UNIVERSITÄT DUISBURG ESSEN

A Structural Model for Coupled Electricity Markets

Commodity Markets and their Financialization, IPAM

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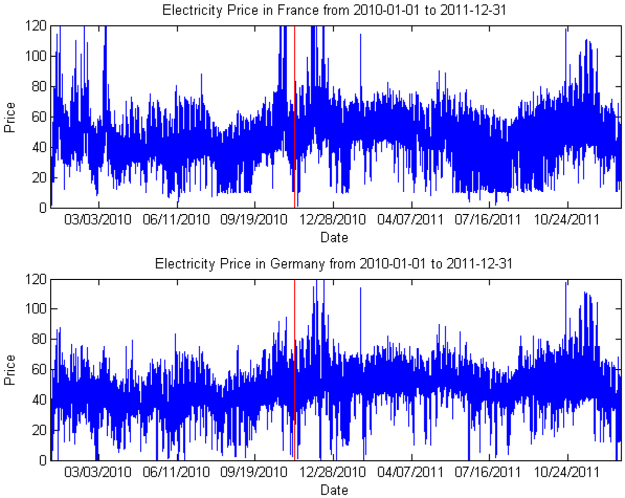
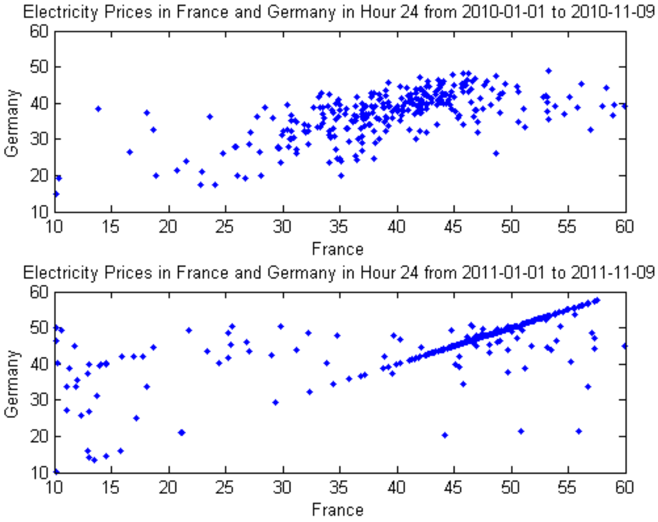
Outline

Agenda

German and French Power Prices from Jan 2010 to Dec 2011



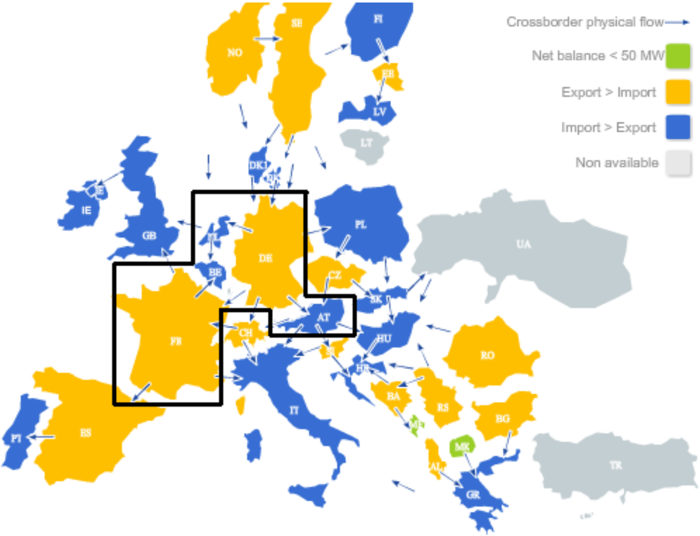
German vs French Power Prices - 2010 and 2011



Market Coupling

- Neighbouring electricity markets are typically coupled via transmission capacities owned by the TSOs.
- Transmission capacities can be integrated in the price finding algorithm of cooperating exchanges via implicit auctioning.
- With implicit auctions players do not receive allocations of cross-border capacity themselves but bid for energy on their Exchange. The Exchanges then use the available cross-border transmission capacity to minimize the price difference between two or more areas.
- The Central Western Europe (CWE) initiative couples Belgium, France, the Netherlands, Germany and Luxemburg.

CWE Region


Crossborder physical flow
Net balance < 50 MW
Export > Import
Import > Export
Non available
NO
SE
FI
EE
LV
LT
DK1
IE
GB
PL
UA
DE
BE
CZ
SK
AT
CH
FR
HU
RO
HR
BA
RS
IT
ES
BG
MK
GR
TR

Market Coupling II

- The North-Western- European (NWE) Region was implemented in February 2014. It consists of the power exchanges APX, Belpex, EPEX SPOT and Nord Pool Spot and 13 TSOs from the involved countries.
- In May 2014, Spain and Portugal joined; in February 2015, Italy coupled with France, Austria and Slovenia. As a result, the coupled area is called Multi-Regional Coupling and covers now 19 countries, standing for about 85 % of European power consumption.
- A similar deployment is also planned for the intraday timeframe.

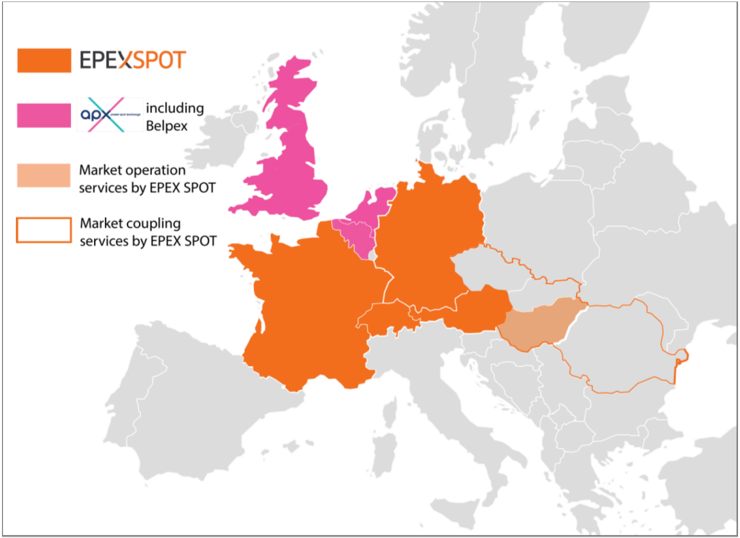
NWE Coupling

REGIONAL IMPLICIT AUCTIONS		
	CWE	Price coupling
	Austria	AT price coupled to GE/CWE (no congestion)
	BritNed / IFA	GB in price Coupling
	Nordic + Estonia	Price coupling, also Poland via Swepol
	NWE	Price Coupling
	Italy - Slovenia	Price coupling
	Mibel (Iberia)	Price coupling
	Czech - Slovak	Price coupling

Press release 17. April 2015

- The Power Exchanges EPEX SPOT and APX Group, including Belpex, intend to integrate their businesses in order to form a Power Exchange for Central Western Europe (CWE) and the UK.
- The integration of EPEX SPOT and APX Group will further reduce barriers in power trading in the CWE and UK region. Overall, the integration will lead to a more effective governance and further facilitate the creation of a single European power market fully in line with the objectives of the European electricity regulatory framework.

Markets covered by APX Group and EPEX SPOT



Agenda

- Motivation
- Basic Market Coupling
- A Structural Model for Coupled Markets
- Futures in Coupled Markets
- Options in Coupled Markets
- Application to the French-German Market

Formal Definitions

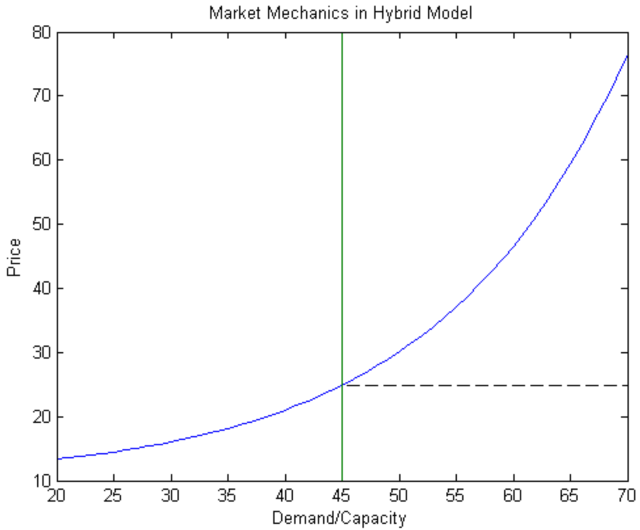
- A Market Area is a set of nodes and edges in an electric network, for which a unique energy price is calculated ('spot' i.e. day-ahead).
- Two market areas A and B are interconnected, if there exists an edge, which connects a node in A with a node in B.
- An edge which connects two market areas is called interconnector.
- The sum over the available capacities of all interconnectors between A and B is called available (cross boarder) transmission capacity (ATC).
- 'Market coupling uses implicit auctions in which players do not actually receive allocations of cross-border capacity themselves but bid for energy on their exchange. The exchanges then use the available cross-border transmission capacity to minimize the price difference between two or more areas.' (EPEX SPOT)

Economic Assumptions

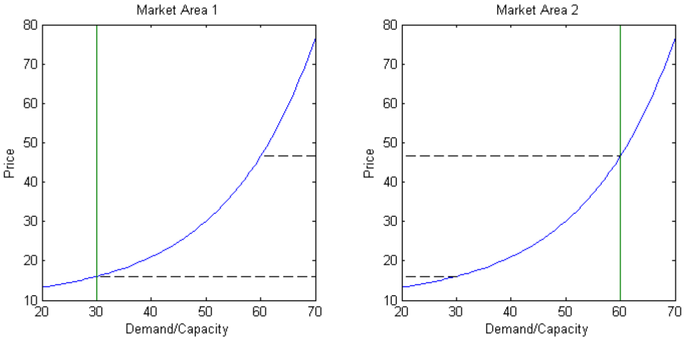
Starting point for our model is the following structure of a hybrid model

- price independent demand
- market supply curve has exponential shape
- fuels prices shift market supply curve multiplicatively
- market clearing price is given as intersection of supply and demand

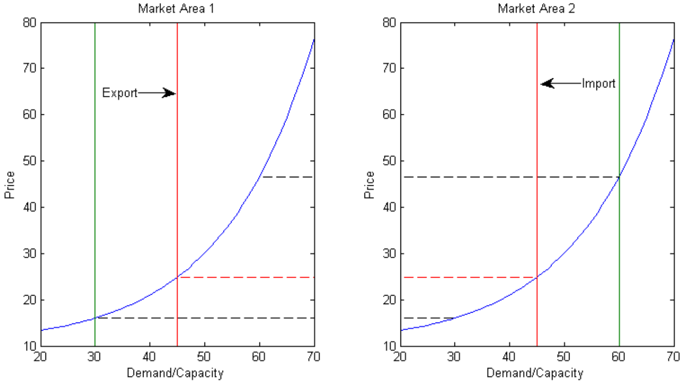
Market Mechanism



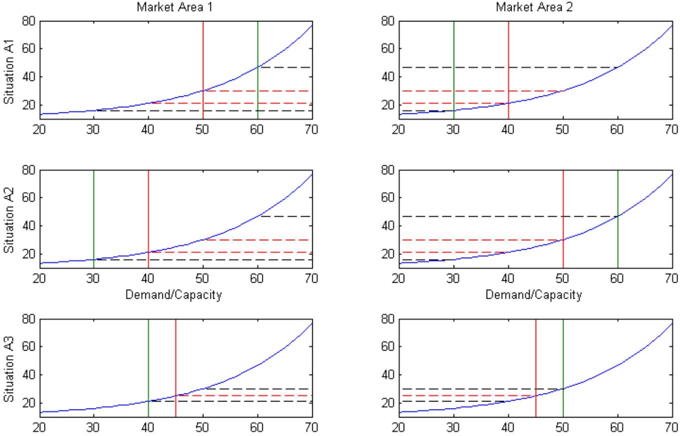
Market Mechanism - two Markets



Market Mechanism - Coupling



Market Mechanism - Coupling



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Model for Demand and Fuel

Let

- $D_t^1 = f^1(t) + \tilde{D}_t^1$ be demand in country 1,
- $D_t^2 = f^2(t) + \tilde{D}_t^2$ be demand in country 2 and
- S_t the average of fuels prices used to produce electricity

such that

$$Z_t\,|_{\mathcal{F}_s} \equiv \begin{pmatrix} \tilde{D}_t^1 \\ \tilde{D}_t^2 \\ \ln(S_t) \end{pmatrix} |_{\mathcal{F}_s} \sim F_{s,t}(x)$$

with $F_{s,t}$ being any elliptical distribution function.
Example: $F_{s,t} = N\left(\mu(s,t), \Sigma(s,t)\right)$.
Define for any Matrix $B \in \mathbb{R}^{m\times 3}$:

$$BZ_t|_{\mathcal{F}_s} \sim F_{s,t}^B$$

Model for the Market Supply Curve

We assume the Market Supply Curve in Country $i \in \{1, 2\}$, C^i, to be given as a function of capacity ξ and fuels price S:

$$C^i(\xi, S) = Se^{a_i + b_i \xi} + c.$$

I.e. we assume

- constant production capacities
- production costs consist of fuels cost and fuel price independent costs (labour costs,...).
- exponential dependence of the market clearing price on demand.

Cross Border physical Flows

We denote the physical flow from country 2 to country 1 by E_t. The maximum capacity is restricted and depends on the direction of the flow:

$$E_t \in [E_{\min}, E_{\max}], \; E_{\min} \leq 0, \; E_{\max} \geq 0.$$

Note that, if

- $E_{\min} = E_{\max} = 0$, markets are not connected and thus, pricing might be done independently.
- $E_{\max} = -E_{\min} \to \infty$, the interconnector is never congested and thus, one unique market price for both markets exists at all hours.

Cross Border physical Flows in case of coupled markets

In interconnected markets, only the electricity which is not imported has to be produced. Thus, the electricity price is determined as

$$P_t^1(D_t^1, E_t, S_t) = C^1(D_t^1 - E_t, S_t) = S_t e^{a_1 + b_1(D_t^1 - E_t)} + c.$$

Here, E_t is the imported amount and $D_t^1 - E_t$ is the residual demand which has to be satisfied by local production. Define:

$$\begin{aligned} A_1 &= \{\omega \in \Omega : P_t^1(D_t^1, E_{\max}, S_t) \geq P_t^2(D_t^2, -E_{\max}, S_t)\} \\ A_2 &= \{\omega \in \Omega : P_t^1(D_t^1, E_{\min}, S_t) \leq P_t^2(D_t^2, -E_{\min}, S_t)\} \\ A_3 &= \Omega \setminus (A_1 \cup A_2) \end{aligned}$$

Then, the cross border flow in case of coupled markets is

$$E_t^*(\omega) = \begin{cases} E_{\max} & , \text{if } \omega \in A_1 \\ E_{\min} & , \text{if } \omega \in A_2 \\ \frac{a_1 - a_2}{b_1 + b_2} + \frac{b_1}{b_1 + b_2} D_t^1(\omega) - \frac{b_2}{b_1 + b_2} D_t^2(\omega) & , \text{if } \omega \in A_3 \end{cases}$$

Market Clearing Prices

Given the cross border physical flow which minimizes price differences between countries, the resulting electricity price for country 1 may be stated as:

$$P_t^1(\omega) = P_t^1(D_t^1, E_t^*, S_t) = \begin{cases} C^1(D_t^1(\omega) - E_{\max}, S_t(\omega)) & , \text{if } \omega \in A_1 \\ C^1(D_t^1(\omega) - E_{\min}, S_t(\omega)) & , \text{if } \omega \in A_2 \\ C^m(D_t^1(\omega) + D_t^2(\omega), S_t(\omega)) & , \text{if } \omega \in A_3 \end{cases}$$

The function C^m can be viewed as the aggregated market supply curve for both countries and is given by

$$C^m(\xi, S) = Se^{a_m + b_m \xi} + c$$

with $a_m = \frac{a_1 b_2 + a_2 b_1}{b_1 + b_2}$ and $b_m = \frac{b_1 b_2}{b_1 + b_2}$. Equivalent results hold for P_t^2 in country 2.

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Distribution of the market clearing prices

Defining $P_t = \left(P_t^1, P_t^2\right)^T$ we find the distribution function:

$$F_{P_t|\mathcal{F}_s}(x) = \mathbb{Q}(P_t \leq x|\mathcal{F}_s)$$
$$= \mathbb{Q}\left(\{P_t \leq x\} \cap A_1|\mathcal{F}_s\right) + \mathbb{Q}\left(\{P_t \leq x\} \cap A_2|\mathcal{F}_s\right) + \mathbb{Q}\left(\{P_t \leq x\} \cap A_3|\mathcal{F}_s\right)$$
$$= F_{s,t}^{M_1}(d_1(x)) + F_{s,t}^{M_2}(d_2(x)) + \left(F_{s,t}^{M_3}(d_3^u(x)) - F_{s,t}^{M_3}(d_3^l(x))\right)$$

with

$$d_1(x) = \begin{pmatrix} \ln(x_1 - c) - a_1 + b_1 E_{\max} \\ \ln(x_2 - c) - a_2 - b_2 E_{\max} \\ a_1 - a_2 - (b_1 + b_2) E_{\max} \end{pmatrix}, \quad M_1 = \begin{pmatrix} b_1 & 0 & 1 \\ 0 & b_2 & 1 \\ -b_1 & b_2 & 0 \end{pmatrix}$$

$$d_2(x) = \begin{pmatrix} \ln(x_1 - c) - a_1 + b_1 E_{\min} \\ \ln(x_2 - c) - a_2 - b_2 E_{\min} \\ -a_1 + a_2 + (b_1 + b_2) E_{\min} \end{pmatrix}, \quad M_2 = \begin{pmatrix} b_1 & 0 & 1 \\ 0 & b_2 & 1 \\ b_1 & -b_2 & 0 \end{pmatrix}$$

$$d_3^u(x) = \begin{pmatrix} \ln(\min(x_1, x_2) - c) - a_m \\ -a_1 + a_2 + (b_1 + b_2) E_{\max} \end{pmatrix}, \quad d_3^l(x) = \begin{pmatrix} \ln(\min(x_1, x_2) - c) - a_m \\ -a_1 + a_2 + (b_1 + b_2) E_{\min} \end{pmatrix}, \quad M_3 = \begin{pmatrix} b_m & b_m & 1 \\ b_1 & -b_2 & 0 \end{pmatrix}$$

Futures prices in the structural model

We consider futures with hourly delivery. Denote by $F^i(s,t)$ the futures price of electricity in country i at time s for delivery in t. Under a risk-neutral measure we have

$$
\begin{aligned}
F^1(s,t) = \mathbb{E}_s^Q[P_t^1] &= \int_\Omega P_t^1(\omega)\mathbb{Q}(d\omega) \\
&= \int_{A_1} C^1\left(D_t^1(\omega) - E_{\max}, S_t(\omega)\right)\mathbb{Q}(d\omega) \\
&+ \int_{A_2} C^1\left(D_t^1(\omega) - E_{\min}, S_t(\omega)\right)\mathbb{Q}(d\omega) \\
&+ \int_{A_3} C^m\left(D_t^1(\omega) + D_t^2(\omega), S_t(\omega)\right)\mathbb{Q}(d\omega)
\end{aligned}
$$

and equivalent for country 2.

Futures prices in the structural model II

Assume

$$Z_t|_{\mathcal{F}_s} \equiv \begin{pmatrix} \tilde{D}_t^1 \\ \tilde{D}_t^2 \\ \ln(S_t) \end{pmatrix} |_{\mathcal{F}_s} \sim N(\mu(s,t), \Sigma(s,t)),$$

then

$$\begin{aligned} & \int_{A_1} C^1\left(D_t^1(\omega) - E_{\max}, S_t(\omega)\right) \mathbb{Q}(d\omega) \\ = \quad & c \cdot \Phi\left(\frac{a_1 - a_2 - (b_1 + b_2)E_{\max} - \overline{b}_3^T \mu}{\sqrt{\overline{b}_3^T \Sigma \overline{b}_3}}\right) \\ & + e^{a_1 - b_1 E_{\max} + \overline{b}_1^T \mu + \frac{1}{2}\overline{b}_1^T \Sigma \overline{b}_1} \Phi\left(\frac{a_1 - a_2 - (b_1 + b_2)E_{\max} - \overline{b}_3^T \mu - \overline{b}_3^T \Sigma \overline{b}_3}{\sqrt{\overline{b}_3^T \Sigma \overline{b}_3}}\right) \end{aligned}$$

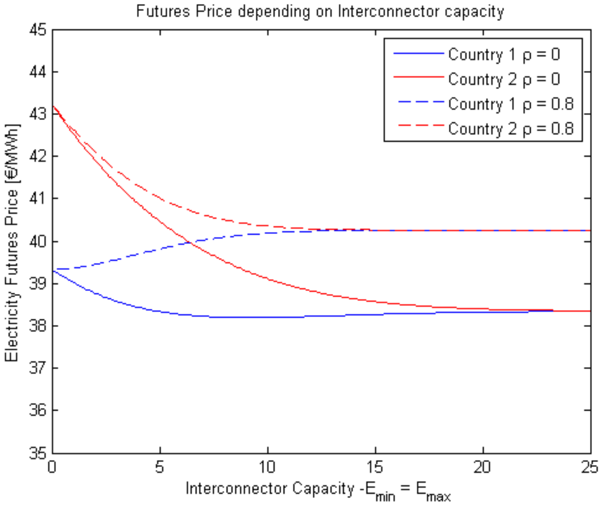
where $\overline{b}_3 = (-b_1, b_2, 0)^T$.

Futures prices with delivery period

Prices for futures with delivery in a set $\mathbb{T}$ of hours are given as

$$F^i(s, \mathbb{T}) = \frac{1}{|\mathbb{T}|} \sum_{t \in \mathbb{T}} F^i(s, t).$$

Example of futures prices



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Plain Vanilla Calls

Consider a plain vanilla call which is written on the electricity spot price in country 1 with delivery at a future time t. Its payoff is

$$\left(P_t^1 - K\right)^+$$

and its value at time s is

$$V_s = \mathbb{E}_s^{\mathbb{Q}}\left[\left(P_t^1 - K\right)^+\right].$$

Again, we use the decomposition

$$\left\{\omega \in \Omega : P_t^1 \geq K\right\} = (A_1 \cap B_1) \cup (A_2 \cap B_2) \cup (A_3 \cap B_3)$$

with

$$\begin{aligned}
B_1 &= \{\omega \in \Omega : C^1(D_t^1 - E_{\max}, S_t) \geq K\} \\
B_2 &= \{\omega \in \Omega : C^1(D_t^1 - E_{\min}, S_t) \geq K\} \\
B_3 &= \{\omega \in \Omega : C^m(D_t^1 + D_t^2, S_t) \geq K\}.
\end{aligned}$$

Plain Vanilla Calls II

According to the partition of the region of exercise, the value of the call might be written as

$$
\begin{aligned}
V_s &= \mathbb{E}_s^{\mathbb{Q}}\left[\left(P_t^1 - K\right)^+\right] \\
&= \int_{A_1 \cap B_1} C^1(D_t^1 - E_{\max}, S_t)d\mathbb{Q} + \int_{A_2 \cap B_2} C^1(D_t^1 - E_{\min}, S_t)d\mathbb{Q} \\
&+ \int_{A_3 \cap B_3} C^m(D_t^1 + D_t^2, S_t)d\mathbb{Q} - K\left(\mathbb{Q}\left(A_1 \cap B_1\right) + \mathbb{Q}\left(A_2 \cap B_2\right) + \mathbb{Q}\left(A_3 \cap B_3\right)\right).
\end{aligned}
$$

Plain Vanilla Calls III

In the case of $F_{s,t} = N(\mu(s,t), \Sigma(s,t))$ we get

$$V_s = e^{a_1 - b_1 E_{\max} + \mu(s,t)^T \bar{b}_1 + \frac{1}{2}\bar{b}_1^T \Sigma(s,t)\bar{b}_1} \Phi_2 \Big(d_4, M_4 \big(\mu(s,t) + \Sigma(s,t)\bar{b}_1 \big), M_4 \Sigma(s,t) M_4^T$$

$$+ e^{a_1 - b_1 E_{\min} + \mu(s,t)^T \bar{b}_1 + \frac{1}{2}\bar{b}_1^T \Sigma(s,t)\bar{b}_1} \Phi_2 \Big(d_5, M_5 \big(\mu(s,t) + \Sigma(s,t)\bar{b}_1 \big), M_5 \Sigma(s,t) M$$

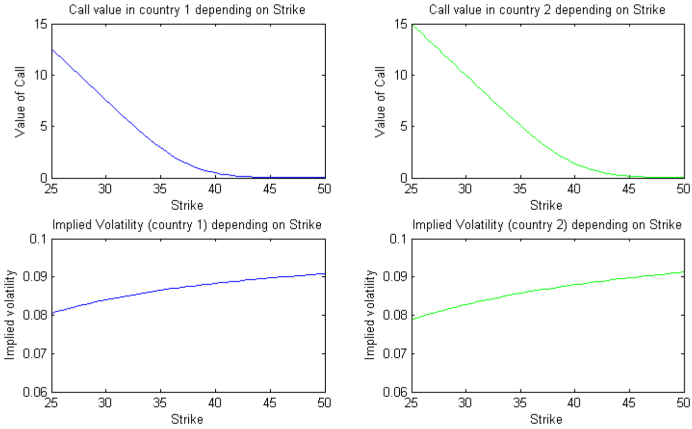
$$+ e^{a_m + \mu(s,t)^T \bar{b}_m + \frac{1}{2}\bar{b}_m^T \Sigma(s,t)\bar{b}_m} \Big(\Phi_2 \Big(d_6^u, M_6 \big(\mu(s,t) + \Sigma(s,t)\bar{b}_m \big), M_6 \Sigma(s,t) M_6^T$$

$$- \Phi_2 \Big(d_6^l, M_6 \big(\mu(s,t) + \Sigma(s,t)\bar{b}_m \big), M_6 \Sigma(s,t) M_6^T \Big) \Big)$$

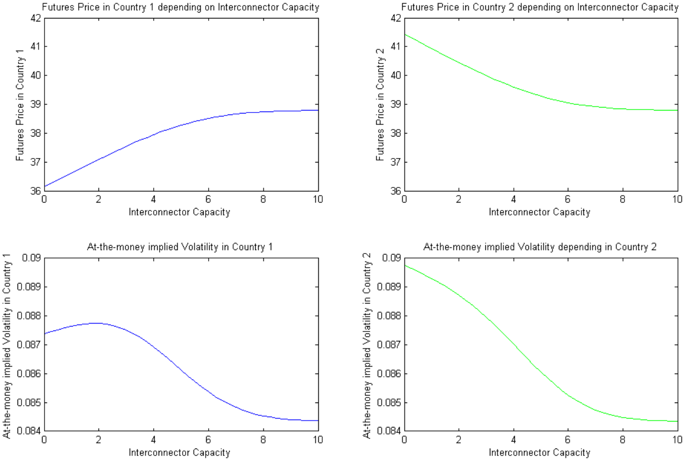
$$- \tilde{K} \Big(\Phi_2 \Big(d_4, M_4 \mu(s,t), M_4 \Sigma(s,t) M_4^T \Big) + \Phi_2 \Big(d_5, M_5 \mu(s,t), M_5 \Sigma(s,t) M_5^T \Big)$$

$$+ \Phi_2 \Big(d_6^u, M_6 \mu(s,t), M_6 \Sigma(s,t) M_6^T \Big) - \Phi_2 \Big(d_6^l, M_6 \mu(s,t), M_6 \Sigma(s,t) M_6^T \Big) \Big)$$

Call option price depending on Strike



Implied at-the-money volatility depending on Interconnector capacity



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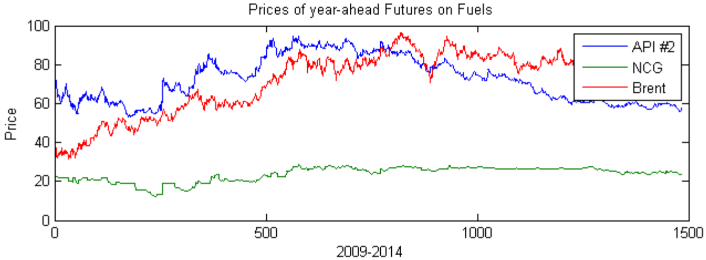
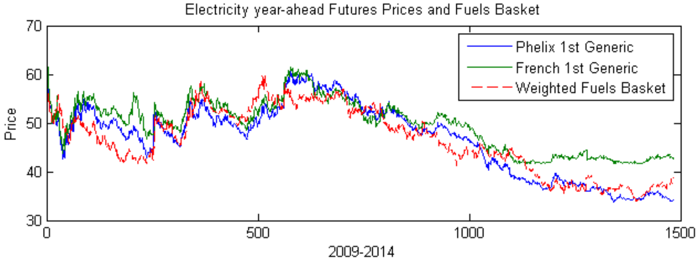
Construction of a Fuel Basket





Modeling the Fuels Basket

We assume that the fuels basket price S_t follows the following simple SDE:

$$d\ln(S_t) = k^S(\theta^S - \ln(S_t))dt + \sigma_S dW_t^S.$$

We use daily data from 2012 to calibrate the model which yields the following parameters:

κ^S	θ^S	σ_S
5.99	3.69	0.2028

Table : Annualized parameters for fuels basket

Market Supply Curves

Denote by $\tilde{D}_t^i$ the realized expected day-ahead demand in country i at time t and $\tilde{P}_t^i$ the realized day-ahead price. Then, $\tilde{E}_t = E_t(\tilde{D}_t^1, \tilde{D}_t^2, a_1, a_2, b_1, b_2, c, E_{\min}, E_{\max})$ denotes the realized expected day-ahead exchange and $P_t^i(\tilde{D}_t^i, \tilde{E}_t, a_i, b_i, c, E_{\min}, E_{\max})$ the model implied electricity price.

We determine the parameters of the market supply curve by minimizing

$$\sum_{i=1}^{2} \sum_{t \in \mathbb{T}} \left\| \tilde{P}_t^i - P_t^i(\tilde{D}_t^i, \tilde{E}_t, a_i, b_i, c, E_{\min}, E_{\max}) \right\|^2 \to \min .$$

Market Supply Curves - Parameters

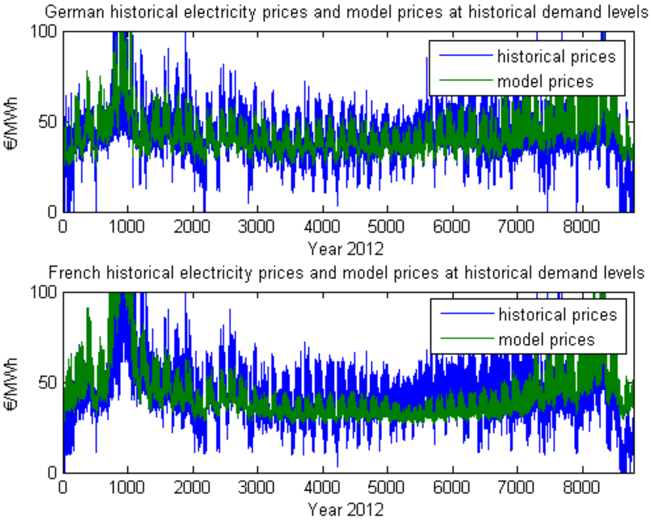
We find the following parameters:

Germany		France		Interconnector	
Parameter	Value	Parameter	Value	Parameter	Value
a_1	-2.35	a_2	-3.72	E_{min}	-3.5
b_1	0.035	b_2	0.054	E_{max}	2.8
c	3.08	c	3.08		

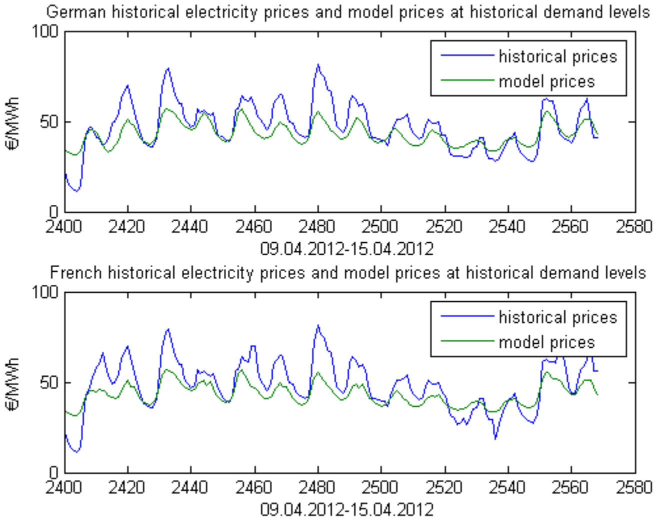
Table : Estimates of model parameters for the German and French market

- Market supply curve in France in more convex as in Germany.
- Sharp increases in electricity prices occur at higher demand levels in France.

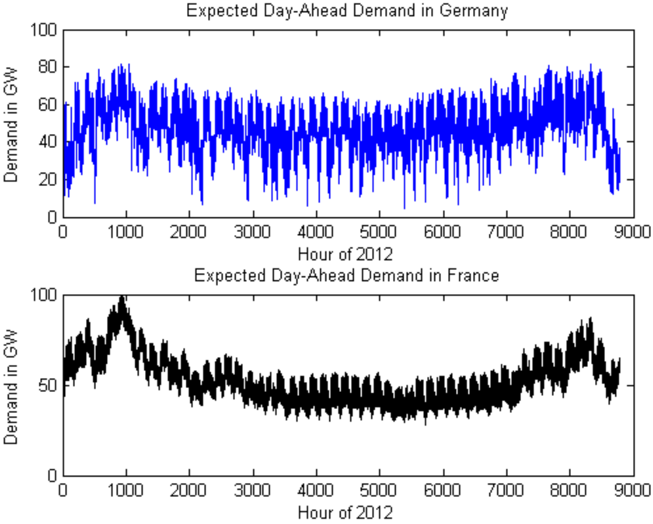
Market Supply Curves - Model Fit



Market Supply Curves - Weekly Fit



Expected Day-Ahead Demand in 2012 - France and Germany



Expected Day-Ahead Demand - Model

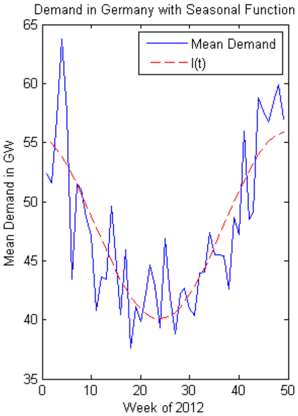
We assume that demand D_t can be modeled as the sum of a deterministic function $f(t)$ and a stochastic part X_t:

$$D_t^i = f^i(t) + X_t^i$$
$$dX_t^i = -\kappa^i X_t^i dt + \sigma_i dW_t^i.$$

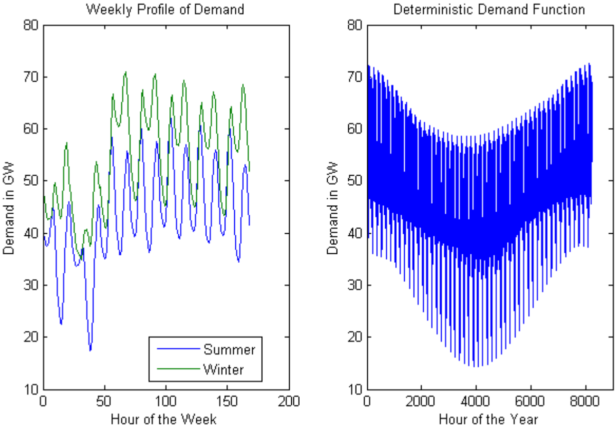
The deterministic function consists of a time varying weekly shape and a level adjustment:

$$hour(t) = \text{hour of the week of t}$$
$$week(t) = \text{week of t}$$
$$\lambda(t) = \frac{1 - \cos(\frac{2\pi week(t)}{52.3})}{2}$$
$$l(t) = x_1 \sin(\frac{2\pi week(t) - x_2}{52.3}) + x_3$$
$$f(t) = \lambda(t) f^{summer}(hour(t)) + (1 - \lambda(t)) f^{winter}(hour(t)) + l(t)$$

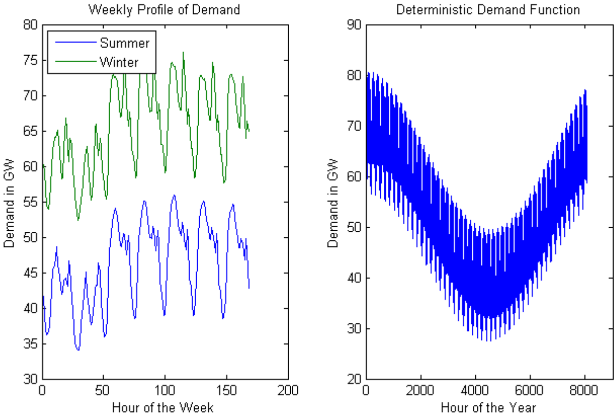
Expected Day-Ahead Demand - Seasonality



German Demand - Weekly patterns and deterministic Part



French Demand - Weekly patterns and deterministic Part



Demand - Stochastic Part

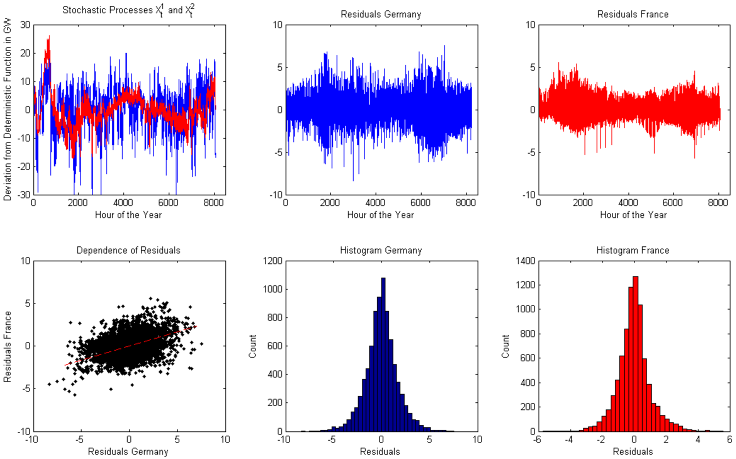
For the stochastic parts of the two demand processes we find the following annualized parameters:

Germany		France		Correlation	
Parameter	Value	Parameter	Value	Parameter	Value
κ_1	219.48	κ_2	139.39	$dW_t^1 dW_t^2$	0.33 dt
σ_1	156.90	σ_2	97.22		

Table : Estimates of model parameters for the German and French market

This translates into $X_t|\mathcal{F}_s \sim N(X_0 e^{-\kappa_i(t-s)}, \frac{\sigma_i^2}{2\kappa_i}\left(1 - e^{-2\kappa_i(t-s)}\right)$.

Demand - Stochastic Part



Joint Distribution of Risk Factors

We assume that demand in France and Germany and the fuel basket form a multivariate normal distribution:

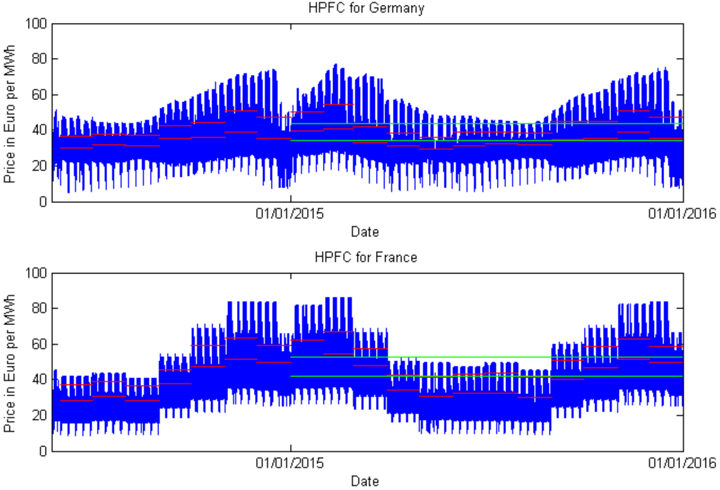
$$\begin{pmatrix} D_t^1 \\ D_t^2 \\ \ln(S_t) \end{pmatrix} |_{\mathcal{F}_s} \sim N\left(\mu(s,t), \Sigma(s,t)\right)$$

with parameters

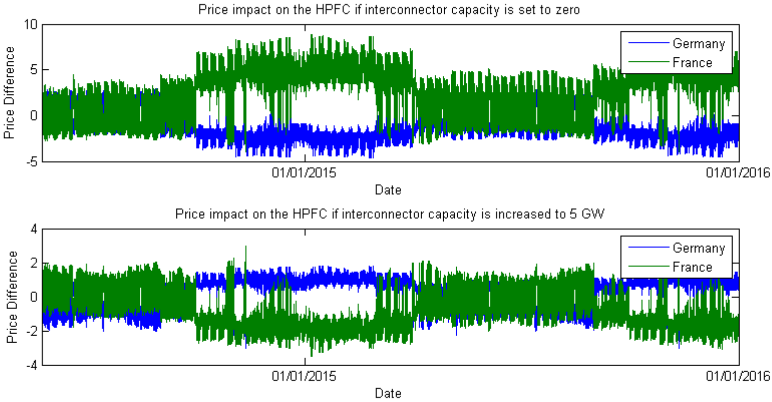
$$\mu(s,t) = \begin{pmatrix} f^1(t) + X_s e^{-\kappa_1(t-s)} \\ f^2(t) + X_s e^{-\kappa_2(t-s)} \\ S_s e^{-\kappa_S(t-s)} + \theta_S\left(1 - e^{-\kappa_S(t-s)}\right) \end{pmatrix}$$

$$\Sigma(s,t) = \begin{pmatrix} \frac{\sigma_1^2}{2\kappa_1}\left(1 - e^{-2\kappa_1(t-s)}\right) & \frac{\sigma_1\sigma_2\rho}{\kappa_1+\kappa_2}\left(1 - e^{-(\kappa_1+\kappa_2)(t-s)}\right) & 0 \\ \frac{\sigma_1\sigma_2\rho}{\kappa_1+\kappa_2}\left(1 - e^{-(\kappa_1+\kappa_2)(t-s)}\right) & \frac{\sigma_2^2}{2\kappa_2}\left(1 - e^{-2\kappa_2(t-s)}\right) & 0 \\ 0 & 0 & \frac{\sigma_S^2}{2\kappa_S}\left(1 - e^{-2\kappa_S(t-s)}\right) \end{pmatrix}.$$

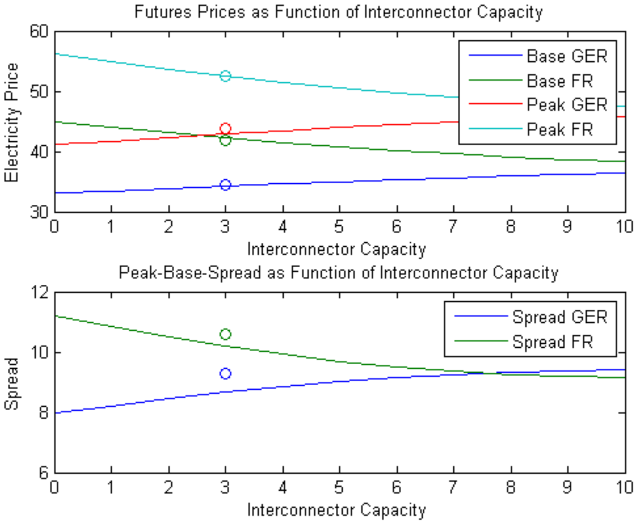
HPFC at 2014-05-21



Effects of Interconnector Capacity on HPFC



Effects of Interconnector Capacity on Traded Products



Effects of Interconnector Capacity on Power Plants - Example

As an example, we study the effect of interconnector capacity changes on the value of a virtual power plant contract. Let the contract be specified as follows:

- Duration of the contract: 2015-01-01 to 2015-12-31
- Plant location: Germany
- Plant Capacity 1 MW
- Marginal Costs 50Euro/MWh
- No ramping time
- No start-up or shut-down costs.

I.e. the plant is basically a strip of calls on the hourly electricity price in Germany during the year 2015 with Strike 50.

Example - VPP Profitability

Int. Cap.	Base	Peak	FLH	Intr. Val.	Value	'Extr.' Val.
-3.5/2.8	34.42	43.70	864	5,601	9,426	3,825
0	33.11	41.09	573	3,887	7,534	3,647
2	33.85	42.29	738	4,723	8,435	3,712
5	34.95	43.97	985	6,430	10,246	3,816
10	36.34	45.76	1,312	8,905	12,640	3,734

Table : Power plant profitability depending on interconnector capacity

Conclusions + Literature

- We presented a two-market-one-fuel structural model and analysed spot, futures and option prices using semi-analytical expressions.
- The model allows to study the effect of interconnector capacity on spot, futures and option prices.
- Clémence Alasseur and Olivier Féron (EDF) extended the model to the two-market-multi-fuel case.
- Füss, Mahringer and Prokopczuk (St. Gallen) study the empirical effect of market coupling in the CWE area and present a theoretical discussion of implicit and explicit coupling schemes.

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