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Energy Sustainability

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ABSTRACT: This paper provides insight in the time-varying relation between electricity futures prices and fundamentals in the form of prices of contracts for fossil fuels. As supply curves are not constant and different producers have different marginal costs of production, we argue that the relation between electricity futures prices and futures prices of underlying fundamentals such as natural gas, coal and emission rights are not constant and vary over time. We test this view by applying a model that linearly relates electricity futures prices to the marginal costs of production and calculate the log-likelihood of different time-varying and constant specifications of the coefficients. To do so, we formulate the model in state-space form and apply the Kalman Filter to observe the dynamics of the coefficients. We analyse historical prices of futures contracts with different delivery periods (calendar year and seasons, peak and off-peak) from Germany and the U.K. The results indicate that analysts should choose a time-varying specification to relate the futures price of power to prices of underlying fundamentals.

JEL Codes: Q41, Q48, C51

Keywords: Electricity futures prices, prices of fossil fuels, time-varying coefficients, statespace model

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1 Introduction

The owner of a power plant has the option to convert an energy source into electricity at every moment during the lifetime of the power plant. We assume that this lifetime is divided in hours, mimicking the micro structure of many day-ahead markets[1]. During the lifetime of the plant, the plant owner has a series of hourly options to convert an energy source into electricity; he can exercise an option to produce power or not at any hour during the lifetime of the power plant[2]. The timing of the exercise decision depends on the markets in which the plant operates and the risk from changes in power prices that he is willing to accept. If he only trades in day-ahead markets, he decides every day how much to produce in every hour tomorrow. He might decide to produce tomorrow between 6pm and 7pm and not between 3am and 4am for instance. The option to produce is not transferable (if the plant does not produce during an hour, that production capacity cannot be stored and used in another hour) and the owner decides to produce or not and he makes this decision for every hour of the day. As a result, the profit from the power plant is uncertain as the day-ahead prices and fuel costs are variable and difficult to predict far ahead in the future[3].

If the plants owner also trades in futures markets, in addition to day-ahead markets[4], he has an opportunity to make his future income less uncertain, more predictable. He then can sell a futures contract committing to deliver, for instance, a flow of 1 MW against a fixed price in every hour during the delivery period specified in the contract. With the futures contract, the plant owner fixates the selling price for a part of his output during a future delivery period, thereby making his revenues more certain. The uncertainty that remains is the costs of the fuels needed (and emission rights if applicable) since profits decline on the volume sold against a fixed price when fuel costs rise. How can the plant owner deal with this situation? This resembles how a market maker (or traders) in equity futures contracts[5] deals with risk. When that market maker sells a futures contract to deliver a stock against a fixed price at a future moment in time without having the stock in his portfolio, he faces the risk that the stock price rises between the moments of sale and delivery such that, as a consequence, he has to purchase to stock against a higher price than the futures price. The risk origins from not having the stock in his portfolio and he can easily eliminate the risk by purchasing directly the stock after he has sold the futures contract and store the stock in his portfolio until delivery. The purchasing costs to eliminate his risk is equal to the stock price plus financing costs. Knowing the costs of the risk eliminating strategy, a risk averse market maker will charge a futures price that is at least equals

[1]This assumption can easily be relaxed and the remaining discussion can be based on shorter time intervals, depending on the application at hand.

[2]We abstract from maintenance periods, during which the power plant is not operational, here for convenience.

[3]There is a huge amount of literature that documents the dynamics of day-ahead power prices such as seasonality, mean reversion, time-varying volatility and sudden price spikes. We refer to Huisman [2009], Janczura and Weron [2010] and Fleten et al. [2014].

[4]Day-ahead contracts can be seen as one-day futures contracts, but we apply the European convention here and see one-day futures as day-ahead contracts and to define futures contracts as contracts that deliver into periods farther away than one day. We assume no differences between forward and futures contracts in this paper.

[5]Or market makers in any other financial assets such as currencies and interest rates products.

the purchasing costs. When the stock market is competitive and perfectly liquid, the market futures price equals the costs of the risk eliminating strategy as otherwise a risk free arbitrage opportunity emerges.

This thinking is based on the theory of storage as originally proposed by Kaldor [1939], Working [1948], Telser [1958] and Brennan [1958]. The theory relates the price of a futures contract on an asset to costs of holding inventories of the asset to eliminate risks (storage and financing costs) and benefits (also called convenience yield) from holding the asset (such as dividends in case of a stock). Let us apply this thinking to the situation of the plant owner who sold a futures contract to deliver power against a fixed price during some future time period. Suppose that the plant converts a (fossil) fuel into electricity and that futures contracts are traded on that specific fuel for the same delivery period as the sold electricity futures contract. This applies for instance to coal and natural gas fired power plants as relatively liquid futures markets for coal and gas exist. The plant owner can almost eliminate his risk from selling an electricity forward by purchasing the appropriate amount of fuel and emission rights contracts. After doing so, the owner is almost free of risk as he sold power against a fixed price, purchased the fuel and emission rights against a fixed price and has the plant to convert the fuel into power during the delivery period. He is not perfectly free of risk as the power plant might break down. This risk, however, is manageable for the plant owner through maintenance. Assuming that the plant owner is risk averse, he will purchase the appropriate amount of fuel and emission rights contracts after selling a power futures contract to eliminate risk. And knowing this strategy, he will charge a price in relation to these costs of the fuel and emission rights. If electricity, fuel and emission rights futures markets are liquid and competitive and if we assume that all power plants in the market use the same fuel to convert fuel into power with the same efficiency and that there is no risk of plant failure, the futures price of electricity equals the value of the fuel and emission rights futures contracts needed to eliminate risk, just as in equity futures markets[6]. Based on this argument, one expects a direct relation between the futures price of electricity and the futures prices of the fuel and emission rights.

That we compare the risk eliminating strategy of an equity market maker and the plant owner is done on purpose to emphasise the interesting difference between stock and electricity. Every equity market maker has access to exactly the same stock. When equity market makers compete, they can apply the exact same risk eliminating strategy using the exact same stock; the exact same underlying asset that can be stored. In electricity markets, the underlying asset, electricity, cannot be stored (at least not yet in an economically efficient way) and power plants compete in conversion technology. One power plant (a.k.a. market maker) converts natural gas into power. Another converts coal into power. In addition, plants differ in efficiency (the amount of fuel needed to produce one unit of power). In addition, some producers have no

[6] This reasoning also holds in case there is no futures market for the underlying fuel as long as the fuel can be purchased in spot markets and stored in which case the electricity futures price relates to the value of the fuel needed purchased in the spot market plus storage and financing costs and convenience yields if any.

fuel costs at all, such as solar and wind power plants[7]. Furthermore, it takes time to increase or decrease the production volume of a fuel fired power plant (ramping times), a power plant owner might be willing to sell against losses in some hours in order to make profits in others (must-run situations). The dynamics of price setting in power futures markets differ from equity and other financial markets for that reason. And, as a consequence, the futures price of electricity might not directly relate to the price of one specific fuel. This is what is found in different studies about the relation between electricity futures prices and futures prices of underlying fuels. Emery and Liu [2002] show evidence for a relation between electricity futures prices and futures prices of fuels in terms of a co-integration relationship between gas and electricity futures prices of the American California-Oregon Border and Palo Verde markets. Mohammadi [2009] examines long-term relations and short-run dynamics between electricity prices and prices for coal, natural gas and oil using annual U.S. data covering the period 1960–2007. Similar to Emery and Liu [2002], the relations are examined by testing for co-integration and using a vector error-correction model. Mohammadi [2009] only finds significant long-term relations between coal and electricity prices and an unidirectional short-run causality from coal and natural gas prices to electricity prices. Redl et. al [2009] examine the relationship between risk premiums of fuel markets and electricity using the German EEX and the Nord Pool futures contracts. In this model, the futures price of electricity is a function of primary fuel costs (gas or coal) and the costs for carbon emissions. The EEX electricity prices show higher correlation with gas and coal than the Nord Pool electricity prices. This can be explained by the fact that gas and coal are more often the marginal fuels for generating electricity than they are for Nord Pool where electricity is mainly generated by hydro power. This was confirmed by Povh and Fleten [2009]. They modeled the relationship between long-term futures contract prices on fuels (such as oil, coal and natural gas), the price of emission allowances, imported electricity and the long-term price of electricity forwards for the Nord Pool market. The cointegration analysis reveals a long-run relationship between all variables except for natural gas. The mutual interactions of electricity, gas and carbon prices in the UK were quantified by Fezzi and Bunn [2009]. Energy producers vary in the technology of energy supply and the prices of energy futures contracts relate to the prices of these different technologies.

The literature about pricing electricity forwards contracts develops in two streams. Within the first stream, futures prices are obtained from a stochastic multi-factor process mostly derived from the Schwartz [1997] stochastic models for commodity prices. Lucia and Schwartz [2002] is a direct application to power futures prices (among others). futures prices are seen as stochastic in this stream, consisting of different stochastic factors such as long and short term price developments and convenience yields. Prices do not directly relate to underlying fundamentals such as fuels or the market structure although the stochastic processes reflect these fundamentals somehow. We focus in this paper on the second stream. Within this stream forward electricity prices relate to fundamentals. Deng [2000] relate fuel and electricity prices to model the value of electricity generating and transmission assets. Carmona et al. [2013] propose a structural model

[7] The marginal costs of hydro power depends on the reservoir levels and the option to delay production. See Huisman et. al [2013].

for spot and derivative electricity prices using a stochastic model of the bid stack. The model has a multi-fuel setting such that each fuel can set the market price and become the marginal fuel. Dong and Liu [2007] use storable fuels (natural gas and coal) in their model for electricity spot prices and futures prices are derived through a Nash bargaining process. According to Falbo et al. [2010] the value of a futures contract is equal to the sum of the expected marginal production cost and the spread option embedded in spot selling. Pirrong and Jermakyan [1999] and Pirrong and Jermakyan [2000] model the equilibrium price as a function of two state variables, electricity demand and the futures price of the marginal fuel. Routledge et al. [2001] derive the equilibrium futures prices by explicitly considering the conversion option of gas and other fuels to electricity (the model is in fact the Routledge et al. [2000] approach for pricing commodity futures contracts adapted to deal with electricity market specifics). Bessembinder and Lemmon [2002]'s equilibrium model implies that the relationship between forward power price and the future spot price is a function of both expected demand and demand variance. As a consequence, the futures price will generally be a biased forecast of the future spot price, with the forward premium positively related to the skewness of the wholesale price and negatively related to the variance of the wholesale price. Suenaga and Williams [2005] extend the Bessembinder and Lemmon [2002] model with fuel prices.

All these studies price electricity forwards by seeing futures prices as a biased predictor of future spot prices, they assume that the supply stack during the trading period of a futures contract is constant, or assume that all producers have the same supply function. They need these assumptions to derive futures price models. The objective of this paper is not to derive electricity futures price formulas but to examine the price formation process during the lifetime of an electricity futures contract seen from the risk reduction strategies of power producers. We focus on the relation between the power futures price and prices of fuel and emission forwards assuming that different power producers use different conversion technologies.

The idea of time-variation in the relation between electricity prices and explanatory variables is not new. Karakatsani and Bunn [2008] show, for the British market, that a model explaining changes in day-ahead (a one-day futures contract) electricity prices with market fundamentals (supply and demand variables) and time-varying coefficients exhibits the best predictive performance for day-ahead prices. We extend this thinking from day-ahead prices to futures prices and examine the relation between electricity futures prices and futures prices of underlying fuels and emission rights. Our study assumes a linear relation between electricity futures prices and the prices of underlying fuel futures prices and compares the fits of different specifications of the model in terms of allowing coefficients to be time-varying or not. By doing so, we test the hypothesis that a model with constant coefficients explains variation in electricity futures prices best against the alternative that allowing for at least one time-varying parameter explains better. Section 2 discusses the methodology that we apply and how we formulate and test different hypotheses.

2 Methodology and data

We expect that the price of a power futures contract relates in a time-varying manner to the prices of underlying fuel futures contracts. We test this view as follows. Let $F_{p,t,T}$ be the price of a power futures contract at time t for delivery of 1 MW during the future period of time T. Let $M_{c,t,T}$ be the value of a portfolio at time t that contains the appropriate amount of coal futures contracts and emission rights contracts need for producing power with a coal fired plant during delivery period T. We call this the marginal cost of future production for a coal fired power plant. Similarly, $M_{g,t,T}$ is the marginal cost of future production for a gas fired power plant. To determine appropriate amounts, we assume an average coal plant with efficiency 0.38 (one unit of fuel generates 0.38 units of power) and that emits 0.971 tonnes of CO_2 per one MWh of power produced (net)[8]. The marginal cost of future production equals

$$M_{c,t,T} = ((F_{c,t,T}/29.31)/0.2777) * (1/0.38) + 0.971 * F_{e,t,T}, \qquad (1)$$

for the average coal producer. $F_{c,t,T}$ is the price of a coal futures contract and $F_{e,t,T}$ is the price of a futures contract that allows to emit carbon (both prices are observed at time t and deliver during period T). The numbers 29.31 and 0.2777 convert the coal futures contract from tonnes into MW. For an average natural gas power producer, the marginal cost of future production equals

$$M_{g,t,T} = 2 * F_{g,t,T} + 0.404 * F_{e,t,T}. \qquad (2)$$

$F_{g,t,T}$ is the price of a futures contract that delivers gas during period T. The numbers 2 and 0.404 in equation 2 apply to an average plant and are obtained from Bloomberg. We relate the price of a power futures contract linearly to the average coal and gas plant marginal cost of future production:

$$F_{p,t,T} = a_t + b_t M_{c,t,T} + c_t M_{g,t,T} + v_t, \qquad (3)$$

where v_t is an error term and a_t, b_t, and c_t are parameters. Our goal is to test whether or not the price of a power futures contract relates in a time-varying manner to the prices of underlying fuel futures contracts. To do so, we test the null hypothesis that the parameters a_t, b_t, and c_t are constant against the alternative that at least one of the parameters is time-varying:

H_0: a_t, b_t, and c_t are constant

versus

H_1: at least one of a_t, b_t, c_t is time-varying.

We have not discussed what we mean with time-varying. The coefficients a_t, b_t, and c_t are unobservable and we have to assume their dynamics. One way to test is to apply rolling regressions to observe whether the coefficients change over time. We prefer a different approach

[8] We obtained the efficiency rates and the number of emission rights for average coal and gas plant from Bloomberg.

which makes it possible to better compare the fits of different specifications of the model. It's is convenient to represent the model in state-space[9] to capture the dynamics of the observed $F_{p,t,T}$ in terms of the unobserved (3x1) state vector $\eta_t = (a_t \; b_t \; c_t)'$. The following equation described the dynamics of the state-vector:

$$\eta_{t+1} = \eta_t + w_{t+1}, \tag{4}$$

where the (3x1) vector w_t is taken to be IID N(0,Q) with Q being a (3x3) covariance matrix. We assume that the coefficients are mutually independent, i.e. that the non-diagonal elements of Q are zero. The observed variable $F_{p,t,T}$ is presumed to be related to the state vector through the observation equation:

$$F_{p,t,T} = H_t \eta_t + v_t, \tag{5}$$

where H_t is the (1x3) vector $H_t = (1 \; M_{c,t,T} \; M_{g,t,T})$ and v_t is the IID N(0,R) measurement error. Having defined these, we apply the Kalman Filter to obtain estimates for the unobserved coefficients in the vector. We estimate Q, R and the initial η_0 using maximum likelihood.

We test the null hypothesis against the alternative by comparing the log-likelihood of the constant parameters model with various specifications of the time-varying parameters model. Likelihood ratio tests help us then to observe whether the time-varying parameters model, consistent with H_1, fits better than the constant parameters model consistent with H_0. Likelihood ratio tests suit as the the constant parameters specification is in fact a restricted version of the time-varying specification as a parameters assumed to be constant has zero variance in the transition equation 4; that is, we set the diagonal element in Q, that contains the variance of the parameter to be held constant, to zero. We then test the hypothesis H_0 against an alternative, by comparing the likelihood under H_0 against the likelihood of a specification under H_1 where at least one of the variances in Q is set to zero.

2.1 Sample selection

To observe whether our findings are consistent over contract types and countries we analyse prices of peak load and non-peak load futures contracts in Germany and in the United Kingdom. We selected those countries as power is produced by coal and gas (among other sources) in both countries and active futures markets exist for coal and gas. Secondly, the German and U.K. power markets are not (directly) connected such that we may assume that the supply and demand conditions in Germany vary independently from the U.K. and vice versa (apart from being dependent on coal and gas). By examining two different markets, we can compare the results between the two countries to conclude whether results are consistent.

[9]We follow Hamilton [1994] in describing the model in state-space form.

2.2 Data

To estimate the parameters, we use the complete history of prices of the German (The European Energy Exchange (EEX)) calendar year 2013 base load[10] and peak load[11] contracts and the U.K. (The Intercontinental Exchange (ICE)) October 2013 and April 2013 base load and peak load seasonal contracts[12]. The delivery period of the base load contract overlaps the delivery period of the peak contract as peak delivery takes place during the peak part of the day and base delivery is for the whole day. We use the base load and peak load price to calculate the implied off peak price to observe the price of two non-overlapping delivery periods (peak and off peak), consistent with market practice. The implied off peak prices[13] are calculated as (24 $\times$ base load price $-12\times$ peak load price) / 12. We then examine the non-overlapping peak and off peak prices.

The EEX calendar year futures contract starts trading approximately six years before delivery. The sample period for the calendar year 2013 contracts that we examine is from 2 July 2007 through 5 December 2012, yielding 1369 daily closing price observations (€/MWh). The natural gas futures prices in €/MWh are from the NetConnect Germany (NCG) futures contract traded on the EEX. The coal prices in \$/1000 tonnes and the emission rights derivative prices in €/tonne are obtained from the yearly Amsterdam-Rotterdam-Antwerp (ARA) coal futures contract and the European Carbon Future (ECF) futures contract traded at the EEX. The ICE seasonal futures contract starts trading approximately 7–8 consecutive seasons before delivery. The price series for both seasonal contracts range from February 16th, 2010 until March 27th, 2013 for the April 2013 seasonal futures contract and September 26th, 2013 for the October 2013 seasonal futures contract, having 805 and 935 daily closing price observations, respectively (£/MWh). The natural gas futures contract prices in £/therm[14] are from the National Balancing Point (NBP) seasonal futures contracts traded on the ICE. The coal prices in \$/1000 tonnes and the emission rights in €/tonne futures prices are obtained by the yearly Amsterdam-Rotterdam-Antwerp (ARA) coal futures contract and the EU allowances (EUA) futures contract traded at the ICE. The currency conversion is made by using the exchange rate provided by Reuters. All data is obtained from Bloomberg, Thomson Reuters Datastream and Montel database.

Figures 1, 2 and 4 show the price history of the marginal cost of future production with coal and natural gas plants (as in eq. (1) and (2)) and the power futures prices. Table 1 provides summary statistics.

[10] Delivering 1 MW during any hour of the day.

[11] Delivering 1 MW from Monday to Friday between 8 am and 8 pm.

[12] Seasons always comprise a strip of Apr–Sep or Oct–Mar.

[13] Delivering 1MW from Monday to Friday outside the 8 am and 8pm period.

[14] The following formula is used to convert the gas price from £/therm into £/MWh $F_{g,t} * \frac{3.6(\frac{GJ}{MWh})}{0.1055(\frac{GJ}{therm})} * \frac{1}{100}$

Figure 1: Power futures prices and marginal cost of future production (Germany; calendar 2013).

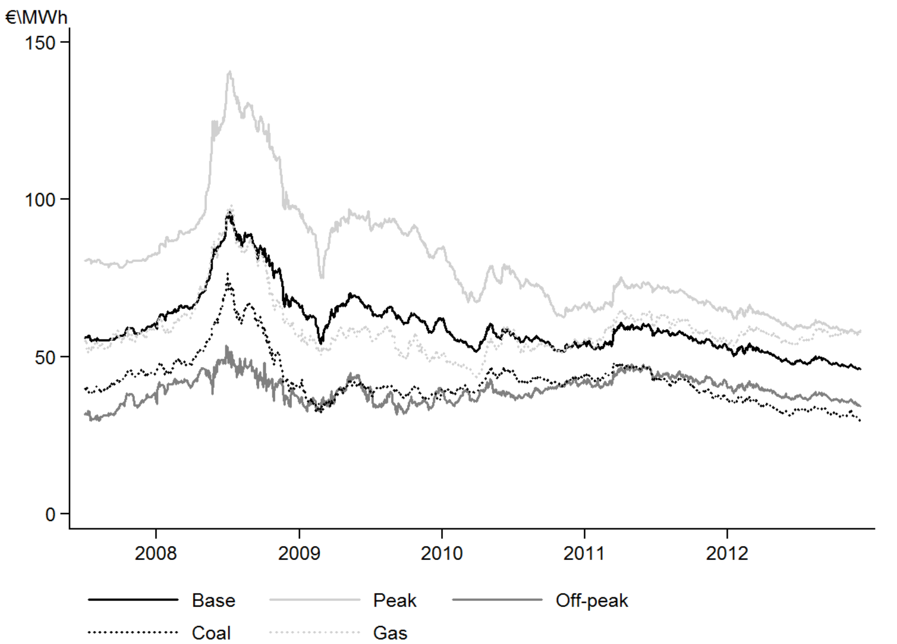


Figure 2: Power futures prices and marginal cost of future production (UK; April - September 2013).

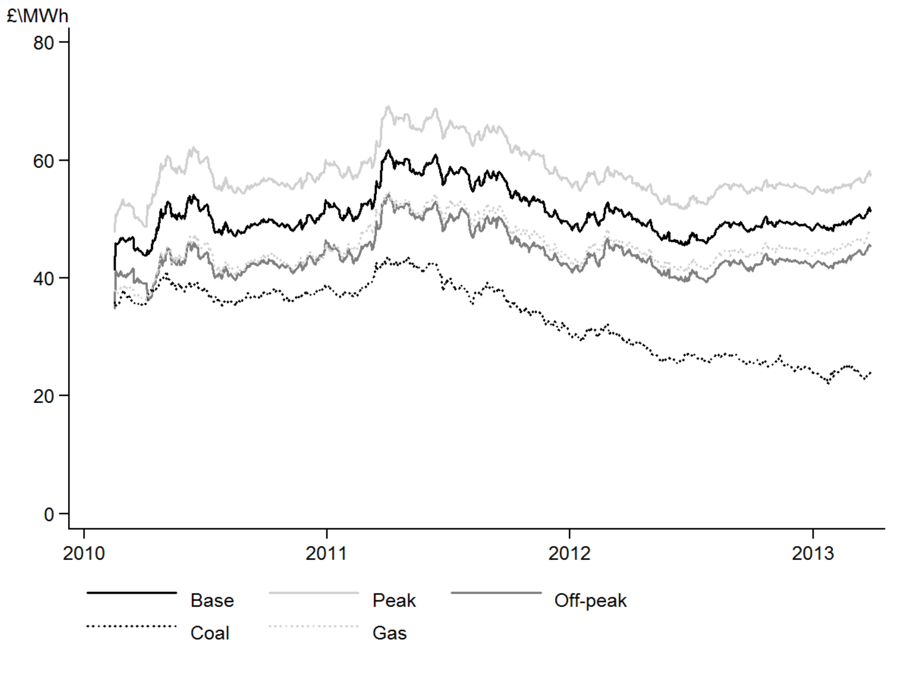


Figure 3: Power futures prices and marginal cost of future production (UK ; October 2013 - March 2014.

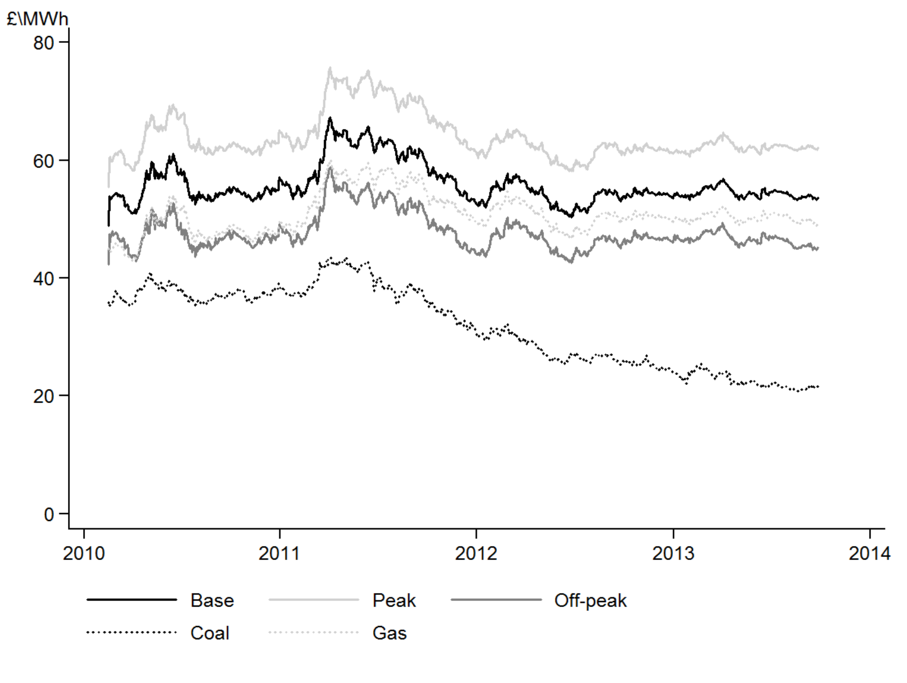


Table 1: Descriptive statistics for power futures prices and marginal cost of future production with coal and natural gas.

EEX Cal 2013	Peak	Off-peak	Coal	Natural Gas
Mean	80.350	39.431	42.313	58.905
St.dev	18.350	4.177	7.993	9.208
Observations	1384	1384	1384	1384
ICE Apr 2013	Peak	Off-peak	Coal	Natural Gas
Mean	57.942	44.064	33.310	45.335
St.dev	4.330	3.503	5.948	3.791
Observations	805	805	805	805
ICE Oct 2013	Peak	Off-peak	Coal	Natural Gas
Mean	63.965	47.787	31.729	50.880
St.dev	3.864	3.046	6.784	3.382
Observations	935	935	935	935

Notes: Descriptive statistics of the daily peak and off-peak power prices and the forward marginal cost of production with coal and gas between July 2007 and December 2012 for the EEX Cal 2013 contract and from February 2010 until March 2013 for the ICE April 2013 seasonal futures contract and September 2013 for the ICE October 2013 seasonal futures contract.

3 Results

Table 2 shows the log-likelihoods of the different parameter specifications for model 3. The table shows the results for the peak and off-peak load contracts for delivery during 2013 in Germany and during two seasons in 2013 in the U.K. The first row with results in the table shows the log-likelihoods for that specification in which both a_t and b_t are assumed to be constant and c_t is set to zero using peak load contracts. This specification relates the futures price of electricity linearly to a constant term and the marginal cost of future production for a coal fired plant with constant, that is not time-varying, coefficients. Using all the prices during the life time of the futures contracts, we have calculated the log-likelihood that the model fits the data and for Germany that log-likelihood equals -4,414.796. For the U.K. contracts, the log-likelihoods equal -1,586 for the April-September 2013 delivery contract and -1,749 for the October 2013 through March 2014 delivery contract. The log-likelihoods are meaningless in itself, but help to compare the fits of different specifications. For instance, when we consider the second row, the one that includes the marginal cost of future production with a gas plant instead of a coal plant with constant parameters, we observe that the log-likelihood is less for Germany (4,545 instead of 4,415 for the specification in row 1) but higher for the U.K. contracts. The higher the log-likelihood, the more likely it is that the model fits the data. Hence, we conclude that the model that consists of the marginal cost of future production with a gas plant fits the data better for the U.K. contracts but not for the German contract. When we include both the marginal cost of future production with a coal plant and a gas plant (the third row), we observe that the log-likelihoods are higher than in the two previous rows, meaning that out of these three specifications, this one is most likely to describe the data for all the contracts that we examine. When we consider constant parameters only, we want to include both the marginal cost of future production with a coal and gas fired power plants to fit the data.

But likelihoods dramatically increase when we allow one or more parameters to vary over time. All the rows with t.v. (time-varying) for some of the parameters have higher log-likelihoods than the constant parameters specifications. This holds for all the contracts that we examine, for peak and off-peak load, for Germany and the U.K. and for calendar year and seasonal contracts. Without assessing the significance of this result for now, it is clear that allowing at least one of the parameter to vary over time makes the model more likely to fit the data. This is in line with our view that we expect that the price of a power futures contract to relate in a time-varying manner to the prices of underlying fuel futures contracts. To test this more formally, we compare the log-likelihood of a specification under our null hypothesis that parameters are constant with one specification under the alternative hypothesis that at least one of the parameters is time-varying. Using the likelihood ratio test, we then assess whether the log-likelihood under the alternative hypothesis is significantly higher than the one under the null hypothesis. For instance, let's focus on peak load contracts and compare the log-likelihoods in rows three and sixteen for the German contract. That is, we focus on a model that includes a constant term and the marginal cost of future production with a coal and gas plant and compare the fits of the specification in which all parameters are assumed to be constant (null hypothesis) with the specification that all parameters are time-varying (the alternative hypothesis). The log-likelihood under the null hypothesis is -4,414.796 and the log-likelihood of the second is -633.519. The test statistic equals $D = -2 \times (LL_{H_0} - LL_{H_1}) = -2 \times (-4,414.796 - -633.519) = 7,562.554$. The statistic D is Chi-squared distributed with degrees of freedom equal to the difference in the number of free parameters between the specifications. Under the alternative hypothesis, we have three more parameters in this case, as all σ_a, σ_b, and σ_c are free under the alternative hypothesis and restricted to zero under the null hypothesis. Hence, the degrees of freedom of the Chi-squared distribution is three. The value of the test statistic D is so large that the p-value, the probability that we falsely reject the null that the parameters are constant, equals zero. This also holds when we compare the other constant parameters specifications in rows 1 and 2 for all the contracts that we examine. We therefore find compelling support to reject the null hypothesis of constant parameters against the alternative that at least one of the parameters is time-varying, supporting our view that we expect time-variation as the dependence of electricity futures prices on the prices of underlying fuels varies over time as demand for futures contracts progresses over the supply curve.

Table 2: Log likelihoods for different specifications of the model $F_{p,t,T} = a_t + b_t M_{c,t,T} + c_t M_{g,t,T} + \sigma v_t$.

	a_t	coal b_t	gas c_t	Germany 2013	UK Apr 2013	UK Oct 2013
				Peak load futures		
1.	const	const	—	-4,414.796	-1,585.742	-1,748.653
2.	const	—	const	-4,544.917	-954.169	-1,204.952
3.	const	const	const	-4,378.618	-365.641	-664.435
4.	const	t.v.	—	-584.879	123.304	201.312
5.	const	—	t.v.	-609,527	541.150	750.206
6.	const	t.v.	t.v.	-558.130	612.183	786.488
7.	const	t.v.	const	-554.462	**616.265**	**790.837**
8.	const	const	t.v.	-554.900	541.291	750.690
9.	t.v.	const	—	-689,815	113.679	176.444
10.	t.v.	—	const	-714.980	560.397	744.241
11.	t.v.	const	const	-648.493	561.245	744.848
12.	t.v.	t.v.	const	-542.726	615.640	790.113
13.	t.v.	const	t.v.	**-538.383**	557.236	750.178
14.	t.v.	t.v.	—	-573.140	109.950	215.719
15.	t.v.	—	t.v.	-590.058	556.508	749.694
16.	t.v.	t.v.	t.v.	-546.286	611.712	785.998
				Off peak load futures		
1.	const	const	—	-2,665.872	-1,491.563	-1,557.524
2.	const	—	const	-2,638.203	-601.486	-1,046.676
3.	const	const	const	-2,604.051	-378.624	-720.037
4.	const	t.v.	—	-642.181	88.927	76.619
5.	const	—	t.v.	-674.112	444.732	487.128
6.	const	t.v.	t.v.	-633.377	516.262	548.570
7.	const	t.v.	const	**-629.935**	**520.218**	**552.664**
8.	const	const	t.v.	-634.934	453.471	492.903
9.	t.v.	const	—	-771.892	60.978	24.359
10.	t.v.	—	const	-809.168	468.451	495.389
11.	t.v.	const	const	-762.445	475.789	501.764
12.	t.v.	t.v.	const	-630.118	519.679	552.122
13.	t.v.	const	t.v.	-635.589	471.628	497.514
14.	t.v.	t.v.	—	-642.361	94.425	83.570
15.	t.v.	—	t.v.	-674.312	464.298	491.144
16.	t.v.	t.v.	t.v.	-633.519	515.860	548.219
# observations				1,383	804	934

Notes:

Table 2 shows more than only support for our time-varying parameters claim. We have printed the most likely specification, the one with the highest log-likelihood, in bold face. The most likely specifications reveal how the electricity futures prices relate to the marginal cost of future production. We find one dominant specification; one that applies to all contracts except for the Germany peak load contract. The dominant specification includes both the marginal cost of future production with a coal plant and a gas plant as explanatory variables and has the coefficient for the coal plant time-varying and the others constant. Figures 5 through 9 show the behaviour of the coefficients over time for these contracts. Let us take Figure 6 as an example for discussion; it shows the results for the U.K. peak contract for delivery from April through September 2013. The top graph shows that price of the electricity futures contract exceeds the marginal cost of future production with gas and coal for most of the time. The second graph shows the value of a_t, which value is 16.242 and remains constant by assumption as the most likely specification is one for which a_t is constant. This parameter estimate, and all others for the most likely specifications, are listed in Table 3. The third graph shows the value for b_t, the coefficient for the marginal cost of future production with coal, which value is estimated to be -0.016 at the start of the sample (see b_0 in Table 3) and varies over time with a standard deviation $\sqrt{Q_b}$ equal to 0.006 per day; i.e. a very low standard deviation[15]. The fourth graph shows the value for the coefficient c_t, which is the one for the marginal cost of future production with gas. It's value is 0.937 (see Table 3) and remains constant by assumption. Figure 6 shows that the coefficient b_t declines over time, which makes sense as the electricity futures price seems to follow the marginal cost of future production with gas with an apparent constant spread reflected by the constant a_t and the almost unity estimate for the constant c_t and the marginal costs of coal deviation more and more from the marginal costs of gas over time. From this we conclude that this specification captures the dynamics in the relation between electricity futures prices and the marginal cost of future production over time.

A different case is the German peak load contract for delivery in 2013. It's characteristics are plotted in Figure 5. From the top graph, we observe that the electricity price converges to the marginal costs of gas over time. Put it differently, the spread declines and this behaviour is apparent from the dynamics of a_t in the second graph. The spread declines after observation 600, probably being cause by the increase of P.V. and wind power in the German supply curve. By assumption, the influence of coal remains constant with its coefficient b_t equal to 0.419 (see Table 3). The coefficient c_t for gas varies by assumption. It starts at 0.06 and changes daily with a standard deviation of 0.011 (see again Table 3). On average, the coefficient c_t is not trending and converges to about 0.1 at the end of the sample.

[15]We chose to report the standard deviations $\sqrt{Q}$ instead of the variances Q as the numbers are small and standard deviations have a clear interpretation in case of a normal distribution like 68% of the observations lie in a one-standard deviation interval around the mean.

Table 3: Parameter estimates and the log-likelihood maximising specification of the model $F_{p,t,T} = a_t + b_t M_{c,t,T} + c_t M_{g,t,T} + v_t$.

	Germany year 2013		U.K. Apr–Sep 2013		U.K. Oct 2013–Mar 2014	
	peak	off peak	peak	off peak	peak	off peak
a_0	60.583	13.523	16.242	3.168	18.502	0.212
$\sqrt{Q_a}$	0.223	—	—	—	—	—
b_0	0.419	0.249	-0.016	0.070	0.056	0.102
$\sqrt{Q_b}$	—	0.000	0.006	0.007	0.005	0.006
c_0	0.060	0.156	0.937	0.946	0.893	0.973
$\sqrt{Q_c}$	0.011	—	—	—	—	—
$\sqrt{R}$	0.000	0.023	0.032	0.054	0.083	0.116
LogLik	-538.383	-629.935	616.265	520.218	790.837	552.664
# observations	1,383		804		934	

Notes: $\sqrt{Q_a}$ is the square root of the first diagonal element in Q; $\sqrt{Q_b}$ and $\sqrt{Q_c}$ are the square roots of the second and third elements in Q.

Figure 4: German peak load power 2013 futures price, marginal cost of future production and coefficients for the most likely model according to Table 2.

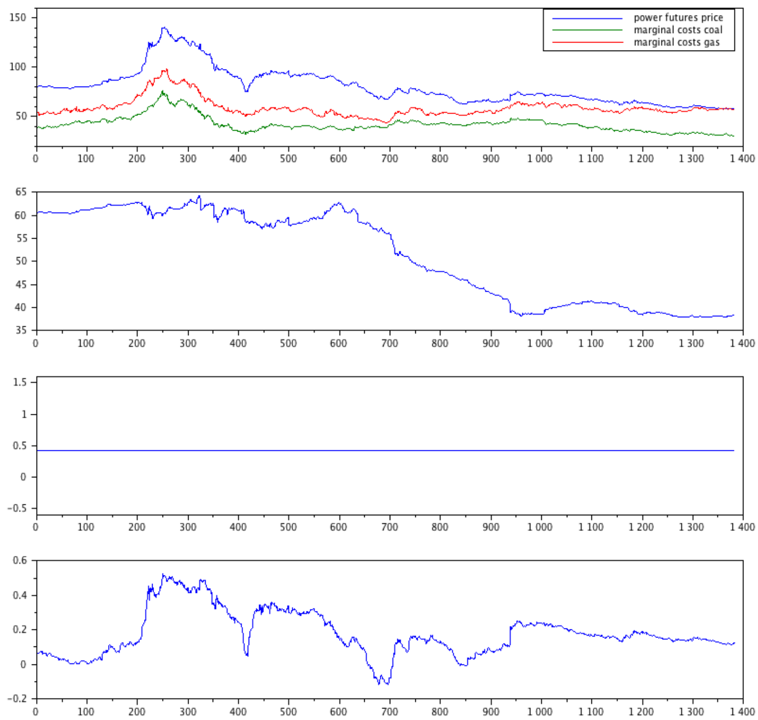


Figure 5: German off peak load power 2013 futures price, marginal cost of future production and coefficients for the most likely model according to Table 2.

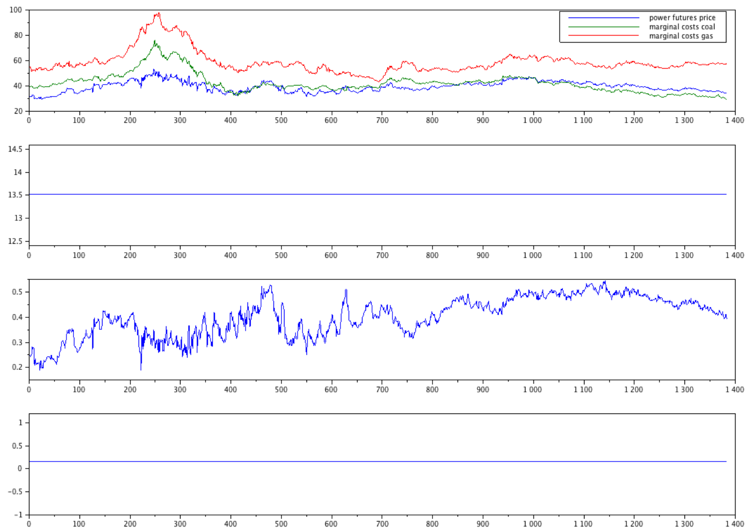


Figure 6: U.K. peak load power April 2013–September 2013 futures price, marginal cost of future production and coefficients for the most likely model according to Table 2.

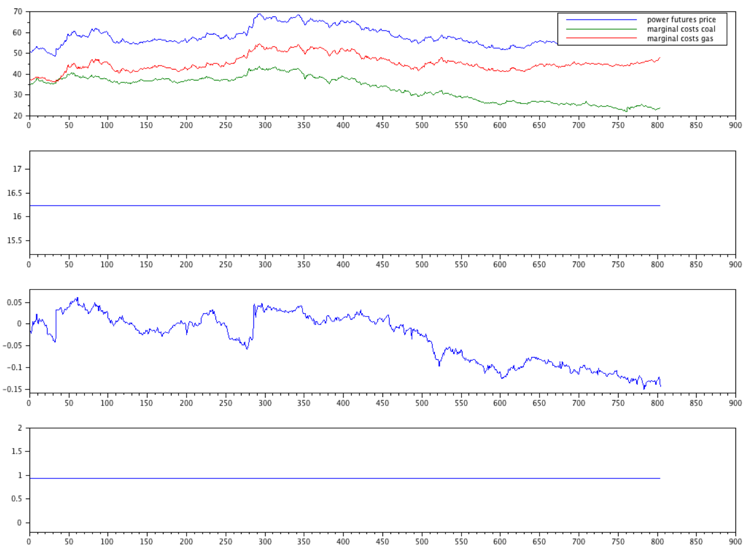


Figure 7: U.K. off peak load power April 2013–September 2013 futures price, marginal cost of future production and coefficients for the most likely model according to Table 2.

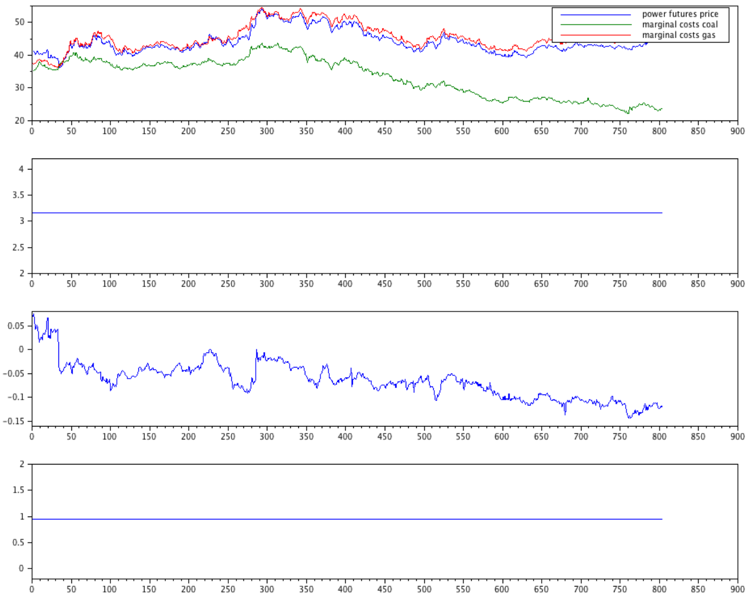


Figure 8: U.K. peak load power October 2013–March 2014 futures price, marginal cost of future production and coefficients for the most likely model according to Table 2.

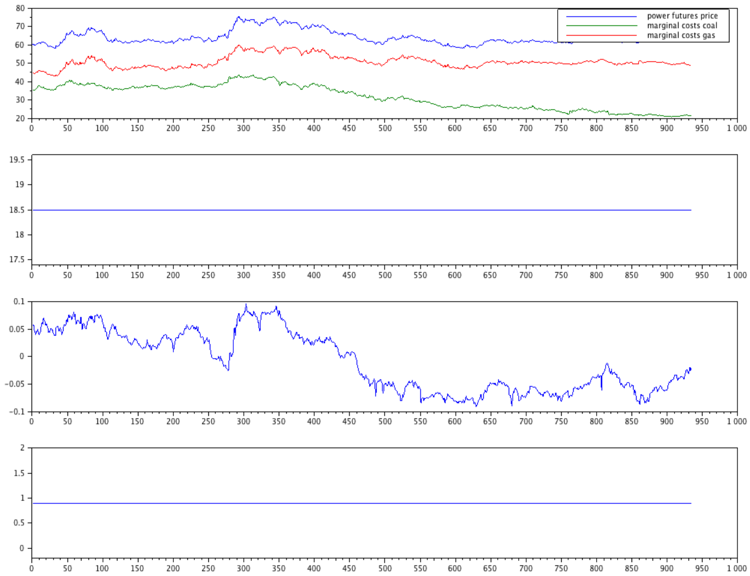
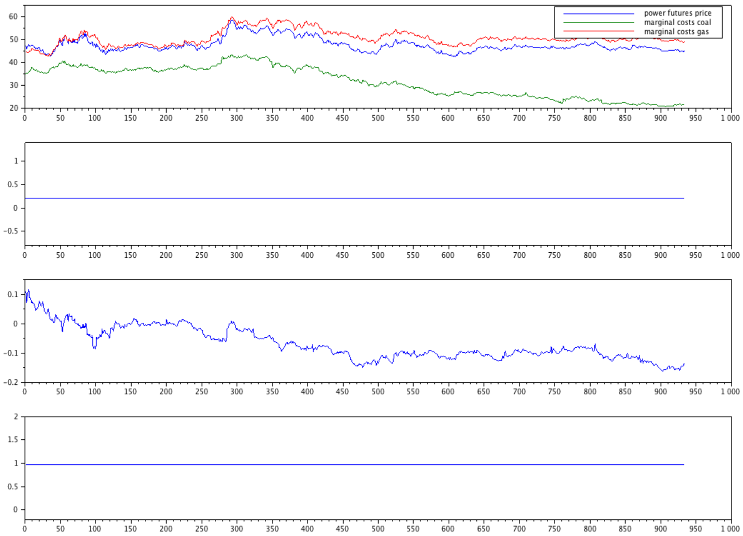


Figure 9: U.K. off peak load power October 2013–March 2013 futures price, marginal cost of future production and coefficients for the most likely model according to Table 2.



The difference in the price evolution of the Germany peak power contract and the other contracts is that the spread a_t declined probably due to the change in the supply curve in Germany due to an increase in renewables. The U.K. contracts show a declining influence of the marginal costs of coal over time, while having a_t constant. For the contracts that we examined, time-variation is either observable in a_t or in one of the marginal costs coefficients b_t or c_t. Again, we conclude that assuming time-variation in one of the parameters is more likely than assuming all coefficients to be constant. But as the exact parameter that needs to be time-varying differs among contracts (and perhaps over sample periods as well), we cannot say ex-ante which of the parameters should be time-varying. That implies that one cannot make a consistent choice which parameters to hold constant and which to allow to vary over time. Looking back at the results of table 2, we observe that the log-likelihoods for those specifications that allow all parameters to be time-varying (in rows 16), do not deviate too much from the most likely specifications. Consider for instance the German peak contract. The optimal specification yields a log-likelihood of -538.383. The specification in row 16 yields a log-likelihood of -546.286. A difference of about 8. These differences are significantly different from zero (according to likelihood-ratio tests), but the deviation from the most likely specification is much less than when we would assume constant parameters. The constant parameters specifications in rows 1, 2 and 3 all yield much lower (more negative) log-likelihoods than the ones in row 16. This holds for all contracts. We therefore conclude that if a practitioner has to choose ex-ante the best specification, he should choose the one in which all parameters are allowed to vary over time.

4 Conclusions

Electricity is a derived commodity that is generated from conversion of various forms of fuels or other fundamental energy sources. This paper focuses on how changes in market-determined prices for future delivery of underlying fuels affect the corresponding prices for future delivery of electricity. We find evidence of a time-varying relation between electricity futures prices and fundamentals being the prices of contracts for fossil fuels. We argue that the reason for this is that supply curves are not constant and different producers have different marginal costs of production (think of gas versus coal). For contracts with different delivery periods (calendar year and seasons, peak and off-peak) from Germany and the U.K., we conclude that one has to choose a time-varying specification to relate the futures price of power to prices of underlying fundamentals.

4.1 Discussion of the results

Our paper supports the view that one better relates the price of a power futures contract to the futures prices of underlying commodities such as coal, natural gas and emission rights in a time varying way. We leave it as future research to determine the exact impact of making the wrong assumption of constant instead of time-varying coefficients, but we take the opportunity to discuss where we see that this could have impact. In the energy sector, natural objects of analysis include spreads, such as the clean spark spread being the difference between the price of electricity and the marginal production costs of a natural gas producer. Or the clean dark spread, being the coal plant counterpart of the clean spark spread. Clean refers to the inclusion of emission costs. These spreads reflect the profits that power plants can lock in and different derivatives such as spread options and swaps are traded to hedge risk of changes in spark spreads. Thinking about spread option pricing, one can make a serious mistake if the option valuation model would assume a relation between the price of electricity and the underlying commodities. Option pricing models that allow for a time-varying relation are then needed.

One can also think about a risk manager measuring the risk of a portfolio of energy contracts. Our results implicates that correlation between electricity prices and underlying commodities vary over time and should be taken into account as such to correctly measure the amount of portfolio risk. This related to cross-hedging issues in which one offsets price risk in one energy commodity by taking an opposite position in an appropriate number of contracts in another energy commodity. This appropriate number is likely to vary if the relationship between the two commodities is time varying.

In this paper, we define time-variation in a simple way. We do not relate for instance changes in the supply curve directly in the coefficients, although one would expect that a change in the supply curve would immediately affect the relation between electricity prices and underlying commodities in a certain way. We leave this issue for future research.

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