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Abstract

We examine the forward market for electricity for indications of misuse of market power. The data source is a unique set of OTC price indications posted by Elsam A/S, the dominant producer in Western Denmark, which is one of the price areas under the Nordic power exchange Nord Pool. The Danish Competition Council (the regulatory government agency) has ruled that Elsam used its dominant position to obtain excessive spot prices over the period July 2003 through December 2006. We show that significant forward premia exist during this period, and that they are related both to spot market volatility and misuse of market power in the spot market, indicating that misuse of market power in the forward market accompanied that which took place in the spot market, according to the regulator's ruling. This is consistent with the hypothesis that Elsam used the forward market to disguise its spot market manipulation. The findings are consistent across forward premium regressions and structural forward pricing models.

JEL Classifications: G13, L12.

Keywords: Electricity, forward prices, market power, OTC prices

1 Introduction

The pricing of electricity in spot and forward markets is of central importance for producers, utilities, distributors, investors, hedgers, risk managers, regulators, and, ultimately, all firms and households, as consumers of power. A delicate issue in this area relates to the possibility of manipulation with prices through misuse of market power on the part of large traders in wholesale markets, whether speculators, retailers, or producers. Addressing this issue in the forward market must account for two main commodity features of electricity, namely, that it is virtually nonstorable, and that it exhibits important short-run and long-run price predictability in the spot market. To the extent that the standard no-arbitrage cost-of-carry forward pricing relation breaks down due to nonstorability of the underlying, forwards may alternatively be priced via expected future spot prices, incorporating the predictability in the spot market, along with suitable risk premia. Recent studies find that premia may be significant, that the sign varies during the day, that premia depend negatively on spot volatility and positively on spot skewness, and that both spot and forward prices exhibit mean reversion and positive skewness.

Mispricing in the spot market may show up as large differences between observed prices and marginal cost of electricity production. Such mispricing in the spot market might be expected to be accompanied by deviations from fair pricing in the forward market, as well, particularly if the mispricing phenomenon stems from misuse of market power by dominant traders active in both spot and forward markets. Indeed, a trader who is able to move spot prices in a certain direction may attempt to move forward prices in the same direction, too, to maintain the relation between spot and forward prices that would prevail in an atomless market, thus masking the deviation from fair pricing. We investigate this possibility empirically in the present paper.

We exploit a unique data set on forward prices posted as daily bid and ask prices for delivery during peak hours or continuously through both peak and off-peak hours by Elsam A/S (now Dong Energy, after a 2006 acquisition), the dominant producer of electricity in Western Denmark during the period of our analysis. Western Denmark is one of the price areas under the Nordic power exchange Nord Pool, one of the oldest spot and forward electricity markets in the world. Nord Pool is organized as a wholesale market accessed principally by producers and intermediaries (power marketers and utilities). As a dominant market participant in Western Denmark, Elsam/Dong (henceforth Elsam) is required by Danish competition law not to charge excessive prices for electricity. The Danish Competition Council (the regulatory government agency) has ruled that Elsam misused its dominating position in the period July 1, 2003, through December 31, 2006, by posting excessive prices in the Nord Pool spot market. Specifically, 2,384 trading hours have been identified where the company has violated competition legislation. The resulting losses to ultimate consumers are substantial, with estimates ranging between \$48 mio. and \$160 mio.,[1] and hit broadly across the population, with per capita losses upwards of \$100 (including all age groups).

The spot market misuse case is complex, since electricity may be supplied to Western Denmark not only by Elsam (and small decentralized producers in the area, including wind power production), but also through cables from Norway and Sweden (both Nord Pool members) and Germany. Two types of bottlenecks may arise in Western Denmark. When congestion, i.e., the cables from Norway and Sweden carrying electricity to Western Denmark at capacity, has coincided with higher spot prices in Germany than on Nord Pool, Elsam has supposedly been able to charge high prices, at or just below the German level, and higher than Nord Pool prices. Furthermore, by posting high prices on Nord Pool and withholding production, Elsam has apparently been able to generate such congestion, with electricity from Norway and Sweden filling the cables to Western Denmark, thereby leaving Elsam with monopoly power over the last units sold in this area. On the other hand, during power shortages in the Nordic countries, e.g., due to low levels in the water reservoirs for power generation, Elsam was apparently able to withhold production sufficiently so as to avoid filling the cables to Norway and Sweden, thereby again obtaining prices in excess of the Nord Pool level.[2] Indeed, the nonstorability

[1] The average exchange rate during the 3.5 year period was 6.1324 DKK (Danish kroner) per U.S. \$. The regulator estimates losses at DKK 187 mio. during the period July 1, 2003, through 2004. Starting on January 1, 2005, CO_2-emission allowances were required for major producers, and were distributed for free by the government in accordance with the Kyoto protocol. Thus, for the 2005-2006 period, losses depend on the extent to which the cost of CO_2-allowances are included in fair spot prices. This cost indicates an exchange price of CO_2-allowances, not an expense paid by producers, who received the allowances for free. If the exchange values of CO_2-allowances are included 100% in the calculation of fair spot prices of electricity, losses are estimated at DKK 111 mio. for the two year period. If they are excluded completely, losses are estimated at DKK 783 mio. The European Union has announced that 100% rollover is excessive. Germany has adopted a 25% rule.

[2] Hylleberg (2004) finds that Elsam was successful in obtaining spot prices close to the highest of those in the surrounding areas (Norway, Sweden, Germany) over the earlier period 2001-2003. Haldrup & Nielsen (2006) fit a regime switching model to spot prices from 2000-2003 and confirm that bottlenecks driven by capacity congestion are important in this market.

feature of electricity implies that misuse of market power may occur even over just a single or a few hours. The Competition Council has among others used daily data on Elsam's spot market bid and ask prices at Nord Pool along with its self-reported production capacity and marginal production cost by plant in order to determine the 2,384 misuse hours. These data are not publicly available.

In this paper, we take as given the regulator's ruling regarding the activities in the spot market, in particular, the exact location of the 2,384 misuse hours in the time series, published in appendices to the ruling, and examine whether the data reveal signs of simultaneous misuse of market power in the forward market. Although such misuse in the forward market would be illegal, as in the spot market, this question has not been raised by the competition authorities. We provide the first empirical investigation of whether misuse of market power in a given forward market accompanies misuse in the underlying spot market.

If Elsam systematically increased forward prices when spot prices were temporarily excessive through manipulation, then apparently speculators would be able to sell electricity forward at the high prices and settle in cash at the subsequent spot price after this had come down, betting that this could not be kept artificially high through contract expiration, and thus profiting at Elsam's expense. In practice, though, short positions require physical power delivery. The regional market in Western Denmark is dominated by producers and retailers (utilities and distributors), and being the dominant producer in the area, Elsam would be expected to set prices so as to become a net seller in the market. If the resulting forward prices were excessive, ultimate consumers would suffer additional losses on this account, beyond those stemming from spot market misuse.

Our empirical investigation shows that forward prices indeed did tend to be excessive during periods when spot prices were excessive, according to the regulator's ruling. A possible explanation of this phenomenon is that Elsam set forward prices so as to disguise its spot market manipulation. If temporarily excessive manipulated spot prices had been accompanied by rational expectations forward prices reflecting lower future spot prices, then Elsam would have given itself away to regulators, who would immediately have noted that the company expected spot prices to be only temporarily high. Of course, whatever the motive for charging excessive prices, the end result is a loss to ultimate consumers (households and firms).

Earlier empirical studies of forward prices in the Nordic market have only examined the official Nord Pool exchange data on closing prices for base contracts for continuous delivery over the 24-hour period, whereas the misuse in the spot market was predominantly during the peak hours from 8 a.m. to 8 p.m. on weekdays.[3] Both the rate of misuse and the concentration within peak hours is stronger in the later part of the period, 2005-2006, than in the earlier part.[4] By considering daily (morning, about 10 a.m.) data on bid and ask price indications from Elsam for over-the-counter (OTC) wholesale trades in both peak and base (continuous delivery) forward contracts, we are able not only to investigate whether misuse of market power in the forward market accompanied that which existed in the spot market, but also to separate the portion of any such misuse that took place in the peak hour contract (which has no exchange traded analog), and to examine in particular whether mispricing was reflected in the ask prices faced by smaller utilities, distributors, and, ultimately, consumers.

The extent to which forward electricity prices reflect expected future spot prices, and the empirical behavior of associated forward premia, is studied by Longstaff & Wang (2004), using data from the Pennsylvania, New Jersey, and Maryland market from June 2000 to November 2002. They find that forward premia are significant and depend negatively on spot volatility and positively on spot skewness, consistent with theoretical predictions in Bessembinder & Lemmon (2002). In addition, they find that both spot and forward prices exhibit mean reversion and positive skewness, consistent with predictions from the model in Routledge, Seppi & Spatt (2001), which extends Routledge, Seppi & Spatt (2000), and that forward prices exhibit stronger serial dependence than spot prices. We test these predictions using univariate analyses as well as multivariate forward premium regressions for Nord Pool exchange prices and Elsam OTC prices, and examine how the results depend on mispricing in the spot market.

Care must be taken in interpreting the results. The model by Bessembinder & Lemmon (2002) assumes competitive equilibrium in a wholesale market accessed by producers and retailers. The spot and forward prices we consider are indeed wholesale prices, and producers and retailers account for the majority of the Nord Pool and OTC trades. On the other hand,

[3] Of the 2,384 hours of misuse, 1,471 are peak hours, and 913 off-peak hours. With 3,120 peak hours and 5,640 off-peak hours in a year, this corresponds to misuse in 13.47% of peak hours and 4.63% of off-peak hours during the 3.5 year period.

[4] According to the regulator's ruling, there were 1,484 misuse hours in 2005-2006, of which 924 peak hours, for a misuse rate of 14.81% during peak hours and 4.96% during off-peak hours. From July 1, 2003, through 2004 there were 900 misuse hours, of which 547 peak hours, for an 11.69% peak hour misuse rate, and 4.17% off-peak.

manipulation with either spot or forward prices represents a deviation from competitive equilibrium, so we use this model as a benchmark against which to judge departures from fair pricing. It does not hold specific predictions regarding the detailed nature of any such departures. In the model, market participants are concerned with mean and variance of profits. Producers sell more power when spot prices are high, so profits are volatile, particularly when spot price variance is high. This generates an incentive to sell in the forward market to create an offsetting exposure, thus explaining the negative relation between forward premia and spot variance, and the possibility of negative premia. Negative net hedging pressure from producers is also behind the classic theories of Keynes (1930), Hicks (1939), Cootner (1960), and others, which predict normal backwardation, i.e., negative forward premia that increase in magnitude with term to delivery. Accordingly, we investigate the role of contract maturity, too. Costless participation by unlimited numbers of speculators would drive forward premia to zero, but informational setup costs as in Hirshleifer (1988) may prevent this from happening, and in practice, the regional market in Western Denmark is dominated by the industry (producers and intermediaries).

Following Bessembinder & Lemmon (2002), a different source of upward pressure on forward prices may stem from the industry itself. Thus, capacity constraints, bottlenecks in interregional transmission, and convex marginal production costs imply a risk of upward spikes in marginal costs which reduce profits, and this generates a positive hedging demand. With nonstorability of power, positive production cost spikes are reflected as positive skewness in spot prices, and hence spot skewness enters forward premia positively. The upshot is that the sign of forward premia is indeterminate in equilibrium. Furthermore, nonstorability prevents inventory smoothing of spot prices, which implies even higher volatility of spot prices and realized premia than in storable commodity markets, where e.g. Fama & French (1987) found significant premia of either sign hard to detect in the first place.

Apart from producers reducing risk by locking in a fixed price in the forward market, thus generating negative hedging pressure, backwardation could be due to positive convenience yields derived from direct ownership of the underlying. With storage costs corresponding to negative yields, near nonstorability of electricity would increase cost of carry, suggesting that contango should be more likely in this market. The theory of storage by Kaldor (1939) and Telser (1958) explains positive convenience yields in terms of the timing option to consume the underlying either now or later. This feature is exploited in the competitive equilibrium model of Routledge et al. (2000). Although the argument appears to rest on storability, Routledge et al. (2001) extend the model to multiple commodities and show how the option element at least to some extent may spill over from storable fuels such as coal, natural gas, and oil, which can be burnt into electricity. This theory implies that spot and forward prices are mean-reverting, due to costly storage and conversion, and hence bounded inventories and prices. The irreversibility of conversion of fuel to electricity implies that conversion occurs when electricity demand is high, which itself tends to lower spot prices in high demand states and hence lower skewness, but when adding costly fuel storability to the model, the net effect is again risk of price spikes and hence increased skewness, now driven by stockouts. As Elsam's production plants are primarily coal fired, the theory is potentially relevant, thus reinforcing the points that the the sign of forward premia is indeterminate, and that skewness may matter.

In this paper, we carry out forward premium regressions to investigate the sign of the premium, the impact of spot variance, skewness, and backwardation, as well as the extent to which periods of spot market misuse were characterized by different forward premia, after controlling for these other determinants. The forward contracts in the Nordic market are fixed-price contracts for delivery over an extended future period (season, quarter, or year), so a high-frequency analysis of forward premia defined as forward prices less average future spot prices is not feasible. Instead, we complement the forward premium regressions with a daily-frequency analysis which is carried out by adopting structural pricing models. The notion is that in spite of nonstorability of the underlying, absence of arbitrage opportunities nonetheless implies the existence of an equivalent martingale measure, under which forward prices are given as expected future spot prices. An assumption on the form of the market price of risk then yields a functional form for the forward price as dependent on the current state variable. Thus, the equilibrium and structural no-arbitrage approaches complement each other as tools of analysis. Each allows representing forward prices as expected future spot prices, adjusting for suitable premia. The equilibrium approach generates endogenous restrictions on forward premia, while the no-arbitrage approach delivers closed-form forward prices, given exogenous premia and an assumed process for the underlying.

Following Schwartz (1997), the proporties of mean-reverting commodity prices may be captured in an Ornstein-Uhlenbeck process based model, taking the current spot price as state variable. Lucia & Schwartz (2002) extend this approach with a deterministic component generating seasonal patterns in an application to Nord Pool data using forward prices over the period December 1998 through November 1999. We take the Lucia-Schwartz model as a starting point for our structural modeling because the mean-reversion and deterministic components help capture the important short-run and long-run predictability in electricity prices, respectively, and for purposes of comparison with this important earlier study of the Nordic market during a period supposedly free of misuse of market power. We extend the model by relaxing the assumption of a constant market price of risk and establish that the extension is empirically warranted. In contrast to previous studies, we consider both exchange and OTC contracts, both full period and separate peak and off-peak contracts, and the possibility of misuse of market power. Because the forward contracts are for long delivery periods commencing in the relatively distant future, we do not explicitly model the possibility of stochastic volatility or jumps in hourly spot prices, but retain a specification emphasizing the important mean-reversion properties and admitting closed-form solutions for forward prices as functions of spot prices.[5]

Our analysis reveals that significant forward premia exist both in exchange and OTC prices. They are negatively related to spot market volatility, consistent with earlier literature, but in contrast with this, spot market skewness does not appear to explain premia. For the OTC contracts, forward premia and risk prices are strongly related to misuse of market power in the spot market, suggesting that misuse of market power in the forward market for electricity indeed did accompany that which took place in the spot market, according to the ruling by the regulating agency. The effect in the peak product, for delivery of electricity during the peak hours from 8 a.m. to 8 p.m., which is the time interval where most of the misuse of market power in the spot market took place, is found to be different from that in the off-peak product. This suggests that the split into these two components, which is made possible by our unique data set, is appropriate. The findings are consistent across forward premium regressions and structural forward pricing models, and are robust to using either bid-ask midpoints or only the posted ask prices most relevant to consumers. Our structural model estimation shows that both the current state variable and a number of variables related to misuse of market power

[5] Geman & Roncoroni (2006) do consider jumps in spot prices, but also emphasize the importance of mean reversion, even building additional mean reversion effects into the model by making jumps negative when the spot price is above a threshold. They do not consider stochastic volatility, forward pricing, or misuse of market power.

in the spot market enter significantly in the market price of risk. As a robustness check, we provide a complementary daily-frequency analysis of the forward basis, i.e., forward price less contemporaneous spot price, and document that the standard arbitrage-relation is violated, consistent with nonstorability of the underlying.

The rest of the paper is laid out as follows. In Section 2, we briefly summarize the background for the case on misuse of market power in the spot market, and we describe the unique data set used in this paper. Section 3 presents the testing framework and the empirical analysis. Section 4 concludes.

2 Background and Data

We use forward electricity price data from Nord Pool, the Nordic power exchange, as well as from Elsam A/S (now Dong Energy), the dominant producer of electricity in Western Denmark during the period under investigation. The forward contracts are for future delivery of electricity in the Nord Pool price area DK1 (Western Denmark), and our data also include the underlying DK1 spot electricity prices, as well as marginal cost of electricity production, the latter assessed according to standard methods based on coal prices. Finally, we use the exact location in the time series of the 2,384 trading hours during which Elsam has been found guilty of misuse of market power in the DK1 spot market by the Danish Competition Council, the government agency regulating public utilities. The information on misuse hours has been published in appendices to this ruling.

To describe the special role played by Elsam, we briefly summarize the case. Starting in the year 2000, several market participants complained regularly that Elsam used its monopoly position to obtain abnormally high spot prices. The Danish Competition Council considered the case, which also involved the electricity producer in Eastern Denmark, Energi E2. Although finding that misuse had taken place, the Council decided on March 26, 2003, to end the case, as Elsam and Energi E2 agreed not to misuse their positions in the respective markets. Still, market participants continued complaining about misuse during 2003 and 2004. The Competition Council reopened the case in June 2005, and ruled on November 30, 2005, that Elsam had violated competition legislation in a total of 900 trading hours during the period July 1, 2003, through December 31, 2004. On March 14, 2006, the European Union Commission approved that all central production of electricity and natural gas in Denmark be joined in the single company Dong Energy, which at that time acquired Elsam, Energi E2, and others, selling off about 35% of Elsam to Swedish Vattenfall. Following an appeal and further investigations, the Competition Appeal Tribunal confirmed the misuse on November 14, 2006, a ruling which Dong Energy has appealed to the Maritime and Commercial Court, the last level before Supreme Court. In addition, the competition authorities investigated possible misuse of market power in the spot market in 2005-2006, and on June 20, 2007, the Competition Council in a decision parallelling that of November 30, 2005, ruled that the misuse had continued throughout the 2005-2006 period, with 1,484 misuse hours during this interval. Dong Energy has appealed the latter ruling to the Competition Appeal Tribunal.

The forward prices from Nord Pool are daily closing prices from 2002 to 2006 for the base contract guaranteeing continuous delivery of electricity to the DK1 area over the 24-hour period each date during the delivery period. The underlying spot market product is a day-ahead contract for delivery (by the hour) of DK1 electricity. The forward delivery periods before 2006 are Winter 1 (January through April), Summer (May through September), Winter 2 (October through December), and the entire calendar year. For delivery in 2006 and later, the three seasonal contracts are replaced by four quarterly contracts, following a standard January cycle.

The forward prices from Elsam/Dong (henceforth Elsam) are also from 2002 to 2006, for the same delivery periods as the Nord Pool contracts, and with the same underlying spot contract. The forward prices are daily email indications of bid and ask prices for over-the-counter (OTC) trades sent out around 10 a.m. to market participants, for base as well as peak contracts, a peak contract guaranteeing delivery during the peak hours from 8 a.m. to 8 p.m. each date during the delivery period, excluding weekends. We have collected all the daily emails sent from 2002 through 2006 by Elsam to market participants and received by Energi Danmark A/S, a utility purchasing electricity from Elsam and distributing to customers.[6]

The Elsam prices are quoted in Danish kroner (DKK) per MWh, as are the hourly DK1

[6]Specifically, the utility name was Energi Danmark-DISAM A/S at the beginning of our sample period in 2002. DISAM A/S was formed in 1993 when several electricity distributors joined in a trading firm. Trading in financial electricity contracts was initiated in 1998. The name was changed to Energi Danmark-DISAM A/S in 2001, after mergers with a number of other firms. Following an additional merger in 2005 with Elektra Energihandel A/S, the company continued operations under the name Energi Danmark A/S. The emails have thus been received under the company names Energi Danmark-DISAM A/S and Energi Danmark A/S over the period 2002 to 2006, and are available from the authors upon request.

spot prices (24 per day), obtained for the 2002 to 2006 period from Nord Pool. The Nord Pool forward contracts are quoted in Norwegian kroner (NOK) for delivery in 2005 and earlier, and in Euro thereafter. For each contract, the data include a System price and one CfD (contract for difference swap) price for each price area under Nord Pool. To get a Nord Pool forward price comparable to the Elsam base price, we add the CfD price for DK1 to the Nord Pool System price and multiply the result by the forward exchange rate measured in DKK per NOK (DKK per Euro for delivery in 2006 and later) with delivery matching the electricity forward, using the observed spot exchange rate and the interest differential (covered interest parity).

In Denmark, the marginal producer burns coal into electricity. Marginal costs of production are calculated from coal prices according to standard methods, with allowances for contributions to overhead and a markup. Including the latter two should render the cost measure conservative when assessing potentially excessive electricity pricing. As coal on hand is either burnt into electricity or stored, the opportunity cost is given by its value in the forward market. Next month delivery prices[7] are obtained from Reuters. The prices are in U.S. dollars per ton, and forward exchange rates (DKK/$) are obtained from spot rates and the interest differential. A standard of .1358 tons of coal per MWh is applied, along with a marginal efficiency in production of .40, obtained from the Danish Energy Authority, for a final consumption of .3395 tons of coal per MWh. Overhead is set to DKK 35 per MWh (2003 prices). A conventional 10% markup is included, so marginal costs are assessed as (.3395∗forward price of coal in DKK + overhead)∗1.10 + exchange price of CO_2-emission allowances, with the last term only included from 2005 on. Below, we verify that the resulting series indeed yields a conservative cost measure.

Summary statistics for spot prices and marginal costs appear in Table 1. The first line of the table contains statistics for hourly spot prices. From these, the coefficient of variation (the ratio of standard deviation to mean) is considerable, at about 50%, for the hourly frequency. Consistent with the empirical findings in Routledge et al. (2001) and Longstaff & Wang (2004), skewness is positive and strongly significant (asymptotic standard errors in parentheses), and the first order autocorrelation coefficient is well below unity, consistent with mean reversion. The large coefficient of kurtosis is consistent with the type of outliers (possibly stemming from

[7]The McCloskey Group's API2 price, net as received, inclusive of freight insurance cost, for Amsterdam, Rotterdam, Antwerp port system delivery.

production cost spikes or stockouts) also generating skewness. The total number of hours is 43,820, of which 159 are associated with zero spot prices. The next line of the table shows that when restricting attention to non-zero prices and taking logarithms, excess kurtosis remains strongly significant. The third line is for daily prices averaged across the 24-hour period. Sample size is now 1,826, and excess kurtosis is much lower, at 11.2, and insignificant at conventional levels. The coefficient of variation is now 37%. Mean reversion remains, with the autocorrelation coefficient at .69 and precisely estimated, and there is some positive skewness, but much less than in the hourly data. There are no zero observations among the daily average prices, and taking logarithms leaves both skewness and excess kurtosis insignificant.

There are 156 days with at least one misuse hour, according to the ruling by the regulator. We classify these as misuse days throughout. When excluding these, the resulting daily series of length 1,670 (fifth line) exhibits slightly lower mean, variance, skewness, and kurtosis, and slightly higher autocorrelation, compared to the series which includes misuse (third line), and all these moments are more precisely estimated. The coefficient of variation drops to 35%. This is consistent with the notion that observations on misuse days are different on average, add volatility and outliers, and are less similar to the foregoing observation, possibly because they are set according to a different mechanism than spot prices on days without misuse of market power.

The next (sixth) line of the table shows statistics for daily marginal costs. They are about 40 DKK (roughly 16%) less on average than daily prices. Furthermore, they are less variable and exhibit lower skewness and kurtosis, and possibly a unit root (no mean reversion). The drop in marginal cost when excluding misuse days (line seven) is less than the drop in spot price, and the other moments are nearly unchanged, too. The statistics are consistent with the notions that spot prices are somewhat higher than marginal costs, and that spot prices differ more between misuse and non-misuse days than do marginal costs.

Figure 1 shows the time series plots for daily spot prices and marginal costs, confirming that spot prices exhibit large positive outliers, whereas marginal costs do not, and that spot prices are more volatile and hover above marginal costs during much of the five-year period. Figure 2 compares our marginal cost measure with that published by NENA,[8] showing that

[8]Founded in 1997 under the name Nordic Energy Analysis, NENA is the oldest analysis firm in the Nordic countries within the area of Nordic and European power and emission markets, and a major supplier of independent analyses, servicing producers, distributors, banks, and traders throughout Europe. Our marginal cost

our measure, which includes allowances for overhead and markup, is indeed conservative, lying above the alternative measure almost throughout the period. The only exception is the period around January 1, 2005, when CO_2-allowances were introduced, as our measure only includes the price of allowances from February 11, the start of CO_2 exchange price data, whereas the NENA series includes estimates of the previous missing prices back to January 1 when emission allowances were initially granted, so that the NENA curve jumps above ours for a brief period around the turn of the year 2005.

The last four lines of Table 1 show statistics for the daily averages across peak hours from 8 a.m. to 8 p.m. each day excluding weekends, respectively across the remaining off-peak hours. Compared to the daily 24-hour averages in the third line, peak (off-peak) prices have higher (lower) mean, variance, skewness, and kurtosis, and lower (higher) autocorrelation. The two time series are exhibited in Figure 3, showing that peak prices usually hover above off-peak prices and are more volatile, with large, positive outliers. Furthermore, excluding misuse days (only 8 of these occur during weekends, so 148 are common) reduces the first four moments of peak prices and increases their serial dependence, whereas it does not make much of a difference for off-peak prices. These observations are consistent with the notion that the misuse of market power mainly affected spot prices during peak hours, where it added volatility and positive outliers, weakened the link between prices and marginal costs, and made some prices less similar to those of the previous day.

A list of the 23 overall forward contract names in our data set is presented in Table 2. The contract name identifies the delivery period, as described above. Corresponding to each contract name (delivery period) there is an official Nord Pool contract for base period delivery, and Elsam OTC base, peak, and implicit off-peak products. The table reports the respective launch dates, as well as the lengths of the delivery periods in days. The reported period lengths are precise for base contracts for continuous delivery across the 24-hour period 7 days a week. The length of the delivery period in days is shorter for peak contracts, approximately 5/7 of that for equivalent base contracts, since peak contracts are for delivery during peak hours from 8 a.m. to 8 p.m., excluding weekends. Off-peak contracts have the same length of delivery as equivalent base contracts. From the table, the OTC base product typically starts trading before the corresponding official Nord Pool contract. By the end of our sample period,

formula corresponds to those used by NENA and Point Carbon, the two leading analysis firms.

December 31, 2006, the last contract, for 2009 delivery, had not yet been introduced on Nord Pool, whereas it was available in the OTC market since January 2, 2006. The peak product is always launched simultaneously with or later than the OTC base product. The delay from base to peak introduction is several times about a year or more, up to more than 20 months, in the case of contract 21, the 2007 year contract that started trading nearly 3 years prior to delivery in the base market and about 15 months before delivery in the peak market.

The trading period for a given contract is from launch until the beginning of delivery. There is about 260 trading days in a year, and we have this number of daily forward price observations on several Nord Pool contracts launched a year prior to delivery, in particular contracts 4, 8, 12, 17, and 21, the first five of the year contracts in Table 2. We have 35 daily price observations on the 2008 year contract as this was launched in November just before the end of our sample period. The minimum number of trading days and hence price observations for Nord Pool contracts with delivery periods starting before or at the end of our sample period is for contract 14, second quarter of 2006, with 129 trading days. Besides the year contracts mentioned, we also have 260 days of price observations for the three 2007 quarter contracts (from January 2, 2006 launch through the end of our sample period). We have even more data on the OTC contracts, which are usually introduced earlier. Exceptions are the quarter contracts for 2007 where the OTC products were launched after the Nord Pool contracts, but we still have 211 daily prices for the first quarter OTC base contract for which the trading period is contained within our sample period (we have 130 and 64 observations on the second and third quarter base contracts). The other base contracts with trading periods contained in our sample period have more observations, up to 797 in case of Winter 2, 2005, launched more than two years before the equivalent Nord Pool contract. The number of daily price observations for the OTC peak product ranges from 91 for Winter 1, 2004 and the 2004 year contract (contracts 5 and 8 in the table) to 706 observations on contract 16 in the table, the fourth 2006 quarter contract launched only a day after the corresponding OTC base contract and nearly two years prior to the start of Nord Pool exchange trading.

Descriptive statistics for the forward prices similar to those for spot prices and marginal costs from Table 1 appear in Table 3. From the first line, the average closing price on Nord Pool during the period across forward contracts for DK1 delivery is about 284, compared to about 252 for spot prices from Table 1. The match is apparently much closer for the full set of 10,068 Elsam OTC prices for the base (24 hours each day in the delivery period) contracts, which average about 254. Although the delivery periods are common to the Nord Pool and Elsam contracts in Table 3, the OTC base contracts generally start trading earlier than the exchange counterparts (see Table 2), and this is in part the reason for the difference in average prices. When restricting attention to contract-day observations that include both a Nord Pool and an Elsam price, the two are in fact very close, as documented in lines four through eight of the table, marked 'Common contracts.' Also shown in Table 3 are statistics for the OTC peak product, as well as the off-peak product, whose price is given implicitly based on the observed prices of the corresponding base and peak contracts.[9] For the peak and off-peak contracts, statistics are shown both for bid-ask midpoints and ask prices, as the latter are most relevant to customers buying forward electricity.[10] Like in the case of spot prices, peak prices are higher and more volatile (and off-peak prices lower and less volatile) than base prices. All the OTC forward prices show positive skewness, consistent with Longstaff & Wang (2004) and Routledge et al. (2001), at levels near unity and precisely estimated. Excess kurtosis, while modest, is generally significant, too, at conventional levels. Mean reversion is much less than for spot prices, as it should be, given that the contracts are for delivery across an extended interval. Throughout, means and variances are lower when misuse days are excluded. This suggests that the phenomenon of different pricing on misuse days, observed for the spot market in Table 1, extends to the forward market, which has not been the object of investigation by the regulatory authority.

The close match between Nord Pool and OTC base prices when both exist is further documented in Table 4. From the first entry in the table, the Nord Pool price is only 0.1% above the OTC price on average. During the period from July, 2003, through December, 2006, where some of the trading days were subject to misuse of market power in the spot market, the OTC price is actually higher than Nord Pool, but only by 0.04%, and less so when excluding days of spot market misuse, and in both cases the difference is insignificant.[11] Since the OTC price

[9] Let F_b and F_p denote base and peak bid-ask midpoint prices corresponding to a common delivery period. The implicit off-peak price is then given by $F_o = (bF_b - pF_p)/(b - p)$, where b and p are the numbers of base respectively peak hours in the delivery period, and hence $b - p$ the number of off-peak hours.

[10] For example, the implicit ask price of the off-peak contract from the previous footnote would be $F_o^A = (bF_b^A - pF_p^B)/(b - p)$, with A and B indicating ask and bid, respectively.

[11] Throughout, when restricting attention to the misuse period starting July, 2003, contracts 1, 2, and 4 from Table 2 are not included as their delivery periods commence prior to this date and hence trading ceases.

is quoted around 10 a.m., it might be even closer to the Nord Pool close on the preceding day, which is examined in the second line of the table. The difference is insignificant for the full period, but slightly greater and now significant for the subperiod. Also reported are statistics for the average absolute difference and the root mean squared error. These actually suggest that the OTC price is closer to the previous day's exchange close than to that later the same day, which makes sense for a morning quote. All in all, there is nothing in the numbers that suggest that the Elsam base contract is out of line with Nord Pool. The impression is confirmed by Table 5, showing correlations between the OTC base price and the preceding and following exchange close. From the first two lines of the table, the correlation with the previous close is highest, for the full period and the subperiod, and also when excluding spot misuse. From the next two lines, the same holds when taking logarithm of all forward prices. The remainder of the table shows correlations between changes in prices, respectively log-prices, confirming that these are similar for both timings of the exchange close. From the two tables, we conclude that the Nord Pool and base prices are consistent, both with and without misuse days included. This shows that there is nothing unusual about our OTC data, relative to the official exchange data, judging from the Nord Pool and corresponding base contracts, and so we will continue to analyze also our special peak and off-peak forward price data.

Finally, on the data, the apparent near unit root behavior of marginal costs (Table 1) as well as forward prices (Table 3) suggests the relevance of a formal stationarity test. Table 6 shows results of Dickey-Fuller (DF) and augmented DF (ADF) tests. The null hypothesis is a unit root, and the DF test rejects in favor of stationarity (mean reversion) for the five-year period for the logarithms of base, peak, and off-peak spot prices, but does not reject a unit root in marginal cost (asymptotic p-values in parentheses). The ADF test with 10 lags confirms the results for the full period. However, for the misuse period starting in July, 2003, the evidence against a unit root also in marginal costs increases, as the p-value drops to 3%. Indeed, when excluding misuse days, the p-values suggest that marginal costs are even farther from a unit root process than peak-hour prices, although a unit root would be rejected for all series at the conventional 5% level in this case. Based on these findings, we will account for mean reversion in the subsequent analysis, but not make special allowance for the possibility of unit roots.[12]

[12] Lucia & Schwartz (2002) and Haldrup & Nielsen (2006) also conclude against a unit root in spot prices in the Nordic market.

3 Testing Framework and Empirical Results

The standard arbitrage-based relation between forward and spot prices is

$$F_{t,T} = S_t e^{r_{t,T}(T-t)}, \tag{1}$$

where S_t is the spot price at time t, $F_{t,T}$ is the forward price at time t for delivery at time $T > t$, and $r_{t,T}$ is the interest rate at t on a riskless zero-coupon bond maturing at T. The arbitrage relation may not hold in the electricity market as electricity is not easily stored.

The expectations hypothesis and extensions give rise to the relation

$$F_{t,T} = E_t(S_T)e^{-(k_{t,T}-r_{t,T})(T-t)}, \tag{2}$$

where $E_t(S_T)$ is the conditional expectation given information available at time t of the future spot price S_T. Here, $k_{t,T} - r_{t,T}$ is the risk premium required by investors in the forward market. Under risk neutrality, $k_{t,T} = r_{t,T}$, we have the expectations hypothesis in its usual unbiased form,

$$F_{t,T} = E_t(S_T), \tag{3}$$

and this relation holds in general if the expectation is under the risk neutral measure. Positive risk premia are equivalent at this level to negative values of the forward premia given by

$$P_{t,T} = F_{t,T} - E_t(S_T). \tag{4}$$

We consider forward contracts for delivery not at a point in time such as T above, but rather at every time point in an interval, say, from T_1 to T_2, where $t < T_1 \leq T_2$. The forward price of such a contract should therefore be

$$F_{t,T_1,T_2} = \frac{1}{T_2 - T_1 + 1} \sum_{T=T_1}^{T_2} F_{t,T}. \tag{5}$$

Thus, we compare the observed forward prices F_{t,T_1,T_2} to the predictions from (5), inserting a number of alternative theoretical values for $F_{t,T}$. We consider in turn forecasting properties and forward premia, with (3) as point of departure, structural forward pricing models, and, as a robustness check, forward basis regressions motivated by (1).

3.1 Forecasting Properties and Forward Premia

Consider first the unbiased expectations hypothesis (3). In this case, the forward price is the best forecast of a sample average of future spot prices,

$$F_{t,T_1,T_2} = E_t \left(\frac{1}{T_2 - T_1 + 1} \sum_{T=T_1}^{T_2} S_T \right). \tag{6}$$

As the average of spot prices on the right hand side does not depend on t, observed forward prices F_{t,T_1,T_2} for multiple different $t < T_1$ are being compared to the same future quantity. Hence, to get a more precise estimate of the expectation, we may take average of the left hand side across all time periods t for which we have forward price data for the given contract, say, from t_1 to t_2, where $t_1 < t_2 < T_1$,

$$\frac{1}{t_2 - t_1 + 1} \sum_{t=t_1}^{t_2} F_{t,T_1,T_2} = E_t \left(\frac{1}{T_2 - T_1 + 1} \sum_{T=T_1}^{T_2} S_T \right). \tag{7}$$

If we have N contracts, indexed by $i = 1, ..., N$, we may therefore calculate the relevant N sample forward premia,

$$P^i = \frac{1}{t_2^i - t_1^i + 1} \sum_{t=t_1^i}^{t_2^i} F^i_{t,T_1^i,T_2^i} - \frac{1}{T_2^i - T_1^i + 1} \sum_{T=T_1^i}^{T_2^i} S_T, \tag{8}$$

for $i = 1, ..., N$, which are the relevant sample analogues of (4). The forward premia (8) show the extent to which the forward prices fail to predict the future spot prices, on average. Such failure may be due to (i) risk premia, $k_{t,T} \neq r_{t,T}$ in (2), (ii) the arbitrage based relation (1) holding better than the expectations hypothesis, after all, even though electricity is not easily stored, or (iii) manipulation with forward and/or spot prices, such as misuse of market power.

Forward premia for different contract classes are reported in Table 7. From Longstaff & Wang (2004), we expect that forward premia may be significant, but that they could change magnitude and even sign during the day. Heteroskedasticity and autocorrelation consistent standard errors based on Newey & West (1987) are reported in parentheses, for robustness both against the serial dependence in spot and forward prices documented above and in previous studies of the Nordic market (Haldrup & Nielsen (2006) show strong dependence in spot prices and Lucia & Schwartz (2002) in both spot and forward prices) and against potential heteroskedasticity likewise consistent with the predictions from Routledge et al. (2001). The first column of the table shows that forward premia generally are negative, and significantly so for base contracts using bid-ask midpoints, as well as for the off-peak product, whether using midpoints or ask prices. The finding of significant premia is a result in itself, considering that Fama & French (1987) found significant premia of either sign hard to detect in storable commodity markets that should permit more inventory smoothing than electricity markets. In particular, forward premia have not been driven to zero by speculators in the DK1 regional market. The market is largely dominated by the industry, possibly due to informational setup costs as in Hirshleifer (1988), preventing speculators from entering. Estimated premia are considerable in magnitude, e.g., about 17% of the average spot price level from Table 1 in case of base contracts.[13]

Forward premia on Nord Pool are insignificant, as are those for peak contracts, suggesting higher forward premia for the peak product than off-peak. The findings of time variation in premia during the day and higher forward premia during peak hours than off-peak hours are consistent with Longstaff & Wang (2004). When using marginal costs rather than average spot prices across the relevant hours (base, peak, or off-peak intervals), premia are higher, and in this case positive for the peak product. The second and third columns of the table show forward premia on days without misuse of market power in the spot market, respectively on misuse days only. In all cases, point estimates are higher on misuse days than on non-misuse days for the same contracts. Indeed, from the last column of Table 7, the difference between forward premia on misuse and non-misuse days is positive and borderline significant for both the peak and off-peak products, with robust t-statistics in the vicinity of 2 in all cases. Thus, the results sugget that forward market pricing might be different on days with misuse of market power in the spot market, with higher forward prices in such instances.

Following Bessembinder & Lemmon (2002), one reason for negative premia could be negative dependence on spot price variance, an effect that was confirmed empirically by Longstaff &

[13] Our sample period for forward as well as spot prices ends on December 31, 2006 and sample premia are calculated for contracts whose trading and delivery periods are contained in the misuse period July, 2003 through December, 2006.

Wang (2004). Thus, we next investigate the nature of the forward premia P^i by regressing them on a variety of explanatory variables, including spot variance. From Bessembinder & Lemmon (2002), spot price skewness might matter for forward premia, too, so we calculate both the spot variance

$$Var^i = \frac{1}{T_2^i - T_1^i} \sum_{T=T_1^i}^{T_2^i} (S_T - \overline{S}^i)^2, \tag{9}$$

where $\overline{S}^i = \sum_{T=T_1^i}^{T_2^i} S_T/(T_2^i - T_1^i + 1)$ is the relevant average spot price during the delivery period, and the spot skewness

$$Skew^i = \frac{1}{T_2^i - T_1^i} \sum_{T=T_1^i}^{T_2^i} \left(\frac{S_T - \overline{S}^i}{\sqrt{Var^i}} \right)^3, \tag{10}$$

for each contract $i = 1, ..., N$. In addition, we calculate the average degree of misuse of market power in the spot market during the forward trading period. Thus, let D_t^M be the dummy indicating whether there was misuse or not in the spot market on date t, according to the ruling by the competition authorities. Average spot market misuse is then defined as

$$\overline{M}_f^i = \frac{1}{t_2^i - t_1^i + 1} \sum_{t=t_1^i}^{t_2^i} D_t^M (S_t - \widehat{S}_t), \tag{11}$$

$i = 1, ..., N$, where $\widehat{S}_t$ is marginal cost. Thus, $\overline{M}_f^i$ is a measure of excessiveness of spot pricing on days when misuse took place, according to the regulator. The relevant forward premium regression is

$$P^i = \alpha + \beta Var^i + \gamma Skew^i + \delta Mat^i + \rho \overline{M}_f^i + \varepsilon^i, \tag{12}$$

where Mat^i is the average term to maturity (delivery) across all delivery dates and trading dates used in computing the forward premium P^i, and ε^i is the regression error.

Results from the forward premium regression (12) appear in Tables 8 and 9. The results in the first line of Table 8 are for all Nord Pool contracts. Consistent with Longstaff & Wang (2004), the coefficient β on spot price variance is negative, at -10.0, and strongly significant, with a t-statistic of -3.6 (robust standard errors in parentheses). Next, in a set of three separate regressions, we investigate which additional explanatory variable may enter the specification, along with spot variance. Firstly, the role of skewness is not confirmed in these data, as the effect of $Skew^i$ shown in the second line of the table is insignificant at conventional levels (t-statistic about -1.5), whereas the coefficient on variance remains significant at level 3.7% or higher in a one-sided test ($t = -1.8$). From Table 1, average skewness in daily base prices is 1.8, and $-.31$ for the logarithms, whereas the comparable numbers for Nord Pool during the earlier period in Lucia & Schwartz (2002) are 1.2 and $-.38$, so it is not an overall drop in skewness in our sample period that is behind the lack of a role of skewness in explaining premia.[14] From the third and fourth lines of the table, maturity and misuse do not have any significant explanatory power, either. Nord Pool premia are primarily explained by spot variance, with the expected negative sign.

The next set of four regressions, for the OTC base contract bid-ask midpoints, shows that spot market variance again gets a significantly negative coefficient when entered individually, or along with skewness, which is itself insignificant. Maturity now enters the relation negatively, with a strongly significant coefficient $\delta < 0$ ($t = -2.8$). The fit is improved, with the regression explaining 59% of the variation in forward premia, the highest obtained for the base contracts, and much higher than the 34% explained by spot variance and skewness. Thus, the forward market for base contracts is strongly backwardated, consistent with hedging pressure to sell from producers, as in the theories of Keynes (1930), Hicks (1939), Cootner (1960), and Bessembinder & Lemmon (2002), or possibly with positive convenience yields stemming from a timing option as in Kaldor (1939) and Telser (1958) combined with a spill-over effect from the underlying storable fuels, as in Routledge et al. (2001). The last of the four base contract regressions shows that misuse of market power in the DK1 spot market enters significantly, with a t-statistic of 2.1, and the regression explains 51% of the variation in forward premia.

The general picture, that spot variance and maturity enter negatively, misuse enters positively, and skewness is insignificant, is confirmed for all contract classes, i.e., also peak and off-peak contracts, and whether using OTC bid-ask midpoints (Table 8) or the ask prices most relevant to consumers (Table 9), or marginal costs in place of spot prices in the calculation of premia. Backwardation is significant when considering future spot prices in calculation of premia, but not when using marginal costs, although contango is rejected throughout. The

[14] Lucia & Schwartz (2002) do not regress forward premia on skewness, and the lack of explanatory power may well extend to the earlier period. Longstaff & Wang (2004) do not consider any forward contracts longer than day-ahead, and this is more likely a reason for the difference in results regarding skewness.

coefficient ρ on spot market misuse is strongly significant for off-peak contracts, and also for peak contracts when using marginal costs to calculate premia. The robust t-statistics exceed 2.6 in all these cases, consistent with the hypothesis of inflated forward prices accompanying high spot prices during misuse.

Summing up, the two tables confirm the role of spot variance from the literature, but not that of skewness. There is backwardation and significant signs of misuse of market power in the OTC forward contracts, but not in the Nord Pool contracts. Thus, the results clearly show the importance of our unique data set.

3.2 Structural Pricing Models

Even though electricity is nonstorable, absence of arbitrage opportunities still requires the condition $F_{t,T} = E_t^*(S_T)$ from (3), where the expectation is taken under a suitable equivalent martingale measure (risk-neutralized probabilities), indicated using asterisk. Thus, as a supplement to the previous examination of premia, we may in the basic relation (5) use model predictions for $F_{t,T}$ stemming from specific assumptions about the stochastic processes and measure changes involved. This allows for a daily frequency analysis, and thus potentially for extracting more information from the data than in the forward premium regressions above. The natural benchmark model is the Lucia & Schwartz (2002) model, since this has been applied to Nord Pool data using forward prices over the period December 1998 through November 1999, which was supposedly free of misuse of market power. We adopt the Lucia & Schwartz (2002) specification for the spot process under the empirical measure, and consider extensions of their parametrization of the measure change (market price of risk).

The spot price process is modelled in continuous time as

$$\log S_t = f(t) + Y_t, \tag{13}$$

where $f(t)$ is a deterministic function intended to account for seasonality and other long-run predictable factors, and Y_t is a stationary mean-reverting Ornstein-Uhlenbeck process,

$$dY_t = -\kappa Y_t + \sigma dW_t, \tag{14}$$

with zero long-run mean since $f(t)$ captures the mean of $\log S_t$, rate of mean reversion $\kappa > 0$

capturing short-run predictability, and volatility $\sigma > 0$, with W_t a standard Wiener process.[15] Under the risk neutral measure, the process is

$$dY_t = -\kappa(Y_t - \alpha_t^*) + \sigma dW_t^*, \tag{15}$$

with $\alpha_t^* = -\lambda_t \sigma/\kappa$ the risk premium, and λ_t the market price of risk. With these specifications, the relation $F_{t,T} = E_t^*(S_T)$ (using the risk neutral expectation) yields the forward price

$$F_{t,T} = \exp\{f(T) + e^{-\kappa(T-t)}(\log S_t - f(t)) + \alpha_t^*(1 - e^{-\kappa(T-t)}) + \frac{\sigma^2}{4\kappa}(1 - e^{-2\kappa(T-t)})\}. \tag{16}$$

It is natural to consider daily time series data on the spot price S_t and use these to estimate $f(t)$, κ, and σ. Following this, α_t^* is estimated by matching theoretical and observed forward prices. The specification for $f(t)$ is

$$f(t) = \alpha + \beta D_t + \gamma \cos((t + \tau)\frac{2\pi}{365}), \tag{17}$$

where D_t is a weekend dummy and time is measured in days, so that the cosine function captures long-run predictable seasonal swings with annual periodicity. Discrete (daily) realizations of the Y_t process move according to

$$Y_t = \phi Y_{t-1} + u_t, \tag{18}$$

with $\phi = e^{-\kappa}$. It follows that the natural regression framework is

$$\log S_t = f(t) + \phi(\log S_{t-1} - f(t-1)) + u_t. \tag{19}$$

From this, the parameters $(\phi, \alpha, \beta, \gamma, \tau)$ may be estimated using nonlinear regression. In case of peak hour spot prices, weekends are not present, so β in (17) is not estimated, and ϕ in (19) is replaced by $\phi^{1+2\eta}$ whenever t is a Monday and $t-1$ a Friday, meaning that η estimates serial dependence over weekends relative to that on weekdays, with $\eta = 1$ implying equal dependence. Upon estimation, κ is estimated as $-\log\phi$, and σ as the standard deviation of the residuals u_t. These parameters are substituted in the forward price expression (16), so that this only depends

[15] Geman & Roncoroni (2006) include a jump term in this specification, but we retain the continuous version emphasizing the mean reversion features due to our focus on pricing of forward contracts with long delivery periods commencing in the relatively distant future.

on the remaining unknown parameters, namely, those in α_t^*, by slight abuse of notation written as a vector α^*, and this is highlighted by writing $F_{t,T} = F_{t,T}(\alpha^*)$. Next, α^* is estimated as

$$\alpha^* = \arg\min_{\alpha^*} \sum_{i=1}^{N} \sum_{t=t_1^i}^{t_2^i} (F^i_{t,T_1^i,T_2^i} - \frac{1}{T_2^i - T_1^i + 1} \sum_{T=T_1^i}^{T_2^i} F_{t,T}(\alpha^*))^2. \tag{20}$$

The Lucia & Schwartz (2002) assumption is that of a constant market price of risk, $\lambda_t = \lambda$, and hence a constant risk premium $\alpha^* = -\lambda\sigma/\kappa$. We generalize this specification by allowing the risk premium to be an affine function of the state variable, i.e.,

$$\alpha_t^* = \alpha_0^* + \alpha_1^* \log S_t, \tag{21}$$

where t is the current (forward trading) day, i.e., two parameters $\alpha^* = (\alpha_0^*, \alpha_1^*)$ are estimated. Time-varying risk premia are important characteristics of many financial markets, and dependence on the state variable is fully consistent with the no-arbitrage pricing framework. It remains an empirical question whether the generalization is warranted.

Results from estimation of the spot price model (17)-(19) appear in Table 10. Panel A contains estimates both for the underlying of the base contract, i.e., S_t is computed as the average of the 24 hourly spot prices observed for day t, and for marginal costs. Panel B shows estimates using data split up in peak and off-peak periods. The estimation is carried out in OxMetrics 4.10 using both the Broyden-Fletcher-Goldfarb-Shanno (BFGS) and simulated annealing (SA) algorithms, making sure the received results coincide.[16]

The estimates in the first column of Table 10, Panel A, are for the full period, 2002-2006, using all available data, both for days with and without misuse in the spot market, for a total of $T = 1,825$ days. All the parameters are strongly significant (robust Huber (1967) and White (1980) heteroskedasticity consistent standard errors in parentheses). From the estimate of β, spot prices are about 22% less over weekends than on week days. As expected, there is evidence of strong mean reversion of $\log S_t$ toward the seasonal $f(t)$, with ϕ estimated at .72, implying a mean reversion rate κ of .32. The model explains 59% of the variation in log-spot

[16] BFGS is a local, gradient-based algorithm that applies rank-two updates to the Hessian and line search in each iteration and is more efficient than the Davidon-Fletcher-Powell algorithm (Coleman & Li (1996)). The SA algorithm (Kirkpatrick, Gelatt & Vecchi (1983), Corona, Marchesi & Ridella (1987), Szu & Hartley (1987)) searches for a global minimum by sometimes accepting uphill moves according to the Metropolis criterion.

prices, which seems adequate for forecasting and forward pricing. Formally, the Ljung-Box portmanteau statistic is significant, but conventional p-values cannot be trusted in nonlinear models, and the criterion is included mainly as a useful device for model comparison. The explanatory power of the model suggests that it is worth exploiting this simple specification, which allows closed form derivative prices and direct comparison with earlier results for cases without misuse.

Results from the estimation (20) of the forward price model (16) with the generalized risk premium specification (21) appear in Table 11. The estimates in the first four lines of the table use all available contract-day observations in the interval July 1, 2003, through 2006 for which both a forward price from Nord Pool (daily close) and a corresponding OTC base price exist, to facilitate comparison. The remainder of the table uses all available OTC observations. This yields a total of $N = 3,112$ observations on different contracts across different calendar dates with both Nord Pool and OTC prices, and $N = 5,741$ observations when only an OTC price is required. Misuse days are included. The estimates in the first line of the table use Nord Pool contracts which are for 24 hours of delivery throughout the delivery period, and the underlying spot model estimates are those from the full period 2002-2006 estimation in the first column of Panel A of Table 10.

The estimates of both α_0^* and α_1^* in the first line of Table 11 are strongly significant, showing clearly that risk is priced in this derivative market, and, furthermore, that there is strong empirical support for the present generalization to time-varying risk premia of the Lucia & Schwartz (2002) specification, which corresponds to the special case $\alpha_1^* = 0$ in (21). In the estimation, we use marginal cost in place of actual spot price in the risk premium specification, and this is so in the entire table, except the last two lines, where actual spot prices are used for comparison.

The remaining statistics in the first line of Table 11 shows that the model explains most (97%) of the variation in Nord Pool forward prices, that the mean pricing error (average residual) is as little as -0.2%, although significant (robust t-statistic of 6.6), and that the mean absolute error and root mean squared error are 12% and 16%, respectively. The finding that risk is priced is clearly in line with that of significant premia in the previous subsection. Using their simpler model with $\alpha_1^* = 0$, Lucia & Schwartz (2002) found a slightly lower root mean squared error of about 11% over their shorter (one year) sample period, consistent with the possibility of more unpredicted moves in forward prices during our misuse period.[17]

The second line of Table 11 shows the results using OTC prices (daily bid-ask midpoints) for the corresponding base product. The underlying spot price model estimates are again those in the first column of Table 10, Panel A. The estimates of both α_0^* and α_1^* are very similar across the two data sets, confirming the consistency between OTC and official Nord Pool prices.

We now turn to different ways of estimating the spot and forward models, both in terms of model specification and data used, and, in particular, in the treatment of misuse in the spot market for the underlying. The estimation in the second column of Table 10, Panel A, excludes days with misuse in the spot market. Since the spot market is of auction type and electricity is virtually nonstorable, it is reasonable to assume that the spot price process for days without misuse is unaffected by the events on days with misuse. Of course, forward prices will have to account for the possibility of future misuse in the spot market for the underlying, and this will be modelled separately, through the risk premium specification.

Although the differences are not significant, comparison of point estimates in the first and second columns of Table 10 shows that as expected the log-price level α is slightly lower after removing days with misuse. The price drop β over weekends is slightly less when excluding misuse, which mainly occurs on weekdays. Seasonality (γ, τ) is similar with and without misuse. As expected, ϕ is increased, from .72 to .74, when misuse is eliminated, showing that a given day is more similar to the previous if both are normal days without misuse. The corresponding drop in κ is from .32 to .30, i.e., deviations from the seasonal may last longer for periods without misuse. The model fits better to non-misuse data, i.e., the portmanteau statistic is down. Note from the table that sample size is lowered from $T = 1,825$ to $1,669$, since the 2,384 hours of misuse of market power in the spot market are concentrated on 156 days.

When these spot model estimates, obtained by excluding days with misuse in the spot market, are used in the forward model estimation, the results in the third and fourth line of Table 11 are obtained. They are virtually identical to the results in the first two lines, suggesting that misuse of market power in the spot market matters little for forward pricing of Nord Pool and OTC base contracts.

Next, we turn to the unique features of the OTC data, namely, the break-down in peak and

[17] Lucia & Schwartz (2002) also documented that alternative one- or two-factor models for spot prices or their logarithms generated higher RMSEs for forward prices.

off-peak prices, as well as availability of the ask prices faced by customers. Panel B of Table 10 shows the estimates of the spot price models for the peak and off-peak periods, respectively. The peak period estimation uses the average of hourly prices from 8 a.m. to 8 p.m. on weekdays t for S_t, and the off-peak estimation uses the remaining 12 hours before 8 a.m. and after 8 p.m. on weekdays, and the 24-hour average over weekends. The data are again for the 2002-2006 period, so the estimates may be compared to those in the first two columns of Panel A. Not surprisingly, the level α is higher during peak hours and lower during off-peak hours than when using the 24-hour average every day. During peak hours, the fit deteriorates when misuse days are included, both in terms of explanatory power and the higher portmanteau statistic in the first column of Panel B compared to the remaining three, and the autocorrelation ϕ is lower, at .69. Furthermore, the seasonal (γ, τ) is different across peak and off-peak hours. These results suggest that the process is heterogenous and should not be aggregated across peak and off-peak hours, and, in particular, that peak hours are hit worst by misuse. The insignificant estimate of η shows that passage across weekends is no different from that between weekdays. Finally, as marginal costs are about equal during peak and off-peak hours, there is no apparent reason for systematically different pricing during the two periods, so the statistical difference (particularly in α) may be seen as additional evidence of deviation from marginal cost pricing.

Estimates of the forward models for the OTC peak and off-peak contract prices (bid-ask midpoints) appear in the fifth and sixth line of Table 11, respectively. The results in the fifth line (peak contracts) use underlying spot model estimates from the second column of Table 10, Panel B (peak hours), and the results in the sixth line (off-peak contracts) use estimates from the fourth column of Table 10, Panel B (off-peak hours). Spot model estimates excluding misuse days are used. The estimates of both α_0^* and α_1^* in (21) are now different between peak and off-peak hours. The risk premium intercept is more negative and the positive dependence of the risk premium on the fair price (indeed, marginal cost) is stronger for the off-peak product. This pattern is confirmed in the following lines, using ask prices, and also when using spot model estimates based on marginal cost data (these appear in the last two columns of Table 10, Panel A, where ϕ is restricted to .99 to retain a mean-reverting specification, and both weekend and seasonal effects are insignificant), and when using actual spot prices rather than marginal cost in the risk premium. The results confirm that the data should not be pooled across peak and off-peak hours and contracts.

Now, it is possible to zoom in on misuse of market power in the forward model estimation. Again, let D_t^M be the dummy indicating whether there was misuse or not in the spot market on date t according to the ruling by the competition authorities, as in (11). First, we simply permit the intercept α_0^* in the risk premium to depend on whether there is concurrent misuse of market power in the spot market. We continue to use spot model estimates excluding misuse days when estimating the forward models. The notion is that market participants may forecast future spot prices based on their knowledge about what the spot price process would look like without misuse of market power, along with an adjustment in the risk premium to account for any ongoing misuse. Thus, the specification is

$$\alpha_t^* = \alpha_{00}^* D_t^M + \alpha_{01}^*(1 - D_t^M) + \alpha_1^* \log(S_t). \tag{22}$$

Estimates of this specification appear under the label Model 1 in Table 12, separately for peak and off-peak ask prices, which by the results in Table 11 should not be pooled. The spot price model estimates are those from columns two and four of Table 10, Panel B, respectively. It turns out that the estimated risk premium intercepts are very similar for days with and without misuse. Model 2 in Table 12 uses the further generalized risk premium specification

$$\begin{aligned}\alpha_t^* \;=\; & \alpha_{00}^* D_t^M + \alpha_{01}^*(1 - D_t^M) + \alpha_1^* \log(S_t) \\ & + \alpha_{20}^* D_t^M M_t + \alpha_{21}^*(1 - D_t^M) M_t + \alpha_3^* h_t + \alpha_{40}^* e^{-\alpha_{41}^* N_t},\end{aligned} \tag{23}$$

where $M_t = \log(S_t/\widehat{S}_t)$ is the degree of misuse during the day ($\widehat{S}_t$ is marginal cost), h_t is the number of misuse hours on date t, according to the ruling by the Competition Council, and N_t is the number of days since the most recent incident of misuse. The notion is that the risk premium might depend on the extent of misuse on the day, and furthermore be declining as longer time passes since the previous misuse event. The estimates show that the terms involving the current extent of spot market misuse, M_t and h_t, are strongly significant, whereas the last term involving time since last misuse N_t is insignificant.

The final model, Model 3 in Table 12, is obtained by dropping the last, insignificant term in Model 2, i.e., $\alpha_{40}^* = 0$ and $\alpha_{41}^* = 0$ are imposed on (23). Here, all parameters are strongly significant. The results confirm that the risk premium intercept is more negative for the off-peak product than for the peak product, and the dependence on current fair price (marginal cost) is stronger, as in Table 10. Furthermore, the misuse term M_t enters very differently for the two products. For the off-peak product, risk premia are increasing in the difference between spot price and marginal cost, and much more so on misuse days than on non-misuse days (where of course there could still be a difference, i.e., a non-zero M_t). For the peak product, the dependence is similar on non-misuse days, but the risk premium is actually decreasing in M_t on misuse days. The overall effect is complex, though, since the risk premium is increasing in misuse hours h_t, and this effect is strongly significant for both products, but it is numerically almost four times larger in the peak product. All in all, we conclude that there is strong evidence that forward market pricing is different on days with misuse of market power in the spot market. The effect is different on the peak and off-peak products, which makes a split into these two components desirable. One of the features of our unique data set is that it allows such a split.

Estimated and fair risk premia from Model 3 are shown in Figure 4 for the peak product, and in Figure 5 for the off-peak product, in both cases using the parameter estimates based on ask prices from Table 12. Here, estimated premia use observed data for the misuse dummy, spot price (namely, marginal cost), misuse hours h_t and degree M_t, whereas fair premia are calculated using the same parameter estimates but imposing $D_t^M = h_t = M_t = 0$, i.e., the premium is $\alpha_t^* = \alpha_{01}^* + \alpha_1^* \log(S_t)$ as in (21), with S_t given by marginal cost. From the figures, both actual (estimated) and fair premia are clearly time-varying. They are negative in the early part of the period, and turn positive and large around the turn of the year 2005. For comparison, Lucia & Schwartz (2002) found negative premia α^* (positive market price of risk λ) for the earlier period December 1998 through November 1999. The turn of the year 2005 is exactly when CO_2-emission allowances were distributed, in accordance with the Kyoto protocol. Actual (estimated) premia are typically above fair premia for the peak product, but this phenomenon is not present in case of the off-peak product.

Based on the same parameter estimates, estimated and fair forward ask prices for a hypothetical contract with delivery on a single day one month hence appear in Figure 6 for the case of delivery during peak hours, and in Figure 7 for off-peak hour delivery. Consistent with Longstaff & Wang (2004), the forward prices exhibit stronger serial dependence than the corresponding spot prices.[18] Again, an increase in early 2005 is evident for both products, and

[18] The first order autocorrelation coefficient of the logarithm of the forward peak price in Figure 6 is .95

estimates reflecting misuse of market power hover above fair prices in case of the peak product.

Similarly, estimated and fair forward ask prices for quarterly contracts are plotted in three-dimensional graphs against both calendar date and time to delivery in the following exhibits. Figure 8 shows the estimated peak prices. The annual seasonal cycle is evident in the term to delivery dimension. As terms to delivery moves from one day to one year, the associated contracts cover quarterly delivery periods corresponding to the changing seasons from one day to one year ahead. Seasonality is also observed along the other dimension, corresponding to calendar date, with noticable highs in summer and lows in winter. The 3D image clearly reveals that in the summer, when the near (one day to delivery) contract is at a high, the forward curve is correspondingly high in the short end, then dips to a low at about half a year to delivery, to return to a high at the long (here, one year) end. In the winter, forward curves are more likely to exhibit a single (positive) hump at around six months to (summer) delivery. The corresponding fair peak prices, Figure 9, exhibit the same seasonal patterns, but naturally appear smoother than the estimates including the effects of misuse in Figure 8. Figures 10 and 11 show the similar estimated and fair off-peak ask prices. The degree of seasonality in both peak and off-peak prices is clearly strengthened after the introduction of CO_2-emission allowances in early 2005, reflecting the common seasonal in the underlying spot and CO_2-allowances.

All in all, the results from the structural pricing models provide strong evidence that misuse of market power in the forward market accompanied that which took place in the spot market.

3.3 Robustness Analysis

3.3.1 Stochastic Interest Rates

The expectation in (3) has been applied to forward prices. In fact, when the expectations operator is the risk neutral one (the conditional expectation under an equivalent martingale measure, as in the previous subsection), this is the relation for a futures price, and if interest rates are deterministic, forward and futures prices coincide (Cox, Ingersoll & Ross (1981)).

(standard error .01), and for the forward off-peak price in Figure 7 it is .93 (.01). The fair prices exhibited have even higher coefficients, at .99 and .98. These levels of serial dependence are clearly higher than for spot prices, i.e., from Table 1, the autocorrelation coefficient for log spot prices is .71 (.02), and from Table 10, the corresponding coefficient ϕ in the structural model is .69 during peak hours and .77 during off-peak hours (standard errors of .04 and .03).

With stochastic interest rates, the relation for the forward price becomes

$$F_{t,T} = e^{r_{t,T}(T-t)} E_t(e^{-\int_t^T r_s ds} S_T), \tag{24}$$

where $r_t = r_{t,t}$ is the instantaneous short rate, and (3) is an approximation. Another approximation in the analysis is (5). Delivery throughout the interval corresponds to the stream of contracts $F_{t,T_1}, ..., F_{t,T_2}$, with present values $e^{-r_{t,T_1}(T_1-t)} F_{t,T_1}, ..., e^{-r_{t,T_2}(T_2-t)} F_{t,T_2}$, and F_{t,T_1,T_2} is the constant payment so that the total present value of the two streams are equal, the present values of the constant payments being $e^{-r_{t,T_1}(T_1-t)} F_{t,T_1,T_2}, ..., e^{-r_{t,T_2}(T_2-t)} F_{t,T_1,T_2}$. It follows that

$$F_{t,T_1,T_2} = \frac{\sum_{T=T_1}^{T_2} e^{-r_{t,T}(T-t)} F_{t,T}}{\sum_{T=T_1}^{T_2} e^{-r_{t,T}(T-t)}}. \tag{25}$$

This does not require the assumption of deterministic interest rates. We found that our results are robust to using both (24) and (25).

3.3.2 Seasonality

Following Lucia & Schwartz (2002), an alternative specification to (17) is to take the seasonal as

$$f(t) = \alpha + \beta D_t + \sum_{i=2}^{12} \beta_i M_{it}, \tag{26}$$

where M_{it} is a dummy for month i, and the parameters $(\beta_2, ..., \beta_{12})$ replace (γ, τ) in the estimation of the spot price model by nonlinear regression. As before, the resulting parameters are substituted in the forward price expression. Our conclusions are robust to this variation, too.

3.3.3 Nonstorability

The forward premium regressions and structural models are based on the premise that the standard arbitrage relation $F_{t,T} = S_t e^{r_{t,T}(T-t)}$ from (1) is invalid due to nonstorability of the underlying. On the other hand, storable fuel may be burnt into electricity, thus raising the possibility that the arbitrage relation may nonetheless hold, at least to some degree of approximation. Here, we test our assumption that the relation is in fact invalid empirically, using a complementory daily-frequency forward basis regression analysis. Combining (1) and (5), we have

$$F_{t,T_1,T_2} = \frac{1}{T_2 - T_1 + 1} \sum_{T=T_1}^{T_2} S_t e^{r_{t,T}(T-t)}. \tag{27}$$

This may be rewritten as

$$F_{t,T_1,T_2} = S_t R_{t,T_1,T_2}, \tag{28}$$

where the relevant interest factor is given by

$$R_{t,T_1,T_2} = \frac{1}{T_2 - T_1 + 1} \sum_{T=T_1}^{T_2} e^{r_{t,T}(T-t)}. \tag{29}$$

The extended interest-parity relation (28) suggests a higher-frequency (namely, daily) analysis than in the forward premium regressions. However, it is not necessarily appropriate to regress F_{t,T_1,T_2} directly on $S_t R_{t,T_1,T_2}$ in the daily time series data, since both series are likely to be non-stationary. Instead, it is natural to calculate the forward basis, namely, the difference between the forward and spot prices,

$$B_{t,T_1,T_2} = F_{t,T_1,T_2} - S_t, \tag{30}$$

and examine how this evolves day-to-day, $t = t_1, ..., t_2$, over the trading period for a fixed contract (in particular, fixed T_1 and T_2). From the arbitrage relation (28), the correct basis should be

$$A_{t,T_1,T_2} = S_t R_{t,T_1,T_2} - S_t, \tag{31}$$

so the daily change $\Delta B_{t,T_1,T_2} = B_{t,T_1,T_2} - B_{t-1,T_1,T_2}$ in basis from day $t-1$ to t should be given by $\Delta A_{t,T_1,T_2} = S_t(R_{t,T_1,T_2} - 1) - S_{t-1}(R_{t-1,T_1,T_2} - 1)$, which is a condition on how changes in interest rates and spot prices interact to yield changes in forward prices. The validity of this condition may therefore be examined by regressing $\Delta B_{t,T_1,T_2}$, which involves forward prices, on $\Delta A_{t,T_1,T_2}$, which does not. This regression may now be expanded with changes in the spot variance, skewness, and misuse variables from earlier, but now calculated on a daily frequency, with Var_t the five-day moving average variance of spot prices as of t, $Skew_t$ the corresponding skewness, and $M_t^d = D_t^M(S_t - \widehat{S}_t)$. The final forward basis regression takes the form

$$\Delta B_{t,T_1,T_2} = \alpha + \phi \Delta A_{t,T_1,T_2} + \beta \Delta Var_t + \gamma \Delta Skew_t + \delta \Delta M_t^d + \varepsilon_{t,T_1,T_2}, \tag{32}$$

$t = t_1, ..., t_2$, for a typical contract trading from t_1 to t_2, with fixed delivery period given by (T_1, T_2). The forward basis regression is implemented as a pooled regression across all contracts, with T_1 and T_2 in (32) varying, depending on the contract. A value $\delta = 0$ of the coefficient on changes in misuse indicates that forward prices follow spot prices in lock-step when spot market misuse sets in, thus indicating severe spillover of misuse from the spot to the forward market. A value $\delta = -1$ would indicate no misuse in the forward market, at least to the extent that changes in M_t^d are primarily driven by S_t, as opposed to $\widehat{S}_t$. Estimates between 0 and -1 suggest partial spillover of misuse.

Results from estimation of (32) appear in Table 13, with results for Nord Pool close and OTC bid-ask midpoint data in Panel A, and results for ask prices in Panel B. All estimates of δ are between 0 and -1, in fact between 0 and $-.5$, and significantly different from both 0 and -1, except that the estimate for off-peak ask prices using marginal costs rather than spot prices turns out positive. Potentially, these results would indicate partial, but not full, spillover of misuse of market power from the spot to the forward market. On the other hand, the arbitrage relation appears violated, in that ϕ is significantly different from unity, indeed negative throughout, thus confirming our maintained assumption that nonstorability of electricity matters for pricing in this market.

3.3.4 Specification of Misuse

The Competition Council, the regulatory government agency in this market (see Section 2), has emphasized that the 2,384 misuse hours are a minimum set of hours, implying that misuse may have taken place in more hours. The rulings regarding the 2,384 misuse hours are based on an assumption that 100% of the cost of the CO_2-emission allowances distributed since January 1, 2005, in accordance with the Kyoto protocol should be included in fair spot prices. As the allowances were given to Elsam for free, it may not be fair to charge this cost to consumers. The

European Union has announced that 100% rollover is excessive. Germany has adopted a 25% rule. The resulting marginal cost series corresponding to three different rollover assumptions, namely, 100%, 25%, and 0%, are shown in Figure 12. The curves for the three alternative rollover percentages coincide until February 11, 2005, the start of CO_2 exchange prices. Also shown are marginal costs with 0% rollover but a 34% price variation allowance also applied by the regulator in some of their calculations, and this allowance applies to the entire period.

The regulator has mentioned that misuse in 2005-2006 was in more hours than in 2003-2004, but at a lower intensity. They indicate 547 peak misuse hours and 353 off-peak misuse hours in 2003-2004. For 2005-2006, they indicate 924 peak misuse hours and 560 off-peak misuse hours. This produces 60 misuse days in 2003-2004 and 96 misuse days in 2005-2006. If we reconstruct the set of misuse hours with a lower rollover percentage, we get more potential misuse hours. With 0% CO_2-rollover, we find 4,515 peak misuse hours and 5,885 off-peak misuse hours in 2003-2004 (starting of course July 1, 2003), and 5,951 peak misuse hours and 9,743 off-peak misuse hours in 2005-2006.[19] This produces 539 misuse days in 2003-2004 and 707 misuse days in 2005-2006. With 25% CO_2-rollover (the German case) we find 4,515 peak misuse hours and 5,885 off-peak misuse hours in 2003-2004, and 5,867 peak misuse hours and 8,815 off-peak misuse hours in 2005-2006. This produces 296 misuse days in 2003-2004 and 639 misuse days in 2005-2006. With 0% rollover but 34% price variability compensation, we find 1,993 peak misuse hours in 2003-2004 and 1,562 off-peak misuse hours in 2003-2004, and 5,292 peak misuse hours and 6,764 offpeak misuse hours in 2005-2006. This produces 296 misuse days in 2003-2004 and 666 misuse days in 2005-2006.

The precise specification matters for the assessment of total loss to consumers stemming from the misuse of market power in the forward market. As an illustration, we consider two example contracts, the Winter 1, 2004 contract and the Year 2007 contract (in Table 2, contract numbers 5 and 21). For each, we calculate loss due to misuse on a misuse day and a day without misuse, according to the ruling by the Council. A randomly selected misuse day where the first contract was traded is October 24, 2003, and October 27, 2003, is a non-misuse day. Using Model 3 from Table 12, the loss is 23.98% in the peak product and 24.90% in the off-peak

[19] Here and in the following, we illustrate the importance of the treatment of CO_2-emissions for the results by reidentifying potential misuse hours based on a comparison of observed hourly spot prices and daily marginal costs reflecting the alternative CO_2-rollover assumptions. A more precise assessment of actual misuse hours would require data on Elsam's hourly production capacity, bid and ask price submissions to Nord Pool, and marginal costs by plant, which are not available.

product on October 24, and 23.94% respectively 20.07% in the two products on October 27. Here, the losses are calculated in percent of ask prices, which are also used to estimate the forward price models. CO_2-allowances were only distributed in 2005 and later, so the 2004 contract was not affected by this. In the example, the difference in loss to consumers between the misuse and non-misuse day was mainly in the off-peak product. The picture is similar if using Model 1 from Table 12, with 20.08% respectively 20.05% loss in the peak product on the two dates, and 23.25% respectively 18.39% in the off-peak product.

For the 2007 contract, the loss assessment does depend on how CO_2 is figured into marginal cost. For this contract, an example misuse day according to the regulator is January 9, 2006, and January 6 is a non-misuse day. In this period (2005 on), more misuse days will be identified if a lower CO_2-rollover is applied. With 100% rollover, as in the regulator's calculations, the loss to consumers based on Model 3 from Table 12 is 11.11% in the peak product and −4.92% in the off-peak product on January 6, and 11.81% respectively −4.23% in the two products on January 9. Using Model 1, the peak losses are 7.05% and 7.80%, and the off-peak losses −0.06% respectively 0.64% on the two days.

The numbers are different for other rollover rates, other contracts, and other dates. To illustrate the dependence on rollover rates, we continue the example with the 2007 contract on January 6, 2006 (no misuse) and January 9, 2006 (misuse). If we use 0% rollover, instead of the 100% used by the regulator, the loss based on Model 3 is 45.02% in the peak product and 41.31% in the off-peak product on January 6, and 45.16% respectively 41.24% in the two products on January 9. Here, the spot price model has been reestimated on the smaller number of non-misuse days that remains when judging misuse based on the lower rollover rate. In particular, marginal cost still includes allowance for fixed cost and a 10% mark-up (see Section 2), so even though it does not include CO_2-rollover, hourly spot prices are considered to reflect misuse if they exceed marginal cost, and misuse days are days with at least one misuse hour. With the resulting smaller number of non-misuse days, spot price model estimates are different.

In estimating the forward price models, these new spot price model parameter estimates are used, and the new definitions of misuse days, hours, and marginal cost are used to define the misuse dummy variable D_t^M, the misuse hours h_t, and the degree of misuse M_t in the forward model risk premium specifications (21)-(23). The new forward model estimates are now used to calculate losses. In particular, the marginal cost estimate with 0% CO_2 is inserted into the forward pricing formula when calculating the loss. The only place marginal cost with 100% CO_2 is used is in the risk premium specification when estimating the forward model parameters and defining the forward pricing formula for the loss calculation, since market participants reasonably can be assumed to have expected the 100% rollover which apparantly was behind market pricing. Using these definitions in the example, Model 1 yields losses of 44.15% and 44.31% in the peak product and 41.03% respectively 41.12% in the off-peak product on January 6 and 9, i.e., there is not much difference between losses on the non-misuse and the misuse date, for either specification.

If 25% CO_2-rollover is applied, as in Germany, and marginal cost, misuse hours, as well as spot and forward model estimations are recalculated accordingly, the losses with Model 3 are 35.18% and 35.59% in the peak product on January 6 and 9, and 28.85% respectively 29.09% in the off-peak product on the two dates. With Model 1, losses are 35.11% and 35.45% in the peak product, and 29.88% respectively 30.16% in the off-peak product. In the example, losses are slightly higher in the peak than in the off-peak product, higher with 0% rollover than with 100%, and in between with 25% (the German rule), and there is almost no difference between losses on the two days. It is possible that misuse extended to other days than those singled out using these definitions. In particular, it is possible that there was misuse in the forward market even on days without misuse in the spot market.

If 0% CO_2-rollover is applied, but, following the Competition Council, a 34% price variability compensation is added to marginal cost, beyond allowance for fixed cost and 10% mark-up, then again misuse hours, spot and forward model calculations may be repeated with these new definitions. This produces in the 2007 contract example losses of 40.94% and 41.30% in the peak product, using Model 3, and 39.19% respectively 39.26% in the off-peak product. With Model 1, losses are 43.20% respectively 43.40% in the peak product, and 39.05% respectively 39.18% in the off-peak product on the two dates. In the example, allowing for price variability leads to losses that are slightly greater than when applying the German rollover rule.

Again, losses are different for other dates and other contracts. Losses in the Year 2007 contract on other dates than those two considered so far are illustrated for each of the alternative marginal cost measures in Figure 13 for the peak product, and in Figure 14 for the off-peak product, across the entire trading period, with the misuse date from the example highlighted as a vertical bar. Losses in the peak contract are positive almost throughout, but considerably lower when applying 100% rollover than any of the other rules. Losses for the off-peak contract are positive throughout except when applying the 100% rule. When this is applied, losses turn positive around the middle of the trading period in the example.

Summing up, losses to consumers stemming from misuse of market power in the forward market are considerable in magnitude, and this finding is robust to variations in the definition of marginal cost, as depending on CO_2 treatment and price variability compensation, and to variations in the risk premium specification in the forward pricing model.

4 Conclusion

Our analysis reveals that significant forward premia exist in OTC prices of electricity in Western Denmark. They are negative on average, considerable in magnitude (about 17% of average spot prices in case of base contracts), higher during peak hours than during off-peak hours, and negatively related to spot market volatility, consistent with Bessembinder & Lemmon (2002) and Longstaff & Wang (2004). We confirm that both spot and forward prices exhibit mean reversion and positive skewness, consistent with Routledge et al. (2000), Routledge et al. (2001), and Longstaff & Wang (2004). Nevertheless, spot market skewness does not appear to explain forward premia. Average skewness is in fact higher during our sample period than in the earlier study of the Nordic market by Lucia & Schwartz (2002), so the reason for the lesser role of skewness in explaining premia than that documented in Longstaff & Wang (2004) is more likely that they only consider day-ahead contracts.

During our period of analysis, 2003-2006, forward market pricing was evidently different on days where misuse of market power in the spot market by Elsam (now Dong Energy), the dominant producer in the area, had taken place according to the rulings by the Danish Competition Council, the government regulatory authority. Forward premia exhibit a strong positive relation to misuse of market power in the spot market. A possible explanation of this phenomenon is that Elsam used the forward market to disguise its spot market manipulation. If temporarily excessive manipulated spot prices had been accompanied by rational expectations forward prices reflecting lower future spot prices, then Elsam would have given itself away to regulators, who would immediately have noted that the company expected the spot price to be only temporarily high.

If forward prices during misuse had moved up in lockstep with spot prices as though governed by a standard, fixed forward pricing formula with constant risk premium, then this would presumably have sufficed to disguise spot market manipulation, but our empirical results document even stronger forward market misuse: The estimated risk premium itself increases during spot market misuse, thus increasing forward prices even more. The extent of this effect is different in the peak contract for delivery of electricity during the peak hours from 8 a.m. to 8 p.m., where most of the misuse of market power in the spot market took place, versus in the off-peak contract. Of course, whatever the motive for charging excessive prices, the end result is a loss to ultimate consumers. The empirical findings are consistent across forward premium regressions and structural forward pricing models, and robust to variations in definition of marginal cost, treatment CO_2-emission allowances, risk premium specification, and to using either bid-ask midpoints or only the ask prices most relevant to consumers. Both the separation of the peak from the base prices and of the ask from the midpoint prices are facilitated by our unique OTC data set. All in all, our results suggest that misuse of market power in the forward market for electricity accompanied that which took place in the spot market, according to the ruling by the regulator.

References

Bessembinder, H. & Lemmon, M. L. (2002), 'Equilibrium pricing and optimal hedging in electricity forward markets', *Journal of Finance* **57**, 1347–1382.

Coleman, T. & Li, Y. (1996), 'An interior, trust region approach for nonlinear minimization subject to bounds', *SIAM Journal on Optimization* **6**, 418–445.

Cootner, P. H. (1960), 'Returns to speculators: Telser vs. keynes', *Journal of Political Economy* **68**, 396–404.

Corona, A., Marchesi, M. & Ridella, S. (1987), 'Minimizing multimodel functions of continuous variables with "simulated annealing" algorithm', *ACM Transactions on Mathematical Software* **13**, 262–280.

Cox, J. C., Ingersoll, J. E. & Ross, S. A. (1981), 'The relationship between forward prices and futures prices', *Journal of Financial Economics* **9**, 321–346.

Fama, E. & French, K. (1987), 'Commodity futures prices: Some evidence on forecast power, premiums, and the theory of storage', *Journal of Business* **60**, 55–73.

Geman, H. & Roncoroni, A. (2006), 'Understanding the fine structure of electricity prices', *Journal of Business* **79**, 1225–1261.

Haldrup, N. & Nielsen, M. Ø. (2006), 'A regime switching long memory model for electricity prices', *Journal of Econometrics* **135**, 349–376.

Hicks, J. R. (1939), *Value and Capital*, Oxford University Press, Cambridge.

Hirshleifer, D. (1988), 'Residual risk, trading costs, and commodity futures risk premia', *Review of Financial Studies* **1**, 173–193.

Huber, P. J. (1967), 'The behavior of maximum likelihood estimates under non-standard conditions', *Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability* **4**, 221–233.

Hylleberg, S. (2004), 'On the exploitation of market power in the nordic electricity markets: The case of elsam', *Working Paper No. 2004-05, Department of Economics, University of Aarhus* .

Kaldor, N. (1939), 'Speculation and economic stability', *Review of Economic Studies* **7**, 1–27.

Keynes, J. M. (1930), *A Treatise on Money*, Macmillan, London.

Kirkpatrick, S., Gelatt, C. D. & Vecchi, M. P. (1983), 'Optimization by simulated annealing', *Science* **220**, 671–680.

Longstaff, F. A. & Wang, A. W. (2004), 'Electricity forward prices: A high-frequency empirical analysis', *Journal of Finance* **59**, 1877–1900.

Lucia, J. J. & Schwartz, E. S. (2002), 'Electricity prices and power derivatives: Evidence from the Nordic power exchange', *Review of Derivatives Research* **5**, 5–50.

Newey, W. K. & West, K. D. (1987), 'A simple positive semi-definite, heteroskedasticity and autocorrelation consistent covariance matrix', *Econometrica* **55**, 703–708.

Routledge, B. R., Seppi, D. J. & Spatt, C. S. (2000), 'Equilibrium forward curves for commodities', *Journal of Finance* **55**, 1297–1338.

Routledge, B. R., Seppi, D. J. & Spatt, C. S. (2001), 'The "spark spread": An equilibrium model of cross-commodity price relationships in electricity', *Working Paper No. 1999-15, Graduate School of Industrial Administration, Carnegie Mellon University* .

Schwartz, E. S. (1997), 'The stochastic behavior of commodity prices: Implications for valuation and hedging', *Journal of Finance* **52**, 923–973.

Szu, H. & Hartley, R. (1987), 'Fast simulated annealing', *Physics Letters A* **12**, 157–162.

Telser, L. G. (1958), 'Futures trading and the storage of cotton and wheat', *Journal of Political Economy* **66**, 133–144.

White, H. (1980), 'A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity', *Econometrica* **48**, 817–838.

Table 1: Summary Statistics - Spot Prices and Marginal Costs

Variable	Mean	Variance	Skewness	Kurtosis	Autocorr.	N
Hourly spot price	252.14 (0.6050)	16038 (850.05)	5.774 (1.453)	124.1 (43.80)	0.773 (0.014)	43820
Log of non-zero price	5.422 (0.0026)	0.3028 (0.0091)	-3.640 (0.3762)	40.17 (5.517)	0.868 (0.011)	43661
Daily base price	252.13 (2.167)	8575.9 (728.5)	1.823 (0.7412)	14.18 (7.160)	0.689 (0.017)	1826
Log of daily base price	5.467 (0.0084)	0.1281 (0.0056)	-0.3134 (0.1758)	4.495 (0.8044)	0.708 (0.016)	1826
Daily base excl. misuse	242.49 (2.083)	7247.0 (568.9)	1.580 (0.5975)	11.29 (5.115)	0.740 (0.016)	1670
Marginal cost	212.42 (1.753)	5613.3 (129.1)	0.4527 (0.0539)	1.965 (0.0923)	0.999 (0.001)	1826
Misuse excluded	208.97 (1.816)	5508.1 (139.1)	0.5214 (0.0598)	2.065 (0.1083)	0.999 (0.001)	1670
Peak price	307.41 (3.705)	17904 (3286.1)	4.001 (2.411)	44.93 (33.26)	0.547 (0.023)	1304
Misuse excluded	290.93 (3.350)	12973 (1922.9)	2.828 (1.707)	26.40 (21.07)	0.686 (0.021)	1156
Off-peak price	224.50 (1.722)	5415.0 (348.86)	1.141 (0.4343)	8.579 (3.211)	0.809 (0.014)	1826
Misuse excluded	219.36 (1.773)	5247.5 (382.31)	1.303 (0.5107)	9.864 (3.879)	0.793 (0.015)	1670

Note: Summary statistics are reported for DK1 (Western Denmark) spot prices for the period January 1, 2002, through December 31, 2006. There are 24 hourly spot prices per day. Daily base prices are daily averages of hourly prices across the 24-hour (base) period. Peak prices are daily averages of hourly prices across peak hours from 8 a.m. to 8 p.m., excluding weekends. Off-peak prices are daily averages across the remaining hours (from Midnight to 8 a.m. and from 8 p.m. to Midnight on weekdays, and across the 24-hour period on weekends). Also reported are summary statistics for daily marginal costs, as well as statistics that exclude days with misuse of market power in the spot market, according to the ruling by the Danish Competition Council. Asymptotic standard errors are in parentheses.

Table 2: Forward Contracts

Contract Number	Contract Name	Nord Pool Launch	OTC Base Launch	OTC Peak Launch	Length of Delivery
1	Winter 1, 2003	05-02-2002	08-30-2002	08-30-2002	120
2	Summer, 2003	10-01-2002	08-30-2002	09-12-2002	153
3	Winter 2, 2003	12-27-2002	08-30-2002	09-12-2002	92
4	Year, 2003	01-02-2002	08-30-2002	09-12-2002	365
5	Winter 1, 2004	05-02-2003	08-30-2002	08-27-2003	121
6	Summer, 2004	10-01-2003	08-30-2002	08-27-2003	153
7	Winter 2, 2004	12-23-2003	08-30-2002	08-27-2003	92
8	Year, 2004	01-02-2003	08-30-2002	08-27-2003	366
9	Winter 1, 2005	05-03-2004	09-12-2002	12-09-2003	120
10	Summer, 2005	10-01-2004	09-12-2002	12-09-2003	153
11	Winter 2, 2005	12-28-2004	09-12-2002	12-09-2003	92
12	Year, 2005	01-02-2004	09-12-2002	12-09-2003	365
13	1st Quarter, 2006	05-02-2005	01-15-2004	01-16-2004	90
14	2nd Quarter, 2006	10-04-2005	01-15-2004	01-16-2004	91
15	3rd Quarter, 2006	10-10-2005	01-15-2004	01-16-2004	92
16	4th Quarter, 2006	12-28-2005	01-15-2004	01-16-2004	92
17	Year, 2006	12-29-2004	05-27-2003	01-15-2004	365
18	1st Quarter, 2007	01-02-2006	03-10-2006	03-10-2006	90
19	2nd Quarter, 2007	01-02-2006	07-03-2006	07-03-2006	91
20	3rd Quarter, 2007	01-02-2006	10-03-2006	10-03-2006	92
21	Year, 2007	01-02-2006	01-15-2004	10-06-2005	365
22	Year, 2008	11-13-2006	01-04-2005	N.A.	366
23	Year, 2009	N.A.	01-02-2006	N.A.	365

Note: Contract names define the delivery period. Winter 1 is January 1 through April 30 of the given year, Summer is May 1 through September 30, Winter 2 is October 1 through December 31. Quarter contracts are on a January cycle. Official Nord Pool contracts are all base contracts, for continuous delivery across the 24-hour period 7 days a week, launched on the dates reported in the table. The OTC peak contracts are for delivery during peak hours from 8 a.m. to 8 p.m., excluding weekends. The OTC products are based on the forward price indications sent out by email around 10 a.m. on each trading day starting on the dates reported in the table by Elsam A/S (from 2006 Dong Energy).

Table 3: Summary Statistics - Forward Prices

Variable	Mean	Variance	Skewness	Kurtosis	Autocorr.	N
Nord Pool	284.37	5884.7	0.4360	2.410	0.997	4368
	(1.161)	(105.7)	(0.0454)	(0.0966)	(0.001)	
Misuse excluded	278.40	5828.4	0.5124	2.470	0.997	3751
	(1.247)	(115.4)	(0.0504)	(0.1107)	(0.001)	
Base B/A Midpoint	254.05	4747.5	0.9851	3.278	0.998	10068
	(0.6867)	(71.41)	(0.0432)	(0.1232)	(0.001)	
Misuse excluded	250.03	4459.9	1.058	3.527	0.997	8880
	(0.7087)	(75.23)	(0.0494)	(0.1452)	(0.001)	
Nord Pool	289.94	5738.8	0.5544	2.334	0.996	3735
Common contracts	(1.240)	(108.5)	(0.0481)	(0.1037)	(0.001)	
Misuse excluded	284.54	5599.6	0.6393	2.440	0.996	3207
	(1.321)	(118.7)	(0.0543)	(0.1217)	(0.002)	
Base B/A Midpoint	289.53	5738.7	0.5588	2.341	0.996	3735
Common contracts	(1.240)	(108.8)	(0.0486)	(0.1067)	(0.001)	
Misuse excluded	283.98	5580.3	0.6429	2.441	0.996	3207
	(1.319)	(118.3)	(0.0546)	(0.1244)	(0.002)	
Peak B/A Midpoint	339.45	6741.2	1.030	3.152	0.998	5934
	(1.066)	(128.4)	(0.0543)	(0.1543)	(0.001)	
Misuse excluded	333.20	6207.6	1.186	3.681	0.998	5232
	(1.089)	(140.5)	(0.0682)	(0.2114)	(0.001)	
Off-Peak B/A Midpoint	236.17	3505.3	1.028	3.759	0.995	5934
	(0.7686)	(75.59)	(0.0634)	(0.1816)	(0.001)	
Misuse excluded	232.68	3291.9	1.081	3.911	0.994	5232
	(0.7932)	(77.65)	(0.0696)	(0.2000)	(0.001)	
Peak Ask Price	350.55	6587.1	1.012	3.173	0.998	5934
	(1.054)	(126.1)	(0.0545)	(0.1554)	(0.001)	
Misuse excluded	344.36	6078.3	1.166	3.714	0.997	5232
	(1.078)	(138.4)	(0.0687)	(0.2139)	(0.001)	
Off-Peak Ask Price	246.78	3490.9	1.033	3.835	0.995	5934
	(0.7670)	(76.30)	(0.0646)	(0.1854)	(0.001)	
Misuse excluded	243.34	3290.1	1.089	4.019	0.994	5232
	(0.7930)	(79.03)	(0.0717)	(0.2099)	(0.001)	

Note: Summary statistics for the period January 1, 2002, through December 31, 2006, are reported for official Nord Pool closing prices for forward contracts and the forward price indications (bid-ask midpoints and ask prices) for the similar base product (24 hours of delivery each day in the delivery period) sent out by email around 10 a.m. on each trading day by Elsam A/S (from 2006 Dong Energy). Also reported are statistics for both bid-ask midpoints and ask prices for the corresponding peak product with delivery during peak hours from 8 a.m. to 8 p.m. each day in the delivery period, excluding weekends, and the off-peak product with delivery during the remaining off-peak hours from Midnight to 8 a.m. and from 8 p.m. to Midnight on weekdays, and across the 24-hour period on weekends. For each contract, trading ends the day before the beginning of the delivery period, and starts several months before (see Table 2). In addition, statistics are reported that exclude days with misuse of market power in the spot market, according to the ruling by the Danish Competition Council. Asymptotic standard errors are in parentheses.

Table 4: Forward Price Differences

	Full period Jan., 2002-Dec., 2006	Misuse period July, 2003-Dec., 2006	Misuse period Misuse excluded
Mean(Base at $t-$Nord Pool at t)	-0.1222% (0.0361%)	0.0418% (0.0290%)	0.0182% (0.0308%)
Mean(Base at $t-$Nord Pool at $t-1$)	-0.0492% (0.0332%)	0.0810% (0.0244%)	0.0678% (0.0290%)
Mean(Abs(Base at $t-$Nord Pool at t))	1.2842% (0.0292%)	1.1077% (0.0211%)	1.0714% (0.0224%)
Mean(Abs(Base at $t-$Nord Pool at $t-1$))	1.1487% (0.0273%)	0.9544% (0.0171%)	1.0229% (0.0207%)
RMSE(Base at $t-$Nord Pool at t)	2.1978% (0.0355%)	1.6183% (0.0286%)	1.5636% (0.0314%)
RMSE(Base at $t-$Nord Pool at $t-1$)	2.0205% (0.0326%)	1.3472% (0.0238%)	1.3472% (0.0238%)
N	3735	3112	2584

Note: Sample means are reported for the differences between the forward price indications (bid-ask midpoints) for the base product (24 hours of delivery each day in the delivery period) sent out by email around 10 a.m. on each trading day by Elsam and the official Nord Pool closing prices for the corresponding contract (same delivery period) for the same and the previous trading day, respectively. Also reported are the sample means of the corresponding absolute differences, as well as the sample root-mean-squared-error (RMSE) of the differences. All contracts are used, and for all trading days within the indicated periods where prices from both Elsam and Nord Pool are available. For each contract, trading ends the day before the beginning of the delivery period, and starts several months before (see Table 2). In addition, statistics are reported that exclude days with misuse of market power in the spot market, according to the ruling by the Danish Competition Council. Asymptotic standard errors are in parentheses.

Table 5: Forward Price Correlations

	Full period Jan., 2002-Dec., 2006	Misuse period July, 2003-Dec., 2006	Misuse period Misuse excluded
Corr(Base at t, Nord Pool at t)	0.9952 (0.0163)	0.9973 (0.0179)	0.9974 (0.0196)
Corr(Base at t, Nord Pool at $t-1$)	0.9960 (0.0163)	0.9981 (0.0179)	0.9977 (0.0197)
Corr(Log(Base at t), Log(Nord Pool at t))	0.9960 (0.0163)	0.9976 (0.0179)	0.9978 (0.0196)
Corr(Log(Base at t), Log(Nord Pool at $t-1$))	0.9966 (0.0164)	0.9984 (0.0179)	0.9980 (0.0197)
Corr(Δ(Base at t), Δ(Nord Pool at t))	0.3945 (0.0065)	0.4278 (0.0077)	0.4362 (0.0086)
Corr(Δ(Base at t), Δ(Nord Pool at $t-1$))	0.3943 (0.0065)	0.4277 (0.0077)	0.4277 (0.0077)
Corr(Δ(Log(Base at t)), Δ(Log(Nord Pool at t)))	0.4033 (0.0066)	0.4172 (0.0075)	0.4227 (0.0083)
Corr(Δ(Log(Base at t)), Δ(Log(Nord Pool at $t-1$)))	0.4036 (0.0066)	0.4175 (0.0075)	0.4175 (0.0075)
N	3735	3112	2584

Note: Sample correlations are reported between the forward price indications (bid-ask midpoints) for the base product (24 hours of delivery each day in the delivery period) sent out by email around 10 a.m. on each trading day by Elsam and the official Nord Pool closing prices for the corresponding contract (same delivery period) for the same and the previous trading day, respectively. Also reported are correlations for log prices, price changes, and changes in log prices. All contracts are used, and for all trading days within the indicated periods where prices from both Elsam and Nord Pool are available. For each contract, trading ends the day before the beginning of the delivery period, and starts several months before (see Table 2). In addition, statistics are reported that exclude days with misuse of market power in the spot market, according to the ruling by the Danish Competition Council. Asymptotic standard errors are in parentheses.

Table 6: Stationarity Tests

	DF test Full period	ADF test Full period	ADF test Misuse period	ADF test Misuse excluded
Log of base price	−17.7	−4.38	−3.97	−3.25
	(0.000)	(0.000)	(0.000)	(0.001)
Log of peak price	−14.9	−3.87	−2.95	−2.09
	(0.000)	(0.000)	(0.003)	(0.037)
Log of off-peak price	−15.5	−4.24	−3.86	−3.68
	(0.000)	(0.000)	(0.000)	(0.000)
Log of marginal cost	−0.99	−1.13	−2.15	−2.24
	(0.322)	(0.257)	(0.032)	(0.025)

Note: Dickey-Fuller (DF) and augmented DF (ADF, 10 lags) t-statistics are reported for the base price (daily average of hourly spot prices across the 24-hour (base) period), the peak price (daily average across peak hours from 8 a.m. to 8 p.m., excluding weekends), the off-peak price (daily average across the remaining hours, from Midnight to 8 a.m. and from 8 p.m. to Midnight on weekdays, and across the 24-hour period on weekends), and marginal cost. Statistics are reported for the full period January 1, 2002, through December 31, 2006. Also reported are statistics for the misuse period July 1, 2003, through December 31, 2006, as well as statistics that exclude days with misuse of market power in the spot market, according to the ruling by the Danish Competition Council. Asymptotic p-values are in parentheses.

Table 7: Effect of Spot Market Misuse on Forward Prices

Contracts	Forward Premium	Forward Premium Misuse excluded	Forward Premium Misuse days only	Difference Misuse less non-misuse
Nord Pool Close	−8.953 (13.951)	−10.016 (13.951)	−3.653 (13.624)	6.362 (2.299)
Base B/A Midpoints	−42.848 (18.972)	−43.639 (19.456)	−38.461 (17.146)	5.179 (9.379)
Peak B/A Midpoints	−11.844 (26.295)	−14.661 (26.892)	7.507 (23.460)	22.168 (10.180)
Off-Peak B/A Midpoints	−34.748 (12.692)	−36.098 (13.204)	−25.668 (9.592)	10.430 (5.807)
Peak Ask Prices	0.414 (26.503)	−2.361 (27.097)	19.461 (23.690)	21.822 (10.124)
Off-Peak Ask Prices	−24.116 (12.485)	−25.421 (12.972)	−15.362 (9.564)	10.058 (5.679)
Peak Ask Prices MC used for spot	70.980 (20.898)	−2.361 (27.097)	19.461 (23.690)	21.822 (10.124)
Off-Peak Ask Prices MC used for spot	−29.787 (18.001)	−25.421 (12.972)	−15.362 (9.564)	10.058 (5.679)

Note: Forward premia (8) are reported, along with differences between average forward prices across days with misuse of market power in the spot market, according to the ruling by the Danish Competition Council, and average forward prices across other days in the period July 1, 2003, through December 31, 2006. Statistics are reported for official Nord Pool closing prices and the forward price indications (bid-ask midpoints and ask prices) for the similar base product (24 hours of delivery each day in the delivery period) sent out by email around 10 a.m. on each trading day by Elsam. Also reported are statistics for both bid-ask midpoints and ask prices for the corresponding peak product with delivery during peak hours from 8 a.m. to 8 p.m. each day in the delivery period, excluding weekends, and the off-peak product with delivery during the remaining off-peak hours from Midnight to 8 a.m. and from 8 p.m. to Midnight on weekdays, and across the 24-hour period on weekends. For each contract, trading ends the day before the beginning of the delivery period, and starts several months before (see Table 2). Robust Newey & West (1987) heteroskedasticity and autocorrelation consistent standard errors are in parentheses.

Table 8: Forward Premium Regressions

Contracts	Const.	Variance$\times 10^{-3}$	Skewness	Maturity	$\overline{M}_f$	$\overline{R}^2$	p-value
Nord Pool Close	23.629 (13.587)	−10.005 (2.780)				0.28	0.052
	17.216 (14.019)	−6.534 (3.653)	−8.586 (5.564)			0.33	0.108
	52.222 (24.171)	−8.329 (3.839)		−0.167 (0.104)		0.34	0.105
	19.930 (21.703)	−9.600 (3.116)			0.101 (0.283)	0.28	0.163
Base B/A Midpoints	−5.014 (19.614)	−11.618 (3.387)				0.34	0.028
	−5.647 (20.488)	−11.275 (4.111)	−0.848 (6.487)			0.34	0.100
	53.039 (21.608)	−5.791 (3.569)		−0.207 (0.075)		0.59	0.007
	−43.940 (28.846)	−8.518 (3.446)			1.028 (0.479)	0.51	0.021
Peak B/A Midpoints	31.111 (21.294)	−5.986 (1.243)				0.45	0.008
	30.515 (19.395)	−8.105 (1.720)	12.401 (9.637)			0.53	0.016
	107.419 (26.904)	−4.599 (1.161)		−0.259 (0.092)		0.73	0.001
	6.619 (34.718)	−5.054 (1.597)			0.671 (0.536)	0.49	0.024
Off-Peak B/A Midpoints	−3.732 (23.308)	−18.296 (11.012)				0.15	0.166
	−22.385 (25.932)	−14.190 (9.835)	−25.719 (21.872)			0.28	0.169
	23.808 (25.945)	−4.031 (9.079)		−0.156 (0.075)		0.37	0.080
	−53.128 (29.179)	−1.275 (10.916)			6.667 (2.511)	0.41	0.056

Note: Estimates are reported for the forward premium regressions

$$P^i = \alpha + \beta Var^i + \gamma Skew^i + \delta Mat^i + \rho \overline{M}_f^i + \varepsilon^i$$

from (12) of forward premia P^i from (8) on spot variance (9), skewness (10), maturity, and average spot market misuse $\overline{M}_f^i$ from (11). Robust Huber (1967) and White (1980) heteroskedasticity consistent standard errors are in parentheses. Also reported are the adjusted $\overline{R}^2$-statistic and the p-value of overall significance of the regression.

Table 9: Forward Premium Regressions

Contracts	Const.	Variance$\times 10^{-3}$	Skewness	Maturity	$\overline{M}_f$	$\overline{R}^2$	p-value
Peak Ask Prices	43.693	−6.031				0.45	0.008
	(21.411)	(1.254)					
	43.095	−8.157	12.445			0.53	0.016
	(19.550)	(1.713)	(9.666)				
	121.220	−4.623		−0.264		0.74	0.001
	(26.466)	(1.170)		(0.091)			
	18.104	−5.057			0.701	0.50	0.023
	(34.865)	(1.607)			(0.536)		
Off-Peak Ask Prices	6.007	−17.769				0.15	0.178
	(23.408)	(11.137)					
	−12.715	−13.649	−25.813			0.27	0.177
	(25.899)	(9.965)	(21.793)				
	33.409	−3.576		−0.155		0.36	0.086
	(26.121)	(9.070)		(0.076)			
	−43.454	−0.726			6.676	0.40	0.059
	(29.127)	(11.052)			(2.497)		
Peak Ask Prices	88.291	−26.960				0.16	0.159
MC used for spot	(20.218)	(11.628)					
	83.390	−23.998	−14.548			0.19	0.311
	(22.399)	(14.848)	(24.527)				
	130.797	−16.040		−0.149		0.29	0.158
	(26.739)	(16.373)		(0.114)			
	40.837	−11.475			1.414	0.46	0.034
	(27.556)	(11.895)			(0.547)		
Off-Peak Ask Prices	−14.163	−24.332				0.15	0.166
MC used for spot	(18.364)	(10.794)					
	−20.583	−20.451	−19.069			0.22	0.252
	(19.401)	(13.192)	(21.481)				
	29.632	−13.080		−0.153		0.31	0.125
	(26.994)	(14.414)		(0.110)			
	−53.696	−4.613			8.722	0.48	0.027
	(22.408)	(12.331)			(3.081)		

Note: Estimates are reported for the forward premium regressions

$$P^i = \alpha + \beta Var^i + \gamma Skew^i + \delta Mat^i + \rho \overline{M}_f^i + \varepsilon^i$$

from (12) of forward premia P^i from (8) on spot variance (9), skewness (10), maturity, and average spot market misuse $\overline{M}_f^i$ from (11). Robust Huber (1967) and White (1980) heteroskedasticity consistent standard errors are in parentheses. Also reported are the adjusted $\overline{R}^2$-statistic and the p-value of overall significance of the regression.

Table 10: Structural Spot Price Models

Panel A Parameter:	Spot price 2002-2006	Spot price Misuse excluded	Marginal cost 2002-2006	Marginal cost Misuse excluded
α	5.5322 (0.0201)	5.5196 (0.0200)	5.3211 (0.0291)	5.419 (0.0554)
β	−0.2197 (0.0113)	−0.2062 (0.0114)	−0.0001 (0.0005)	−0.000 (0.001)
γ	−0.0963 (0.0241)	−0.0814 (0.0241)	0.0103 (0.0211)	−0.008 (0.024)
τ	−88.4898 (18.2863)	−91.7437 (21.6822)	0.0000 (113.33)	0.002 (339.123)
ϕ	0.7244 (0.0278)	0.7437 (0.0283)	0.9900 (·)	0.9900 (·)
$\overline{R}^2$	0.59	0.58	0.99	0.99
Q_{10}	234.03	208.78	255.66	260.08
T	1825	1669	1825	1669
Panel B Parameter:	Peak hours 2002-2006	Peak hours Misuse excluded	Off-peak hours 2002-2006	Off-peak hours Misuse excluded
α	5.6531 (0.0229)	5.6222 (0.0234)	5.3801 (0.0213)	5.3853 (0.0206)
β			−0.0653 (0.0101)	−0.0623 (0.0106)
η	−0.1445 (0.1130)	−0.1595 (0.1420)		
γ	−0.1222 (0.0288)	−0.0966 (0.0281)	0.0726 (0.0261)	0.0636 (0.0265)
τ	−83.9278 (17.0404)	−89.1551 (21.7523)	85.7736 (26.4489)	79.4846 (28.9867)
ϕ	0.6858 (0.0423)	0.7439 (0.0418)	0.7653 (0.0260)	0.7650 (0.0272)
$\overline{R}^2$	0.53	0.58	0.60	0.57
Q_{10}	184.71	159.51	165.34	146.44
T	1303	1155	1825	1669

Note: Nonlinear regression estimates are reported for the structural spot price models (17)-(19). Robust Huber (1967) and White (1980) heteroskedasticity consistent standard errors are in parentheses. Also reported are adjusted $\overline{R}^2$, the Ljung-Box portmanteau statistic for up to tenth order serial dependence in the residuals, denoted Q_{10}, and sample size T.

Table 11: Structural Forward Price Models

Forward Prices	α_0^*	α_1^*	$\overline{R}^2$	ME	MAE	$RMSE$	N
Nord Pool Full period in spot	−3.7452 (0.0483)	0.7143 (0.0087)	0.97	−0.0185 (0.0028)	0.1286 (0.0016)	0.1575 (0.0017)	3112
Base B/A Midpoints Full period in spot	−3.7497 (0.0491)	0.7152 (0.0089)	0.97	−0.0186 (0.0028)	0.1296 (0.0016)	0.1583 (0.0017)	3112
Nord Pool Misuse excluded in spot	−3.7373 (0.0468)	0.7145 (0.0085)	0.97	−0.0192 (0.0027)	0.1257 (0.0016)	0.1540 (0.0017)	3112
Base B/A Midpoints Misuse excluded in spot	−3.7418 (0.0475)	0.7154 (0.0086)	0.97	−0.0193 (0.0028)	0.1267 (0.0016)	0.1548 (0.0017)	3112
Peak B/A Midpoints Misuse excluded in spot	−4.0644 (0.0381)	0.7683 (0.0071)	0.97	−0.0148 (0.0019)	0.1160 (0.0012)	0.1474 (0.0015)	5741
Off-Peak B/A Midpoints Misuse excluded in spot	−4.3377 (0.0432)	0.8023 (0.0080)	0.98	−0.0188 (0.0019)	0.1126 (0.0012)	0.1438 (0.0014)	5741
Peak Ask Prices Misuse excluded in spot	−3.8418 (0.0371)	0.7337 (0.0069)	0.98	−0.0133 (0.0019)	0.1120 (0.0012)	0.1423 (0.0014)	5741
Off-Peak Ask Prices Misuse excluded in spot	−4.0858 (0.0419)	0.7645 (0.0078)	0.98	−0.0170 (0.0018)	0.1074 (0.0011)	0.1372 (0.0013)	5741
Peak Ask Prices MC for spot, misuse excluded	−3.5746 (0.0658)	0.7461 (0.0121)	0.98	0.0123 (0.0018)	0.1033 (0.0012)	0.1384 (0.0048)	5741
Off-Peak Ask Prices MC for spot, misuse excluded	−4.1565 (0.0451)	0.7759 (0.0084)	0.98	−0.0089 (0.0017)	0.0994 (0.0010)	0.1269 (0.0012)	5741
Peak Ask Prices Spot in premium, misuse excluded	−2.2715 (0.1431)	0.4308 (0.0252)	0.97	−0.0229 (0.0022)	0.1264 (0.0014)	0.1656 (0.0041)	5741
Off-Peak Ask Prices Spot in premium, misuse excluded	−4.0736 (0.0553)	0.7652 (0.0101)	0.97	−0.0190 (0.0022)	0.1279 (0.0015)	0.1697 (0.0021)	5741

Note: Nonlinear regression estimates are reported for the structural forward price models (20)-(21). Robust Huber (1967) and White (1980) heteroskedasticity consistent standard errors are in parentheses. Also reported are adjusted $\overline{R}^2$, the mean pricing error, denoted ME, the mean absolute error, MAE, and sample size N.

Table 12: Alternative Risk Premium Specifications - Ask Prices

Variable	Model 1 Peak	Model 2 Peak	Model 3 Peak	Model 1 Off-Peak	Model 2 Off-Peak	Model 3 Off-Peak
D_t^M	−3.7160	−3.8648	−3.8714	−4.0254	−4.8006	−4.7778
	(0.0396)	(0.0510)	(0.0514)	(0.0438)	(0.0522)	(0.0511)
$1 - D_t^M$	−3.7798	−3.8653	−3.8798	−4.0557	−4.7378	−4.7125
	(0.0377)	(0.0505)	(0.0508)	(0.0424)	(0.0509)	(0.0495)
$\log(S_t)$	0.7209	0.7273	0.7305	0.7583	0.8861	0.8807
	(0.0070)	(0.0089)	(0.0089)	(0.0079)	(0.0095)	(0.0092)
$D_t^M \cdot M_t$		−0.0841	−0.0914		0.6472	0.6410
		(0.0278)	(0.0289)		(0.0421)	(0.0417)
$(1 - D_t^M) \cdot M_t$		0.2821	0.2818		0.3501	0.3473
		(0.0257)	(0.0258)		(0.0159)	(0.0159)
h_t		0.0093	0.0099		0.0027	0.0026
		(0.0010)	(0.0010)		(0.0010)	(0.0010)
$e^{-\alpha_{41}^* N_t}$		0.3076			−0.0168	
		(0.6690)			(0.0072)	
α_{41}^*		2.1660			0.1427	
		(2.1712)			(0.1377)	
$\overline{R}^2$	0.98	0.98	0.98	0.98	0.98	0.98
ME	−0.0129	−0.0103	−0.0103	−0.0169	−0.0133	−0.0134
	(0.0019)	(0.0017)	(0.0017)	(0.0018)	(0.0017)	(0.0017)
MAE	0.1106	0.1027	0.1032	0.1074	0.1042	0.1039
	(0.0012)	(0.0010)	(0.0010)	(0.0011)	(0.0011)	(0.0011)
$RMSE$	0.1410	0.1299	0.1302	0.1370	0.1325	0.1323
	(0.0015)	(0.0015)	(0.0015)	(0.0013)	(0.0013)	(0.0013)
N	5741	5741	5741	5741	5741	5741

Note: Nonlinear regression estimates are reported for the structural forward price models (20)-(23). Robust Huber (1967) and White (1980) heteroskedasticity consistent standard errors are in parentheses. Also reported are adjusted $\overline{R}^2$, the mean pricing error, denoted ME, the mean absolute error, MAE, the root mean squared error, $RMSE$, and sample size N.

Table 13: Pooled Forward Basis Regressions

Panel A	Nord Pool Close	Base B/A Midpoints	Peak B/A Midpoints	Off-Peak B/A Midpoints
Const.	-0.757 (0.256)	-0.097 (0.159)	-0.762 (0.258)	-0.523 (0.111)
$\Delta A_{t,T_1,T_2}$	-33.444 (2.931)	-10.765 (1.573)	-27.366 (3.291)	-26.471 (0.770)
$\Delta Var_t \times 10^{-3}$	0.652 (0.282)	-0.623 (0.192)	-0.316 (0.110)	-1.757 (0.387)
$\Delta Skew_t$	-3.250 (2.060)	-3.783 (1.571)	-1.108 (3.719)	-4.682 (0.787)
ΔM_t^d	-0.464 (0.078)	-0.478 (0.064)	-0.395 (0.099)	-0.159 (0.027)
$\overline{R}^2$	0.82	0.77	0.84	0.71
DW	2.78	2.83	2.87	2.66
N	3471	7766	5723	5723
Panel B	Peak Ask Prices	Off-Peak Ask Prices	Peak Ask Prices MC used for spot	Off-Peak Ask Prices MC used for spot
Const.	-0.768 (0.257)	-0.529 (0.110)	-0.258 (0.071)	-0.268 (0.061)
$\Delta A_{t,T_1,T_2}$	-27.366 (3.291)	-26.473 (0.770)	-13.396 (1.119)	-13.625 (1.036)
$\Delta Var_t \times 10^{-3}$	-0.316 (0.110)	-1.737 (0.386)	6.5×10^{-6} (2.5×10^{-6})	0.115 (0.112)
$\Delta Skew_t$	-1.100 (3.716)	-4.687 (0.788)	0.866 (0.190)	-0.008 (0.152)
ΔM_t^d	-0.395 (0.099)	-0.159 (0.027)	-0.001 (0.001)	0.016 (0.005)
$\overline{R}^2$	0.84	0.71	0.11	0.11
DW	2.87	2.66	2.01	2.28
N	5723	5723	5723	5723

Note: Estimates are reported for the pooled forward basis regressions

$$\Delta B_{t,T_1,T_2} = \alpha + \phi \Delta A_{t,T_1,T_2} + \beta \Delta Var_t + \gamma \Delta Skew_t + \delta \Delta M_t^d + \varepsilon_{t,T_1,T_2}.$$

Robust Newey & West (1987) heteroskedasticity and autocorrelation consistent standard errors are in parentheses. Also reported are the adjusted $\overline{R}^2$ and Durbin-Watson (DW) statistics, and the sample size N.

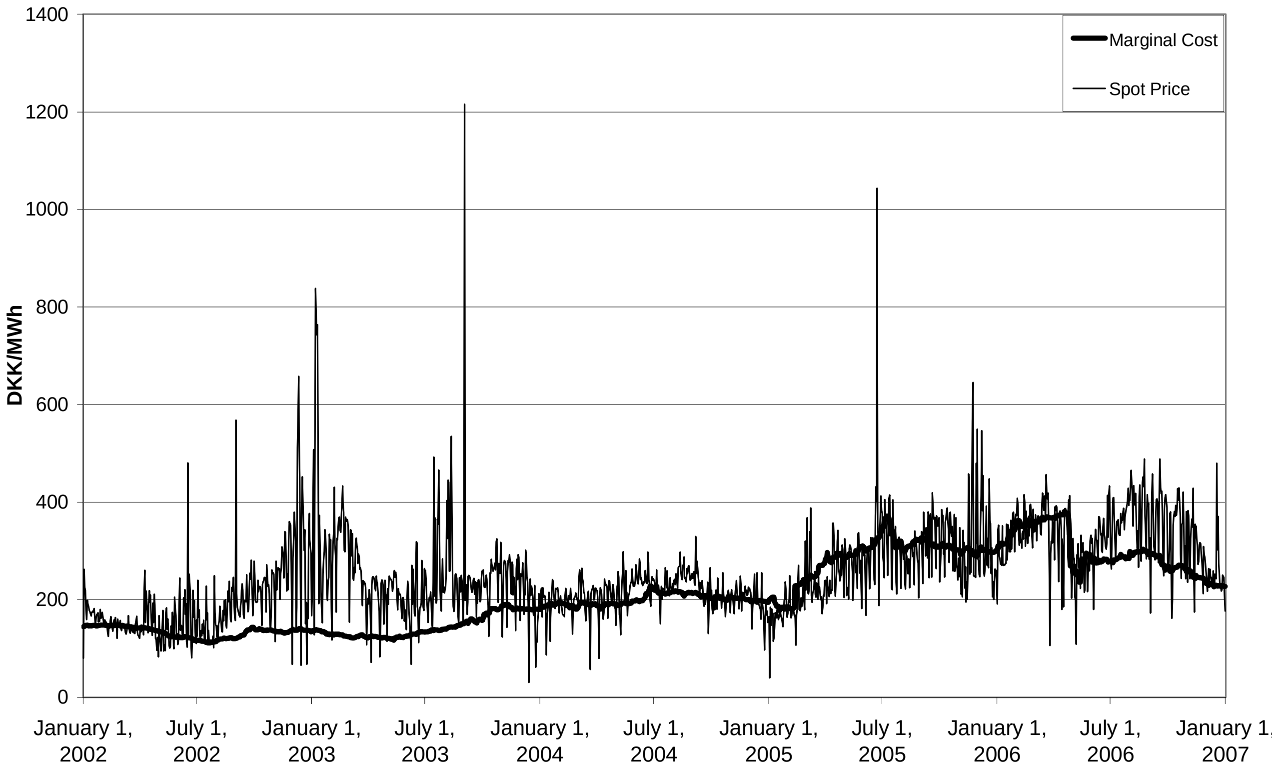

Figure 1: Spot Price and Marginal Cost

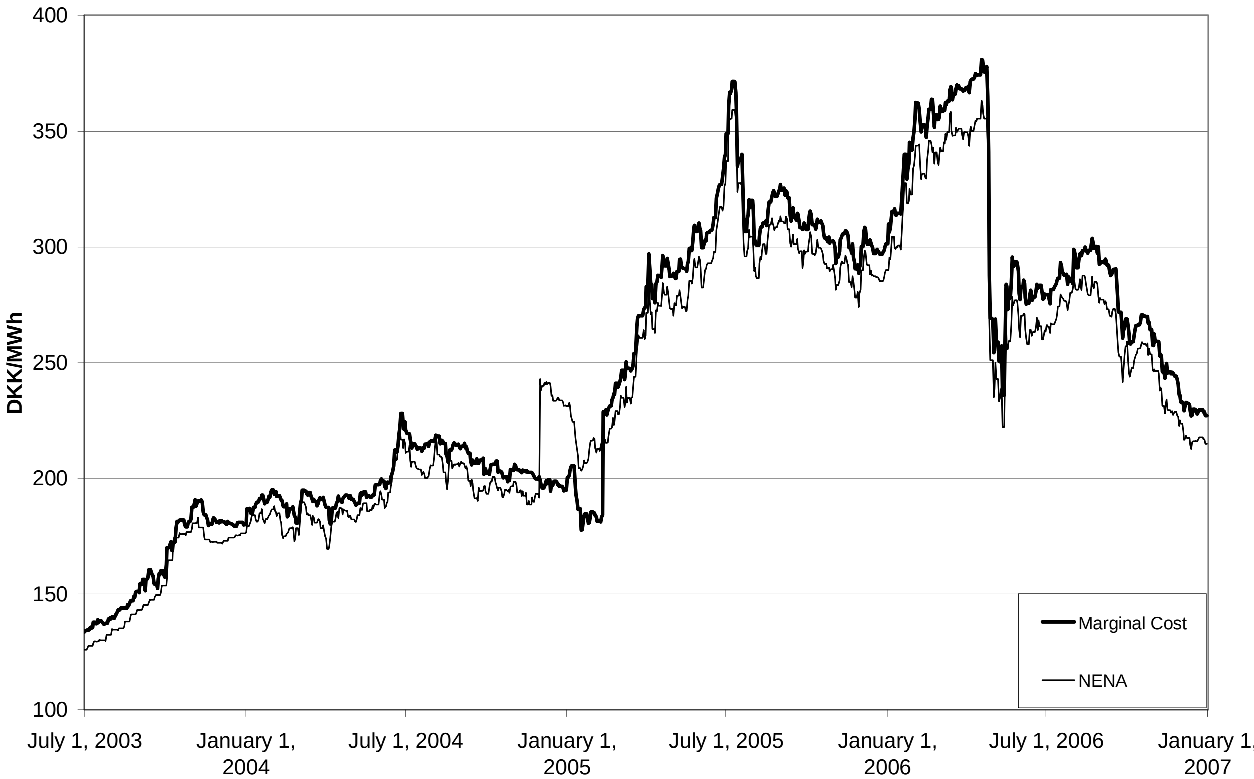

Figure 2: Marginal Cost

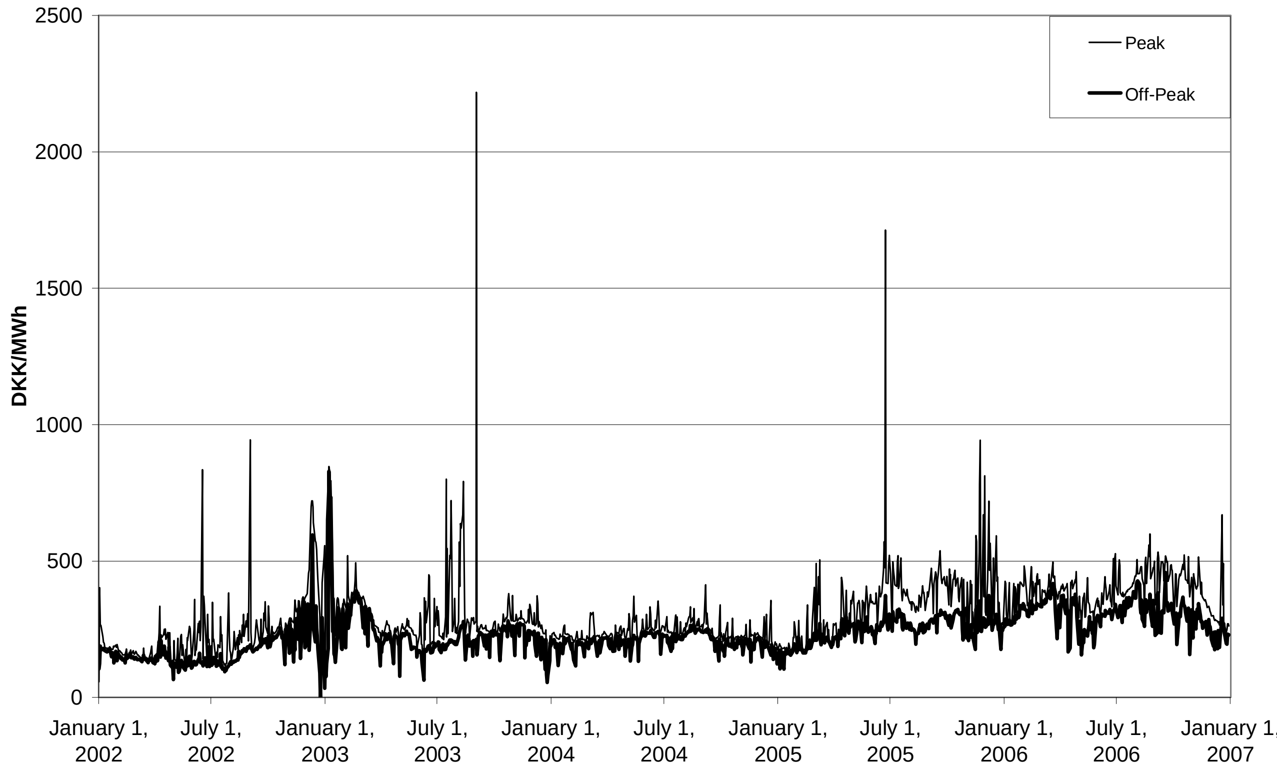

Figure 3: Peak and Off-Peak Spot Prices

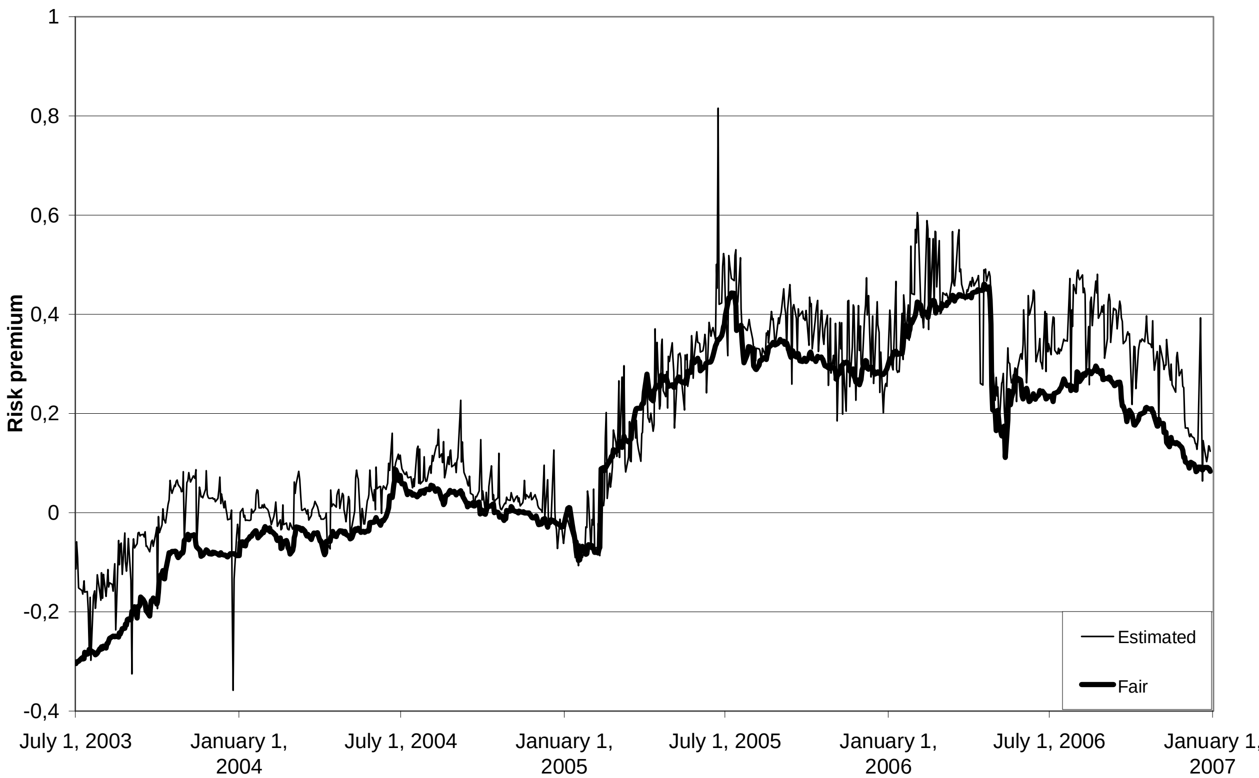

Figure 4: Peak Ask Risk Premium

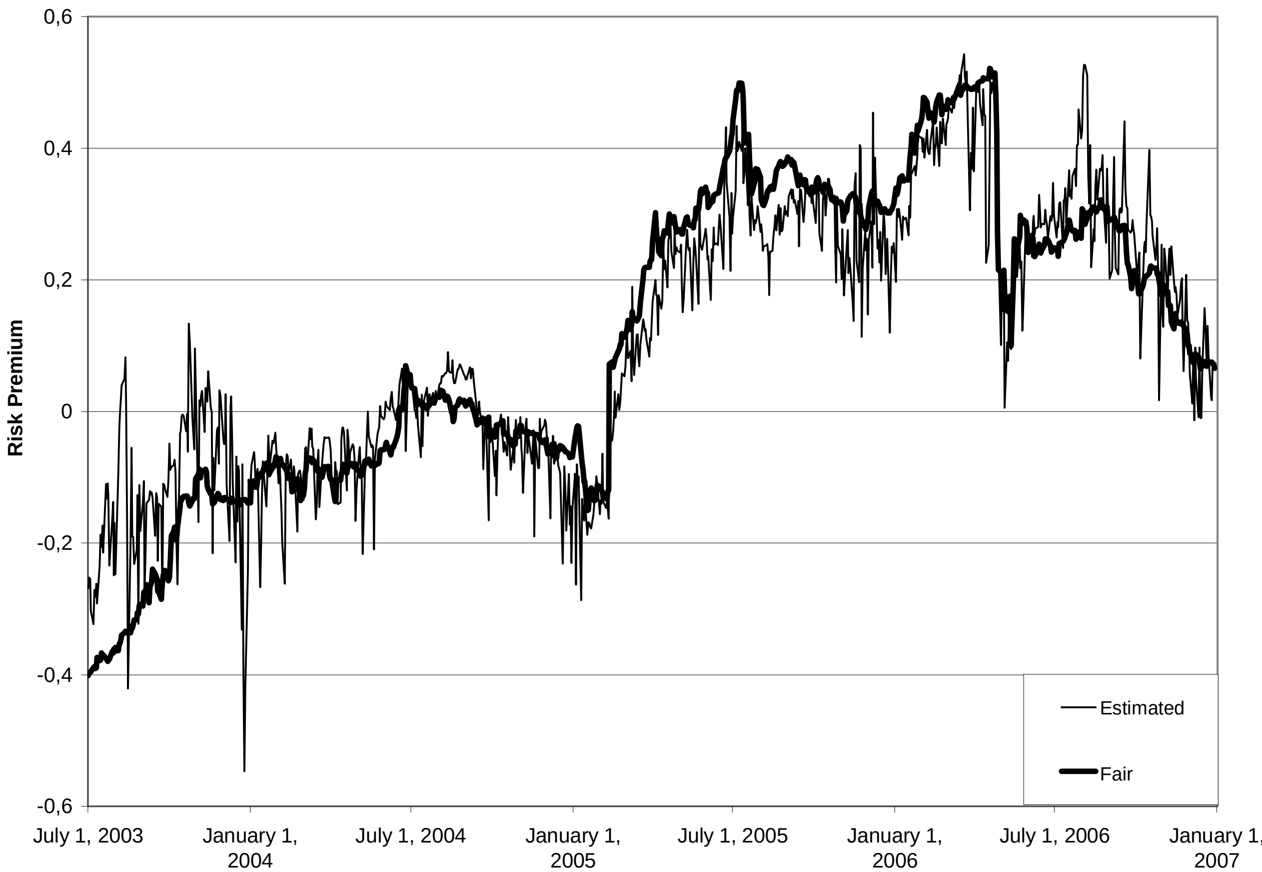

Figure 5: Off-Peak Ask Risk Premium

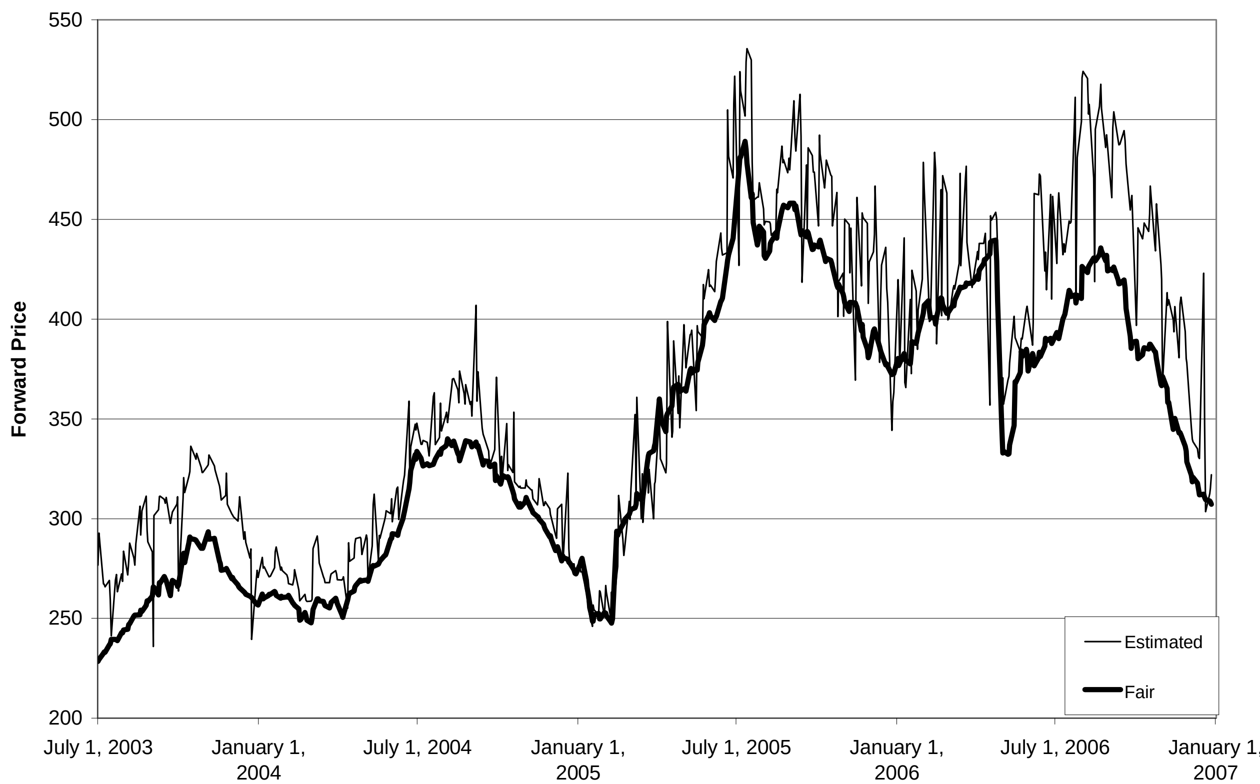

Figure 6: Peak Ask Month-Ahead Forward Prices

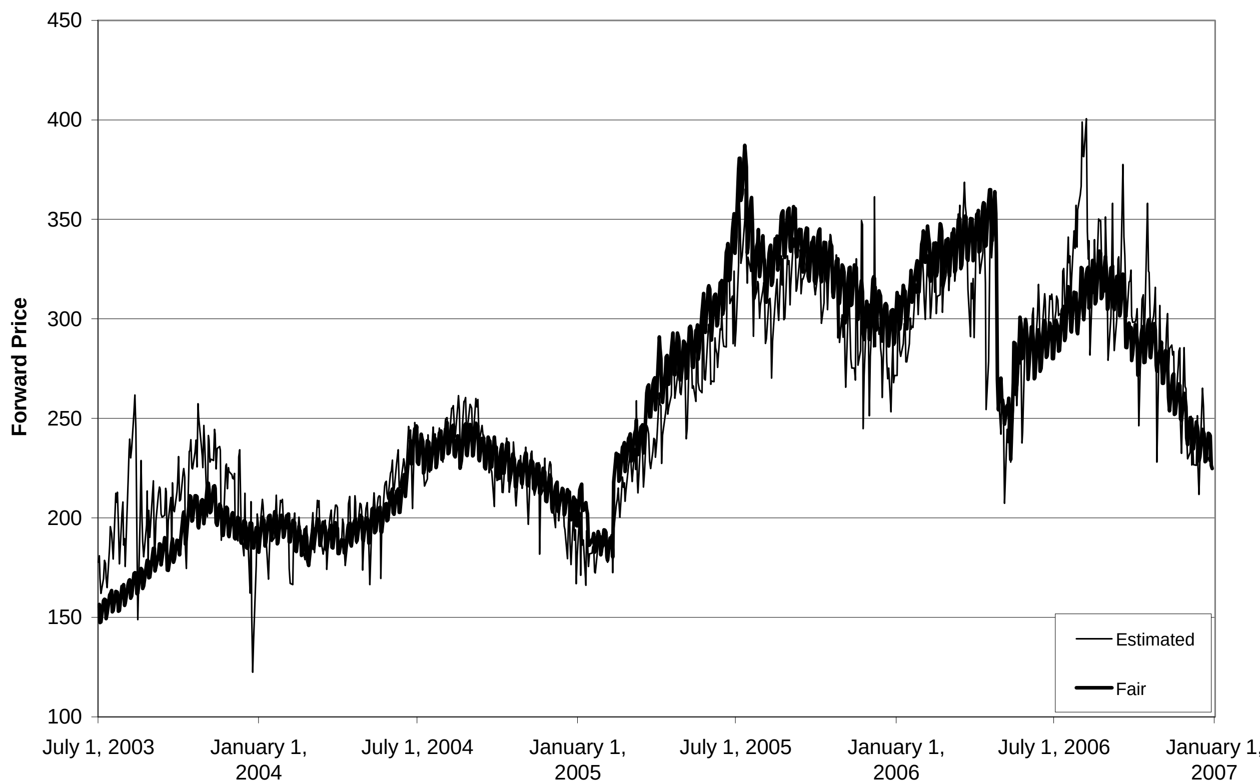

Figure 7: Off-Peak Ask Month-Ahead Forward Prices

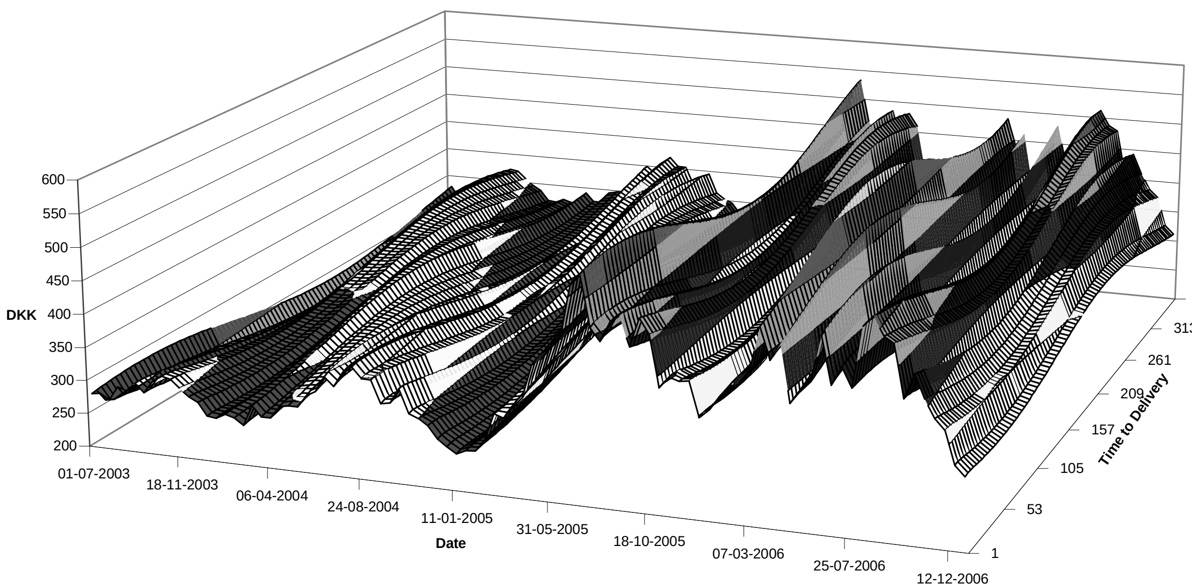

Figure 8: Estimated Peak Ask Forward Prices

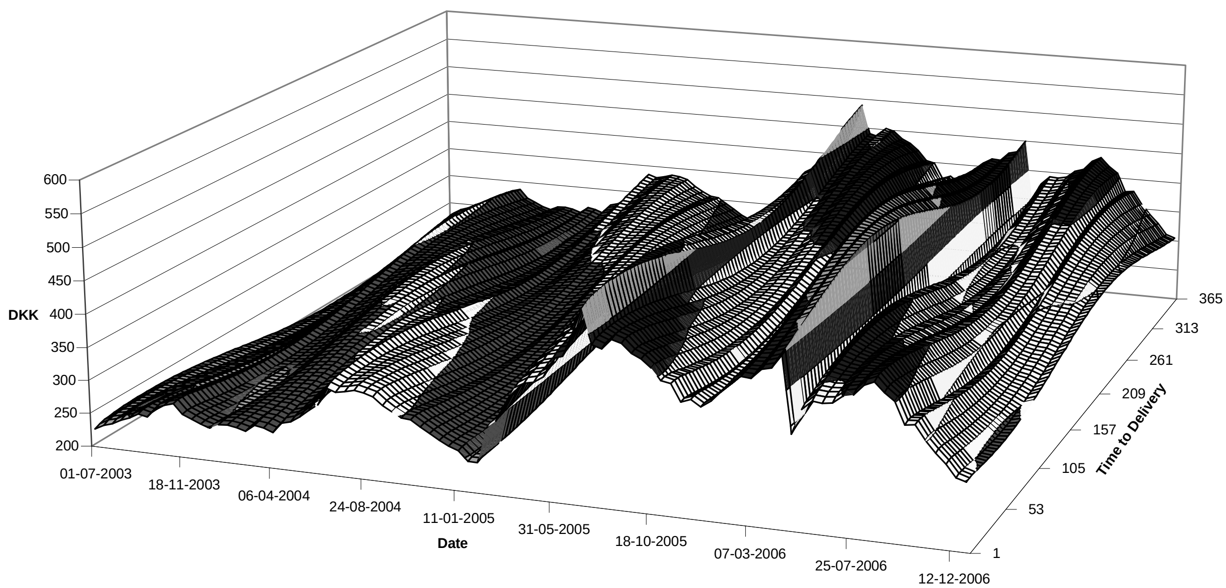

Figure 9: Fair Peak Ask Forward Prices

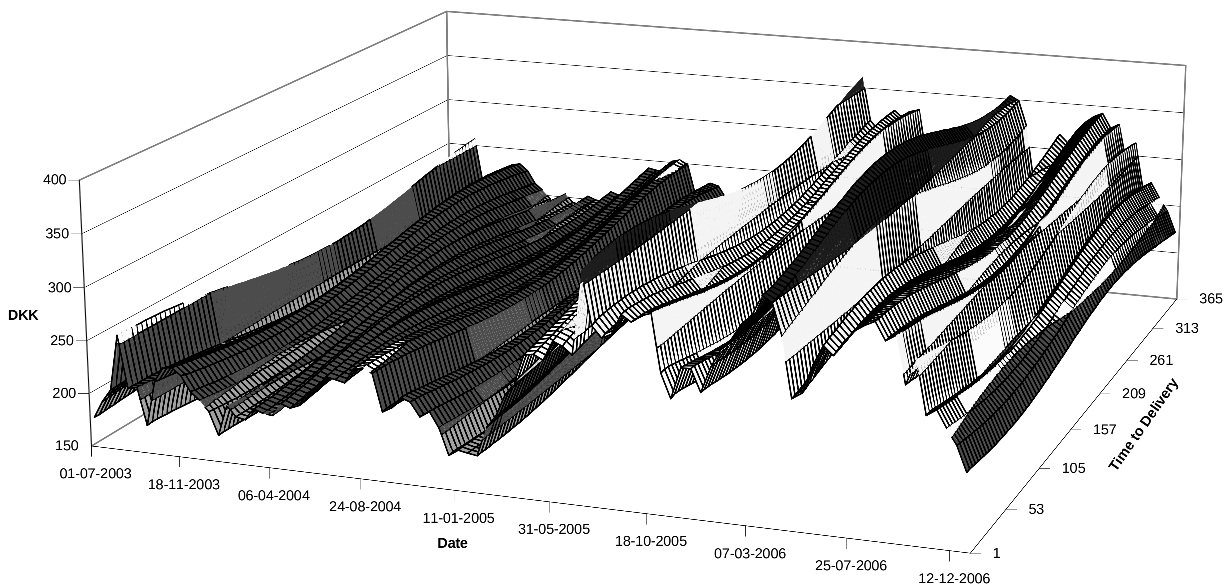

Figure 10: Estimated Off-Peak Ask Forward Prices

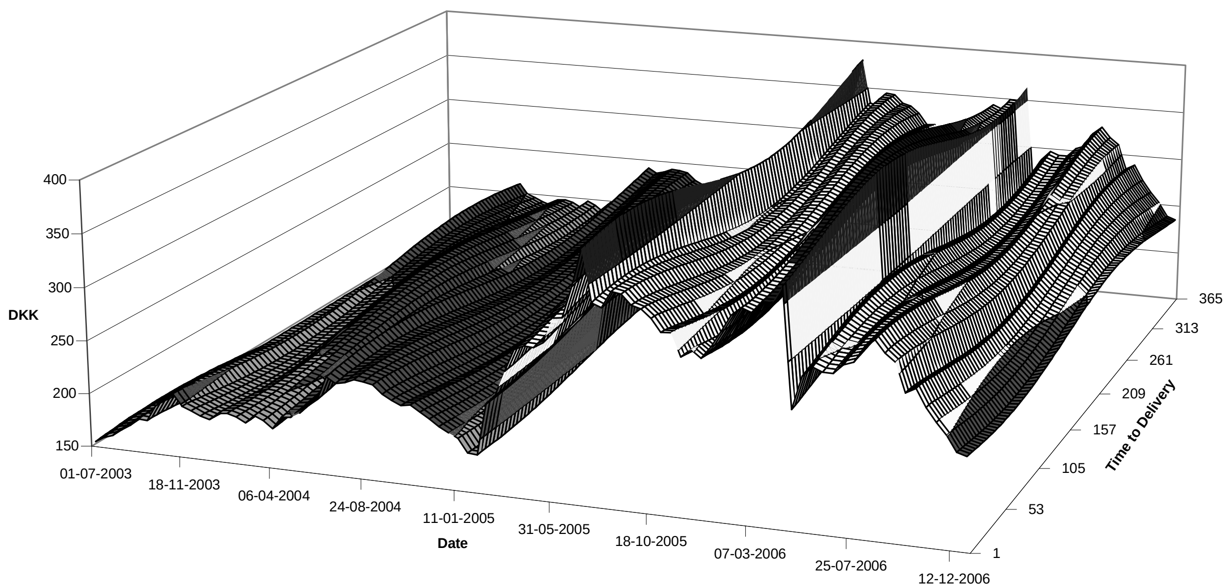

Figure 11: Fair Off-Peak Ask Forward Prices

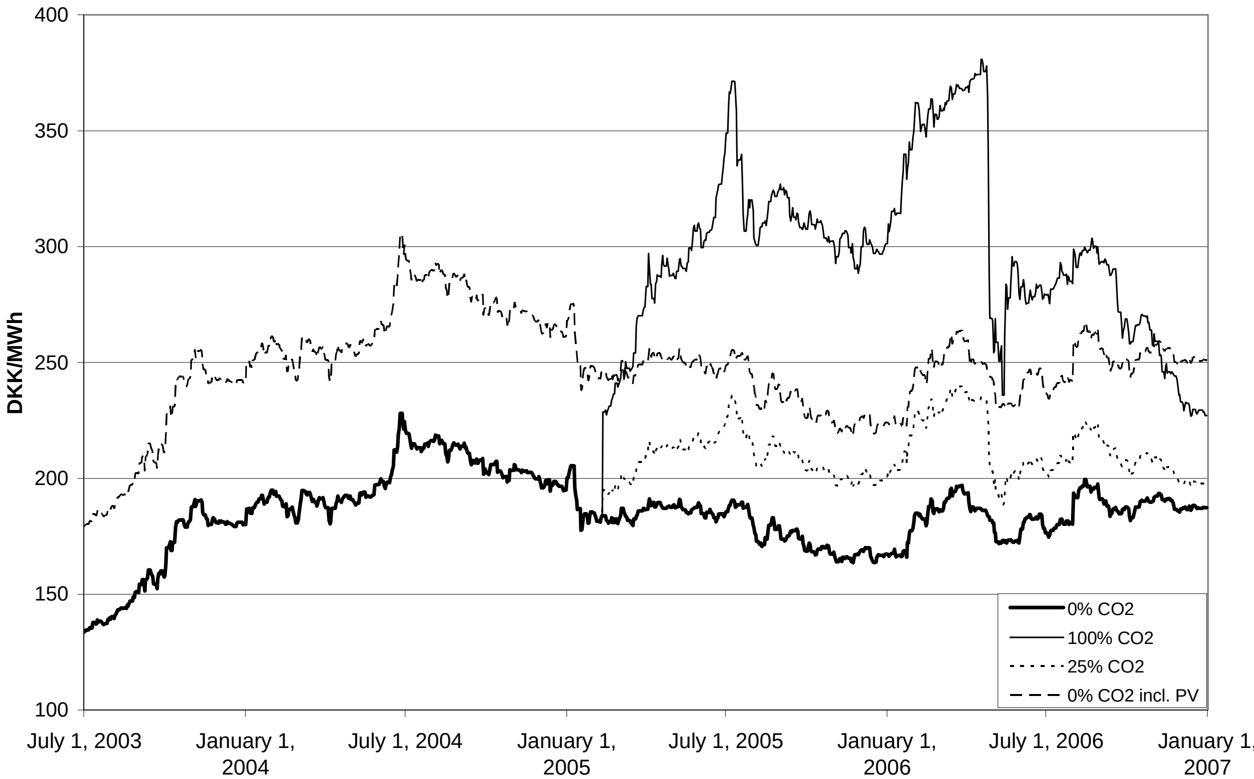

Figure 12: Alternative Marginal Costs

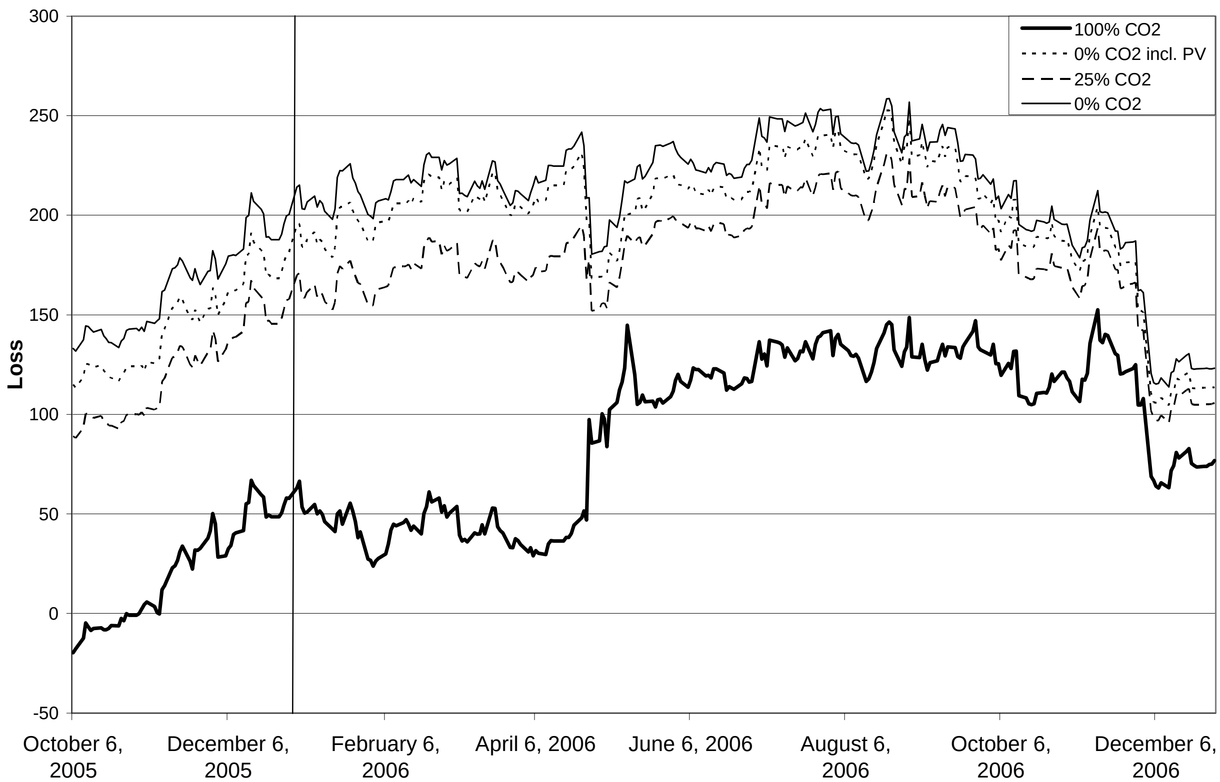

Figure 13: Peak Contract Year 2007

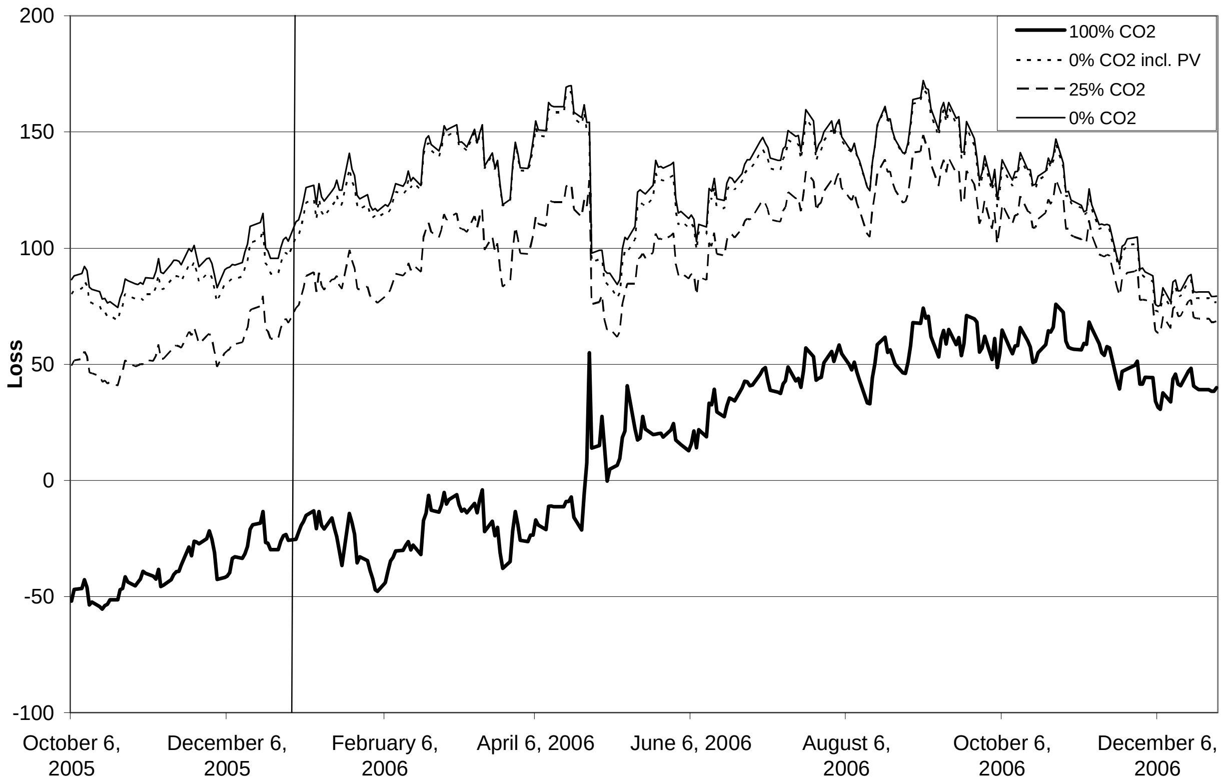

Figure 14: Off-Peak Contract Year 2007

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