electricity Price Volatility and the Marginal Cost of Congestion: An Empirical Study of Peak Hours on the NYISO Market, 2001-2004," *Energy Journal*, Vol. 27, 2006, pp. 157-179.

Karakatsani, Nektaria V. and Derek W. Bunn, "Diurnal Reversals of Electricity Forward Premia," Working Paper, London Business School, February 2005.

Kolos, Sergey P. and Ehud I. Ronn, "Estimating the Commodity Market Price of Risk for Energy Prices," *Energy Economics*, Vol. 30, 2008, pp. 621-641.

Longstaff, Francis A. and Ashley W. Wang, "Electricity Forward Prices: A High-Frequency Empirical Analysis," *Journal of Finance*, Vol. 59, 2004, pp. 1877-1900.

Lucia, Julio J. and Hipolit Torro, "Short-Term Electricity Futures Prices: Evidence on the Time-Varying Risk Premium," Working Paper, University of Valencia, July 2007.

Ockenfels, Axel, "Measuring Market Power on the German Electricity Market in Theory and Practice: Critical Notes on the LE Study," *Energiewirtschaftliche Tagesfragen*, Vol. 57(9), 2007, pp. 12-29.

Ollmar, Fridthjof, "Empirical Study of the Risk Premium in an Electricity Market," Working Paper, Norwegian School of Economics and Business Administration, September 2003.

Pirrong, Craig and Martin Jermakyan, "The Price of Power: The Valuation of Power and Weather Derivatives," Working Paper, University of Houston, December 2005.

Routledge, Bryan R., Duane J. Seppi and Chester S. Spatt, "The Spark Spread: An Equilibrium Model of Cross-Commodity Price Relationship in Electricity," Working Paper, Carnegie Mellon University, May 2001.

Shawky, Hany A., Achla Marathe and Christopher L. Barrett, "A First Look at the Empirical Relation between Spot and Futures Electricity Prices in the United States," *Journal of Futures Markets*, Vol. 23, 2003, pp. 931-955.

Ullrich, Carl J., "Constrained Capacity and Equilibrium Forward Premia in Electricity Markets," Working Paper, Virginia Polytechnic Institute and State University, October 2007.

Weron, Rafal, "Market Price of Risk Implied by Asian-Style Electricity Options and Futures," *Energy Economics*, Vol. 30, 2008, pp. 1098-1115.