A structural risk-neutral model for pricing and hedging power derivatives

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Contents

Looking for a power spot price model

Applications

- pricing of derivatives on the spot
- asset valuation (strip of hourly fuel spread options)
- hedging
- energy market risk management

Model requirements

- realistic
- robust
- tractable
- consistent

Two types of modeling

Modeling futures prices

pros modeling the real available instruments

cons introduction of many parameters to reconstruct hourly futures prices

Modeling spot prices

1. Exogeneous
   - **pros** tractability
   - **cons** correlation
2. Equilibrium
   - **pros** correlation
   - **cons** complexity

Related works

Electricity prices exogeneous dynamics

Deng (00), Benth et al. (03, 07, 09), Burger et al. (04), Kolodnyi (04), Cartea & Figueroa (05), Geman & Roncoroni (06)

Equilibrium model

	Spot	Futures	Options
Pirrong & Jermakyan (00)	×	×	
Barlow (02)	×		
Kanamura & Ohashi (07)	×		
Cartea & Villaplana (08)	×	×	
Coulon & Howison (09)	×	×	
Lyle & Elliot (09)	×	×	×

This talk

Objectives

pricing and hedging power derivatives...

... using an improved version of Aïd, C., Nguyen & Touzi (09) Structural Risk-Neutral model

	Spot	Futures	Options
Aïd, C., Nguyen & Touzi (09)	×	×	
improved SRN model	×	×	×

Initial SRN Model

Variables

n	fuels, $1 \leq i \leq n$
D_t	demand (MW)
C_t^i	capacities (en MW)
S_t^i	fuel prices
h_i	*heat rates* ($h_i S_t^i$ en €/MWh, ↗ en i)

Electricity price (€/MWh)

$$\widehat{P}_t = \sum_{i=1}^{n} h_i S_t^i \mathbb{1}_{\{\sum_{k=1}^{i-1} C_t^k \leq D_t \leq \sum_{k=1}^{i} C_t^k\}}$$

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Initial SRN model

Pros

- Consistency between electricity prices and fuel prices
- Consistency between electricity prices and demand

Initial SRN model

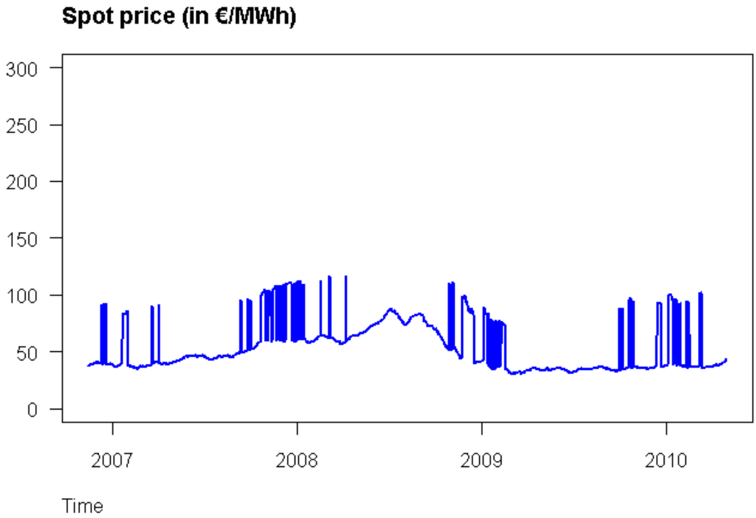
Pros

- Consistency between electricity prices and fuel prices
- Consistency between electricity prices and demand

Cons

- Marginal fuel cost is not the spot price
  1. Non-convex technical constraints
  2. Strategic behaviour (Hortaçsu & Puller, RAND J. of Economics 2008)
  3. Fixed cost recovery problem for peak-load generation plants

Initial SRN Model - illustration



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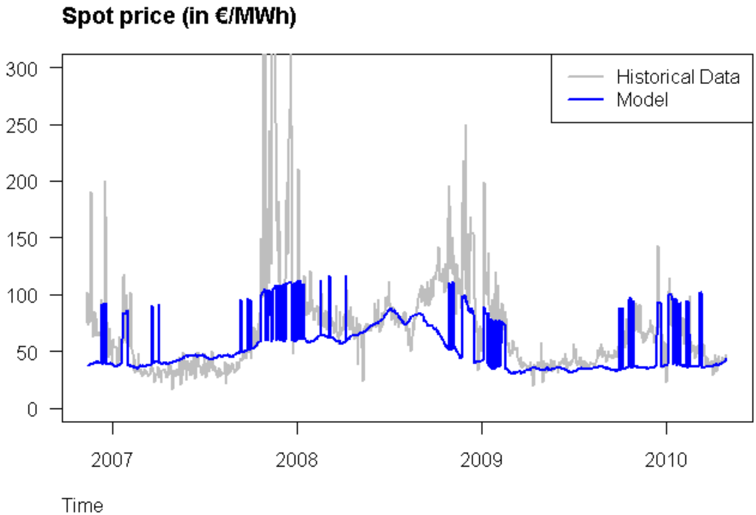

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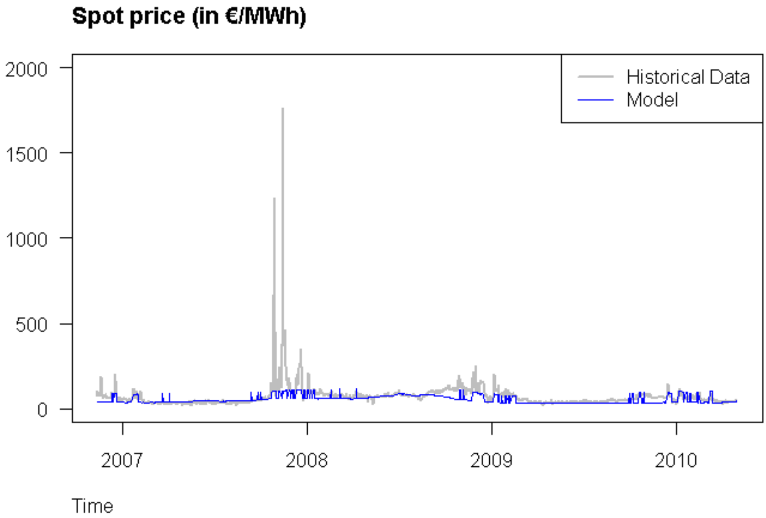

Improved SRN model

- Marginal fuel cost $\widehat{P}_t := \sum_{i=1}^{n} h_i S_t^i \mathbf{1}_{\{\sum_{k=1}^{i-1} C_t^k \leq D_t \leq \sum_{k=1}^{i} C_t^k\}}$

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- Price spikes occur when the electric system is under stress, i.e. $\overline{C}_t - D_t$ is small

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$y_t := \frac{P_t}{\widehat{P}_t}$ **as a (nonlinear) function of** $x_t := \overline{C}_t - D_t$

Improved SRN model - Estimation

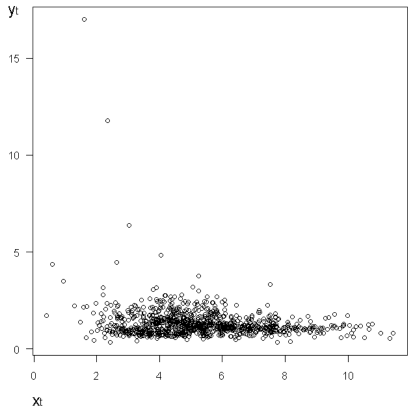


Figure: PowerNext - 19th hours
Nov, 13th 06 to April 30th 10

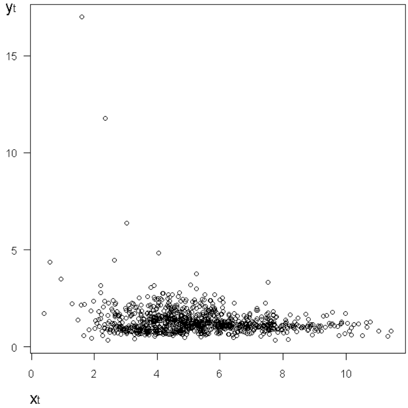
Observation

- Decreasing relation
- Difficult estimation

Idea

- Quantiles

Improved SRN model - Estimation



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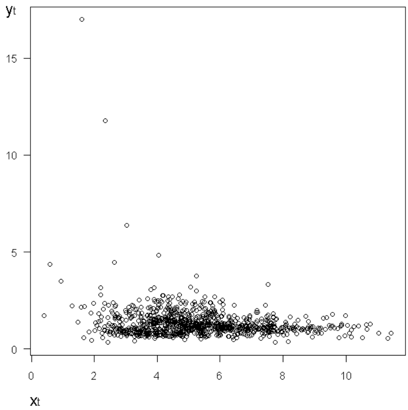

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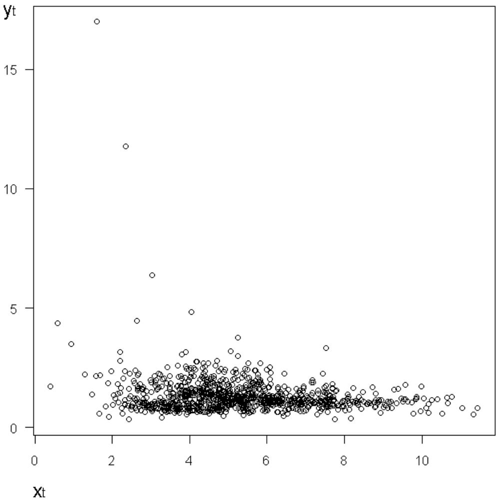

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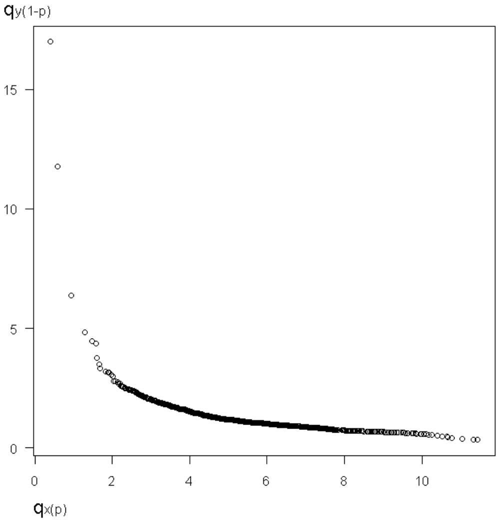

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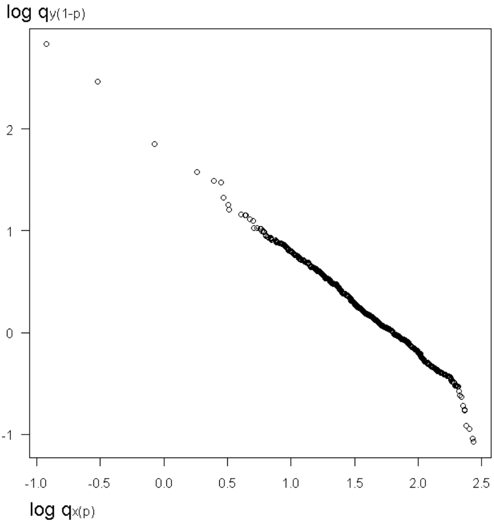

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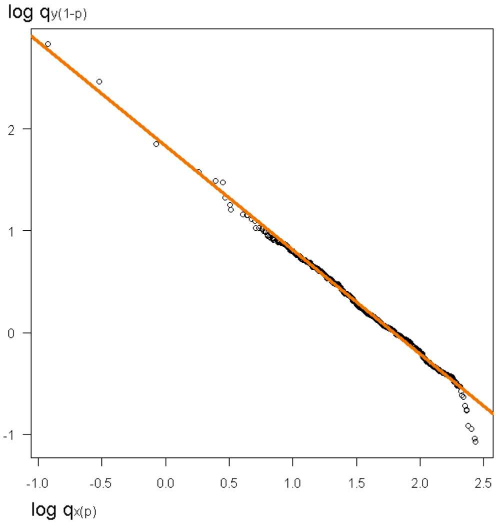

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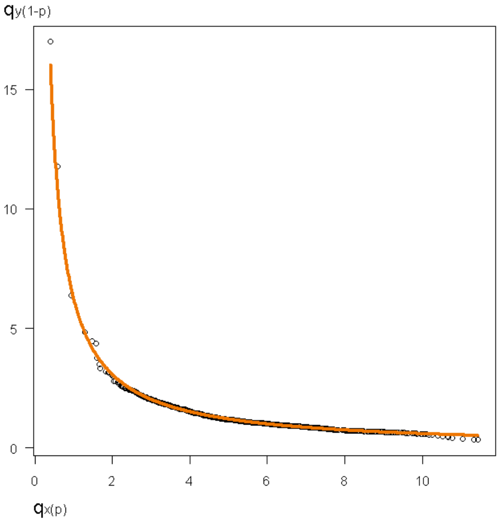

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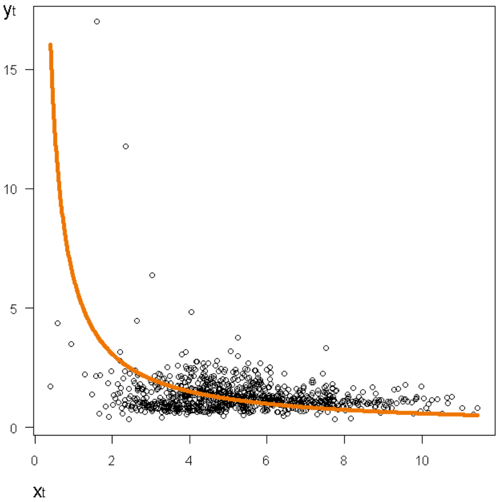


Improved SRN model - Estimation

Estimated relation : $y_t = \frac{\gamma}{x_t^\nu}$

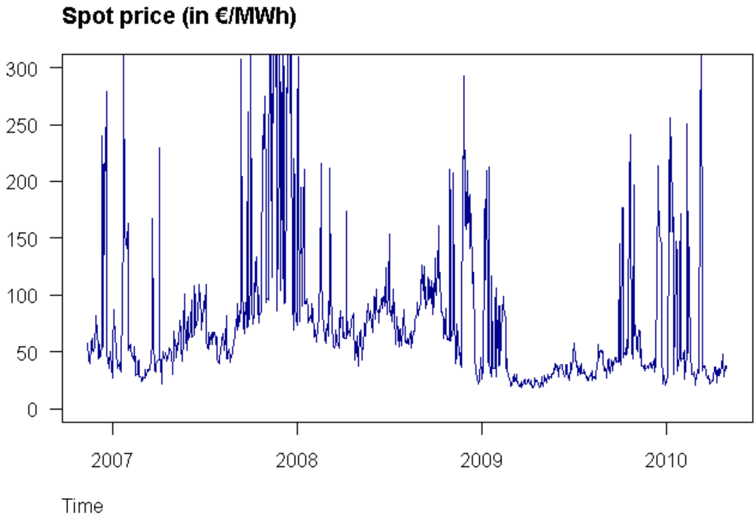
Improved SRN model

$$P_t = g\left(\sum_{k=1}^{n} C_t^k - D_t\right) \times \left(\sum_{i=1}^{n} h_i S_t^i \mathbf{1}_{\left\{\sum_{k=1}^{i-1} C_t^k \leq D_t \leq \sum_{k=1}^{i} C_t^k\right\}}\right)$$

with scarcity function

$$g(x) := \min\left(\frac{\gamma}{x^\nu}, M\right) \mathbf{1}_{\{x>0\}} + M \mathbf{1}_{\{x \leqslant 0\}}$$

Improved SRN model - Back-testing



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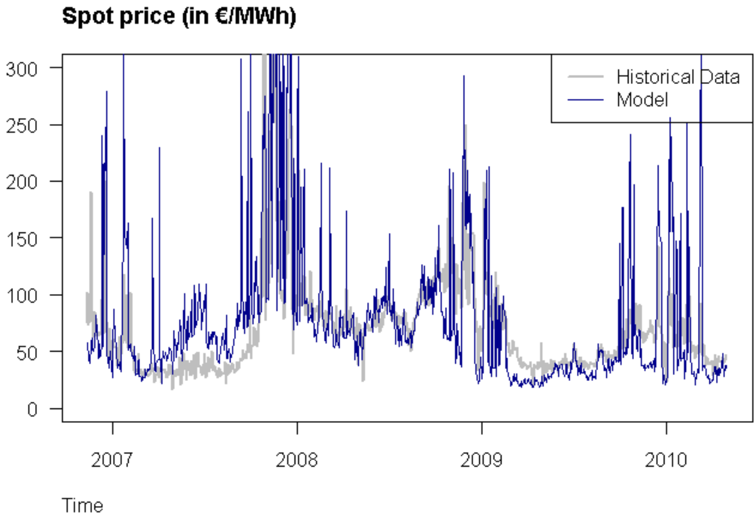

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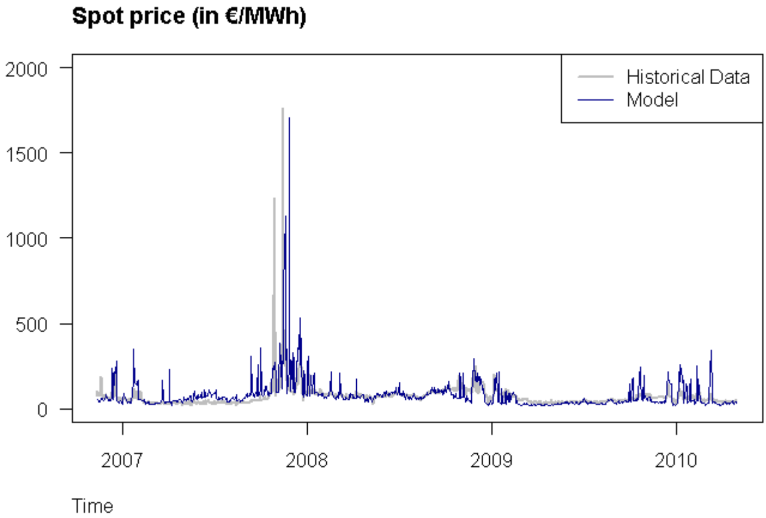

Pricing & hedging

Pricing

- incomplete market
- need for a hedging criterion
- super-replication, utility indifference or mean-variance
- our choice : Local Risk Minimization

Local Risk Minimization (Pham (00), Schweizer (01))

- valuation : expected discounted payoff under $\widehat{\mathbb{Q}}$
- allows to decompose contingent claim into hedgeable part (fuels) and non-hedgeable part (demand, capacities)
- allows explicit formulas

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Dynamics of fuels

Assume r constant, convenience yields and storage costs zero for simplicity.

Fuels

$n \geq 1$ fuels (as coal, gas, oil ...) whose cost $h_i S^i$ to produce 1 MWh of electricity follows

$$dS_t^i = S_t^i(\mu_t^i dt + \sigma_t^i dW_t^{S,i})$$

where $W^{S,i}$ are correlated BMs and coeff's are chosen so that $h_1 S^1 < \ldots < h_n S^n$ (model spreads $Y^i = h_{i+1}S^{i+1} - h_i S^i$ as independent geometric BMs).

NA and completeness assumption

There exists a unique risk-neutral probability $\mathbb{Q} \sim \mathbb{P}$ for S.

Local risk minimization I

Roughly speaking, let X be a multidimensional (discounted) price process

- Introduced by Föllmer-Schweizer (1991)
- Under regularity condition, any payoff H with maturity T

$$H = H_0 + \int_0^T \xi_t^H dX_t + L_T^H$$

where $H_0 \in \mathbb{R}$ and L^H martingale orthogonal to X.

- $\int_0^T \xi dX$ is the hedgeable part, L_T^H the residual risk, $H_0 + L_T^H$ the cost of the strategy
- How to compute H_0, ξ^H, L^H ? Easy when X is a martingale : use Kunita-Watanabe decomposition !

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Local risk minimization II

- When X is not a martingale but not far from being so ...
- Föllmer-Schweizer (1991) : there exists a risk-neutral $\widehat{\mathbb{Q}}$ for X s.t.

$$H = \widehat{\mathbb{E}}[H] + \int_0^T \widehat{\xi}_t^H dX_t + \widehat{L}_T^H$$

- $H_0 = \widehat{\mathbb{E}}[H]$, $\xi^H = \widehat{\xi}^H$, $L^H = \widehat{L}^H$
- $\widehat{\mathbb{Q}}$ is called minimal equivalent martingale measure
- Hobson (2005) : in diffusion models with non-tradable assets, $\widehat{\mathbb{E}}[H]$ is an upper bound for U-indifference bid price.

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Dynamics of demand and capacities

Demand & capacities

$$dD_t = a(t, D_t)\,dt + b(t, D_t)\,dW_t^D$$
$$dC_t^i = \alpha_i\left(t, C_t^i\right)dt + \beta_i\left(t, C_t^i\right)dW_t^{C,i}$$

where W^D, W^C and W^S are independent BMs.

Minimal martingale measure

The minimal martingale measure $\widehat{\mathbb{Q}}$ is given by

$$\widehat{\mathbb{Q}}|_{\mathcal{F}_t} = \mathbb{Q}|_{\mathcal{F}_t^S} \otimes \mathbb{P}|_{\mathcal{F}_t^{C,D}}$$

where $\mathcal{F}_t$ is the filtration generated by W^S, W^D, W^C.

Futures

Under our assumptions, we can prove the following

Futures prices $F_t^e(T) = \widehat{\mathbb{E}}_t[P_T]$

$$F_t^e(T) = \sum_{i=1}^{n} h_i G_i^T(t, C_t, D_t)\, F_t^i(T)$$

with :

$$G_i^T(t,C_t,D_t) = \mathbb{E}_t\left[g\left(\sum_{k=1}^{n} C_T^k - D_T\right) \mathbf{1}_{\left\{\sum_{k=1}^{i-1} C_T^k \le D_T \le \sum_{k=1}^{i} C_T^k\right\}}\right]$$

Futures prices - hedging

Futures price dynamics

$$dF_t^e(T) = \sum_{i=1}^n h_i \left[G_i^T(t, C_t, D_t) dF_t^i(T) + F_t^i(T) dG_i^T(t, C_t, D_t) \right]$$

$$dG_i^T(t, C_t, D_t) = \sum_{k=1}^n \frac{\partial G_i^T}{\partial c_k}(t, C_t, D_t)\beta_k(t, C_t^k) dW_t^{C,k} + \frac{\partial G_i^T}{\partial z}(t, C_t, D_t) b(t, D_t) dW_t^D$$

so that

$$dF_t^e(T) = \theta_t^S dW_t + \theta_t^C dW_t^C + \theta_t^D dW_t^D$$

for adapted suitable processes $\theta^S, \theta^C, \theta^D$, which are explicitly computable.

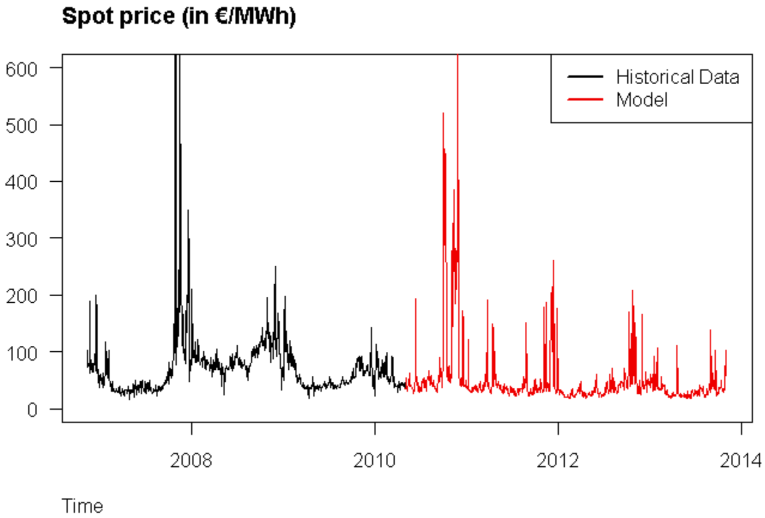
Futures prices - hedging

- To go further, need to choose more specific dynamics for demand and capacities
- deterministic part for seasonality + Ornstein-Uhlenbeck
- G_i^T explicite as function of *extended incomplete Goodwin-Staton integral* :

$$\widetilde{\mathcal{G}}(x, y; \nu) = \int_x^{\infty} \frac{1}{(y+z)^{\nu}} e^{-z^2} dz$$

- ... for which efficient numerical algorithms are provided in Aïd, C. & Langrené (10).

Futures prices - hedging : spot simulations



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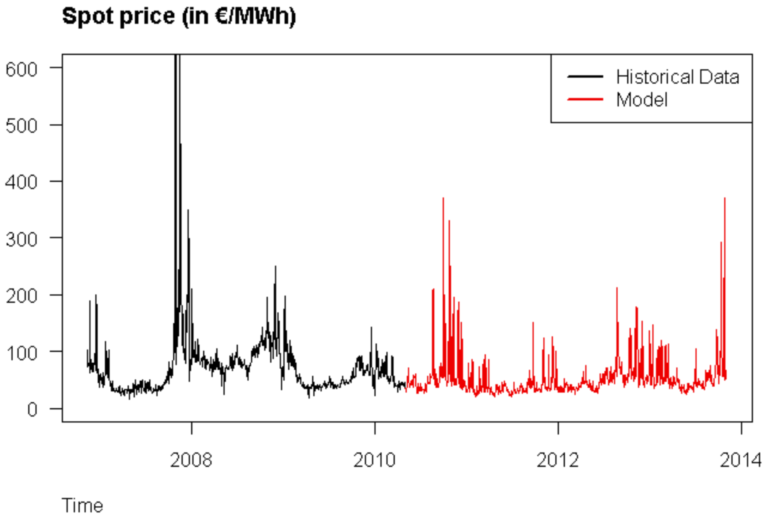

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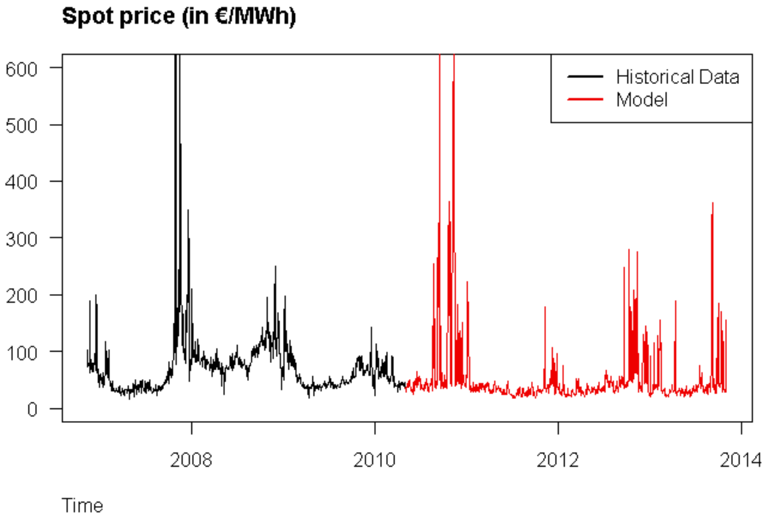

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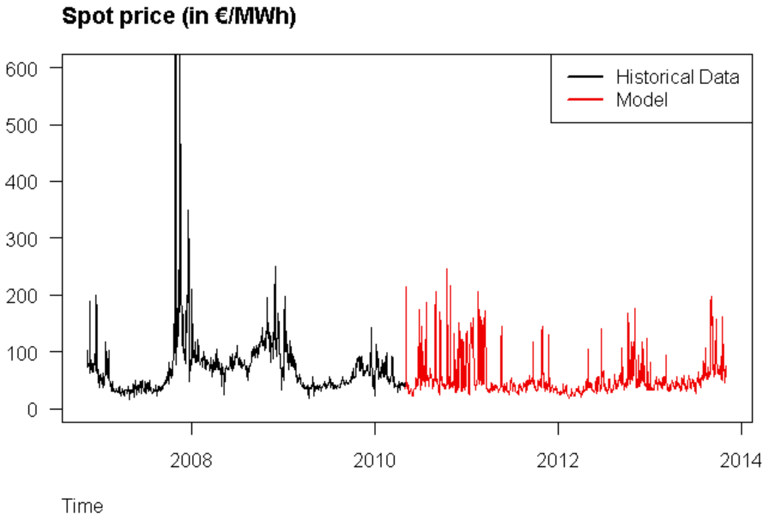

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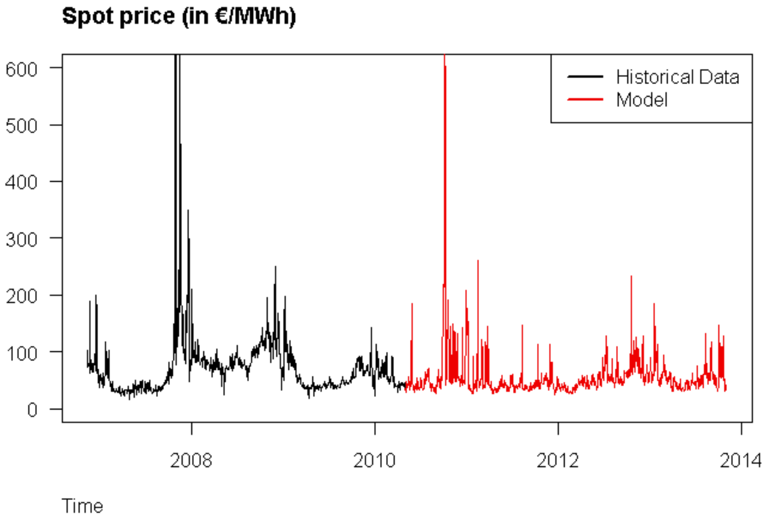

Futures prices - hedging

Numerical test

- Hedging a 3-months electricity futures with a delivery period of 1 hour
- with a daily rebalanced basket of futures contracts on fuels

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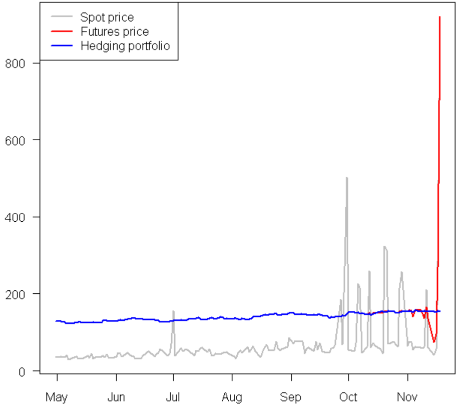
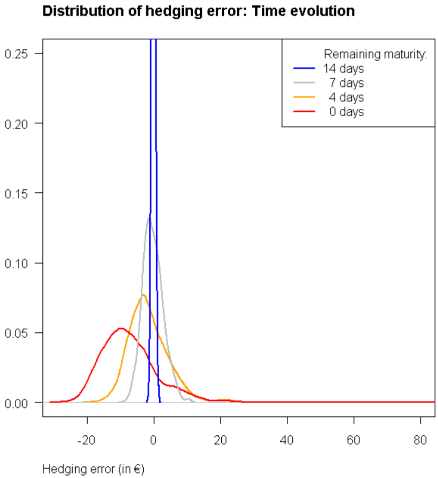
- with a daily rebalanced basket of futures contracts on fuels

Sample paths (in €)



Futures prices - hedging



Remarks

- Positive values are losses
- Far from maturity : perfect hedge ; electricity futures is equivalent to a basket of fuels
- Close to maturity : inefficient hedge

Spread options

Spread option with a 2 fuel model

The price π_0 at time $t = 0$ of a call spread option with pay-off $H = (P_T - h_1 S^1_T - K)^+$ is given by :

$$\pi_0 = \int_{\mathbb{R}^2} f_{C^1_T - D_T}(z) f_{C^2_T}(c) \left\{ \phi_1(c,z) \mathbf{1}_{\{z>0\}} + \phi_2(c,z)\mathbf{1}_{\{z\le 0\}} \right\} dcdz,$$

$$\phi_1 = (g-1) BS_0(\sigma_1, K) \mathbf{1}_{\{g>1\}}$$

$$\phi_2 = g \int_0^\infty \hat{f}_{Y^1_T}(y) BS_0 \left(\sigma_2, \frac{K + (1-g)y}{g} \right) \left(\mathbf{1}_{\{g\le 1\}} + \mathbf{1}_{\{g>1\}} \mathbf{1}_{\{y < \frac{K}{g-1}\}} \right) dy$$

$$+ \left(g Y^2_0 \mathcal{N} \left(\frac{\left(r - \frac{\sigma_1^2}{2}\right) T - \ln\left(\frac{K}{(g-1)Y^1_0}\right)}{\sigma_1 \sqrt{T}} \right) + (g-1)\, BS_0 \left(\sigma_1, \frac{K}{g-1} \right) \right) \mathbf{1}_{\{g>1\}}$$

with $g := g(c+z)$.

Spread options

- semi-explicit formula : numerical integration
- partial hedging with futures on fuels and electricity, semi-explicit formulae for partial hedging strategy (not only for spread options)
- applied on European dark spread (i.e. energy - gas) call option with a period of delivery of 1 hour

Hedging with futures on electricity

Consider $H = \varphi(F^e_T(T^*), F_T(T^*), C_T, D_T)$ with $T^* > T$.

- By Markov, its $\widehat{\mathbb{Q}}$-price in t is $\phi(t, F_t, C_t, D_t)$ with $\phi(t, x, c, z)$ regular
- H's decomposition into hedgeable part/residual risk is

$$H = \widehat{\mathbb{E}}[H] + \int_0^T \widehat{\xi}_t dF_t + \int_0^T \widehat{\xi}^e_t dF^e_t + \widehat{L}_T$$

where

$$\widehat{\xi}^e_t = \frac{1}{||(\theta^C_t, \theta^D_t)||^2} \left(\sum_i \theta^{C,i}_t \beta_i \partial_{c_i} \phi + \theta^D_t b \partial_z \phi \right)$$

$$\widehat{\xi}^i_t = \partial_{y_i} \phi + \frac{h_i G_i^{T*}}{||(\theta^C_t, \theta^D_t)||^2} \left(\sum_i \theta^{C,i}_t \beta_i \partial_{c_i} \phi + \theta^D_t b \partial_z \phi \right)$$

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- SRN electricity spot price model with a scarcity function
- allows futures and derivatives pricing and hedging
- nevertheless, only fuels dependent part can be hedged ...
- ... unless we use energy future for partially hedging demand and capacities risk (see the paper Aïd-C.-Langrené)

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- comparison with "real" quoted futures, calibration dynamics
- utility-based pricing of futures, options ...
- optimal investment/production problem, optimal switching

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