Introduction to electricity risks, markets and trading

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Overview of the course

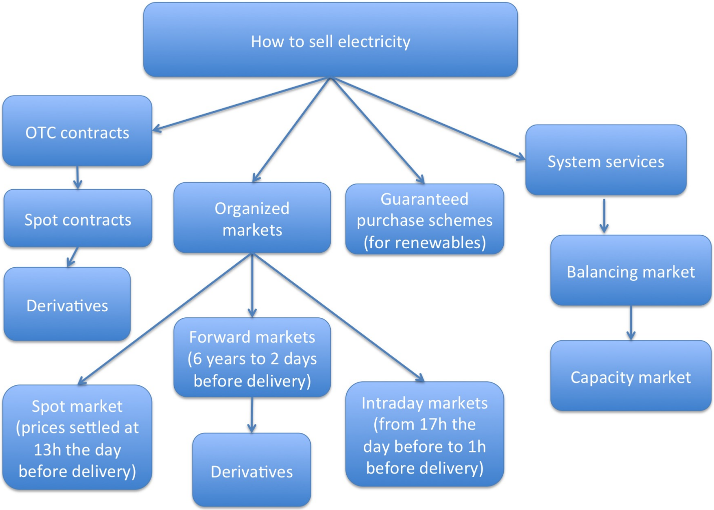
1. **The power generation sector; electricity as a commodity**
   Electricity sector in the world, energy transition. Features of electricity, properties of electricity demand, transport networks. Functioning of electric systems and role of system operators. Network stability and frequency control. Specific risks associated to intermittent renewable electricity generation.
2. **Electricity markets and electricity derivatives**
   Ways to sell electricity. Organization of electricity markets: balancing; intraday, day-ahear, forward and capacity markets. Electricity futures and other derivative products.
3. **Modeling electricity prices and trading in electricity markets**
   Stochastic models for intraday, spot and forward prices. Trading strategies for power producers.

Outline

1 Electricity markets and derivative products

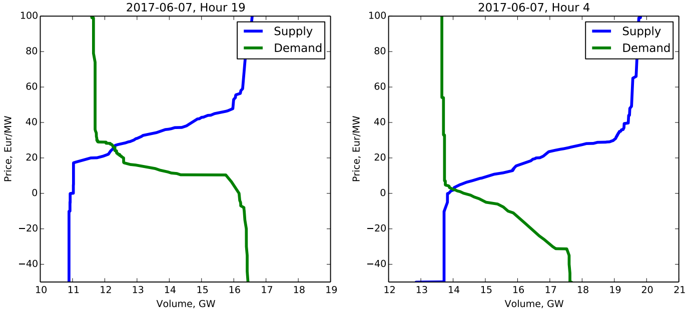
2 Modeling and pricing electricity derivatives

How to sell electricity

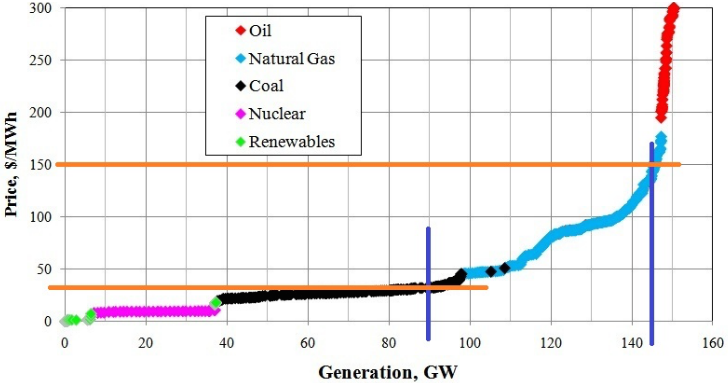


The spot (day-ahead) market (рынок на сутки вперед)

- One of the main trading venues for electricity is the day-ahead market (EPEX Spot in France/Germany).
- In this market trading happens only once: participants submit bids for specific hours of blocks of the next day until 12:00, then at 12:55 the price is fixed and market clears.

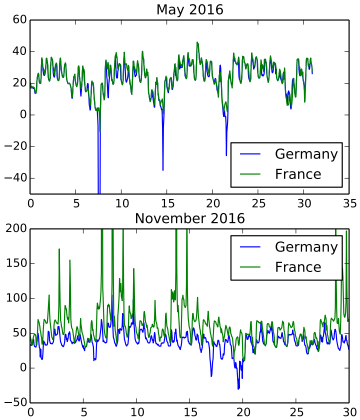


Generation stack (PJM)



Market coupling mechanism

- Each country has its own day-ahead market, but due to market coupling prices in different countries coincide in absence of binding transport constraints
- As long as interconnection capacity permits, demand in one market may be matched by supply in any other market
- If the transport constraints become binding, the prices decouple

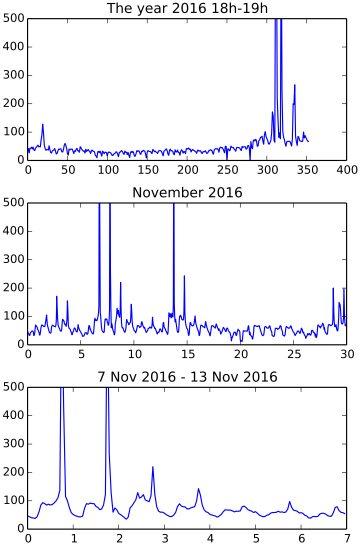


Day-ahead prices in France and Germany. In May, prices are coupled almost all the time, except during negative spikes in Germany. In November, prices are decoupled. Data source: `transparency.entsoe.eu`

Features of spot electricity prices

- Spot electricity prices possess daily, weekly and annual seasonality
- Prices are highly correlated with consumption and in countries where electricity is used for heating / air conditioning, with the temperature
- Due to non-storability, prices exhibit spikes which occur, e.g., in case of plant outage, especially in winter

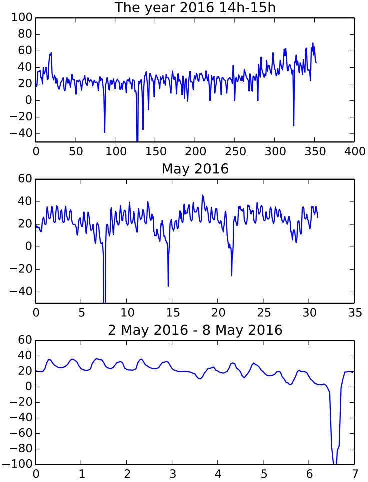
Day-ahead prices in France. Data source: `transparency.entsoe.eu`



Features of spot electricity prices

- Negative prices: since it is costly to shut down coal-fired and nuclear plants, producers are ready to pay to keep the plant running
- This phenomenon is particularly important in Germany due to the large-scale production from renewable sources (at zero marginal cost)

Day-ahead prices in Germany. Data source: `transparency.entsoe.eu`

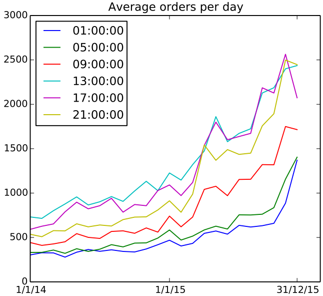


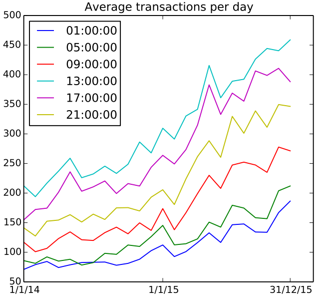
The intraday market

The intraday market opens at 15h and allows continuous trading for each hour/quarter-hour of the next day, up to 30 minutes before delivery.

Every delivery hour of every day corresponds to a different product: the life time of a single product is from 9 to 32 hours.

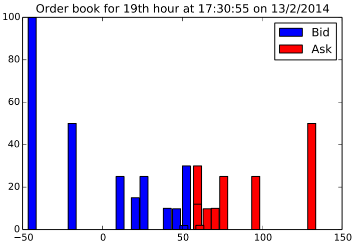
Market liquidity is improving but remains relatively low.





The intraday market

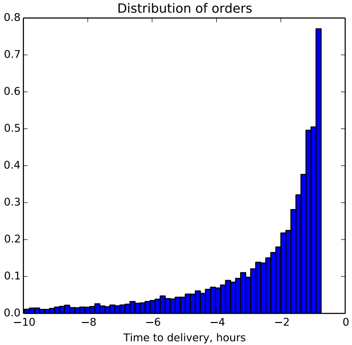
- Trading in intraday markets is order book-based, with a separate order book for each delivery hour.
- Each country has a separate intraday market, but the markets are coupled: if transmission capacity exists, traders in any market see the orders from other markets in their order books.

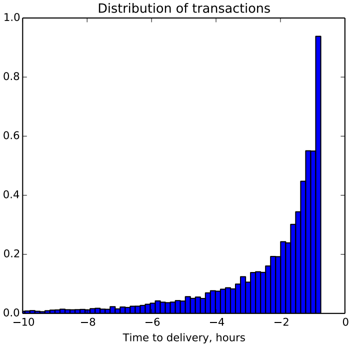


Intraday electricity markets are gradually acquiring the characteristics of other high-frequency markets with automated trading, optimal execution algorithms, presence of arbitrageurs, price manipulation attempts etc.

Intraday market liquidity patterns

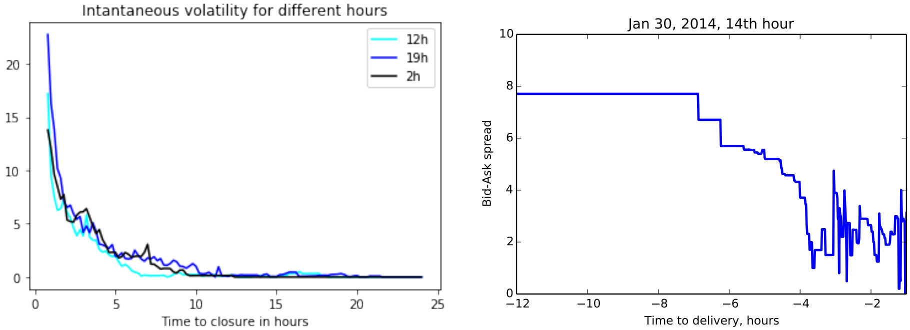
Liquidity only appears a few hours before delivery.





Distribution of orders/transactions as function of time to delivery for all contracts expiring in February 2015.

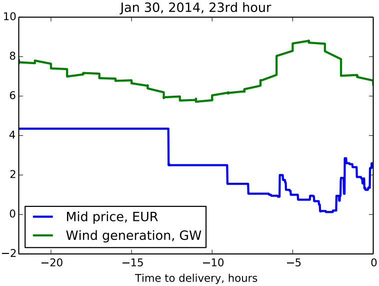
Bid-ask spread and volatility

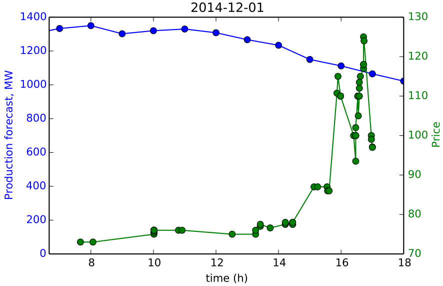


Left: (Normal) volatility averaged over all days of February 2014 (kernel estimator, source: L. Tinsi). Right: bid-ask spread evolution on a typical day.

The intraday market

The development of intraday markets has been fueled by the expansion of intermittent renewables: prices are correlated with renewable production forecasts.





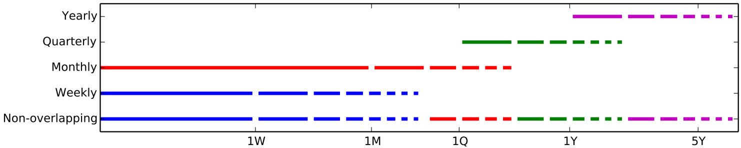
Left: dynamics of intraday price vs. wind production in Germany. Right: dynamics of intraday price for the 19th hour of 12 Dec 2014 vs. the forecast of wind power production in France. Data source: EDF and RTE

The forward market

- Electricity futures contract are traded in the European Energy Exchange (EEX).
- Since electricity is a flow commodity, for each contract, a delivery period is specified. For the German market, EEX offers futures for 6 next years, 11 next quarters, 9 next months, 4 next weeks 2 weekends and 8 days.
- Future contracts come in 3 different flavors: base-load (every hour), peak-load (7h-20h Mon-Fri) and off-peak load.
- This allows to maintain reasonable liquidity while enabling market participants to hedge their positions precisely.

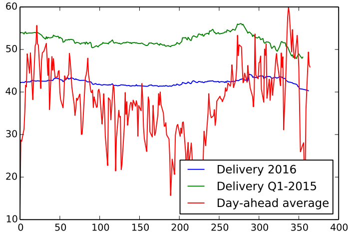
Electricity future contracts

- An electricity future contract (swap) specifies a delivery period
- A future with delivery between T_1 and T_2 settles financially against the average day-ahead price of this period



The forward market

- Futures prices are much less volatile than spot prices, especially for longer delivery periods.
- Due to non-storability of energy, futures prices are not correlated with spot prices and one cannot speak of convergence of futures prices to spot prices.
- Futures for winter delivery are more expensive.



2014 yearly and quarterly base-load futures prices compared to daily average of day-ahead prices. Data source: EDF.

Electricity derivatives: financial

Standard Calls/Puts on electricity futures are traded in power exchanges such as EEX. They can be valued as standard financial options since the underlying is liquidly traded.

Call option gives the right to enter a long futures position at the expiry date of the option, at the specified price (strike price)

Put option gives the right to enter a short futures position at the expiry date of the option, at the specified price

Electricity derivatives: physical

Physical options are embedded in portfolios of energy assets:

- Fuel spreads mimick the profit of a power plant at a given moment in time: the clean fuel spread option pays

$$\left(S^e_T - hS^f_T - gS^c_T\right)^+ ,$$

where

  - S^e is the spot price of electricity;
  - S^f is the spot price of fuel (e.g., gas or coal);
  - S^c is the price of carbon emission allowances;
  - h is the heat rate of the plant;
  - g is the emission rate of the plant.

Electricity derivatives

- Cross-border transmission rights are spread options on the price differential of two neighboring countries (e.g., France vs. Germany). Their pricing is complexified by market coupling (when markets are coupled the spread is zero).
- A tolling agreement mimicks the operation of a power plant over time: it pays

$$\int_0^T \left(S_t^e - hS_t^f - gS_t^c\right)^+ dt.$$

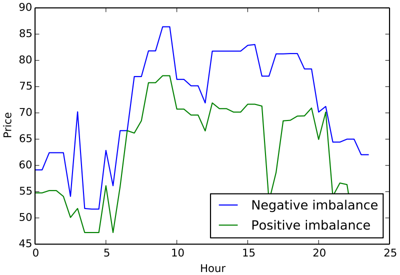
- A swing option is a flexible delivery contract which mimicks a hydroelectric reservoir: the buyer has the right to receive energy (at most $\bar{q}$) on a certain number of days N during a period of time T subject to the constraint that the total consumed power is between $\underline{Q}$ and $\overline{Q}$.

The Balance Responsible Entity system

- Balance Responsible Entities (BRE, responsables d'équilibre) are basic agents of the French electricity markets
- A BRE, declares to RTE its balance perimeter: portfolio of activities such as
  - Physical sites consuming or generating powe
  - Purchases and/or sales on the power exchanges operating in France;
  - Purchases and/or sales of electricity from/to counterparts;
  - Energy exports and/or imports;
  - Sales of energy to RTE to compensate losses.
- All energy production / consumption must be affected to a balance perimeter of a BRE
- All imbalances within the balance perimeter are compensated to RTE using the imbalance price.

Imbalance prices

- In case of system imbalance, the network operator compensates over-producing agents and applies a penalty to under-producing agents.
- The compensation price and penalty are fixed to enable the network operator to recover the cost of using additional generation.

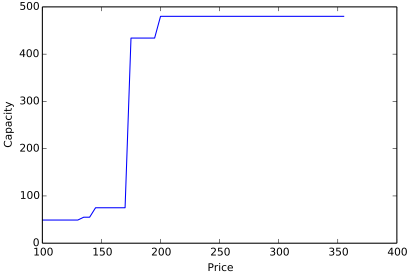


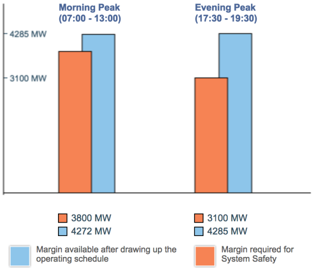
	Balancing trend > 0	**Trend** < 0
Imbalance > 0: actor is paid	$VWAP_u(1-k)$	$VWAP_d(1-k)$
Imbalance < 0: actor pays	$VWAP_u(1+k)$	$VWAP_d(1+k)$

Here $VWAP$ is the volume weighted average price of the balancing and $k = 0.05$.

The balancing mechanism (балансирующий рынок)

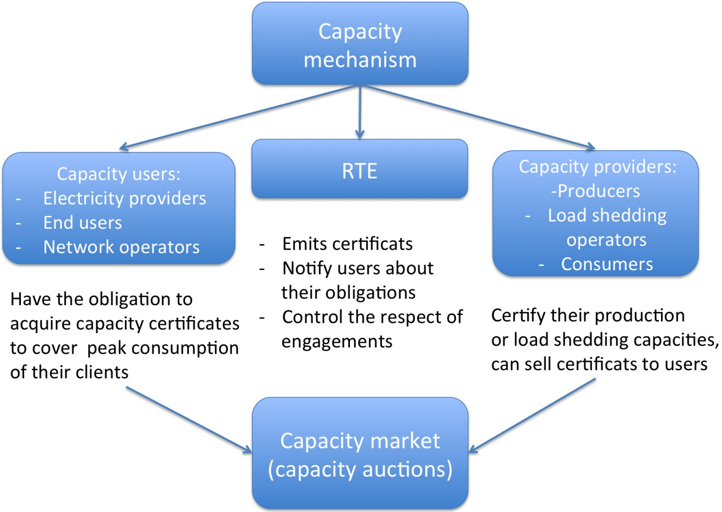
- The balancing mechanism (adjustment market) allows the network operator (RTE) to ensure precise overall balance between generation and consumption for the entire system (reconstitute primary and secondary reserve).
- Market players submit bids for increasing production (or reducing consumption).





Capacity / price curve (left) and available margins on 15/12/2016. Data: RTE

The capacity mechanism/market (рынок мощности)



The capacity mechanism and capacity market

- Annual certification for the coming year
- Via the 'certification perimieter responsible entity', financially responsible for capacity violations
- Two certification methods:
    - Standard method: based on realized values observed during peak periods
    - Normative method (for renewable energies): based on historical production multiplied by a coefficient
- Below 1MW: compulsory agregation
- Below 100MW: possible agregation

Other	4223 MW
Biomass	77.6 MW
Industrial waste	1.5 MW
Load shedding	1740.8 MW
Onshore wind	2004.3 MW
Hydro/river	4469.7 MW
Gaz/coal	8662.4 MW
Hydro/lake	5584.4 MW
Multi-energy	4659.4 MW
Nuclear	55140.6 MW
Pumped storage	3515.9 MW
Oil	2714.3 MW
Solar	232.8 MW

Capacity mechanisms in the EU

- **Strategic reserve:** (Belgium, Germany, Poland and Sweden) A central agency contracts capacity through a competitive tender. The contracted plants cannot participate in the market and are only activated in case of shortfalls.
- **Capacity auction:** (UK) The total required capacity is centrally procured in an auction. The new capacity participates in the energy-only market.
- **Capacity obligation:** (France) An obligation for large consumers or electricity suppliers to contract an amount of capacity linked to their self-assessed future consumption or supply, plus a reserve margin.
- **Reliability options:** (planned in Italy) A capacity provider enters into an option contract with a counterparty. The contract offers the counterparty the option to procure electricity at a predetermined strike price.
- **Capacity payments:** (Italy, Poland, Portugal, Spain, Ireland) Pre-determined fees are set by the regulator and paid to capacity providers. The plants receiving capacity payments continue to participate in the energy-only market.

Ancillary services markets

Ancillary services include capabilities of

- Frequency regulation (FCR/FRR)
- Reactive power generation (reactive power: no net power flow but losses and capacity limits in lines)
- Black start capabilities

Cross-border transmission rights

- Cross-border transmission rights can be purchased at an auction for a period of one year, one month or one day
- Auctions in the EU are held by the Joint Allocation Office, single European entity responsible for cross-border capacity allocation
- The allocated capacities can then be nominated within the limits set by the programming authorisations for each hour of the day, before 15:30 of the previous day (day-ahead prices already known).
- Pay-off of a cross-border transmission right with unit capacity from region with price S^2 to region with price S^1 for a total of T hours:

$$\sum_{t=1}^{T} n_t (S_t^1 - S_t^2)^+,$$

with n_t is the programming authorisation in percentage of the capacity.

Electricity balancing

- The European regulation "Electricity balancing" aiming to create a Europe-wide adjustment market was approved by the European Commission in March 2017 and is now being implemented in the form of pilot projects in 2018–2019.
- The goal is to create a market-oriented framework automatic frequency restoration and primary and secondary reserves at the European scale.

Outline

1. Electricity markets and derivative products
2. Modeling and pricing electricity derivatives

Commodity futures

- For financial futures, cash and carry arbitrage yields

$$F_t(T) = e^{r(T-t)} S_t.$$

- In presence of storage cost c per unit of time and underlying,

$$F_t(T) = e^{(r+c)(T-t)} S_t,$$

- and for underlyings which cannot be sold short,

$$F_t(T) = e^{(r+c-y)(T-t)} S_t,$$

where $y \geq 0$ is the "convenience yield" per unit of time and underlying.

Electricity cannot be stored at large scale at reasonable cost, so this relationship breaks down and one needs to model jointly the spot and future prices.

Electricity future contracts

- An electricity future contract (swap) specifies a delivery period
- A future with delivery between T_1 and T_2 settles financially against the average day-ahead price of this period
- Three modeling approaches:
  - Introduce and model a fictitions instantaneous delivery contract

$$F_t(T_1, T_2) = \frac{1}{T_2 - T_1}\int_{T_1}^{T_2} f_t(T)dT;$$

    ⇒complicated dynamics for swap prices which are the underlying of options;
  - Model directly the swap prices

    ⇒ complicated constraints on the volatility structure;
  - Model the spot price and compute forward prices as risk-neutral expectations of spot price

    ⇒ calibration to the initial forward curve difficult

Modeling instantaneous-delivery contracts

Assume a multifactor log-normal dynamics for $f_t(T)$ under a risk-neutral probability measure $\mathbb{Q}$:

$$\frac{df_t(T)}{f_t(T)} = \sum_{i=1}^{n} \sigma_i(t,T)dW_t^i = \sigma^T(t,T)dW_t,$$

where W^i are independent Brownian motions (risk factors) and σ_i are risk factor volatilities.

- Log-normal modeling may be used for long-dated forwards which are not as volatile as the spot
- The number of factors in electricity markets is quite high since forwards of different maturities are loosely coupled
- This modeling is not compatible with lognormal swap price dynamics, often assumed by the market

Implied spot price dynamics

The spot price may be recovered as $S_t = \lim_{T\to t} f_t(T)$. Itô formula yields:

$$\frac{dS_t}{S_t} = \left(\partial \ln f_0(t) - \frac{1}{2}\sigma^2(t,t) + \int_0^t \sigma^T(s,t)\partial_2\sigma(s,t)ds + \int_0^t \partial_2\sigma(s,t)^T dW_s\right) dt + \sigma^T(t,t)dW_t.$$

- The spot price is not martingale under $\mathbb{Q}$ because it is not traded;
- The spot price dynamics may not be Markovian

Example

Assume an exponential volatility structure: $\sigma_i(t,T) = \sigma_i e^{-\lambda_i(T-t)}$. Then,

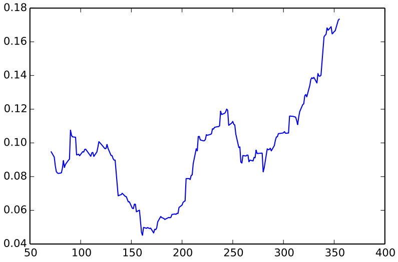
$$S_t = f_0(t)\exp\left(-\frac{1}{2}\int_0^t \|\sigma(s,t)\|^2 ds + \sum_{i=1}^n X_t^i\right)$$

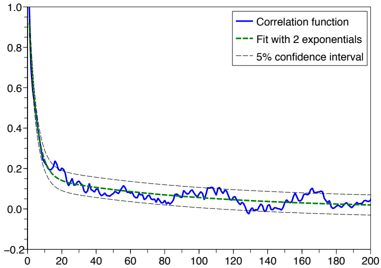
where

$$X_t^i = \sigma_i e^{-\lambda_i t}\int_0^t e^{\lambda_i s} dW_s^i \quad \Rightarrow \quad dX_t^i = -\lambda_i X_t^i + \sigma_i dW_t^i$$

$\Rightarrow$ the spot price is the exponential of a sum of Ornstein-Uhlenbeck processes (may be used to model price spikes)

Example





Volatility (moving 2-month average) of the future contract with delivery Q1-2015 throughout 2014.

Autocovariance function in the of spot price in Germany fitted with sum of 2 exponentials

How many factors?

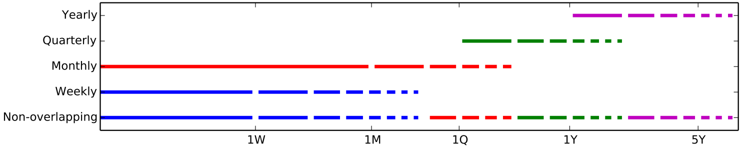
- Due to non-storability of electricity, electricity forward curves exhibit particularly erratic behavior.
- The behavior of weekly futures is very different from the yearly ones, and may not even be Gaussian.
- According to the PCA analysis of Koekebakker and Ollmar (2001) on the Nordpool market,
  - 1 factor explains 68% of the variation of the forward curve;
  - 2 factors explain 75% of the variation;
  - 10 factors are necessary to explain 95% of the variation.

Modeling swap contracts

- An alternative is to model directly the dynamics of traded swap contracts.
- In the presence of overlaps, dynamics is constrained by

$$F_t(T_1, T_2) = \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} f_t(T)dT.$$

- We choose to model the non-overlapping contracts, discarding some information.



A similar log-normal model $dF_t(T_1, T_2) = F_t(T_1, T_2)\Sigma^T(t, T_1, T_2)dW_t$ may be used.

Reduced-form price models

In reduced-form spot price models, one models the day-ahead electricity price directly with a Markov process, and the forward price is deduced by risk-neutral expectation

Usually one models the daily average since intraday structure is complex and irrelevant for forwards

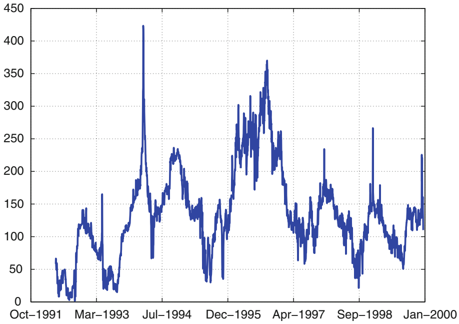
Reduced-form spot price models must respect the following "stylized features":

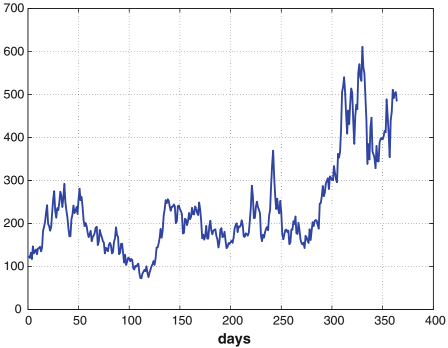
- Seasonality;
- Mean reversion;
- Spikes and non-Gaussian behavior.

The simplest setting: Lucia and Schwartz (2002) model

$$\ln S_t = g(t) + Y_t \qquad \text{(deterministic seasonality)}$$

$$dY_t = -\alpha Y_t dt + \sigma(t) dW_t \qquad \text{(mean-reverting component)}$$





Left: Nordpool system price trajectory. Right: price trajectory in the Lucia and Schwartz model.

Computing forward prices

The authors assume that the forward prices can be computed as risk-neutral expectations:

$$f_t(T) = \mathbb{E}[S_T|\mathcal{F}_t]$$

Under the risk-neutral probability, the dynamics of spot price may be different:

$$dY_t = \alpha(\lambda - Y_t)dt + \sigma dW_t^*.$$

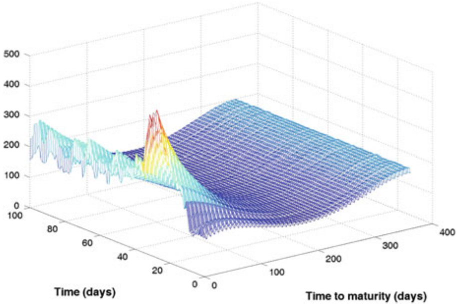
The forward curve admits an explicit expression:

$$f_t(T) = \exp\left(g(T) + Y_t e^{-\alpha(T-t)} + \lambda(1 - e^{-\alpha(T-t)}) + \frac{\sigma^2}{2}\int_t^T e^{-2\lambda(T-s)}ds\right).$$

Computing forward prices

The forward curve in the Lucia-Schwartz model admits the simple log-normal dynamics:

$$\frac{df_t(T)}{f_t(T)} = \sigma e^{-\alpha(T-t)} dW_t^*.$$



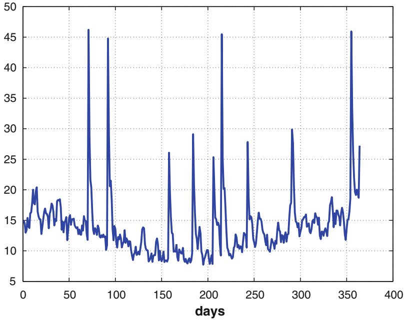
Cartea and Figueroa (2005) model

$$\ln S_t = g(t) + Y_t$$

$$dY_t = -\alpha Y_t dt + \sigma(t) dW_t + J \cdot dq_t$$

where

- $g(t)$ is a deterministic seasonality;
- J is a log-normal proportional jump size;
- q is a Poisson process of jump times.



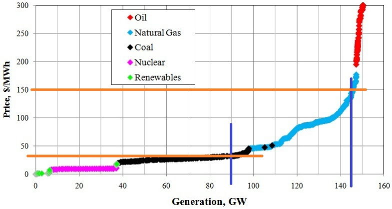
Price trajectory in the Cartea and Figueroa model. Source: Aïd (2015).

In this model, forward prices can be computed explicitly under deterministic market price of risk assumption.

Structural spot price models

- Unlike stock price process which are hardly predictable, electricity prices are related to a multitude of observable factors: consumption, fuel prices, plant outages etc.
- Structural models focus on the price formation mechanism and aim to predict day-ahead prices based on the available information.

- In demand-based models the spot price is obtained by matching a constant supply function with a random inelastic demand.
- In stack-curve models, the supply function is constructed from unit costs and capacities of different generation technologies.



Example of generation stack

Source: **B. Posner** / psu.edu

Demand-based models

- The demand for electricity is described by a stochastic process:

$$D_t = \overline{D_t} + X_t,$$
$$dX_t = (\mu - \lambda X_t)dt + \sigma dW_t,$$

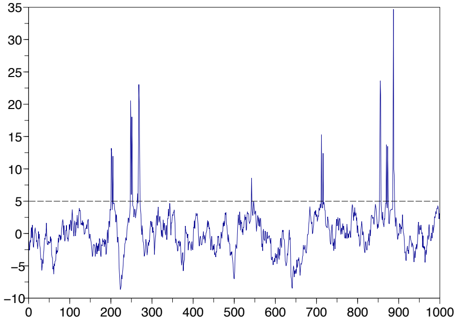
  where $\overline{D_t}$ is the seasonal component and X_t is the stationary stochastic part.
- The price is obtained by matching the demand level with a deterministic supply function which must be nonlinear to account for spikes.
- Barlow (2002) proposes

$$P_t = \left(\frac{a_0 - D_t}{b_0}\right)^{1/\alpha}$$

  for some $\alpha > 0$.
- Kanamura and Ohashi (2004) suggest a "hockey stick" profile

$$P_t = (a_1 + b_1 D_t)1_{D_t \leq D_0} + (a_1 + b_1 D_t)1_{D_t > D_0}.$$

Demand-based models



Spot price trajectory in the demand-based model by Kanamura and Ohashi (2004).

In these models, spikes can only be caused by surges in demand, while in electricity markets spikes can also be due to sudden changes in supply, such as plant outages.

Stack curve model of Aïd (2009)

- The electricity demand D_t can be satisfied with n different technologies;
- Each technology has available capacity C_t^i and fuel cost $h_i S_t^i$, where S^i is the fuel price and h_i is the heat rate;
- The marginal fuel cost is

$$\widehat{P}_t = \sum_{i=1}^n h_i S_t^i \mathbf{1}_{D_t \in I_t^i}, \qquad I_t^i = \left(\sum_{k=1}^{i-1} C_t^k, \sum_{k=1}^{i} C_t^k \right]$$

- The spot price depends on the marginal fuel cost and the reserve margin:

$$P_t = g(R_t) \times \widehat{P}_t, \qquad R_t = \sum_{i=1}^n C_t^i - D_t$$

where g is the *scarcity function*:

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

Electricity derivatives

Standard Calls/Puts on electricity futures are traded in power exchanges such as EEX. They can be valued as standard financial options since the underlying is liquidly traded.

Other options allowing to transfer energy risks are traded over the counter:

- Fuel spreads mimick the profit of a power plant at a given moment in time: the clean fuel spread option pays

$$\left(S^e_T - hS^f_T - gS^c_T\right)^+,$$

  where

  - S^e is the spot price of electricity;
  - S^f is the spot price of fuel (e.g., gas or coal);
  - S^c is the price of carbon emission allowances;
  - h is the heat rate of the plant;
  - g is the emission rate of the plant.