Electricity markets

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Outline

- **ELECTRICITY MARKET DESIGN**
  - The electricity value chain
  - Electricty market microstructure (balancing mechanism)
  - Tools for power generation, typical supply curve in electricity markets
  - Key drivers of European electricity prices
- **MODELLING ELETRICITY PRICES**
  - Main features of power prices
  - Overview of spot and forward models
  - A structural model for electricity prices (Aïd et al., 2011)
  - Factorial models for energy prices (e.g. Kiesel et al., 2008)

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ELECTRICITY MARKET DESIGN

- **Some generalities, the electricity value chain**
- Electricity market microstructure
- Power production tools and drivers of European electricity prices

Main electricity features

Electricity is a local commodity due to the non-storability and transport constraints

- Electricity is a local commodity :
  - Electricity is non-storable

    Present best way to store large volumes of power: hydro-reservoir.

    A too long excess of demand compared to supply may lead to dramatic blackouts (example in July 30th, 2012: India, 670 millions people).

    ⇨ Minute by minute real-time assessment of the equilibrium between demand and supply
  - Electricity transport satisfies specific laws (Kirchhoff's laws).

    In a meshed electricity network, power will go from one point to another using all available paths, causing possible electricity flow interference.

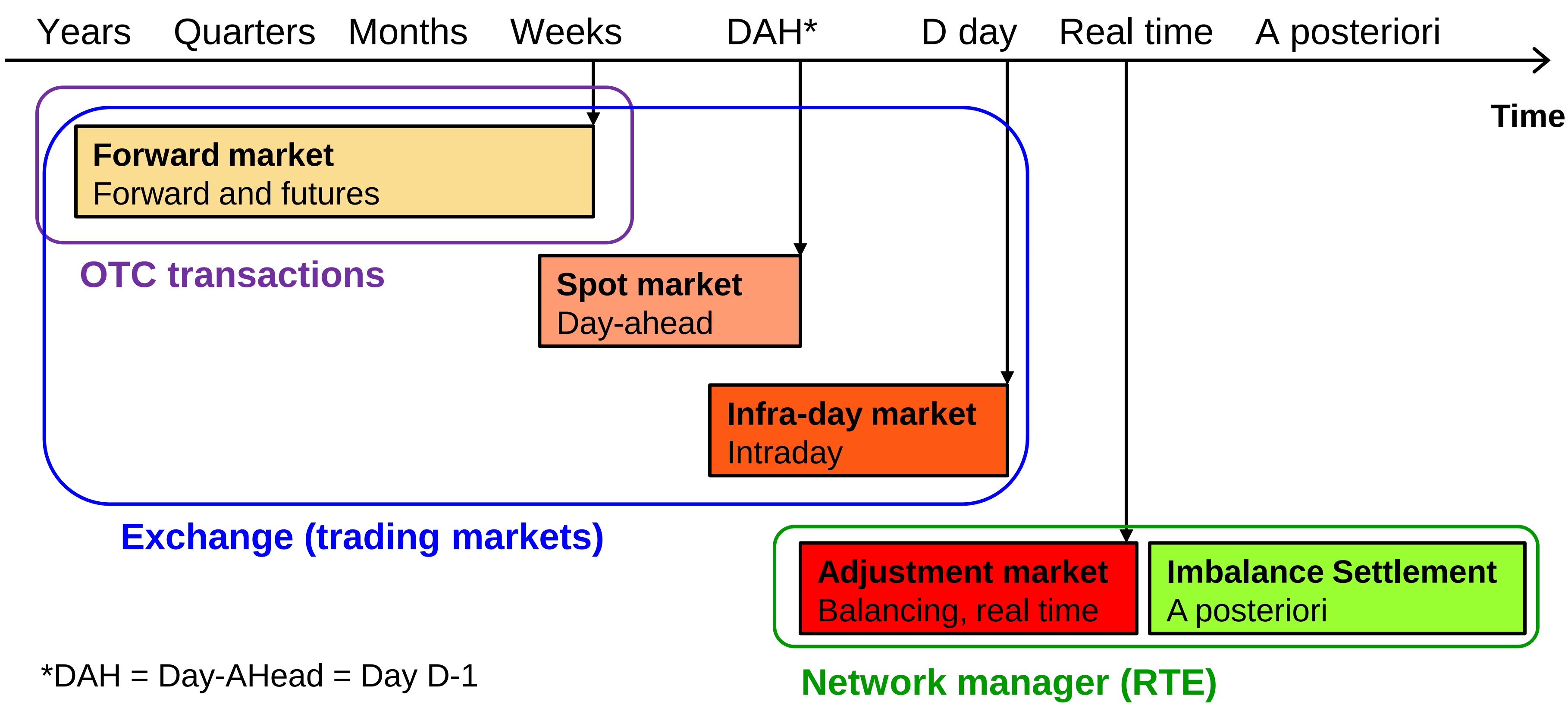
    ⇨ Cross-border trading opportunities, up to transfert capacities available

- A common market structure for a local commodity :
  - Electricity being a local commodity, there are as many electricity markets as they are states…
  - Market microstructure highly depends on national regulation.
  - Nevertheless, common structure emerges driven by the necessary equilibrium between consumption and production.
  - A central role of the Transport System Operator, in France : RTE and in Europe : ENTSO (European Network System Operator).

Electricity markets sequenced by maturity

Common market structure

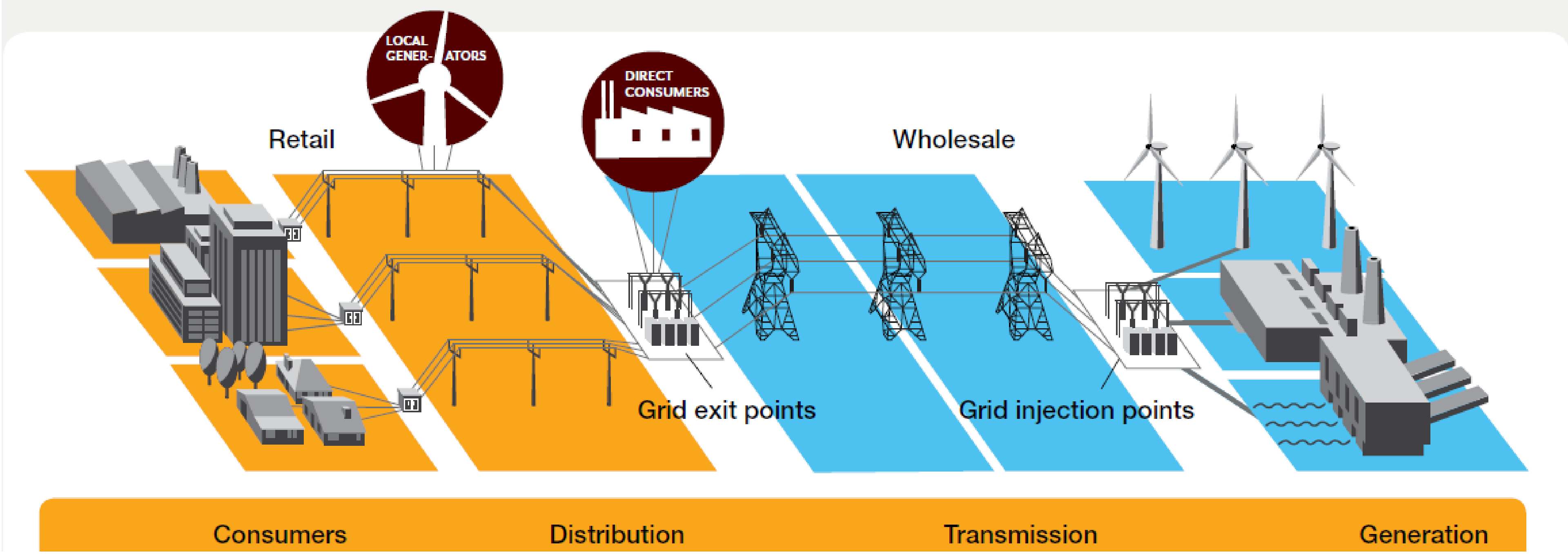
- There is not only one market but a sequence of markets that can be ordered by time horizon.
  - The intraday market and/or balancing mechanism
  - The day-ahead market
  - The forward market

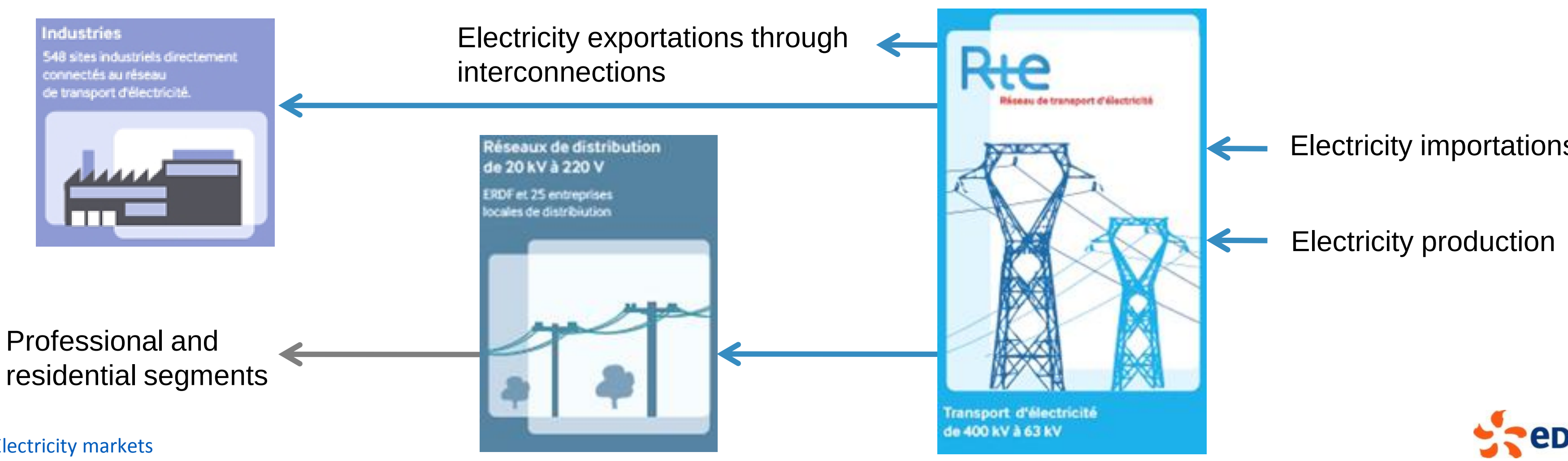


*DAH = Day-AHead = Day D-1

The electricity value chain

General design and the case for France : RTE is the Transport System Operator

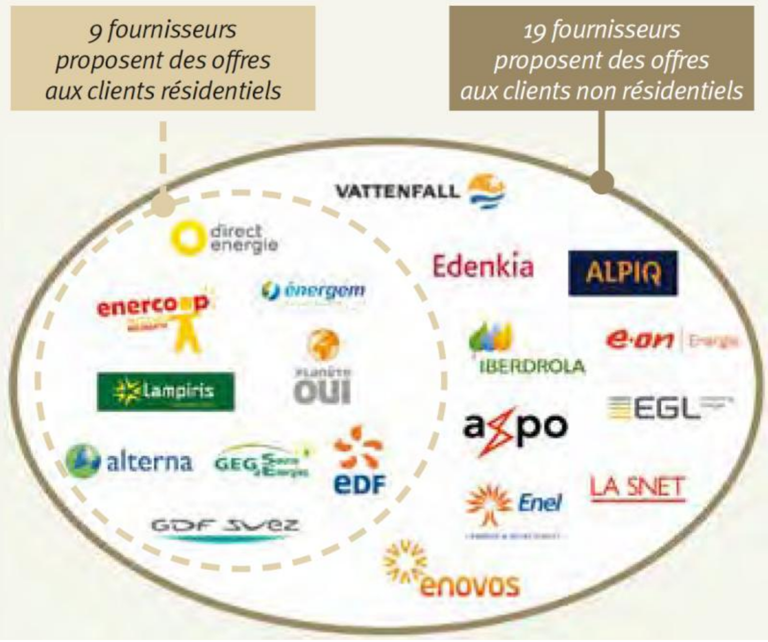


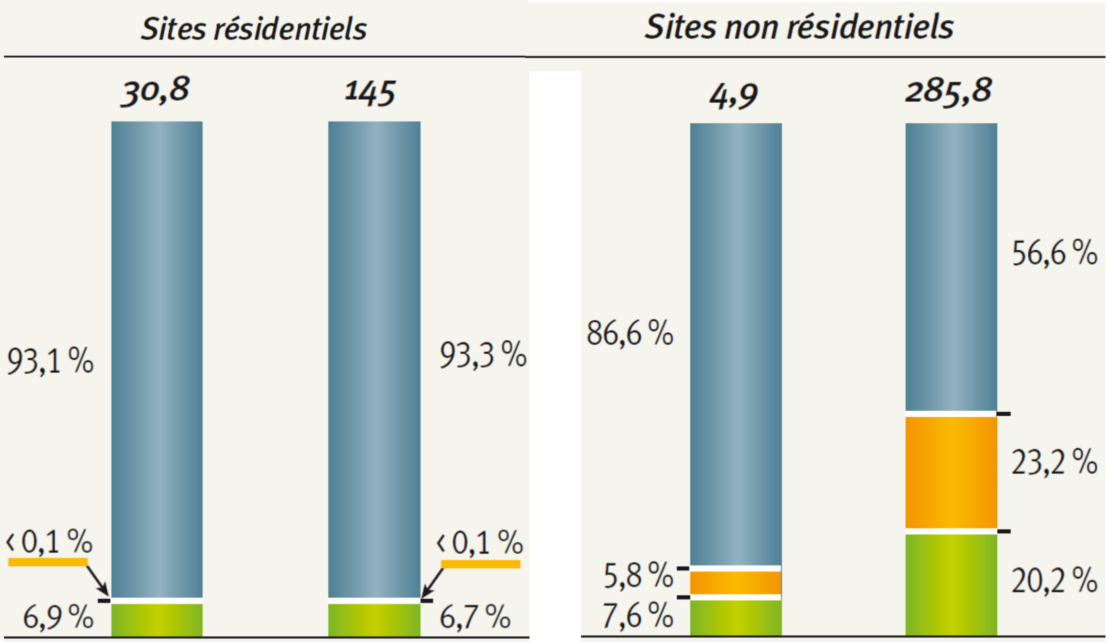


Profile of customers in France

Figures and analysis from CRE (Rapport 2012)

- Deregulation of the electricity market in France since 2007
- New scheme : deregulated and non-integrated due to a legal separation of activities
- All customers (residential or not) can choose between regulated or market-indexed contracts
- In fact, the switching rate (nb of supplier change/total nb of customers) is less than 1.2%





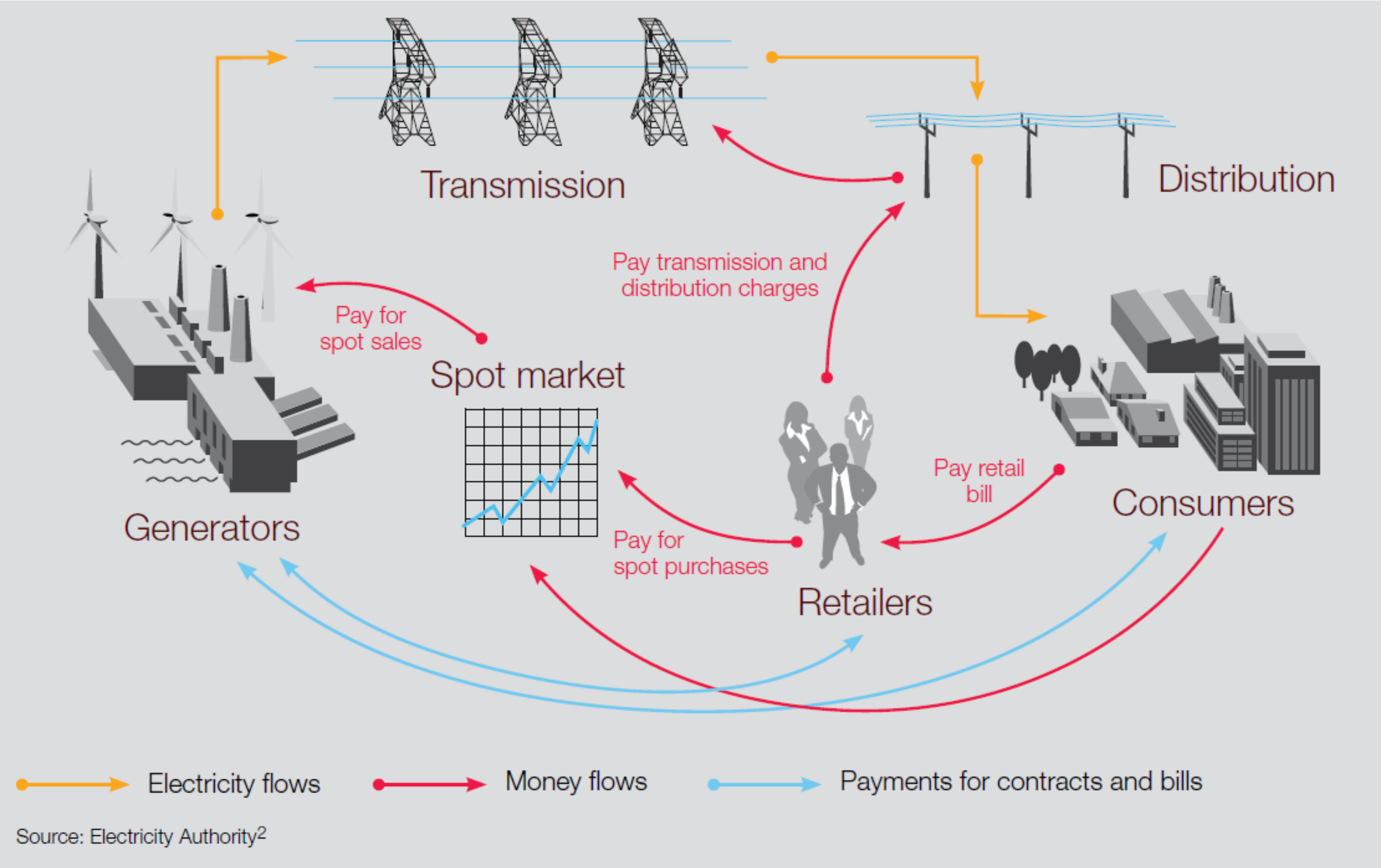
Consumption spots (Mio) & volume (TWh) Consumption spots (Mio) & volume (TWh)

Offres aux tarifs réglementés
Offres de marché fournisseurs historiques
Offres de marché fournisseurs alternatifs

The electricity market actors

Four kinds of actors in competition

- Generators (Producers) / Retailers (Suppliers) / Consumers / Traders
- Producers have naturally a long position, consumers a short position.
- Traders take directional positions to exploit market opportunities.



Participants and money flows in the electricity industry

European power exchanges

Power exchanges in Europe in 2013

ELECTRICITY MARKET DESIGN

- Some generalities, the electricity value chain
- **Electricity market microstructure**
- Power production tools and drivers of European electricity prices

Electricity market structure

Coexistence of different markets

- Two kinds of transactions on electricity markets
  1. Bilateral contracts traded Over The Counter (OTC)
     Standard or specially designed products (power profile, maturity, …) : forwards, options
  2. Trades on energy exchanges (trading markets)
     Standard products with a standardized bid/offer procedure and clearing mechanism
     "Financial" markets: futures, options
     "Physical" markets: Day-1 (spot or day-ahead), intraday (D day)

- Focus first on the intraday market on the D day
  - Ensure the security of the system ⇨ Balancing Mechanism
  - Transparent market price for the cost of imbalance ⇨ Imbalance Settlement Price
  - For this "physical" market :
    First difficulty : Volume alea possible on the D day
    Second difficulty : Network constraints

Electricity market structure

Intraday market : the role of the transport system operator RTE in France

- The actions on the market are made to satisfy a global equilibrium :

  Demand = Supply

  Consumption = Production +/- Exchanges (market purchases and sales)

  Σ withdrawals = Σ injections

- Declarations on Day-1 (16h30): production and consumption plans declared to RTE
- Adjustment mechanism in real time (balancing), with delivery on the transmission system managed by the transport system operator (RTE)

RTE (transport system operator)

- Guarantee the security and reliability of the system and the quality of supply
- Guarantee a non-discriminatory access to the network
- Responsible for the Supply/ Demand equilibrium in France

Declare injections and withdrawals

I-W Imbalance settlement

Balance Responsible Entities (market actors)

- Producers
- Retailers
- Big consumers
- Trading desks
- Responsible in their perimeter for the S/D equilibrium

Electricity market structure

Intraday market : operating reserves and adjustment mechanism

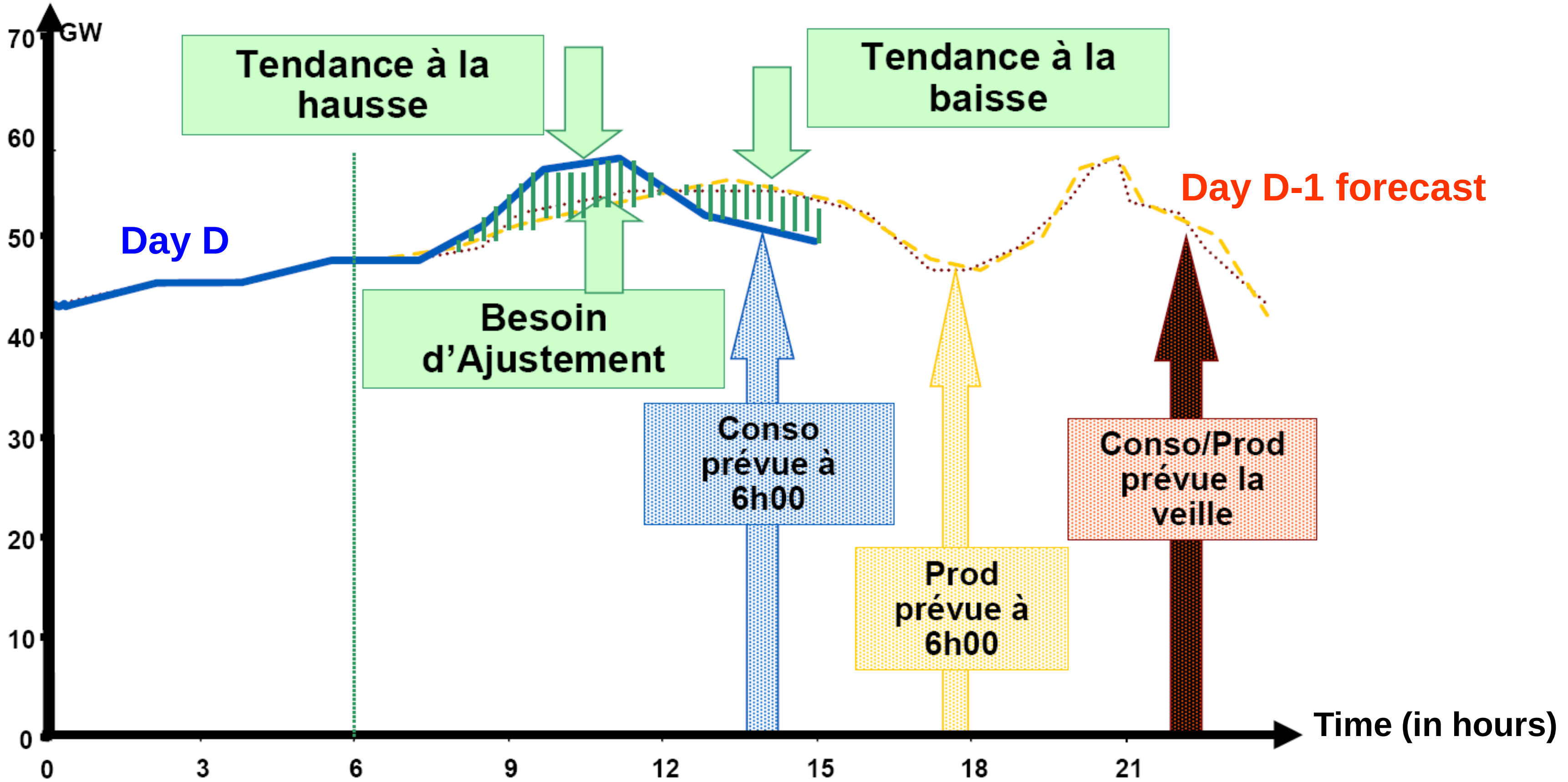
- On day D-1, the global Supply/Demand equilibrium takes in account both the market and OTC transactions.
- In real time (~ seconds to some hours), possible perturbation of this equilibrium :
  - Loss of some power generating units
  - Errors in the consumption or production forecast
  - Network congestions
- ⇨ Since electricity is non-storable, the system has to be balanced.

- The transport system operator RTE has two means : operating reserves and balancing mechanism.
- An operating reserve is a generation that can be mobilised with a short-term notification :
  - Primary reserve : response time < 30 s, automatic device ~500 MW in France
  - Secondary reserve : response time < 3 min, automatic ~600M W in France
  - Tertiary reserve : response time < 15 min, manual ~1500 MW in France
- Beyond, adjustment mechanism : balance responsible entities submit bids and offers to increase or decrease their production or consumption and RTE selects offers based on economic precedence (~30 min)
- A posteriori, each balance responsible entity receives the bill of her imbalances.

Electricity market structure

Focus on the French market : adjustment mechanism

- Bullish trend ⇔ Short system (lack of power)
- Bearish trend ⇔ Long system (supply glut)



Electricity market structure

Focus on the French market : adjustment mechanism and imbalance settlement

- Adjustment mechanism : allow to compensate the power need/glut of the system
  - Bullish trend ⇨ Offers for increasing the power injected (producers) in the system and erasing offers (cut-off injunctions, EJP) for reducing the demand
  - Bearish trend ⇨ Offers for decreasing the power injected in the system (producers)
  - Offers ranked by merit order (RTE)

- Imbalance settlement ("Règlement des écarts")
  - RTE establishes, a posteriori, the bill to be paid or received by any actor, for the differentials observed on its perimeter (injections/withdrawals).
  - Formula based on the spot price and power generation costs
  - Incentive to a vertuous behavior for both producers and consumers
  - Example for EDF: Case of a Bull trend (lack of power)

    If EDF is long (P>C) ⇨ EDF receives the Spot

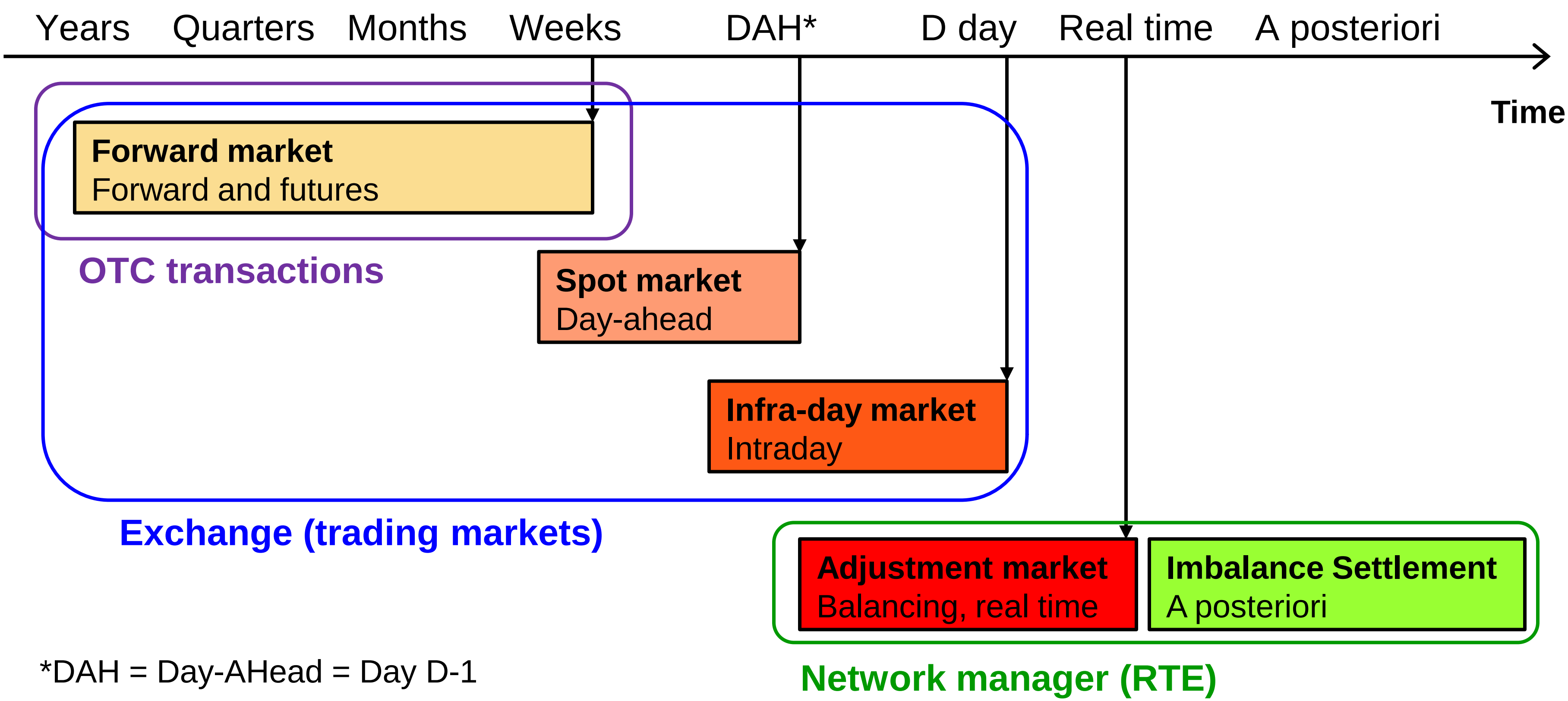
    If EDF is short (P<C) ⇨ EDF needs to pay max(Spot, P_u*)

*P_u = upper weighted average cost of power generation issued from the adjustment mechanism

Electricity markets sequenced by maturity

Common market structure

- Beside this balancing mechanism :
  - an infra-day market for energy delivery for the hours of the day
  - a day-ahead market for energy delivery for the hours of the next day



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Electricity market structure

The day-ahead market : example of Epex Spot

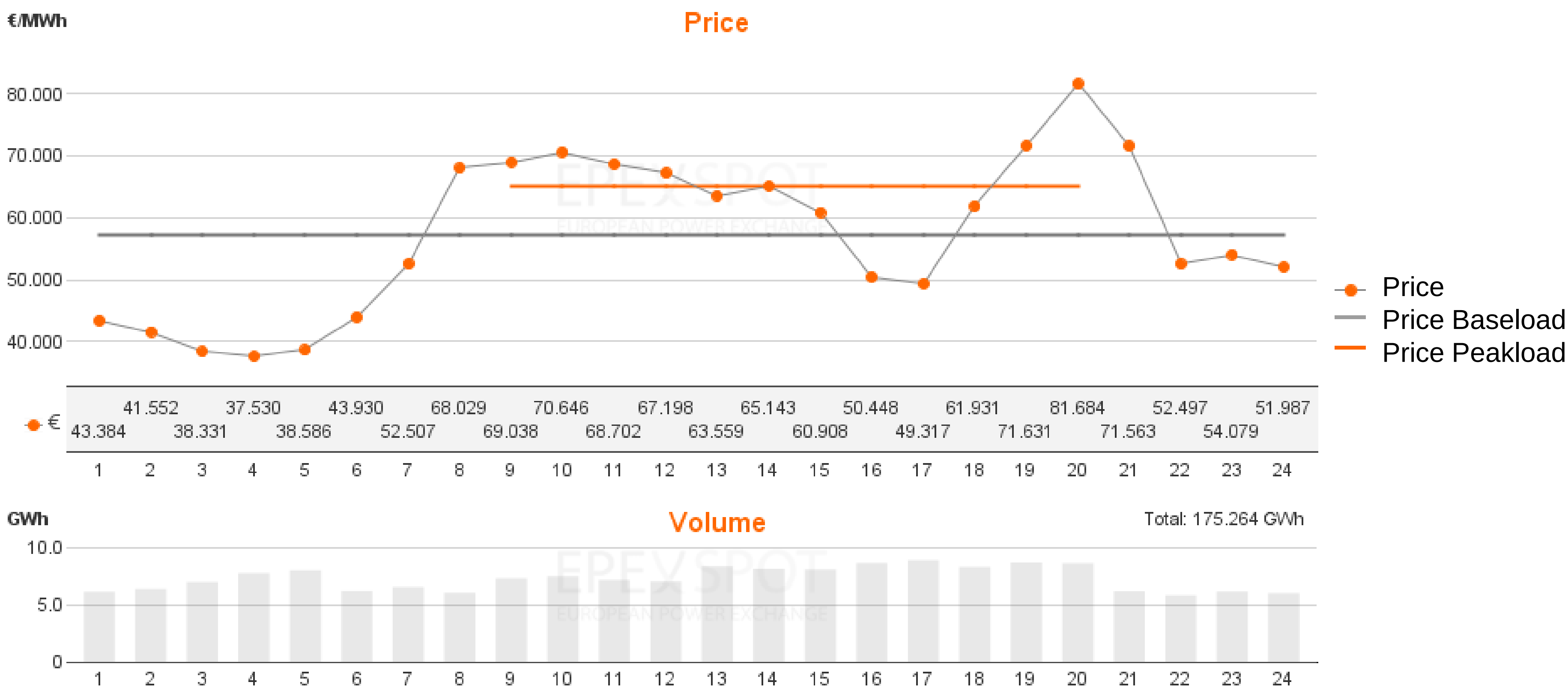
- Day-ahead market : market for energy delivery for the hours of the next day
- Spot price fixing (Epex Spot: at 12h) by crossing the supply and demand curves

Epex Spot Auction on the 27/10/2011 for Friday 28/10/2011 19h-20h

Electricity market structure

The day-ahead market : example of Epex Spot

- This method for fixing is applied for the 24 hour products of the next day.
- Average of some of these hourly prices are called Blocks
- In particular, Baseload and Peakload prices (in France, Peakload ⇔ 8h-20h)



28/10/2011 hourly prices and volumes on Epex Spot (27/10/2011)

Electricity market structure

The day-ahead market : example of Epex Spot

Epex Spot table for France on the 08/09/2011

France | Germany/Austria (Phelix) | Switzerland (Swissix) | MCC

03/09/2011 - 09/09/2011

03/09/2011

France Day Base	Sat, 09/03	Sun, 09/04	Mon, 09/05	Tue, 09/06	Wed, 09/07	Thu, 09/08	Fri, 09/09
Prices (€/MWh)	48.320	43.192	50.644	45.872	44.820	50.414	57.973
Volumes (MWh)	146,529.0	146,485.0	189,179.0	191,767.0	183,754.0	189,819.0	196,516.0
France Day Peak							
Prices (€/MWh)	53.971	46.591	59.864	51.203	56.563	57.951	66.117
Volumes (MWh)	66,152.0	75,296.0	99,643.0	100,446.0	102,213.0	95,089.0	108,294.0

BLOCKPRICES

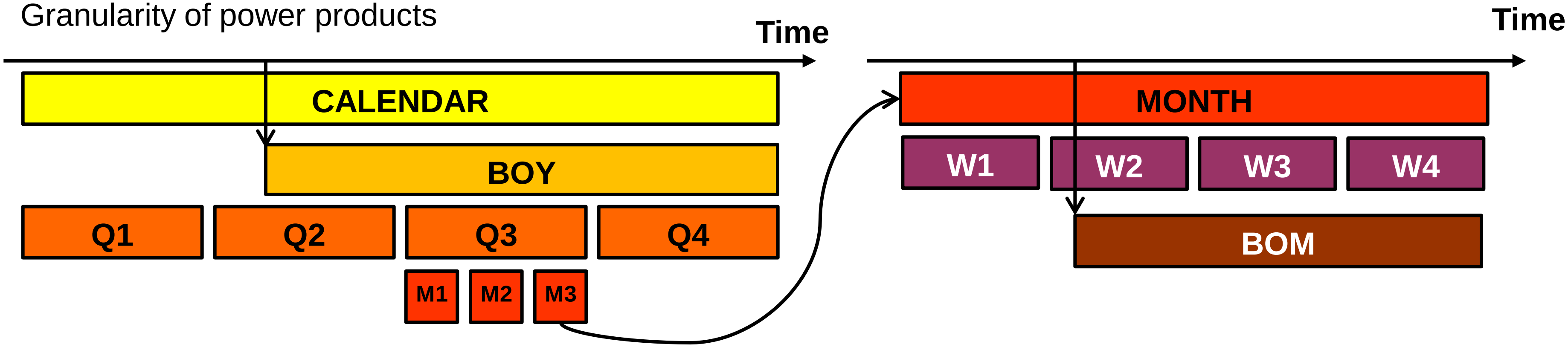
	Sat, 09/03	Sun, 09/04	Mon, 09/05	Tue, 09/06	Wed, 09/07	Thu, 09/08	Fri, 09/09
Middle-Night (01-04)	43.127	40.702	32.842	29.395	12.981	33.111	43.576
Early Morning (05-08)	31.495	25.801	40.469	41.728	30.850	39.744	48.546
Late Morning (09-12)	56.206	47.510	69.738	56.028	56.694	59.951	71.981
Early Afternoon (13-16)	52.978	45.598	59.021	47.260	57.064	58.040	68.367
Rush Hour (17-20)	52.728	46.665	50.833	50.322	55.931	55.863	58.004
Off-Peak 2 (21-24)	53.388	52.877	50.961	50.496	55.401	55.775	57.363
Baseload (01-24)	48.320	43.192	50.644	45.872	44.820	50.414	57.973
Peakload (09-20)	53.971	46.591	59.864	51.203	56.563	57.951	66.117
Night (01-06)	35.875	34.836	28.664	29.327	13.023	31.400	41.728
Off-Peak 1 (01-08)	37.311	33.251	36.656	35.561	21.915	36.428	46.061
Business (09-16)	54.592	46.554	64.379	51.644	56.879	58.996	70.174
Offpeak (01-08 & 21-24)	42.670	39.793	41.424	40.540	33.077	42.877	49.828
Morning (07-10)	47.215	36.616	65.096	55.860	51.985	55.126	64.072
High Noon (11-14)	57.754	49.100	66.797	51.291	58.336	60.839	73.746
Afternoon (15-18)	50.018	43.565	51.992	46.799	53.989	54.294	60.873
Evening (19-24)	54.081	51.745	51.322	51.526	56.717	56.750	57.703

Electricity market structure

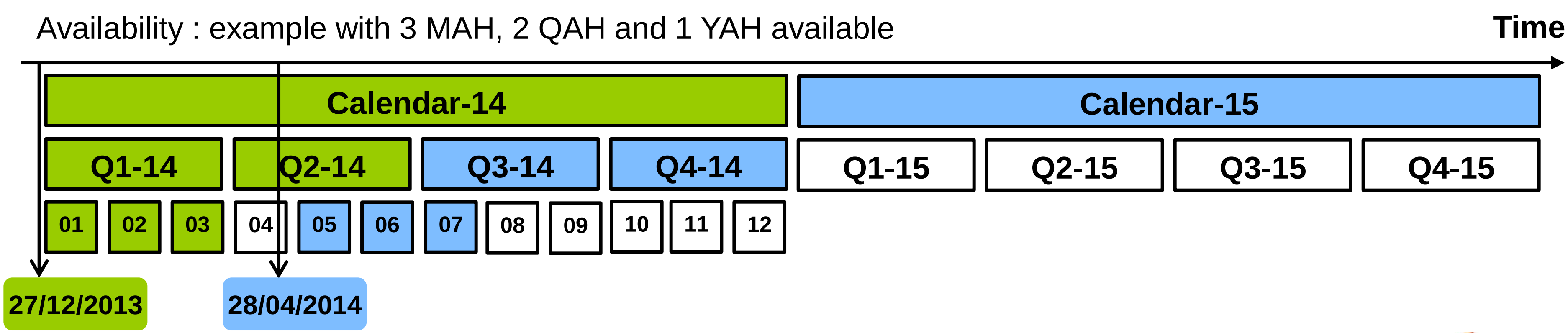
The forward market

- The forward market presents a nested contract structure.
- Two basic characteristics of forward products : maturity and granularity.
- The availability of forward products evolves dynamically.

Granularity of power products



Availability : example with 3 MAH, 2 QAH and 1 YAH available



Electricity market structure
The forward market

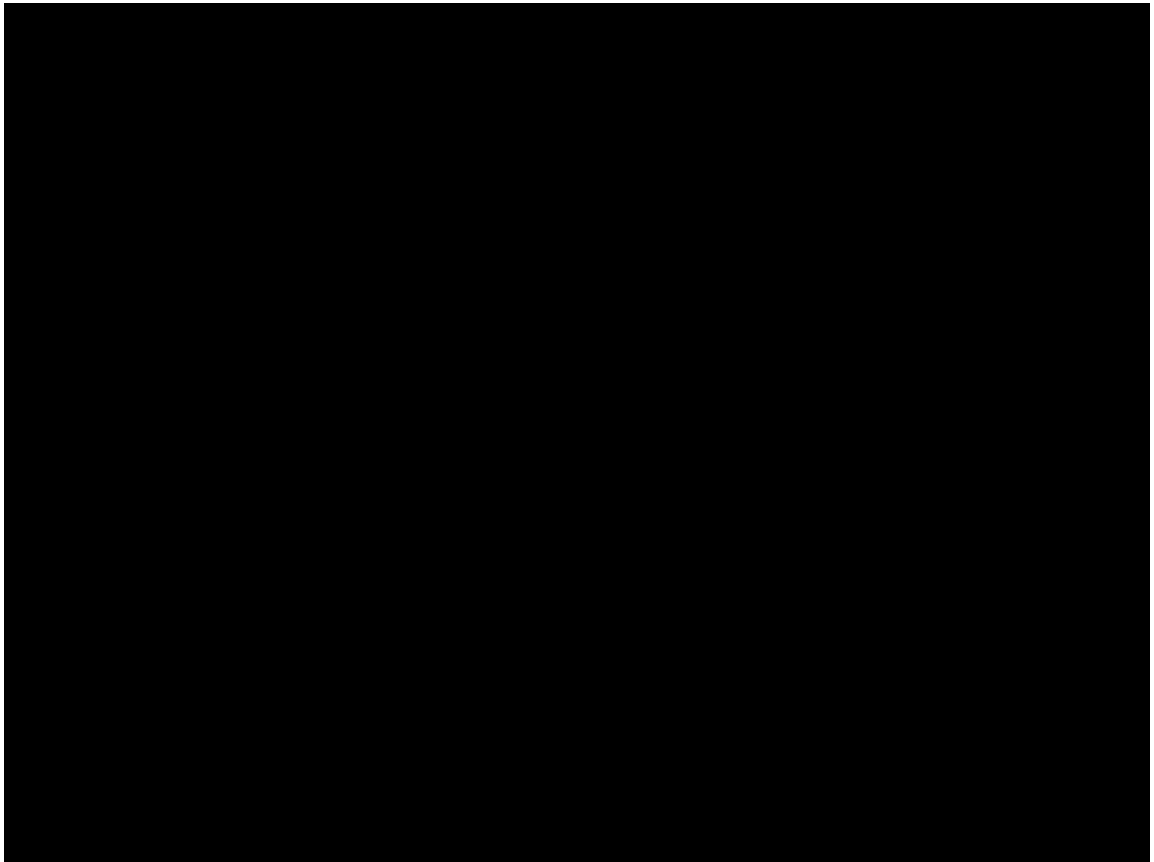
- The forward market corresponds to the market for products with granularities and maturities greater than one day.
- Example of EEX : are available at the same time the following forward products :
  - 6 calendars
  - 11 quarters
  - 9 months
  - 4 weeks
  - 2 weekends
  - 8 days
- In three flavours : Baseload (each hour), Peakload (8h-20h Monday to Friday) and Offpeak
- Thus, 106 contracts are available… to be compared to the 525684 hours in the next six years…

Market horizon : Last delivery date covered by the futures products quoted
Market depth : Available volumes of tradable products
Completeness : Ability to find products on for any market horizons and any granularity

The forward market

Some facts on electricity forward prices

- Forward prices result from an anticipation of the actors of the future supply/demand equilibrium.
- Illustration on the German Baseload forward curve dynamics :
  - Very differentiated behaviour between **spot**, **month** and **yearly** contracts
  - Slow motion of yearly contracts; may exhibit contango or backwardation (report or deport)
  - Seasonal pattern of monthly contracts



The forward market

Some facts on electricity forward prices

- No-arbitrage condition is respected between futures with different but recovering granularities.

- Some practice : At date 15/12/2013, we observed following quotations in €/MWh for power Base futures products :

1MAH	2MAH	3MAH	4MAH	5MAH	6MAH	1QAH	2QAH	3QAH	1YAH
61	60	56	49	47	46			46	51

a) Give the prices of the 1QAH and 2QAH products, missing in the table above.

b) In the same conditions, deduce the price of the October 2014 Base product.

a) 1QAH * 90 = 1MAH * 31 + 2MAH * 28 + 3MAH * 31 ⇨ 1QAH price = 58.9 €/MWh

2QAH * 91 = 4MAH * 30 + 5MAH * 31 + 6MAH * 30 ⇨ 2QAH price = 47.3 €/MWh

b) October 2014 price = 4QAH price

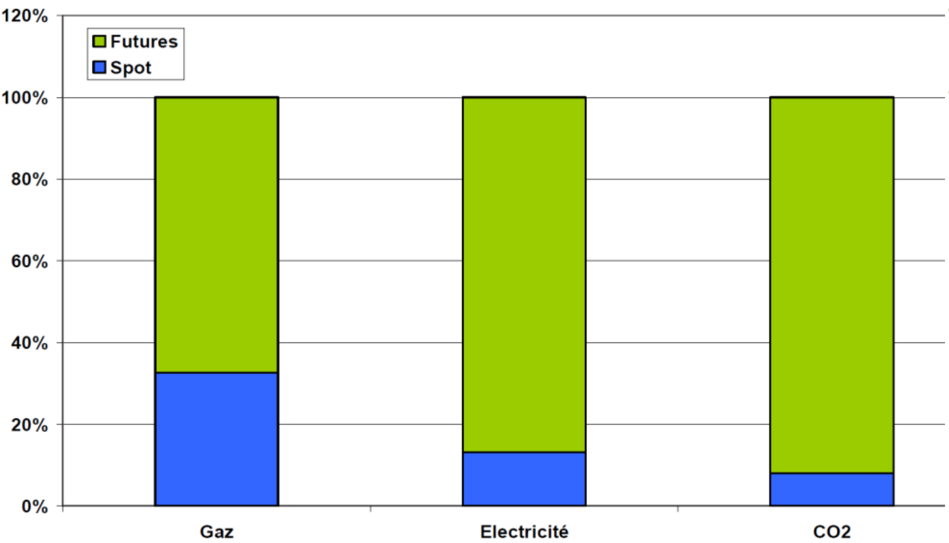
1YAH * 365 = 1QAH * 90 + 2QAH * 91 + 3QAH * 92 + 4QAH * 92 ⇨ 4QAH price = 51.8 €/MWh

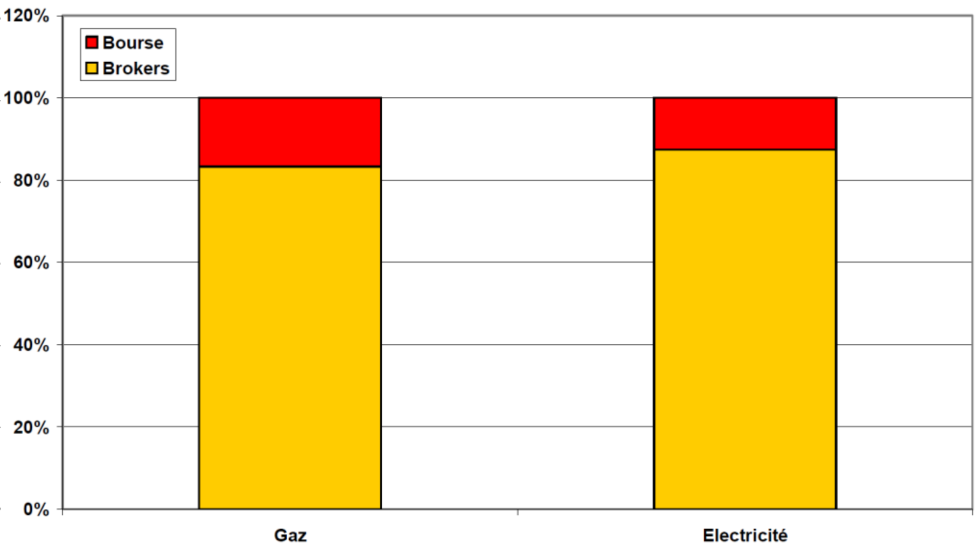
EDF

The spot and forward markets

Some facts on products traded

- Futures are more traded than spot : less volatile, used for hedging (electricity non-storability)
- Trades are mostly made OTC (forward contracts) than through energy exchanges.





Volumes traded in 2010 in France (CRE, 2010)

ELECTRICITY MARKET DESIGN

- Some generalities, the electricity value chain
- Electricity market microstructure
- **Power production tools and drivers of European electricity prices**

Tools for power generation

Electricity is a secondary energy source that can be produced with different technologies.

- Each production tool has its own structure of costs :
  - Fixed / variable costs
  - Link to fuel and CO_2 market prices
- Each production has its specific characteristics :
  - Life of service
  - Efficiency : heat rate, number of hours at nominal capacity
  - Environmental impact

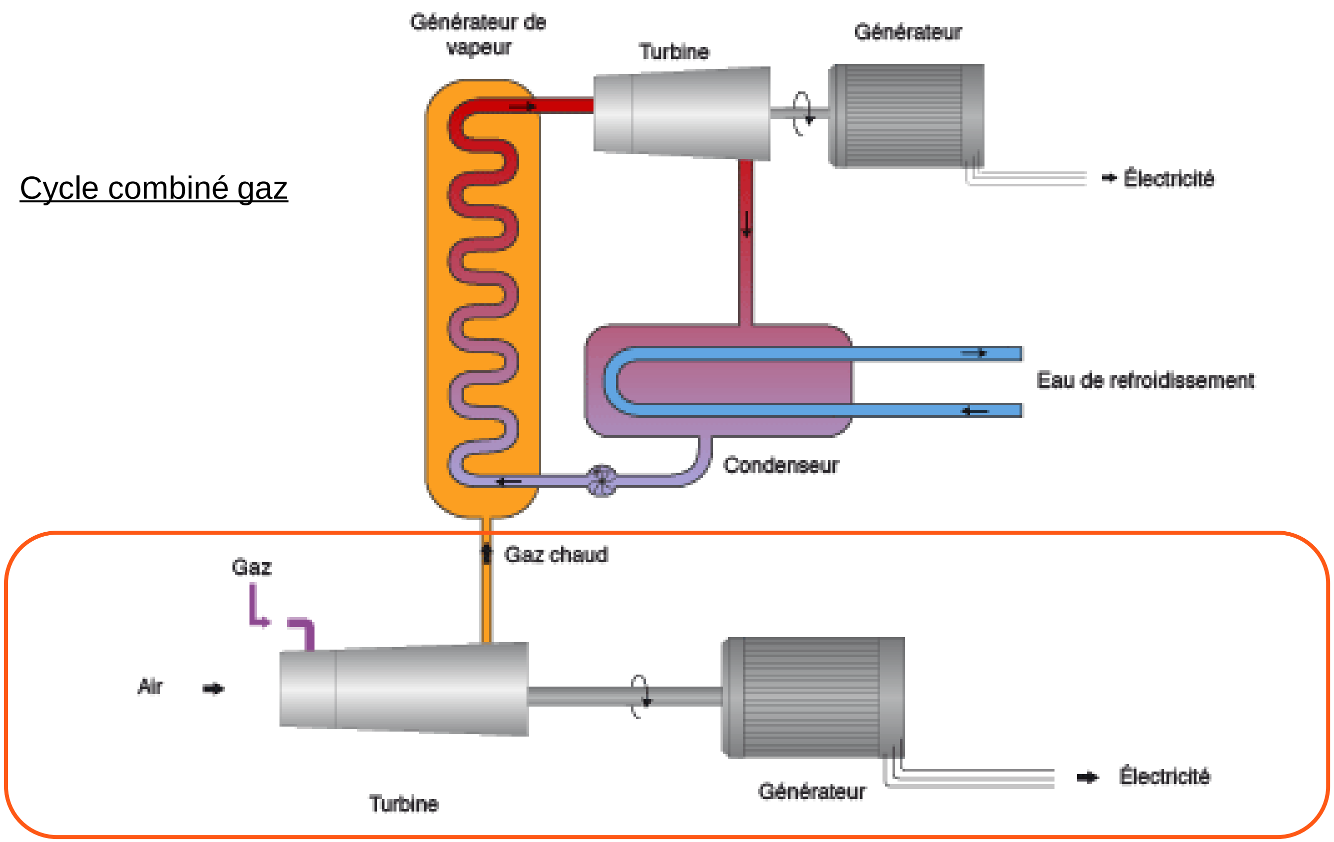
	Coal	CCGT	Nuclear	Hydro	Wind
Construction period	4 y	2-3 y	6-10 y	8-10 y	2-5 y
CAPEX (invest.)	++	+	+++	+++	++
Service life	50 y	25 y	50-60 y	> 100 y	20 y
OPEX (O&M)	++	+	+++	+++	+++
Efficiency	38-42%	57-58%	35%	> 90%	25%
Fuel cost	++	+++	+	-	-
CO_2-NOX emissions	+++	++	-	-	-

Tools for power generation

Zoom on the CCGT technology

- In recent years, fast development of CCGT (Cycle Combined Gas Turbine) in Europe
  - More efficient and flexible technology: quick answer (~1/2 hour) to demand
  - Replace old and polluting fuel-fired and coal-fired power plants
  - With current gas prices, most of first generation gas-fired power plants are no more profitable

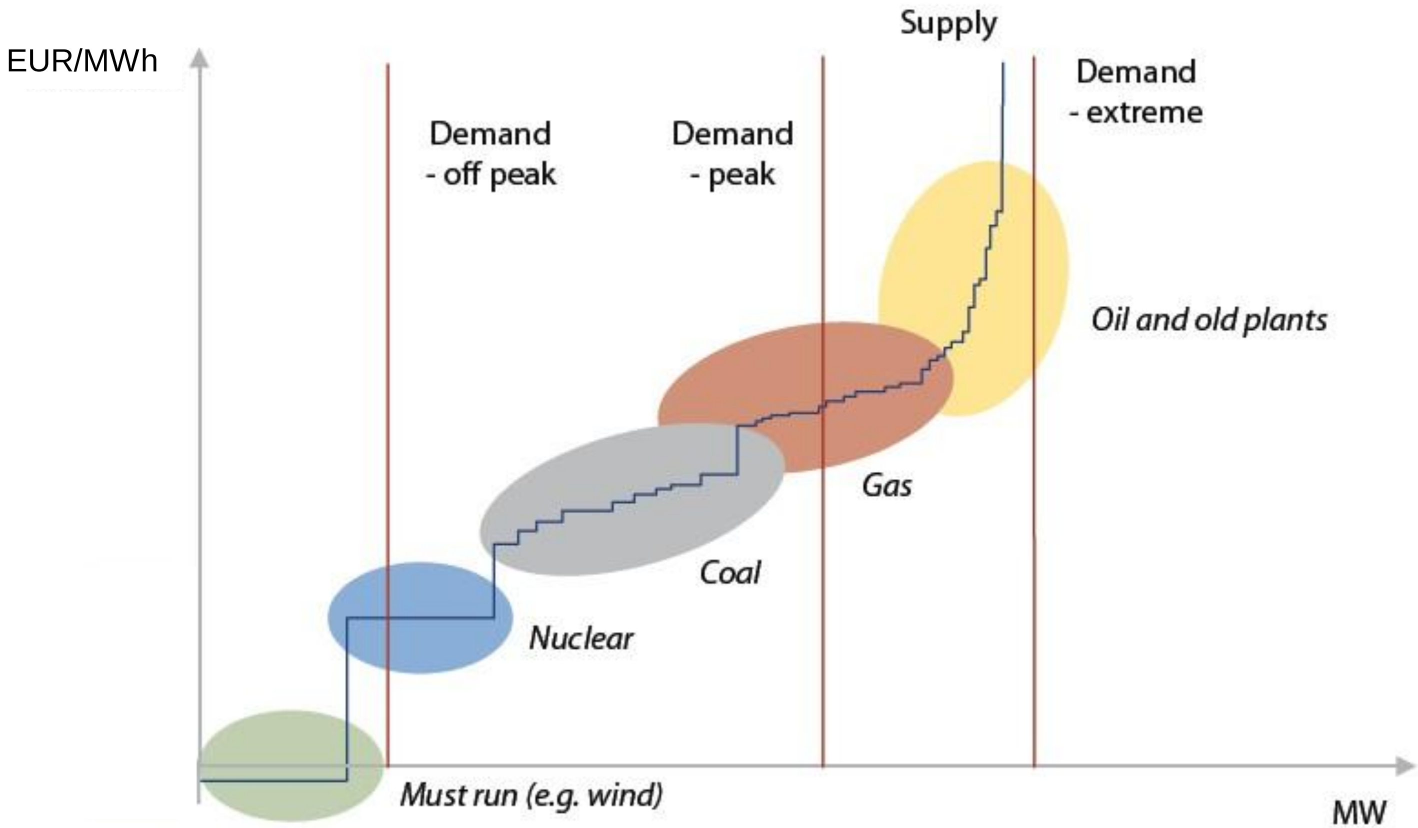
Cycle combiné gaz



Centrale thermique classique

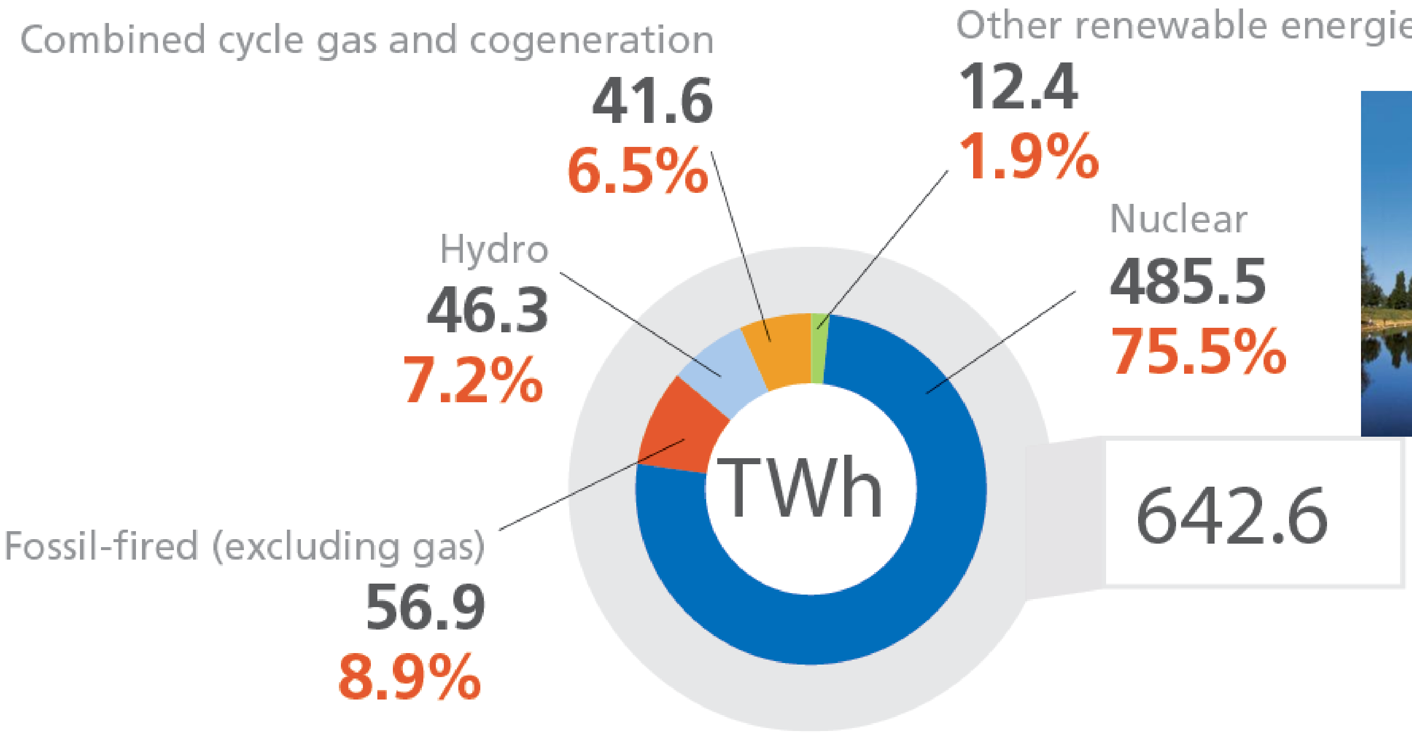
Stack curve in electricity markets

- The supply curve is build by ranking the different means of power generation by merit order.
- The spot price corresponds then to the price matching supply and demand.
- Usually, only the proportional production cost is modelled in this curve (no CAPEX).



Power generating mix

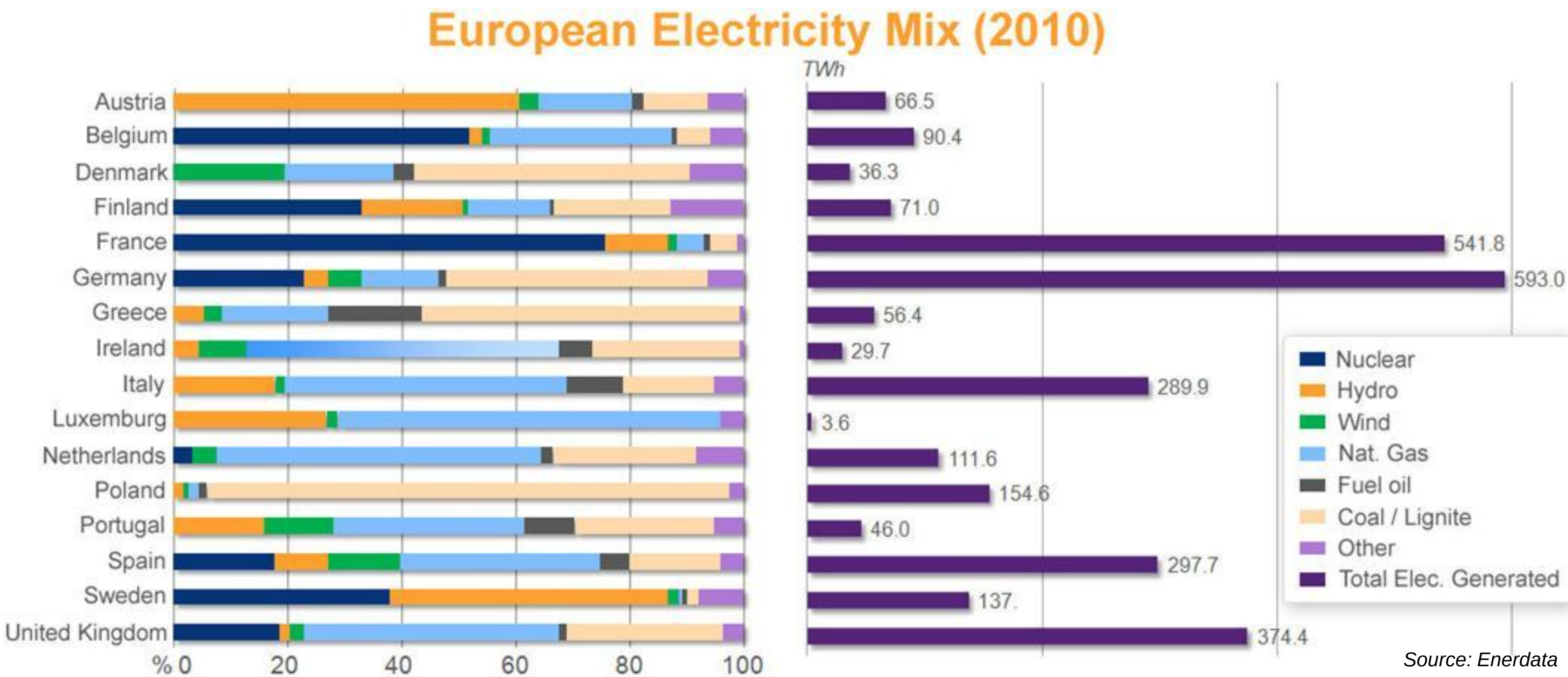
Example of the EDF Group



EDF Group generating mix in 2012

Power generating mix

Overview of European countries

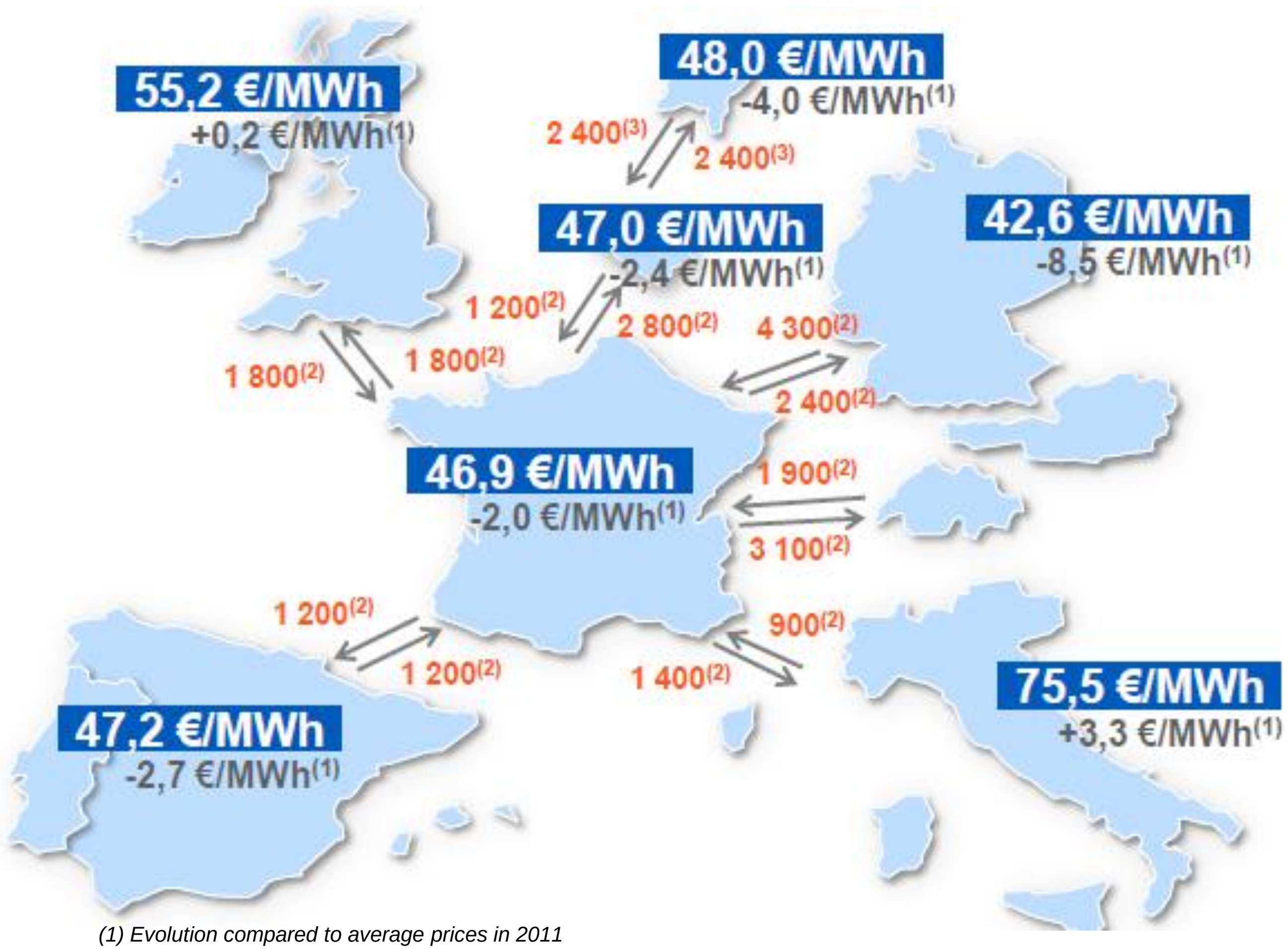


Source: Enerdata

<u>Electricity market share and prices depend on country energy mix</u>

European electricity market

Interconnected but distinct market zones : still fragmented into « electric plates »



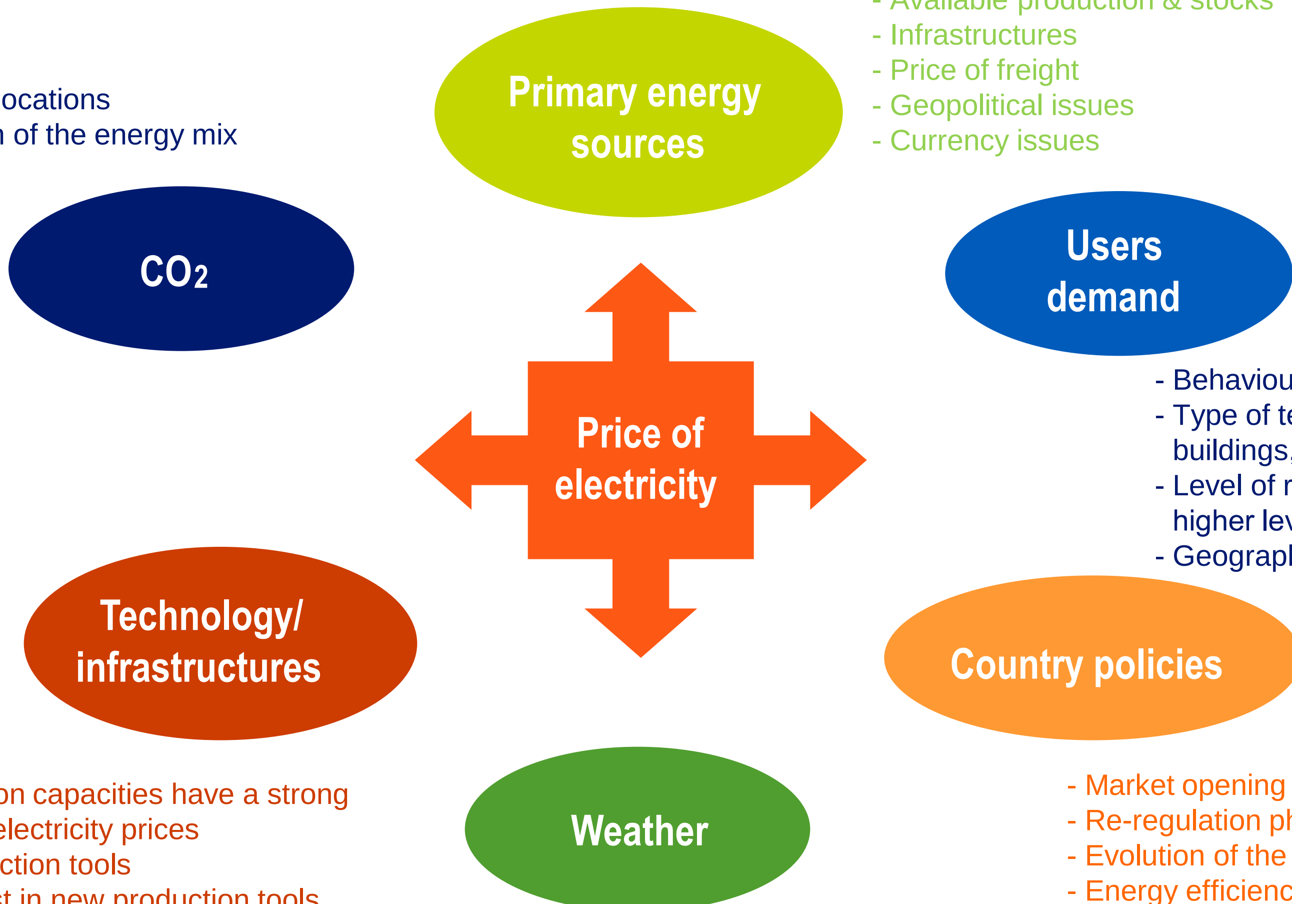
(1) Evolution compared to average prices in 2011
(2) Total annual net capacities calculated by RTE in December 2012 for the year 2013 expressed in MW
(3) Source ENTSOE, in MW

References: RTE, Epex, Belpex, IPEX-GME, OMIE, EDF-T, APX

European electricity average prices and average available commercial capacity in 2012

Electricity market prices

Specific price drivers in each country, depending on several criteria



Primary energy sources

Different energy mix over Europe
- Available production & stocks
- Infrastructures
- Price of freight
- Geopolitical issues
- Currency issues

CO_2

- Quota allocations
- Evolution of the energy mix

Users demand

- Behaviour habits & lifestyles
- Type of technologies, appliances, buildings, vehicles
- Level of resources (larger homes, higher level of comfort expected, …)
- Geographical & weather conditions

Technology/infrastructures

- Interconnection capacities have a strong influence on electricity prices
- Ageing production tools
- Need to invest in new production tools
- Evolution of the energy mix of each country will influence the electricity prices levels in the long-term

Country policies

- Market opening reality
- Re-regulation phenomenon
- Evolution of the future energy mix
- Energy efficiency initiatives
- Carbon-related initiatives

Weather

The weather impacts directly the level of energy production : temperature, wind, precipitation and consumption.

Electricity market : main challenges

- Key factors are changing the world :
  - An increase in the urban population: 50% of people living in cities, 70% by 2050
  - Resource scarcity
  - The need to “decarbonise” energy
  - A plural and multi-polar world (new emerging powers: China, Brazil, India, etc.)
  - An ever-more sprawling, decentralised world (urban systems, local energies, smart grids, etc.)

- Today, the energy markets are facing a difficult equation :
  - Reduction of available resources : oil, gas, ...
  - Ageing production assets : nuclear power plants, ...
  - Environmental issues
  - An increasing demand

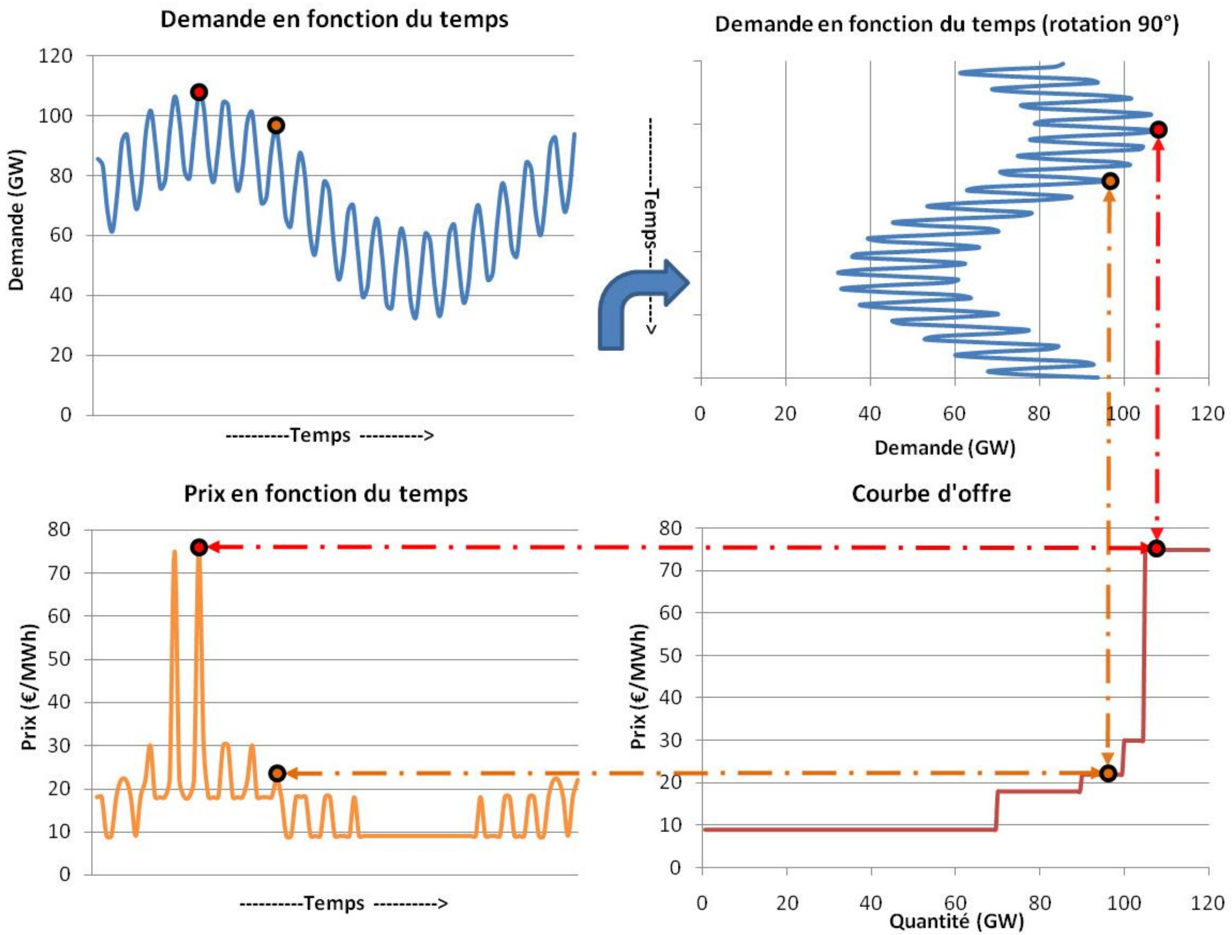
- Precise forecasting are risky. Too many factors can influence the prices...
- Tomorrow, the energy world will be even more uncertain and volatile.

MODELLING ELECTRICITY PRICES

- **Main features of power spot prices**
- Overview of spot and forward models
- A structural model for electricity prices (Aïd et al., 2011)
- Factorial models for energy prices (e.g. Kiesel et al., 2008)

Spot prices resulting from the supply/demand equilibrium

- Market spot prices result from the supply/demand equilibrium.
- Factors/aleas underlying to supply and demand ⇔ Fundamentals factors of spot prices



Qualitative features of electricity spot prices

What are the main features of electricity spot prices ?

- ✓ Correlation to temperature, cloud cover, sunset (lightning)
- ✓ Multi-scale seasonality linked to economic activity, heating, …
  - Annual : seasons/months within the year
  - Weekly : days within the week
  - Daily : hours within the day
- ✓ Calendar effects (vacation, public holiday)

Demand

- ✓ High volatility (higher than on other markets) and seasonal volatility
- ✓ Positive correlation between price level and price volatility
- ✓ Mean-reversion (≠ divergence)
  - Fluctuations around levels representative of the S/D equilibrium
- ✓ Spikes
- ✓ Negative prices !

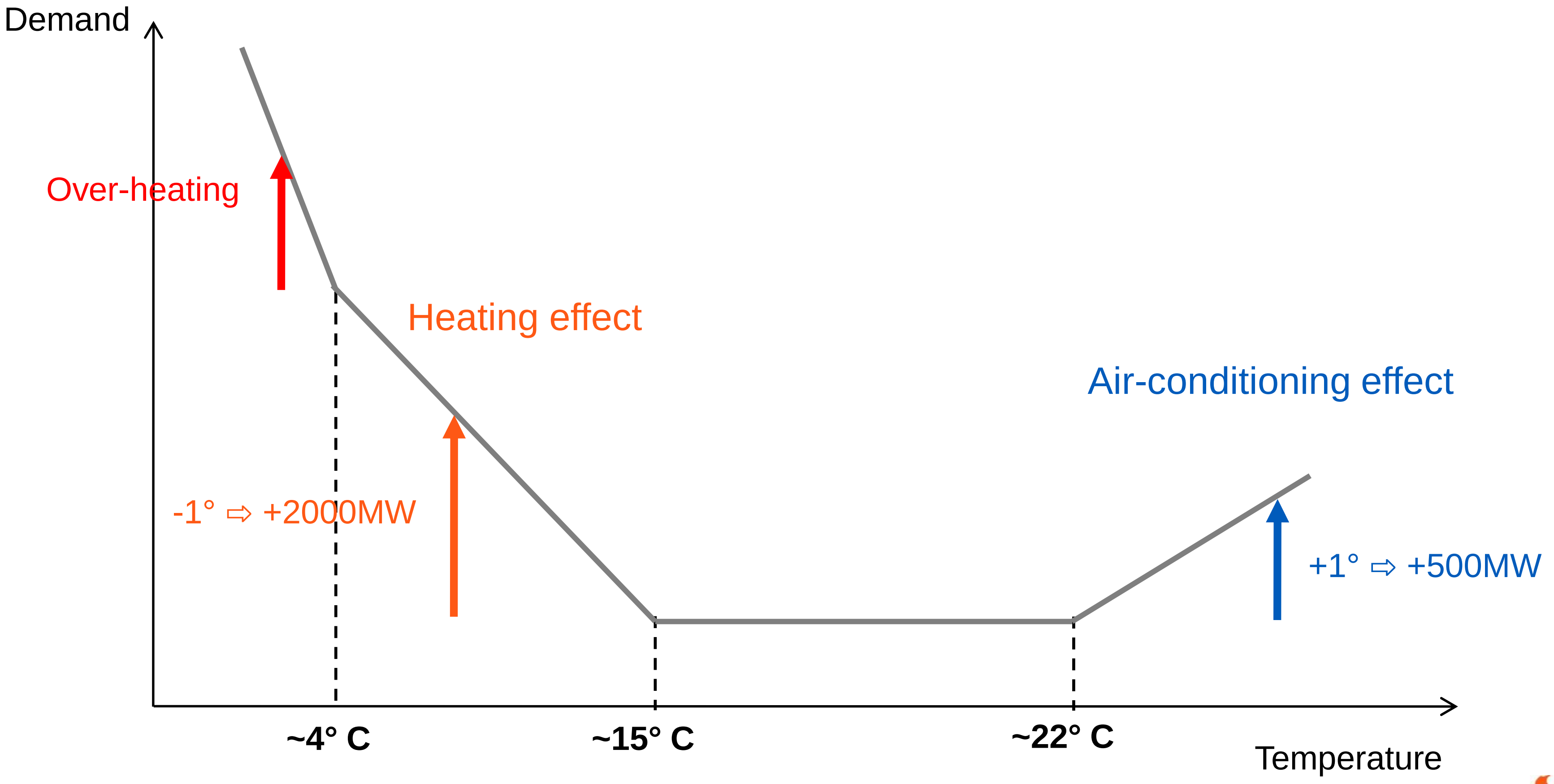
S/D Equilibrium
Non-storability

- ✓ Opposite dependence of volatility to the supply level
- ✓ Correlation to commodity prices (fuel, CO_2, …)

Supply

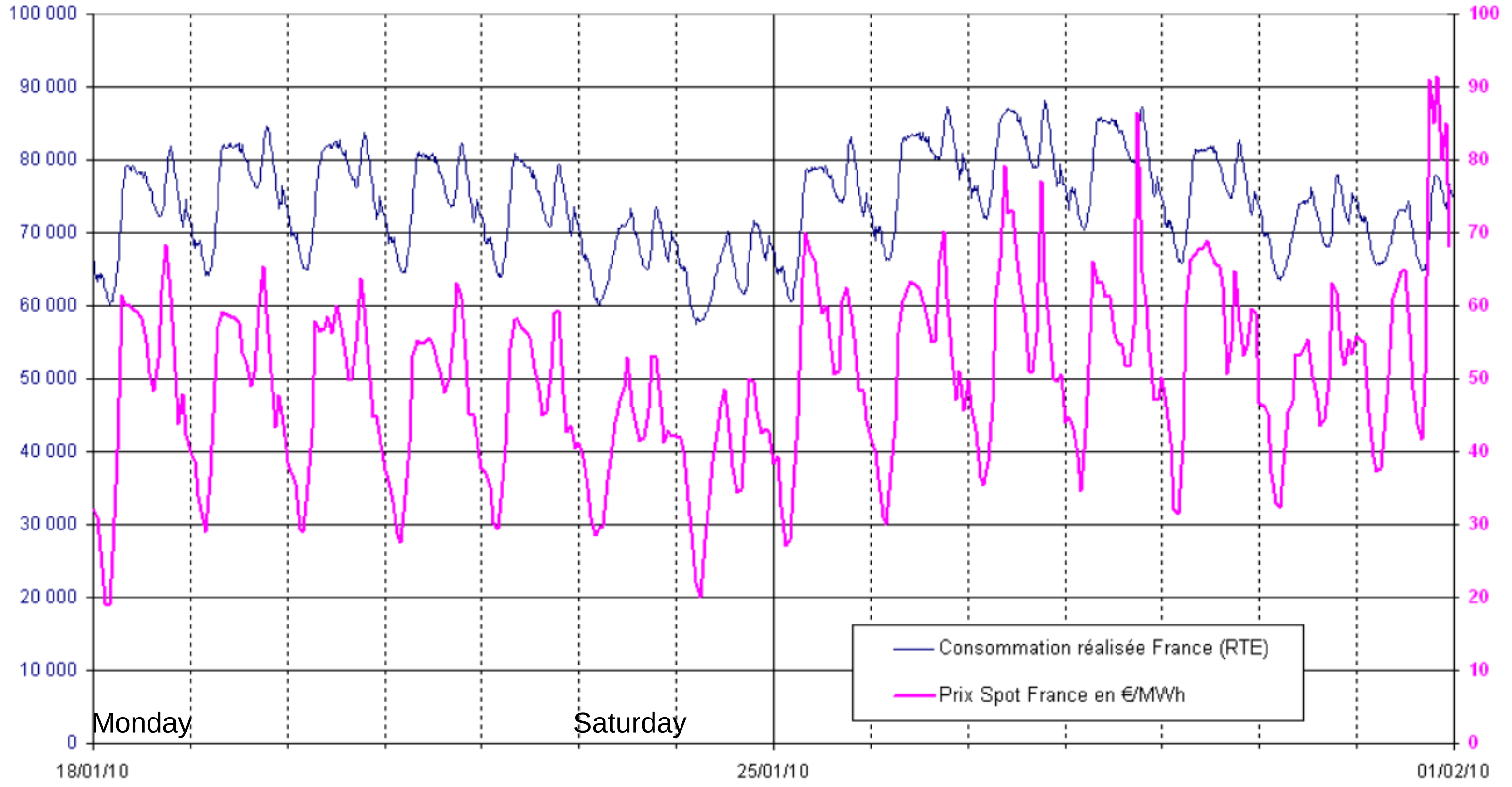
Dependence of demand to temperature

- Temperature effect on demand : illustration of the heating and air-conditioning gradients
- Threshold temperatures for summer and winter are identified.
- The temperature has also an effect on market supply : less depth for market purchase in winter.



Seasonality of electricity spot prices

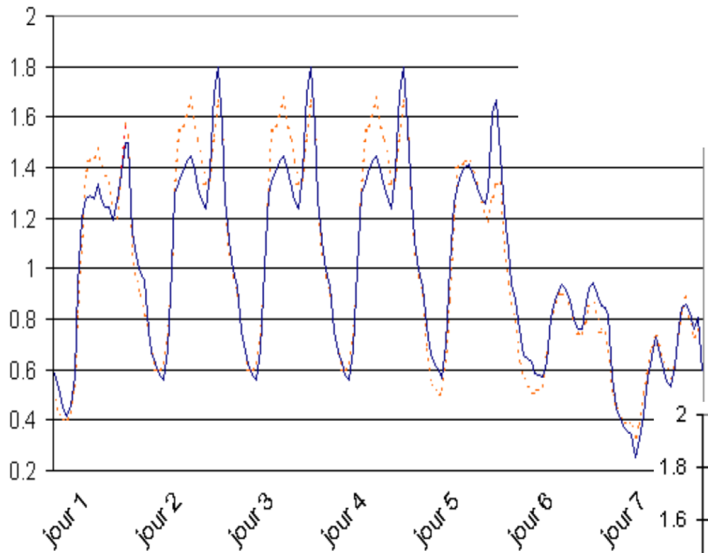
- Weekly and daily seasonality are consequence of the seasonality of demand : high noon (11h-14h) and rush hour (17h-20h) peaks.
- Electricity prices show an hourly shape ⇨ **shaping coefficients** are an usual way to reproduce it.

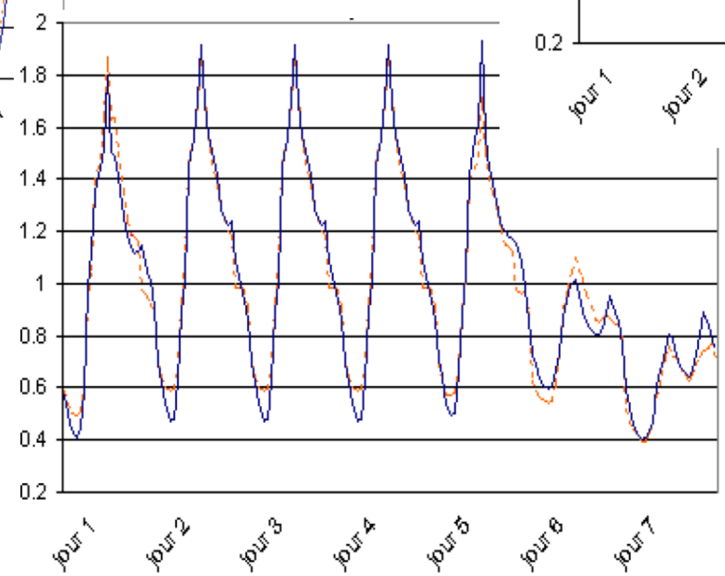


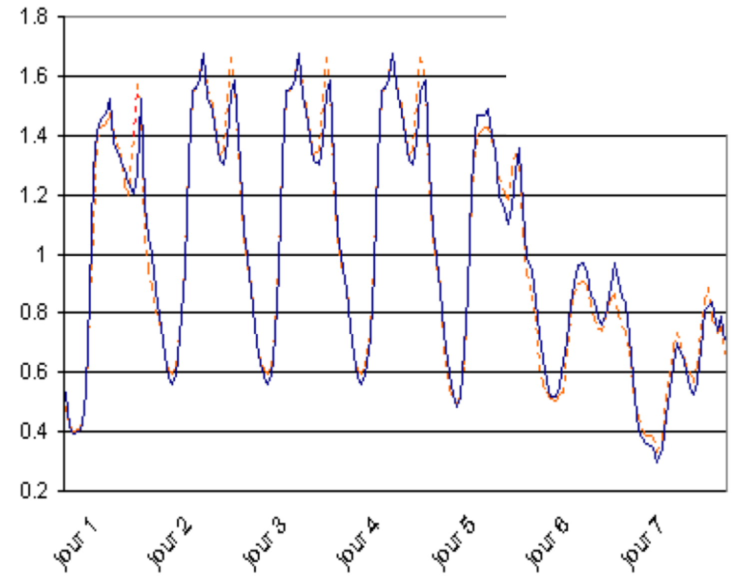
Daily base spot price and consumption on the French market on W3-W4 in 2010 (Epex Spot, RTE)

Shaping coefficients for electricity spot prices

- 168 shaping coefficients used to reproduce the historical daily and weekly seasonality.
- ***For France, which graph corresponds to which month among September, October, November?***

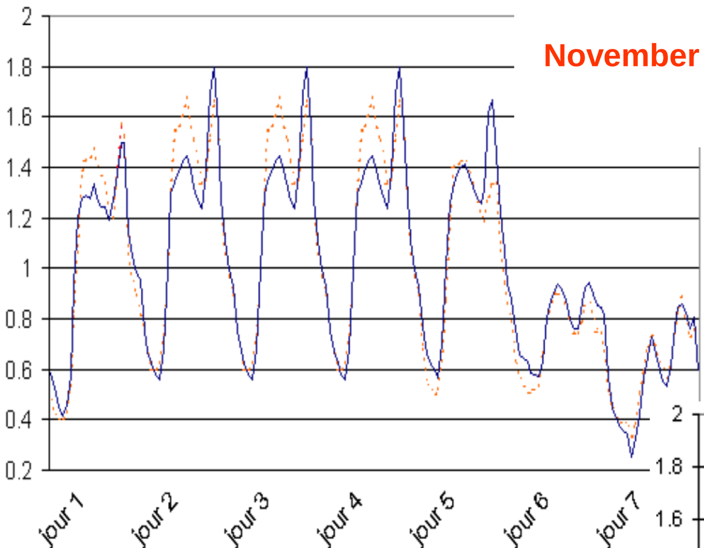


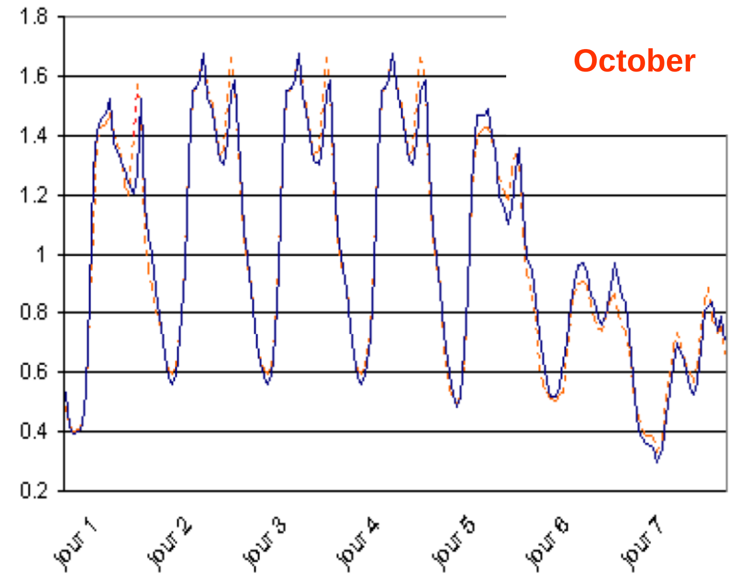


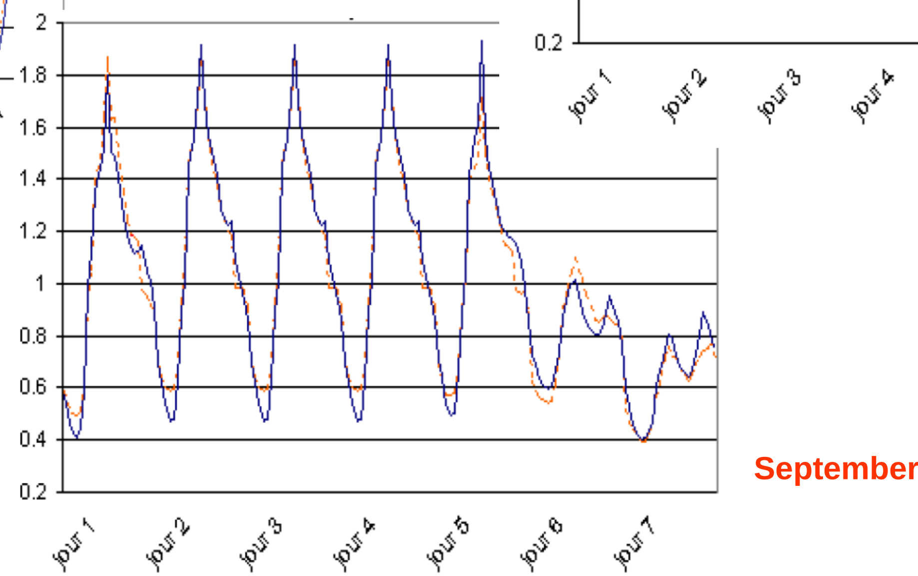


Shaping coefficients for electricity spot prices

- Herebelow, an example of three sets of weekly shaping coefficients for France.







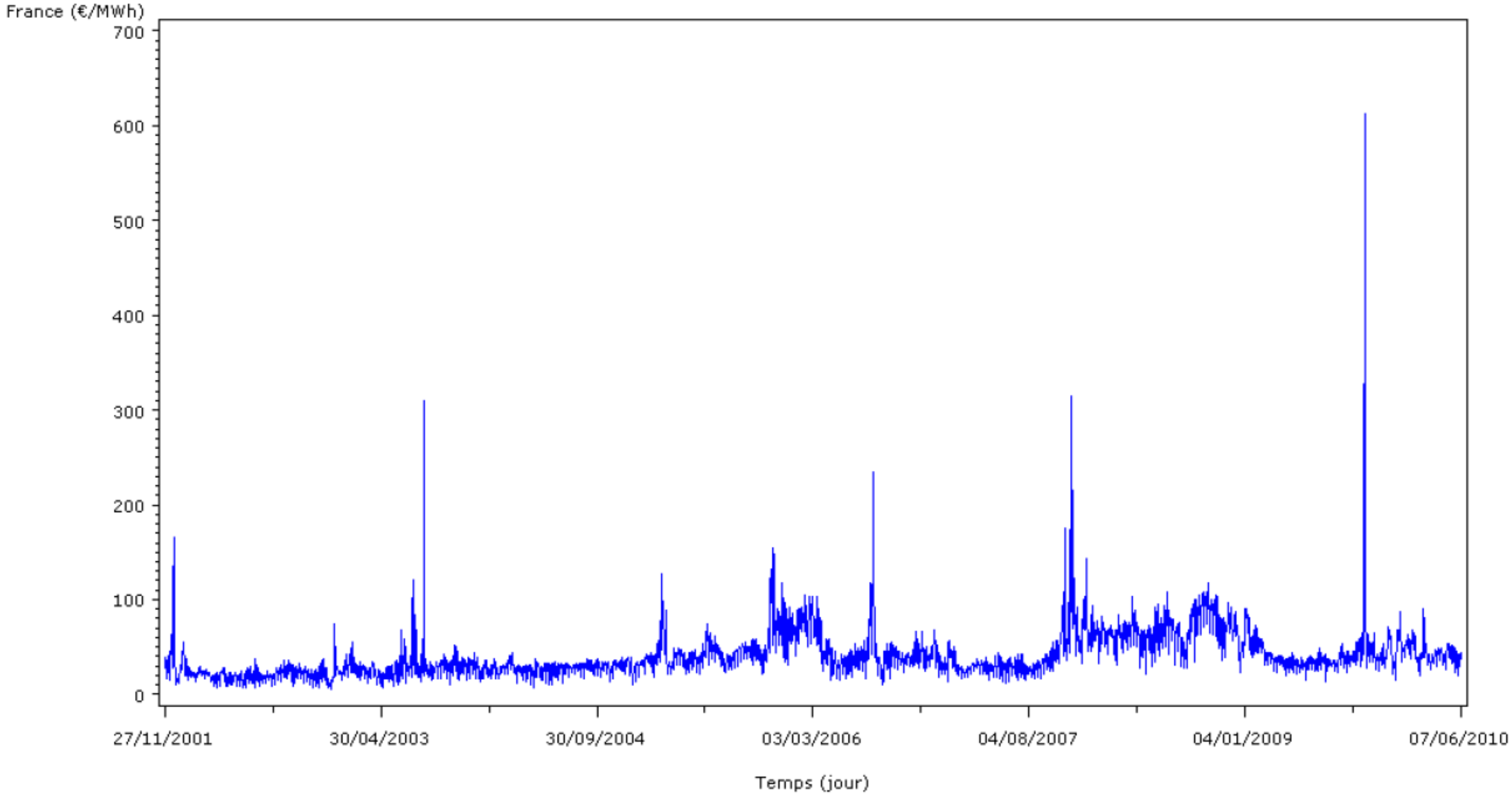
In September, only a midday peak.

In October, midday and evening peaks have a similar amplitude.

In November, the evening peak is really more pronounced (heating).

Mean reverting behavior of electricity spot prices

- Electricity prices are governed by an effect of mean-reversion to trends.
    - Short-term trend : supply/demand equilibrium, adjustment
    - Long-term trend : investments/decommissioning, LT economic cycles

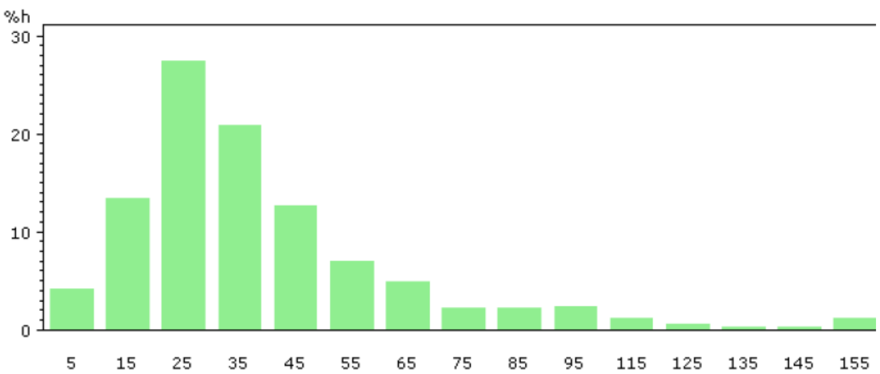


Daily Base spot price on the French market from November 2001 to June 2010 (Epex Spot)

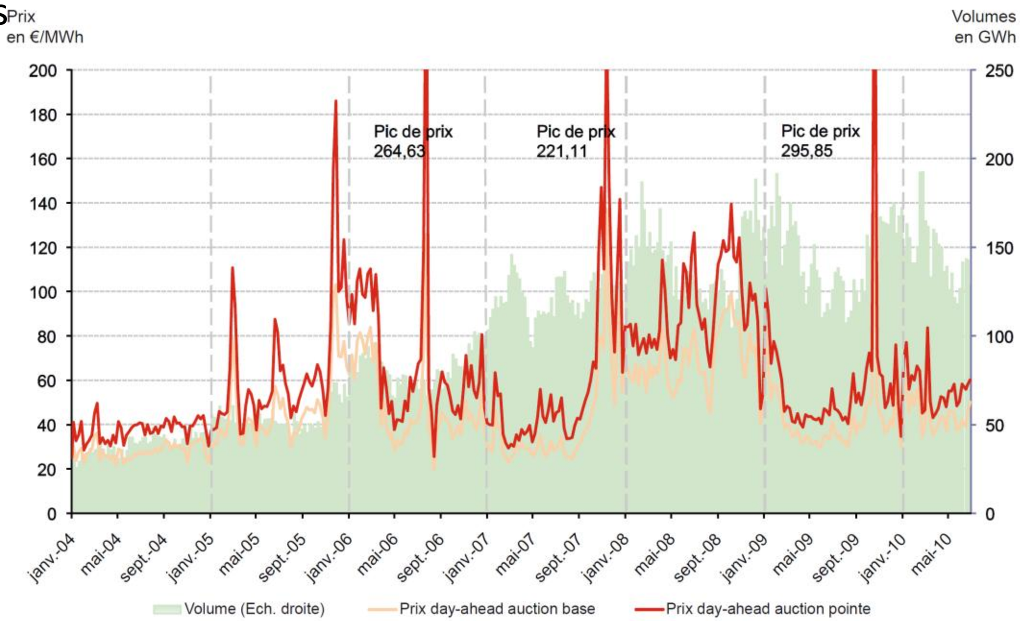
Electricity prices spikes

- A spike (and not a jump !) is a fast upward movement followed by a quick return to the same level.
  - The price distribution is positively skewed : spikes are mostly positive
  - Can be multiplied by 100 in few hours
  - Happen mainly in winter : annual seasonality of spikes (as for the volatility)

- ***Why do spikes happen ?***
  - ✓ due to the non-storability of electricity : cannot absorb demand/supply desequilibrium
  - ✓ rapid demand upward moves and/or sudden power plant decrease in availability (outages)
  - ✓ a seasonal and relatively inelastic demand with respect to prices
  - ✓ the discontinuity of the production costs

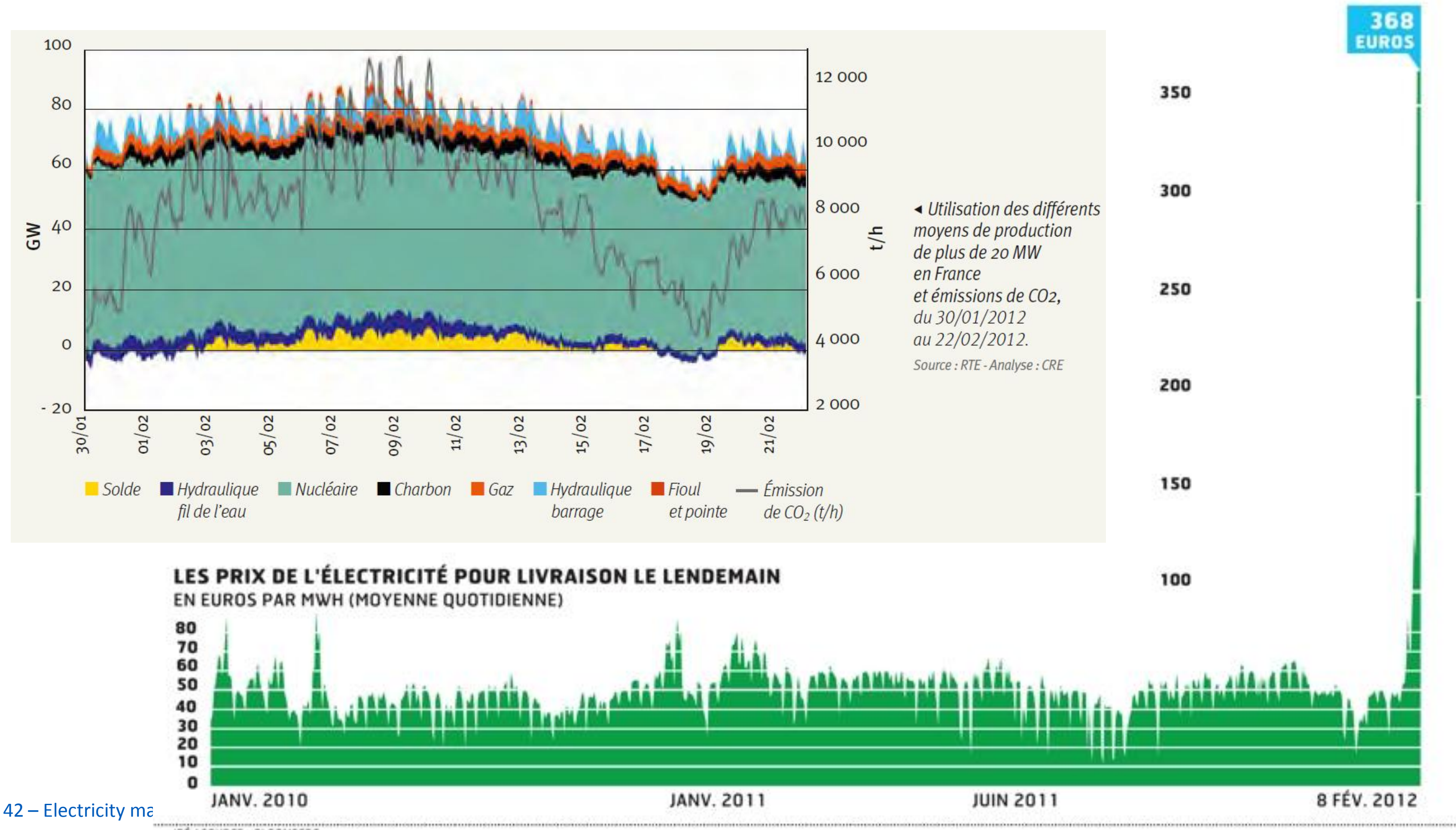


Powernext (2007) prices distribution



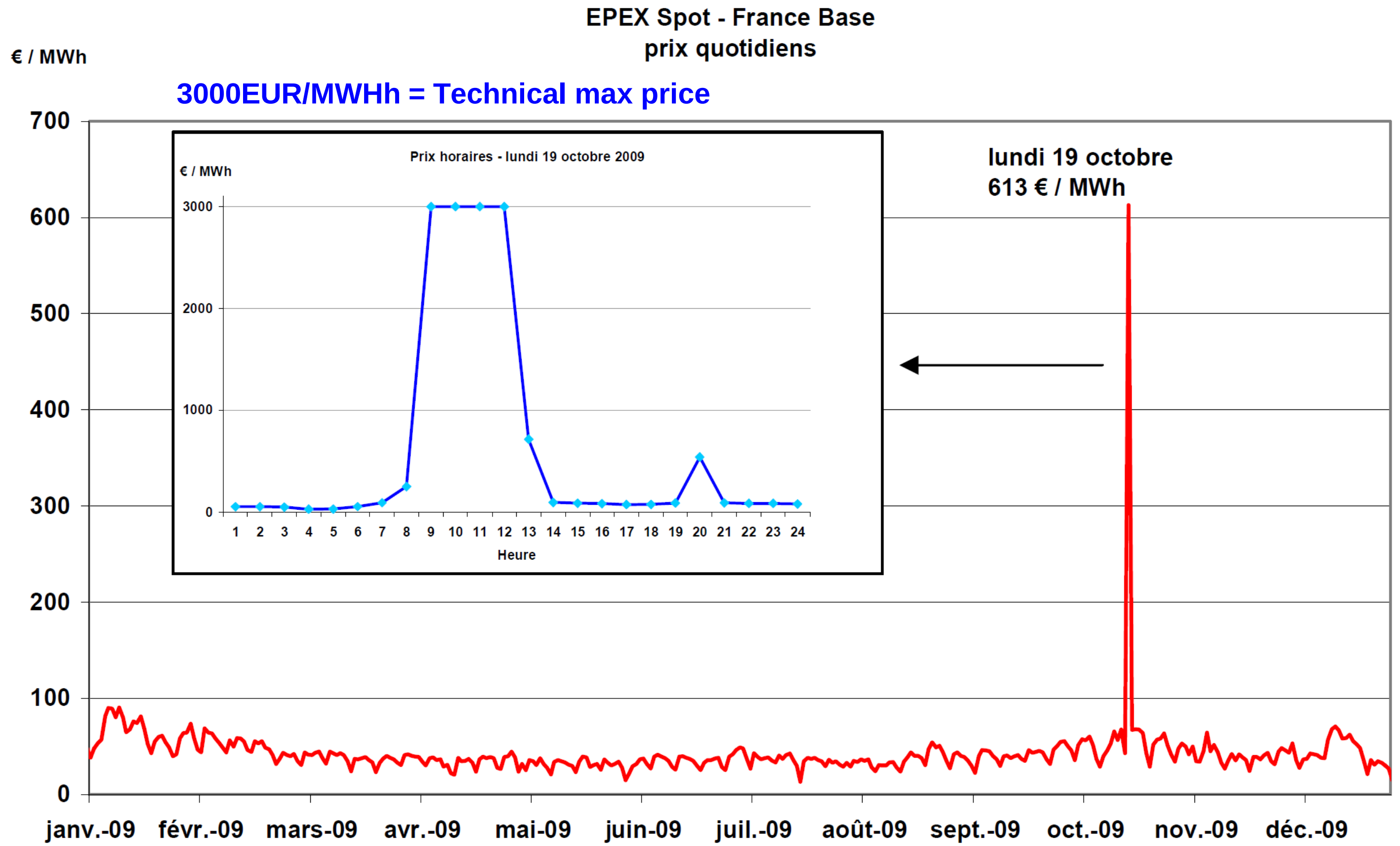
Electricity prices spikes due to a very high demand

- On the 8th February, 2012, in France, exceptionally high demand due to the winter cold spell
  - At 19h, historic record of 102GW demand (last one was in December 2010, with 97 GW)
  - DaH price 10h-11h = 1983€/MWh ⇨ DaH Base price = 368€/MWh



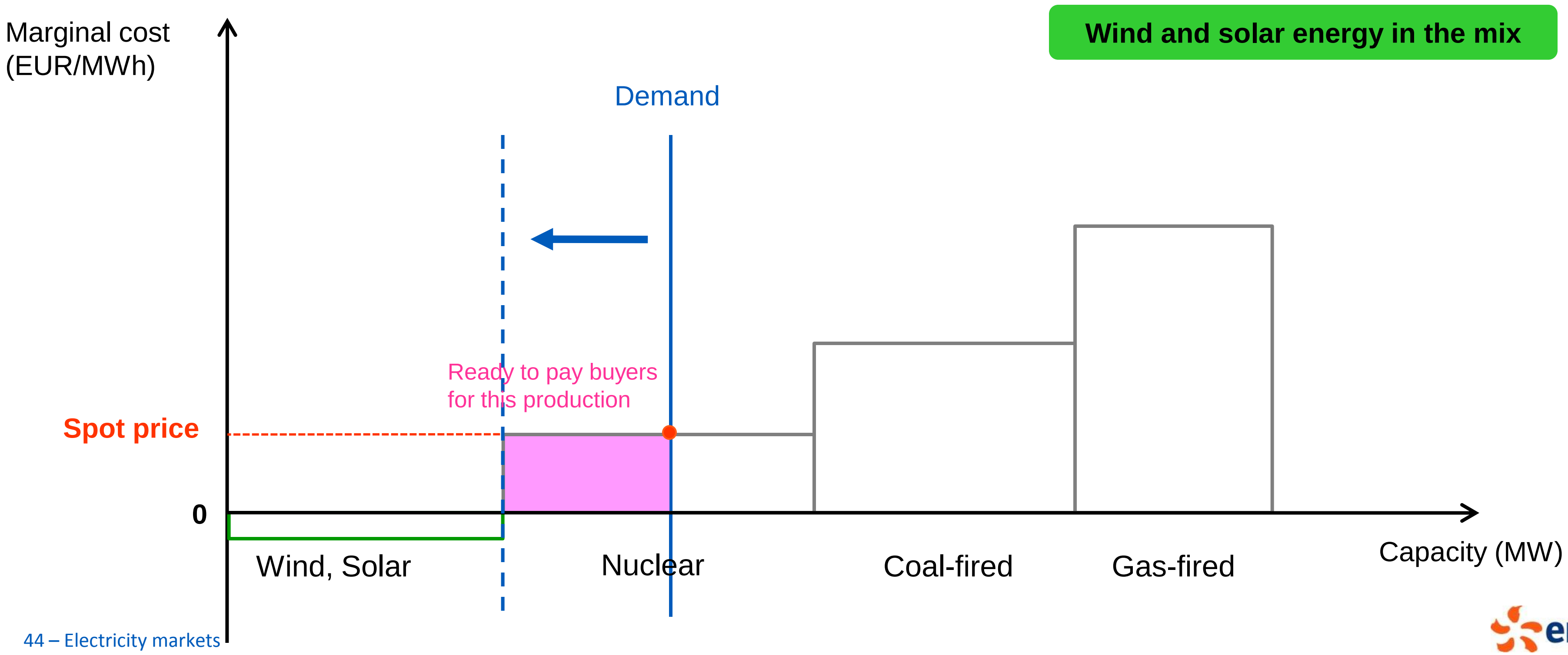
Prices spikes due to a supply/demand desequilibrium

- On Monday 19th October, 2009, production « default » in France (Epex Spot) caused by :
  - An upward in demand forecast (+ 3000 MWh between Friday and Sunday)
  - A very high late morning (9h-12h) demand
  - A downward in supply (- 4100 MWh) due to a shutdown of nuclear and hydro power plants



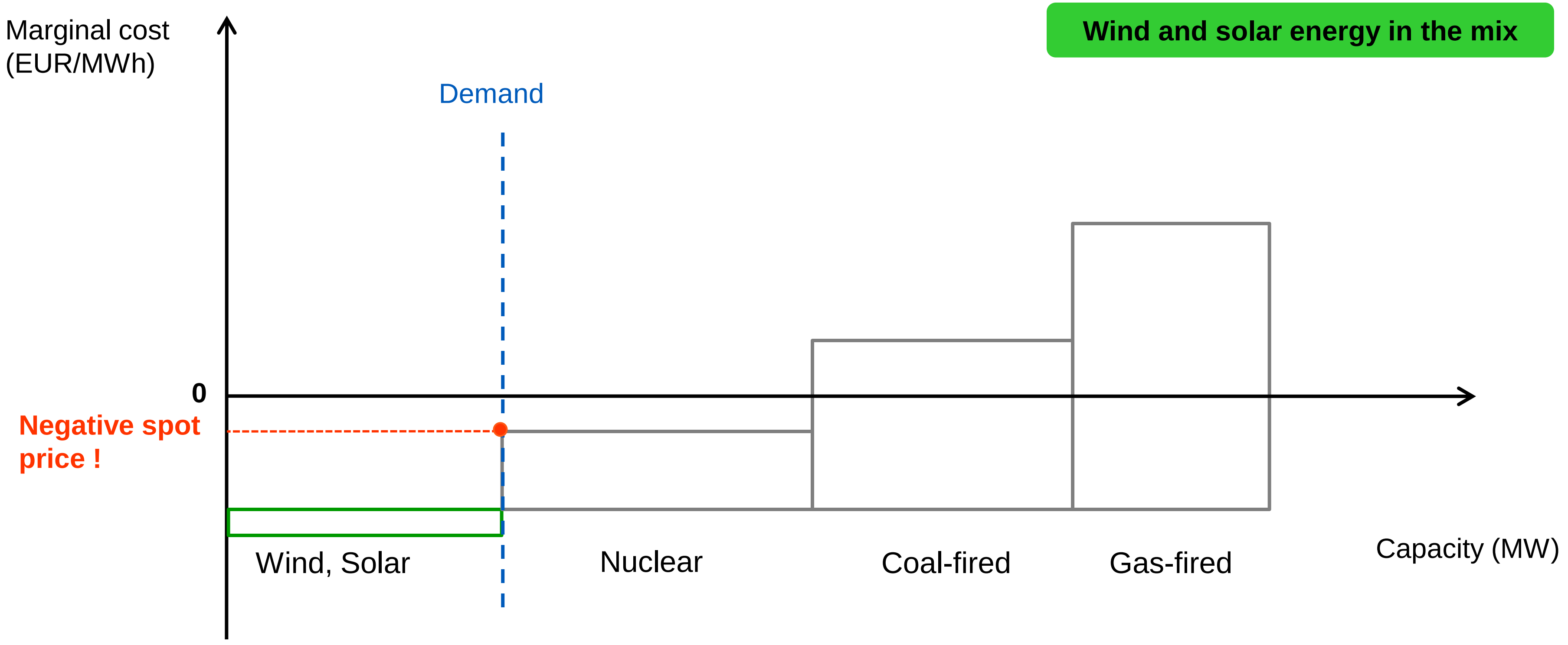
Negative electricity spot prices

- ***When does a negative price appear ?***
  - ✓ In case of a production based on non-flexible mean of power generation
    - Production units that cannot be turned off and on very fast without a very high cost
    - Renewables depending on external factors (wind, solar)
  - ✓ This phenomenon is increased by the priority given to renewables for injection on the network.
  - ✓ In case of a lower demand : in summer, by night, on 25th December, etc.



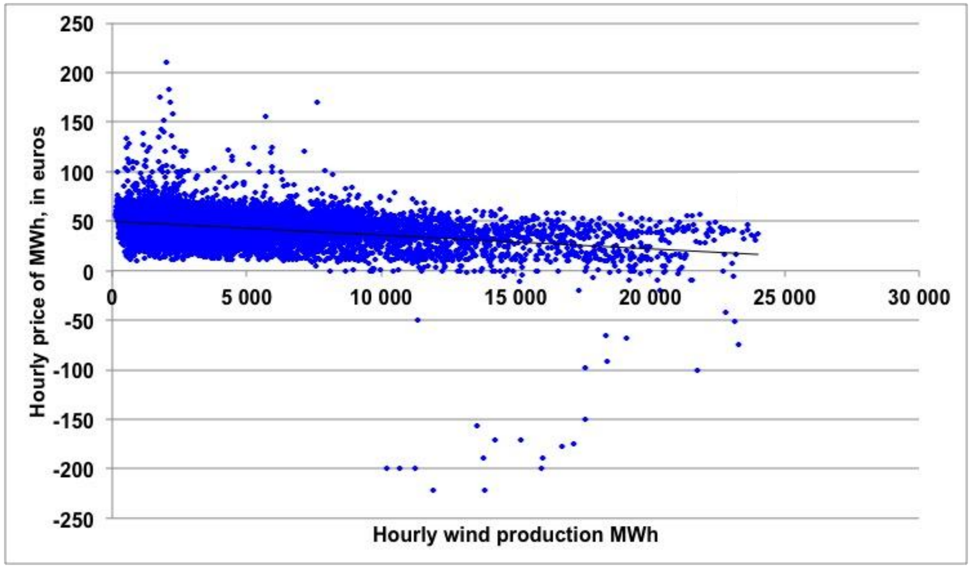
Negative electricity spot prices

- ***What does a negative price mean ?***
  - ✓ This is not a theoretical concept and so, buyers can receive both money and power !
  - ✓ Producers accept negative prices to maintain a minimal production rather than pay stopping and restarting costs : this decision create a supply surplus, that can only be solved by paying buyers their production.



Negative electricity spot prices

- First negative prices appear in Germany from 2007, in France from 2010 (Epex Spot)
- This situation happened for example the 25th December, 2012, in France :
  - Upward in wind production (+60% in comparison to the day before)
  - - 9GW in consumption (public holiday)
  - Saturation of contractual flows from Germany to France (wind over-production in Germany)
- Illustration in Germany, with the effect of wind energy (~30 GW installed capacity in 2012)
  - The stronger the wind, the lower the electricity price !
  - More often negative prices from a certain level of wind production



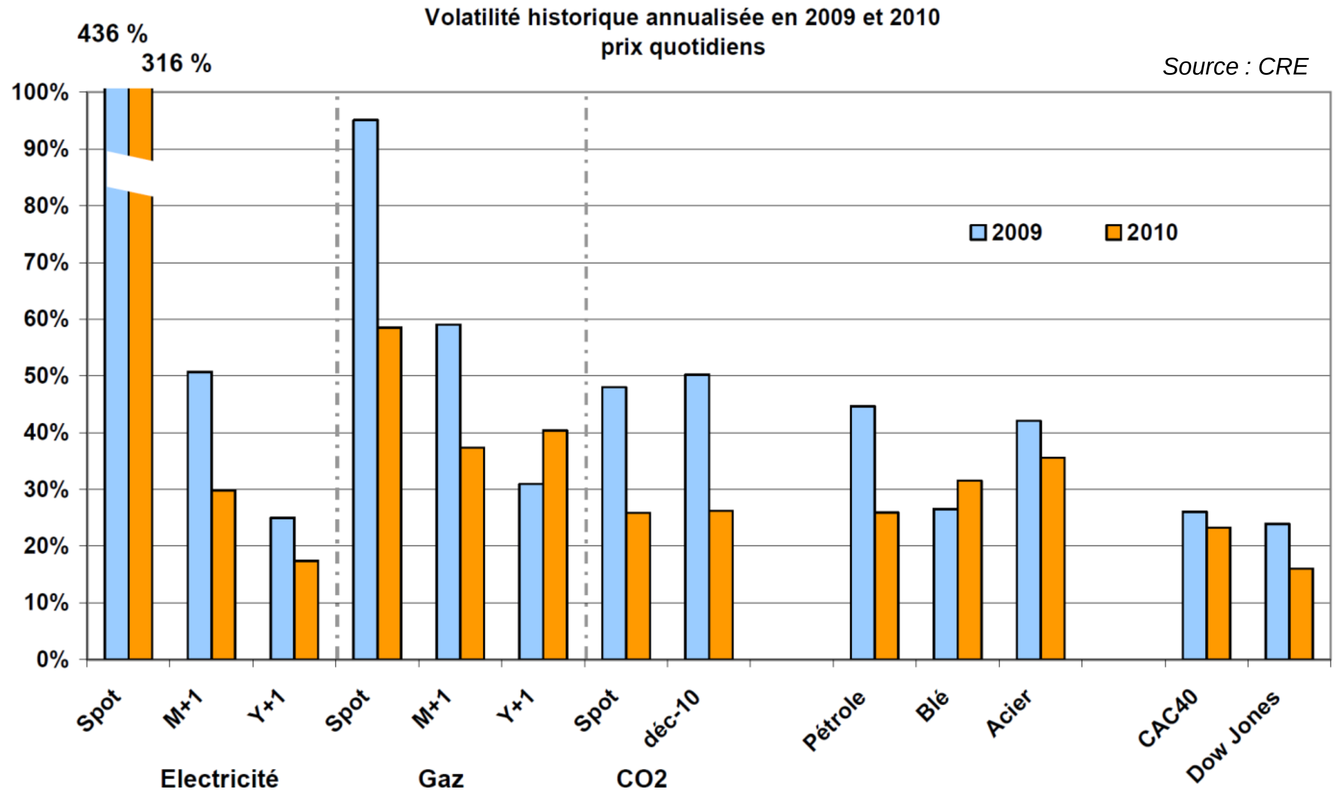
Allemagne, données 2012 (Blog http://www.manicore.com)

MODELLING ELECTRICITY PRICES

- **Main features of power forward prices**
- Overview of spot and forward models
- A structural model for electricity prices (Aïd et al., 2011)
- Factorial models for energy prices

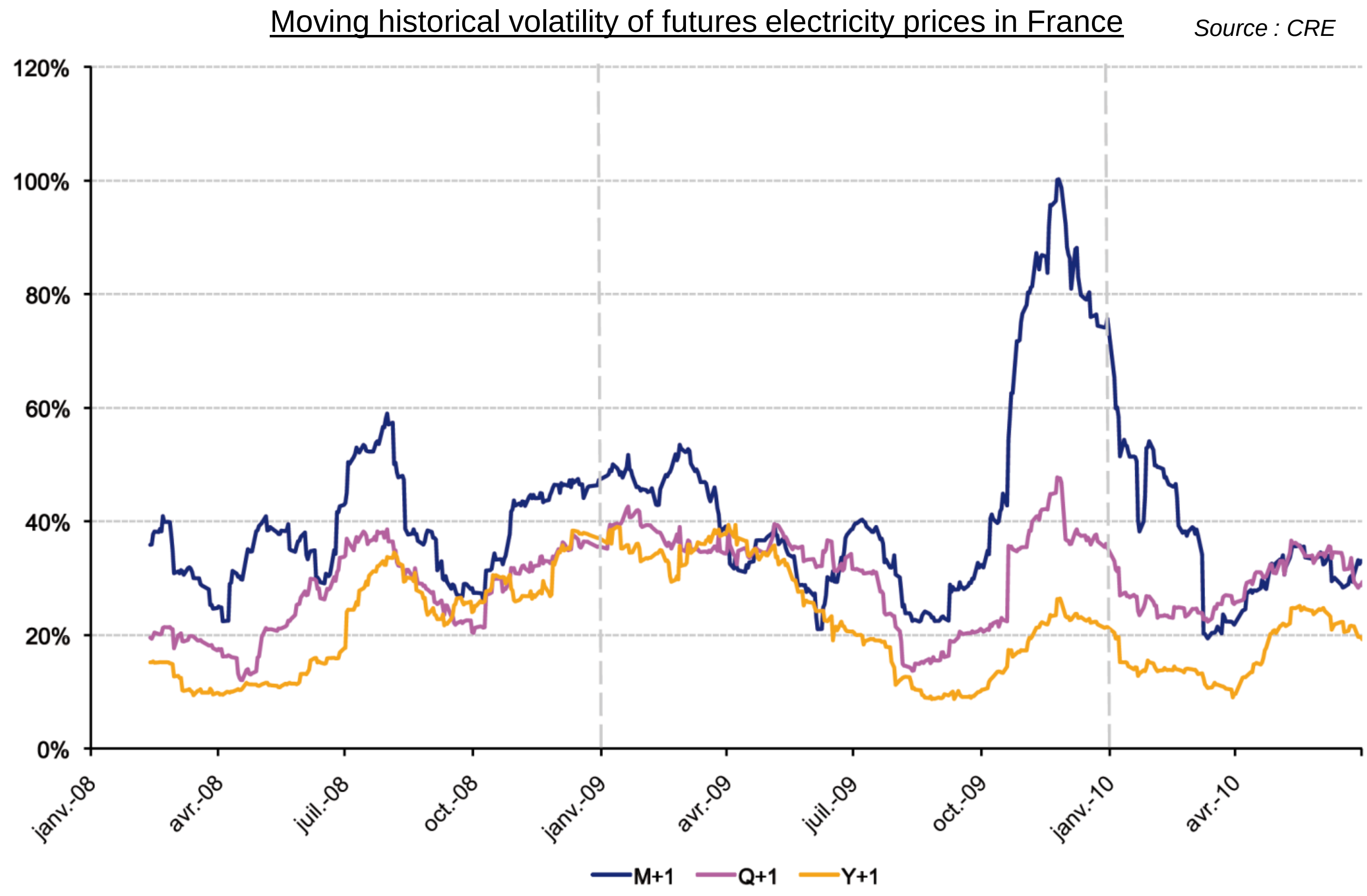
Forward prices : effect of term structure

- The volatility decreases with products granularity.
  - Week/monthly products being more volatile than calendar products
  - Any new information (shock) has an important impact at short-term but its effect is diluted on longer time horizons.



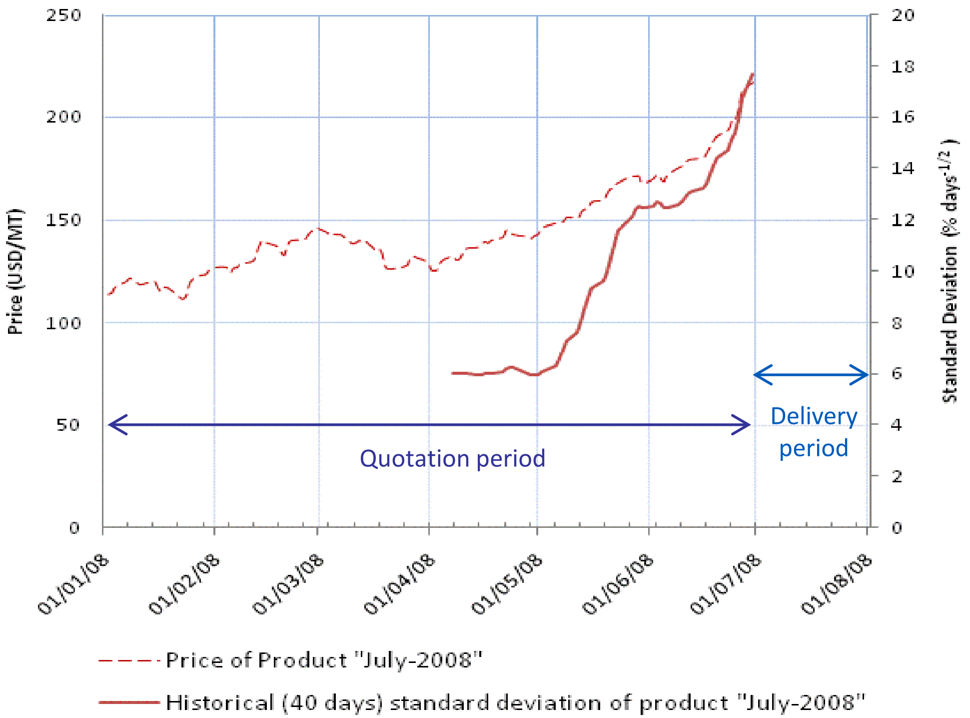
Seasonality of forward prices volatility

- As for spot prices, the volatility of monthly products tends be seasonal.



Forward prices : effect of maturity

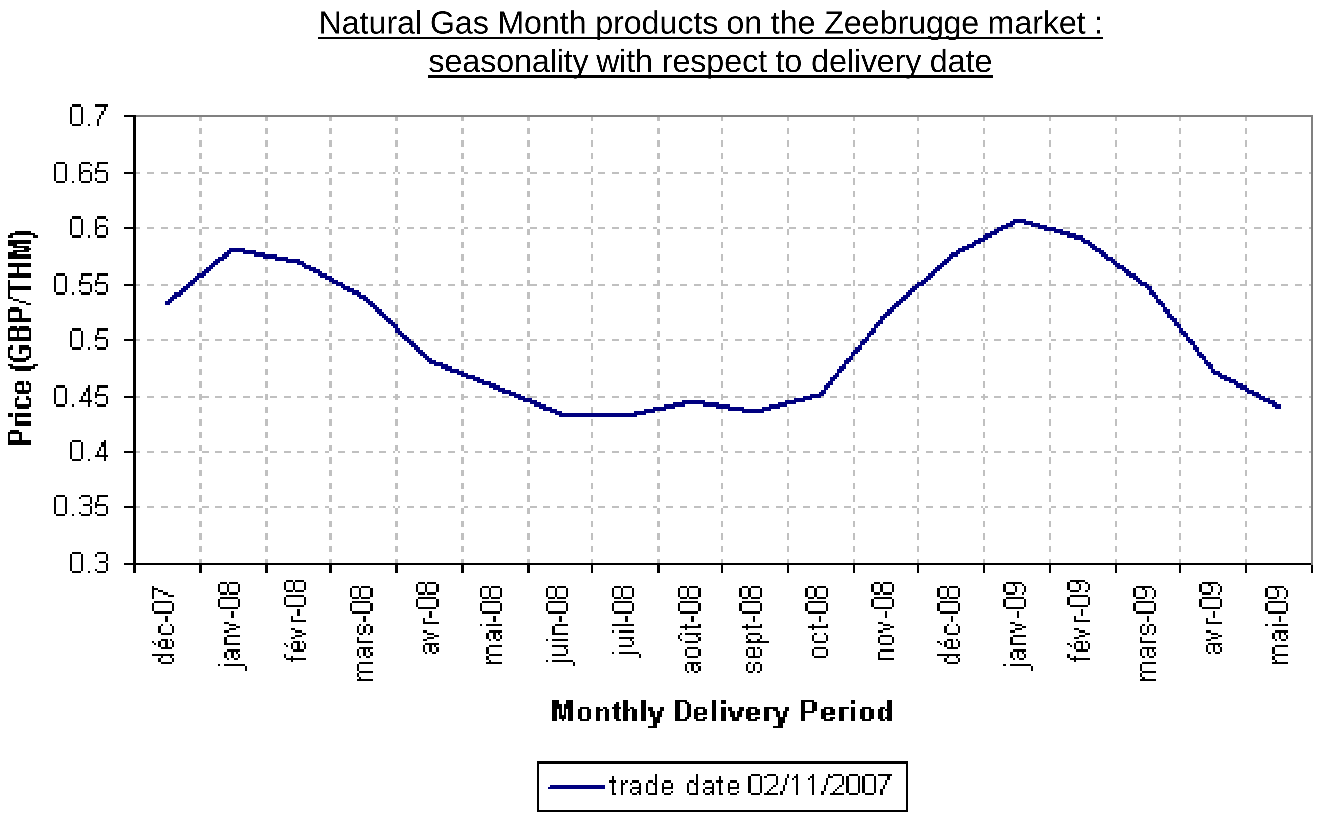
- The volatility increases when the quotation date becomes closer to the delivery date.
  - Samuelson effect : exponential increase when becoming closer to the maturity
  - Linked to the relative effect of available information between short and medium term : possibility or not to adjust production to meet demand



Price level and volatility of a forward product (July 2008)

Seasonality of forward prices

- The forward level depends on the delivery date as well : seasonality.
  - Linked to the way the market anticipates the known cyclic fluctuations of demand
  - Economic activity, weather (heating and air-conditioning)



MODELLING ELECTRICITY PRICES

- Main features of power forward prices
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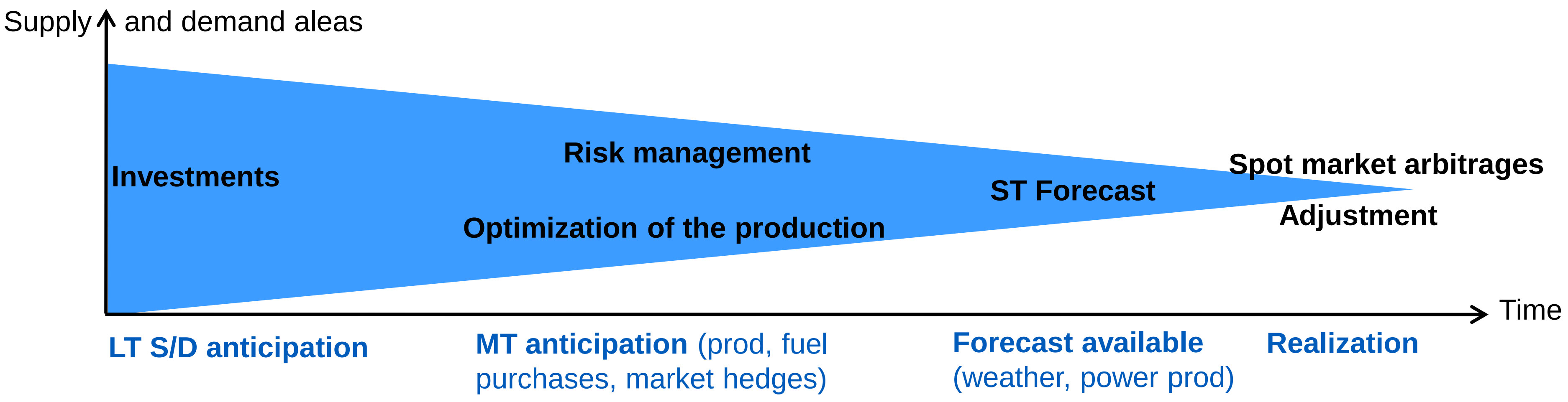
Using electricity and commodity price models

Why do we need price models?

1. Take investments decisions over the long term
   - Based on ecomonic and structural arguments, used for 10-20 years horizon
2. Valuate energy derivatives
   - Physical assets and financial contracts in a context of a competitive market
3. Assess the risk and hedge energy portfolios
4. Propose commercial offers : competitive sales prices but covering the production costs

➧ Models for both spot and forward prices are required.



Electricity prices models

Typology of prices model and their applications

Stuctural models

- Models based on the S/D E
- Integrating exogenous variables
- LT applicatons
- ST forecast : Spot = Marginal cost

Statistic models

- Deal with the price signal
- Calibration on historical prices datas
- Objective prices behavior

Financial models

- Based on stochastic processes
- Inspired by the "financial world"
- Energy derivatives pricing
- Risk management

Convergence assumption

$$S_t = \lim_{T \to t} F(t, T)$$

Spot prices models

+ Model directly the spot price
+ Can provide **closed formulas** for futures prices and options
− Difficult calibration
− Unsatisfying behavior of the **implied forward curve**

Forward prices models

+ Model directly the forward curve
+ **Closed formulas** for options
− Limited number of factors
− Divisibility assumption needed for a **spot convergence**

$$F(t, T) = \mathbb{E}\left[S_T | \mathcal{F}_t\right]$$

No-arbitrage condition

Electricity prices models

How can we represent the electricity prices features in our models ?

- Seasonality
  - Usually represented as a determinisitic component of the price signal
  - Objective : build an initial market forward curve presenting a seasonal shape
  - Discrete method using shaping coefficients or continuous-time method (sine-cosine functions)

- Volatility
  - Log-normality of prices is mostly often assumed (e.g. financial models)
  - Volatility function can be assumed time-dependent
- Mean-reversion : log-prices can be modelled by mean-reverting processes (Ornstein-Uhlenbeck)

- Negative prices : log-normal models become irrelevant…
- Spikes : model with jumps, Lévy-driven stochastic processes, leptokurtic distribution for prices return

- Correlation to commodity prices : multi-dimensional models, structural models
- Correlation to temperature : prices return driven in addition by a stochastic process modelling the temperature level

MODELLING ELECTRICITY PRICES

- Main features of power forward prices
- Overview of spot and forward models
- **A structural model for electricity prices (Aïd et al., 2011)**
- Factorial models for energy prices

A structural model for electricity prices (Aïd et al., 2011)

- Framework : Equilibrium model for spot prices

- Main ideas
  - Marginal fuel = most convenient fuel to produce electricity among the different available fuels
  - The power spot price is given by the marginal fuel cost
  - Correction allowing to take into accound price spikes
  - Forward prices deduced by the no-arbitrage condition :

Forward price = Expected spot price

$$F(t,T) = \mathbb{E}\left[S_T | \mathcal{F}_t\right]$$

- In this model, the electricty spot price is assumed to be determined by :
  - ✓ The demand
  - ✓ The different technologies for power generation
  - ✓ Their capacities
  - ✓ Some scarcity factor

A structural model for electricity prices (Aïd et al., 2011)

Simple case with 2 fuels

- Assume first that there are only 2 technologies for electricity production
- The variables used in this model are :

D_t	Demand (in MW)
C_t^1, C_t^2	Capacities (in MW)
S_t^1, S_t^2	Fuel prices
h_1, h_2	Heat rates with $h_i S_t^i$ in €/MWh

- $h_i S_t^i$ corresponds to the price of the quantity of fuel number i necessary to produce 1 MWh
- After a (random but measurable) permutation, production costs can be ordered among fuels :

$$h_1 S_t^1 \leq h_2 S_t^2$$

- Then, the electricity spot price can be given by the marginal fuel cost :

$$S_t = h_1 S_t^1 \mathbb{1}_{\{D_t \leq C_t^1\}} + h_2 S_t^2 \mathbb{1}_{\{C_t^1 \leq D_t\}}$$

A structural model for electricity prices (Aïd et al., 2011)

General case with n fuels

- More generally, for a set of n technologies for electricity production :

D_t	Demand (in MW)
n	Fuels available $i = 1, \ldots, n$
C_t^i	Capacity for fuel i (in MW)
S_t^i	Price of fuel i
h_i	Heat rate associated to fuel i with $h_i S_t^i$ in €/MWh

- The producer order the fuels from the cheapest to the most expensive (random permutation) :

$$h_1 S_t^1 \leq h_2 S_t^2 \leq \ldots \leq h_n S_t^n$$

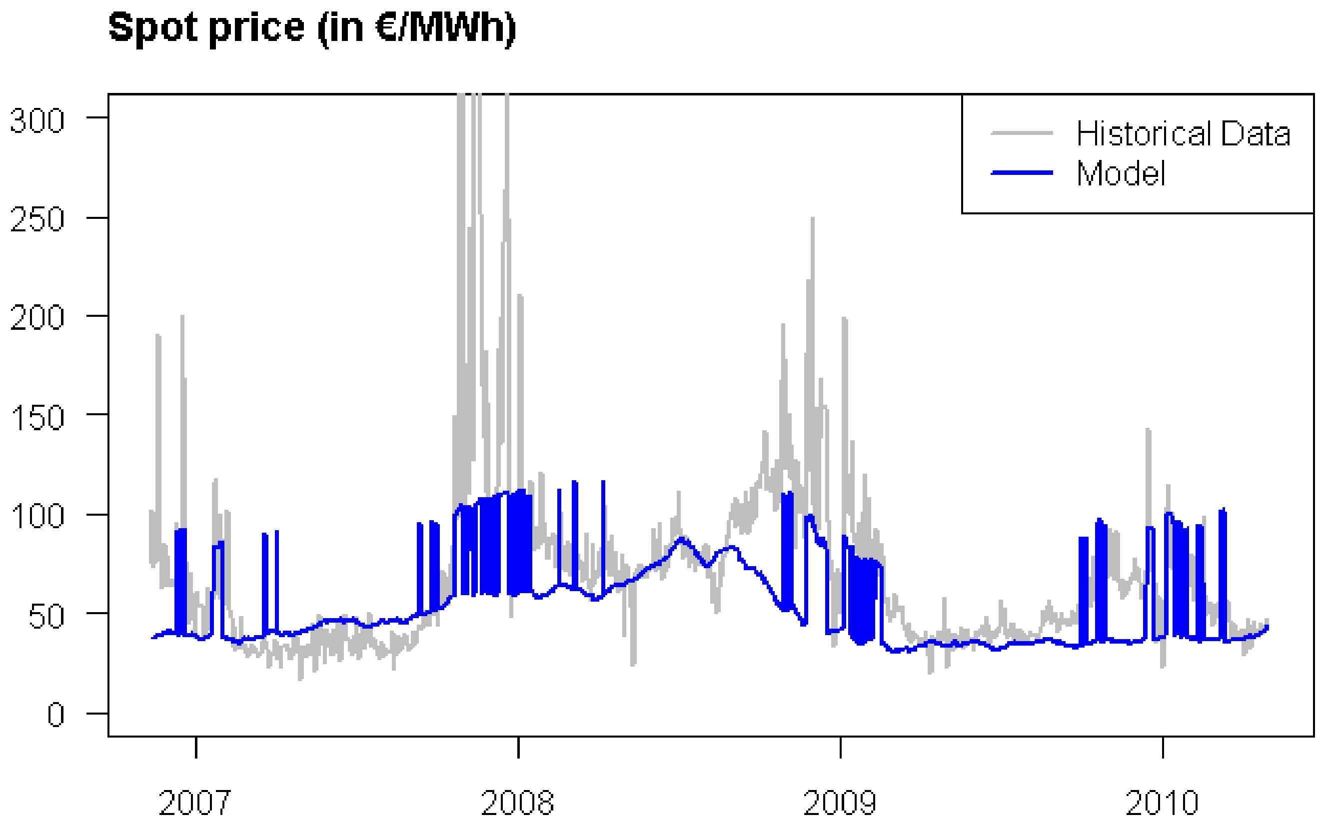
- Then, the spot price given by the marginal fuel cost can be written as :

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

A structural model for electricity prices (Aïd et al., 2011)

Backtesting the model

- Here, model with two fuels: coal and oil.
- Spikes are not modelled by this first model.



Simulation by Aïd et al. with Powernext 19th hours data (13/11/2006 - 30/04/2010)

A structural model for electricity prices (Aïd et al., 2011)

Improving the model to model spikes

- Model based on the fundamental of electricity prices :
  - Consistency between power prices and fuel prices, power prices and demand
  - All variables are observable (but only electricity and fuels are tradable).

- But, the marginal fuel cost is not exactly the market spot price !
  - Technical constraints
  - Strategic behavior, very high starting costs of peak-load generation plants
  - Effect of margin capacity = capacity limit – demand

- Improvement of the model :
  - Include the modelization of price spikes
  - … by multiplying the marginal fuel cost by a factor, allowing the power price to deviate from the marginal fuel price when the demand becomes closer to the capacity limit
  - This factor ⇔ Scarcity of production capacity (non storability of electricity)

A structural model for electricity prices (Aïd et al., 2011)

The model, improved to reproduce price spikes

- The marginal fuel cost modelled as previously :

$$MC_t := \sum_{i=1}^{n} h_i S_t^i \mathbb{1}_{\{\sum_{k=1}^{i-1} C_t^k \leq D_t \leq \sum_{k=1}^{i} C_t^k\}}$$

- Take into account the maximal available power capacity :

$$\bar{C}_t = \sum_{k=1}^{n} C_t^k$$

- Price spikes occur when the power system is under stress, corresponding to a small margin capacity of the system $x_t := \bar{C}_t - D_t$

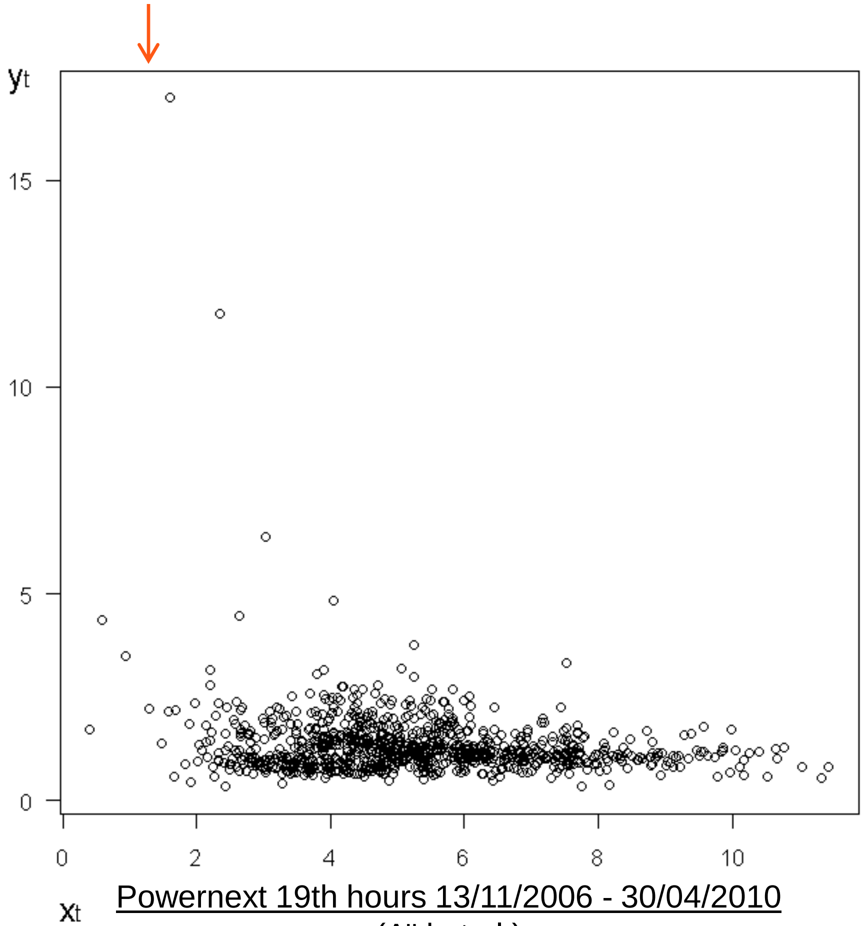
- Scarcity factor estimation ⇨ Observe variable

$$y_t := \frac{S_t}{MC_t}$$

as function of the margin capacity

- Decreasing relation between $y_t := \dfrac{S_t}{MC_t}$ and $x_t := \bar{C}_t - D_t$

High deviationf of spot prices w.r.t. the marginal fuel cost



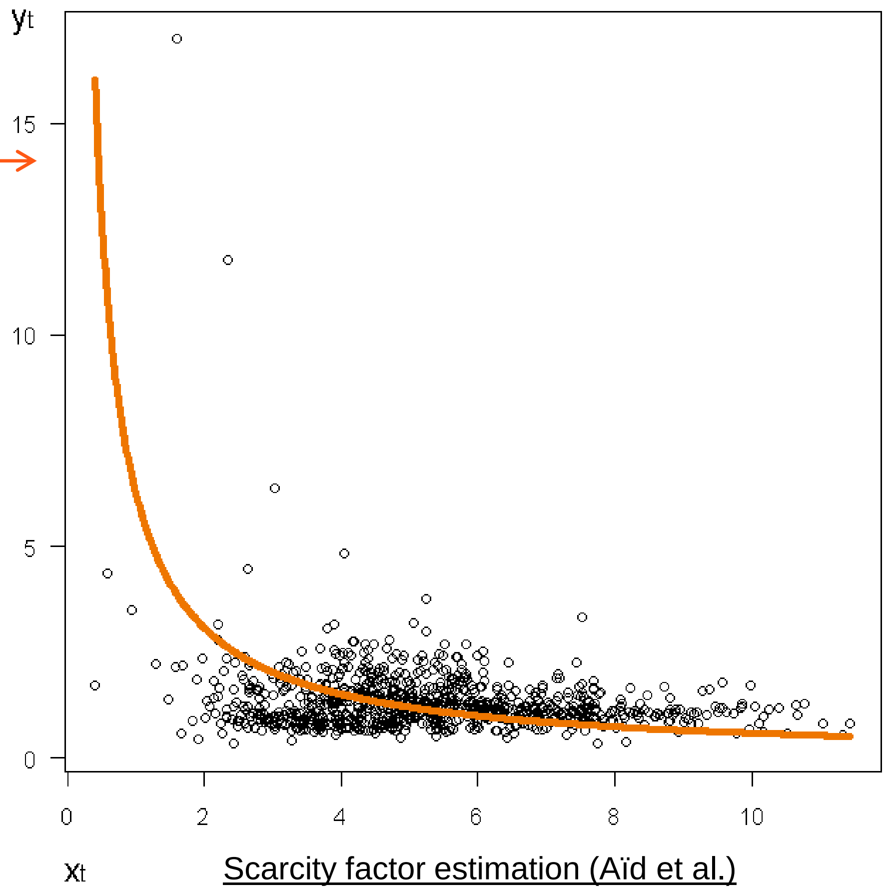
Powernext 19th hours 13/11/2006 - 30/04/2010 (Aïd et al.)

A structural model for electricity prices (Aïd et al., 2011)

The model, improved to reproduce price spikes

- Use a quantile estimation to fit the relation between $y_t := \frac{S_t}{MC_t}$ and $x_t := \bar{C}_t - D_t$
- ⇨ Estimated relation : $y_t = \frac{\gamma}{x_t^{\nu}} \quad \gamma, \nu > 0$

High deviationf of spot prices w.r.t. the marginal fuel cost →



Scarcity factor estimation (Aïd et al.)

A structural model for electricity prices (Aïd et al., 2011)

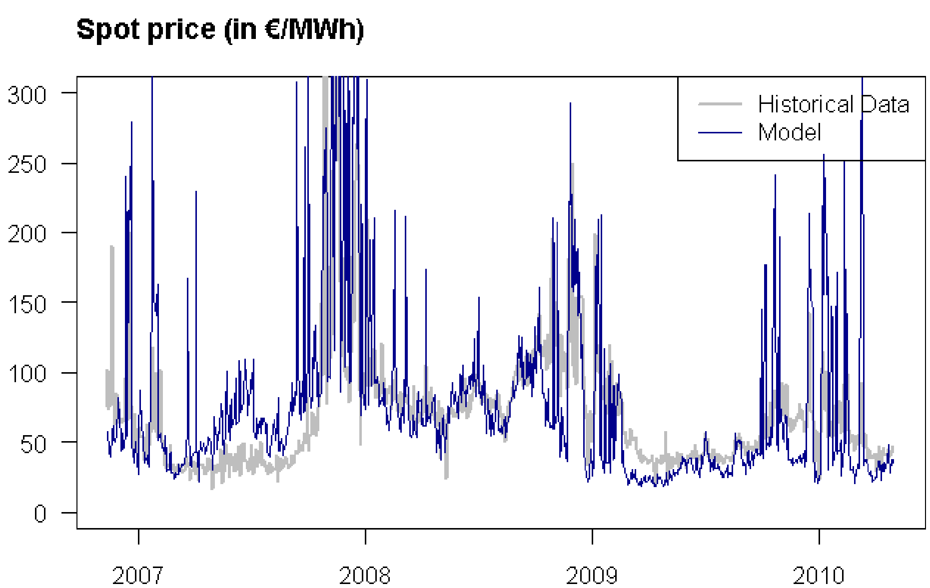
Backtesting the improved model

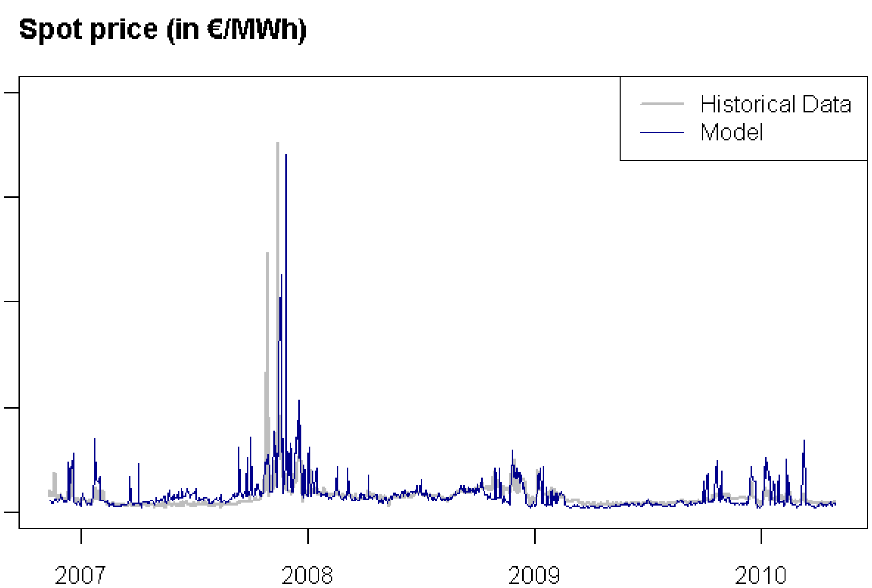
- Final modelization for electricity spot prices :

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

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

- Parameter *M* is used for matching the high cap on electricity spot prices defined on the considered power exchange (cf. technical maximal price of 3000 €/MWh).





Simulation by Aïd et al. with Powernext 19th hours data

A structural model for electricity prices (Aïd et al., 2011)

Pricing energy derivatives in this model

- In this model, forward prices can be retrieved by the no-arbitrage condition.

- Unitary forward prices are equal to :

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

  in which G^T is a conditional expectation of the scarcity function.

- This equation shows that in this model, an electricity forward is represented as a basket of fuels forwards with stochastic weights driven by electricity demand and production capacities.

- Under some assumptions, we can get quasi-analytical formulas for futures and options' prices.
- Typical assumptions assumed in Aïd et al. :
  - Fuel spot prices are independent from electricity demand and production capacities
  - Diffusion models (geometric Brownian motion) for fuels spreads $Y_t^i = h_i S_t^i - h_{i-1} S_t^{i-1}$
  - Diffusion models (deterministic seasonality + Ornstein-Uhlenbeck process) for demand and capacities

MODELLING ELECTRICITY PRICES

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- **Factorial models for energy prices (e.g. Kiesel et al., 2008)**

Forward curve modelling by factorial models

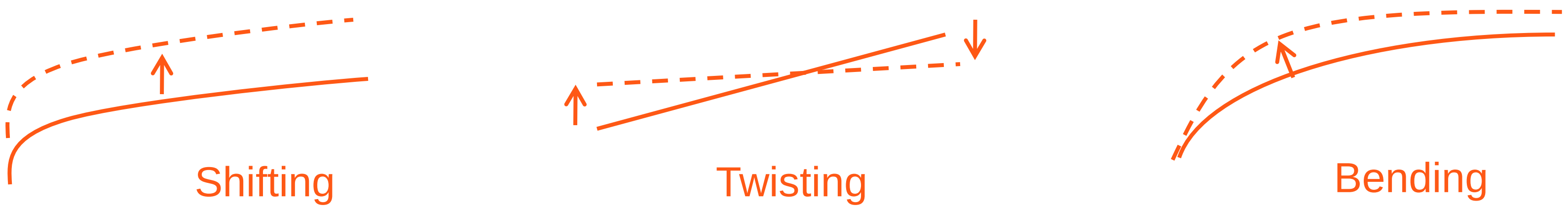
Diffusion models for the forward curve

- Factorial models are close to HJM models used for the yield curve (interest rates).

- Level-Slope-Curvature approaches
  - Based on historical futures prices…
  - Principal Component Analysis (PCA) aims at determining factors (that is principal components) in order to explain as much of the total variation of the data as possible
  - Allows to order the factors by major contribution

- A PCA shows that 95% of the forward curve dynamics can be modeled by 3 factors :

1. Level factor (or Shifting effect) : upwards or downwards movement of the forward curve
2. Slope factor (or Twisting effect) : tilting of the curve (curve extremities inversion)
3. Curvature factor (or Bending effect) : curve distortion



Forward curve modelling by factorial models

Some basics on factorial models

- Basic decomposition of the (unitary) forward price in a factorial model :

$$F(t,T) = F(t_0,T)Y(t,T)$$

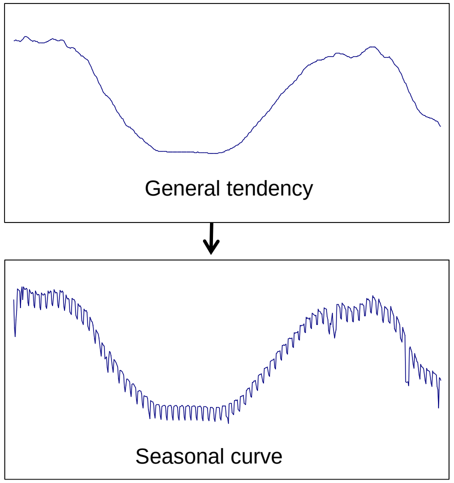
Initial forward curve

Stochastic part (diffusion term)

<u>Initial forward curve</u>

- Deterministic seasonality
- Typically an hourly curve

$$(F(t_0,T))_{T \geq t_0}$$

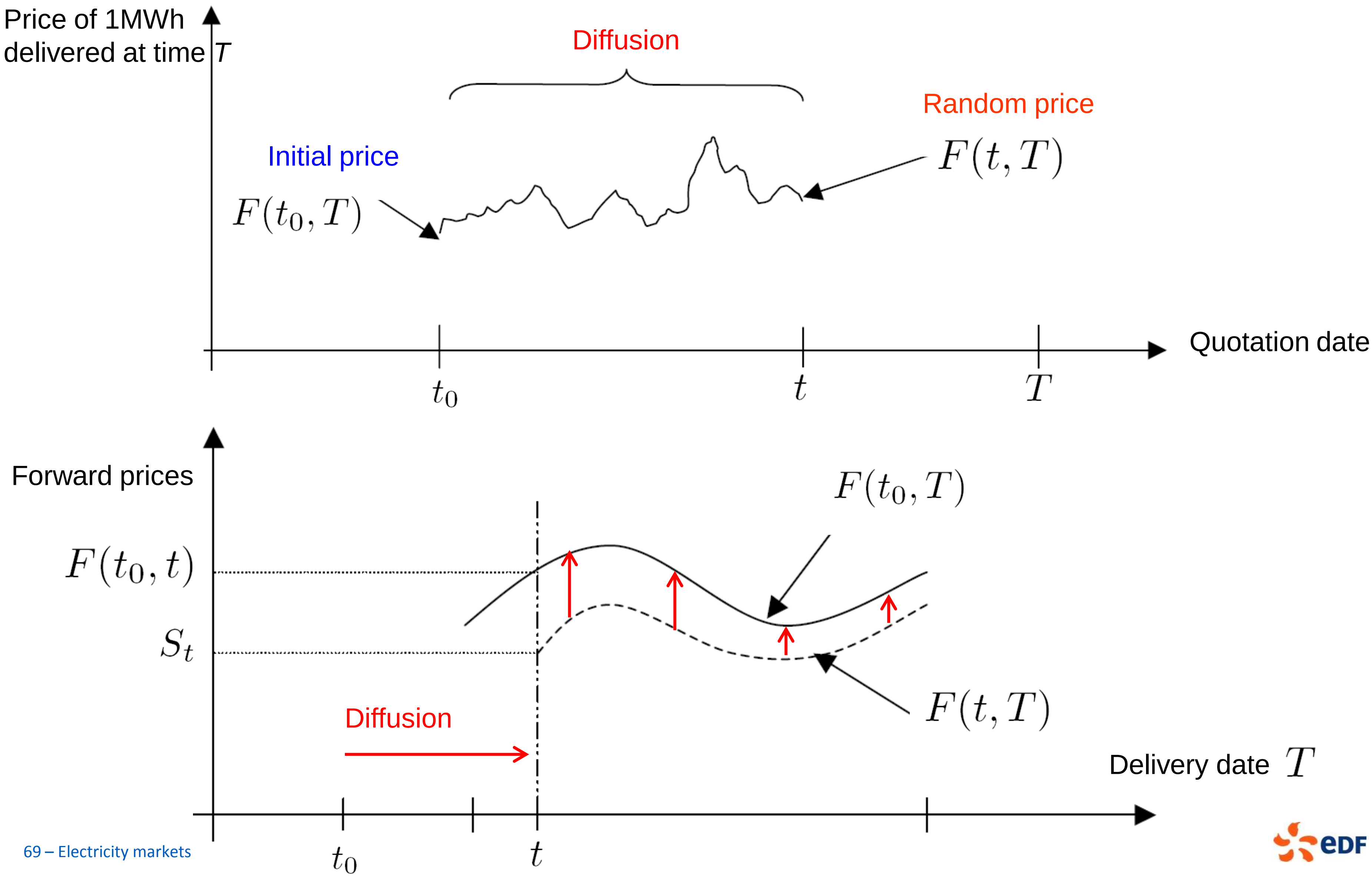


<u>Diffusion calibration</u>

- Depending on a limited nb of stoch. factors
- Typically, restriction to 2 or 3 factors
- Corresponds to fitting volatility functions
- Maturity-dependent volatility

Forward curve modelling by factorial models

Notations : t_0 = start of the diffusion, ~~t = future~~ observation date, T = start of delivery



Forward curve modelling by factorial models

Case of a constant volatility…

- One Gaussian factor : Geometric Brownian motion ⇨ This is the Black model.
- Log-normal dynamics of the prices :

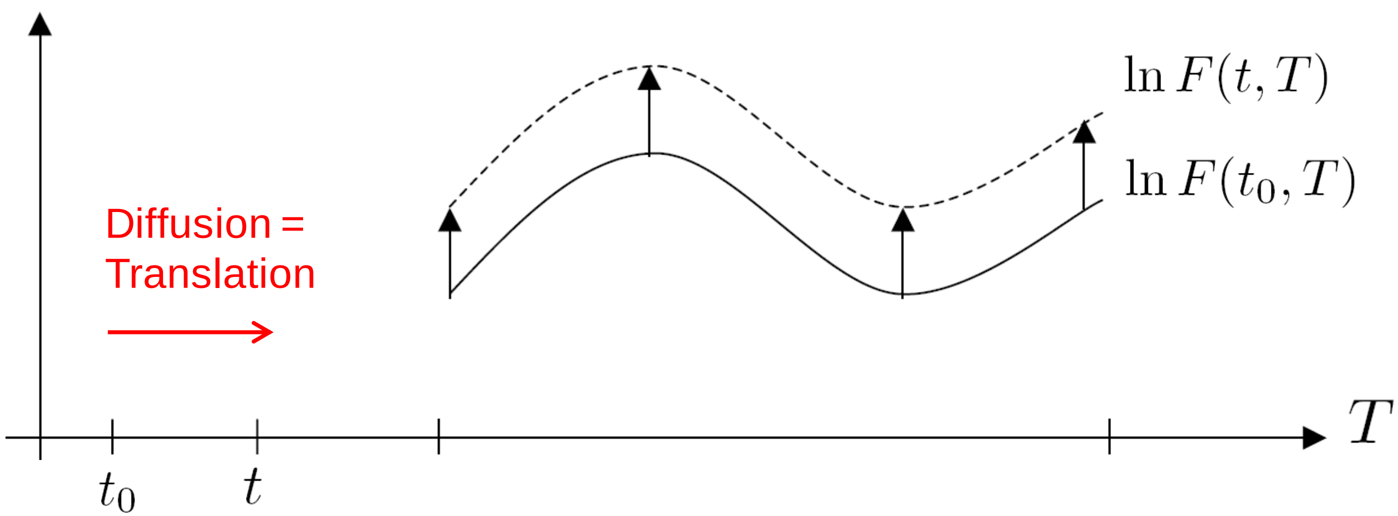
Initial price

$$\frac{dF(t,T)}{F(t,T)} = \sigma dW_t \Rightarrow F(t,T) = \boxed{F(t_0,T)}\boxed{\exp\{-\frac{1}{2}\sigma^2(t-t_0)+\sigma\left(W_t - W_{t_0}\right)\}}$$

Diffusion term

- In this case, the diffusion does not depend on the maturity.
- For the log-forward curve, the deformation consists here in a translation.

$$\ln F(t,T) = \ln F(t_0,T) - \frac{1}{2}\sigma^2(t-t_0) + \sigma^2(t-t_0)\varepsilon, \varepsilon \sim \mathcal{N}(0,1)$$



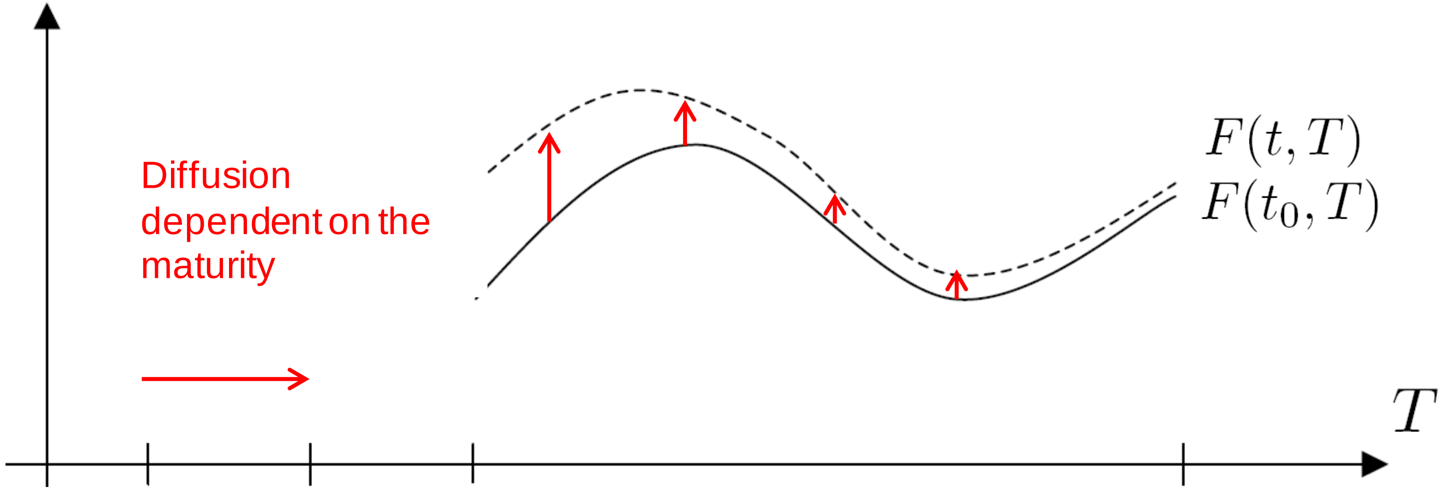
Forward curve modelling by factorial models

Case of an exponentially weighted volatility

- Model by Clewlow and Strickland : mean-reverting model with one Gaussian factor

$$\frac{dF(t,T)}{F(t,T)} = \sigma e^{-a(T-t)} dW_t \quad \begin{cases} \ln F(t,T) & = \ln F(t_0,T) - \frac{1}{2} e^{-2a(T-t)} \operatorname{var}(X_t) + e^{-a(T-t)} X_t \\ X_t & := \int_{t_0}^{t} \sigma e^{-a(t-s)} dW_s \sim \mathcal{N}\left(0, \frac{\sigma^2}{2a}\left(1 - e^{-2a(t-t_0)}\right)\right) \end{cases}$$

- Model the dependence of the volatility functions w.r.t. the maturity : the deviation of the forward curve w.r.t. the initial forward curve decreases as the maturity increases ⇨ Mean-reverting



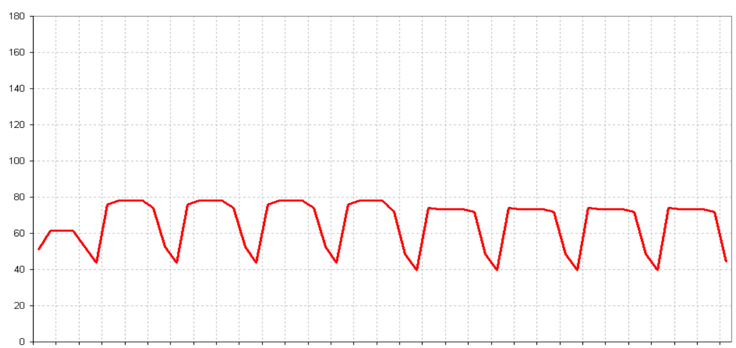
- Model by Kiesel et al. (2008) : allows to better represent the mooves of the forward curve
  - 2 correlated Gaussian factors
  - Short term : exponentially weighted volatility
  - Long term : constant volatility

Forward curve modelling by factorial models

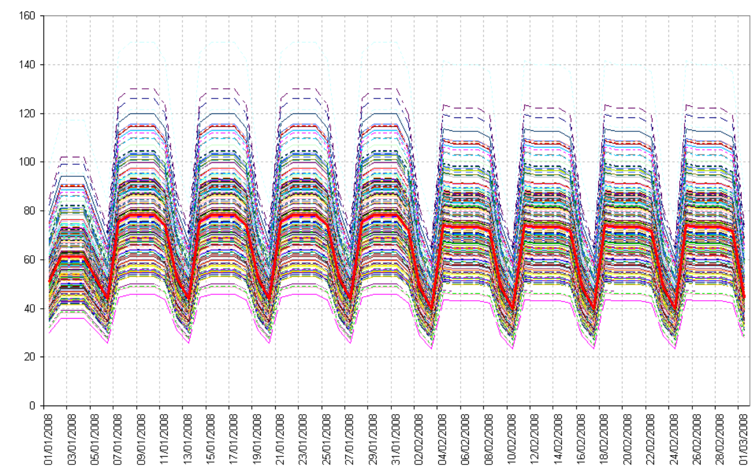
Illustration with a one factor model

- Diffusion of the forward curve with a single and constant volatility
  - The initial forward curve incorporates the seasonality effect.
  - The forward curve is shifted by a same diffusion factor, whatever the maturity.

- Example with t_0 = 01/12, t = 15/12, forward maturities from 01/01/2011 to 01/03/2011



Diffusion



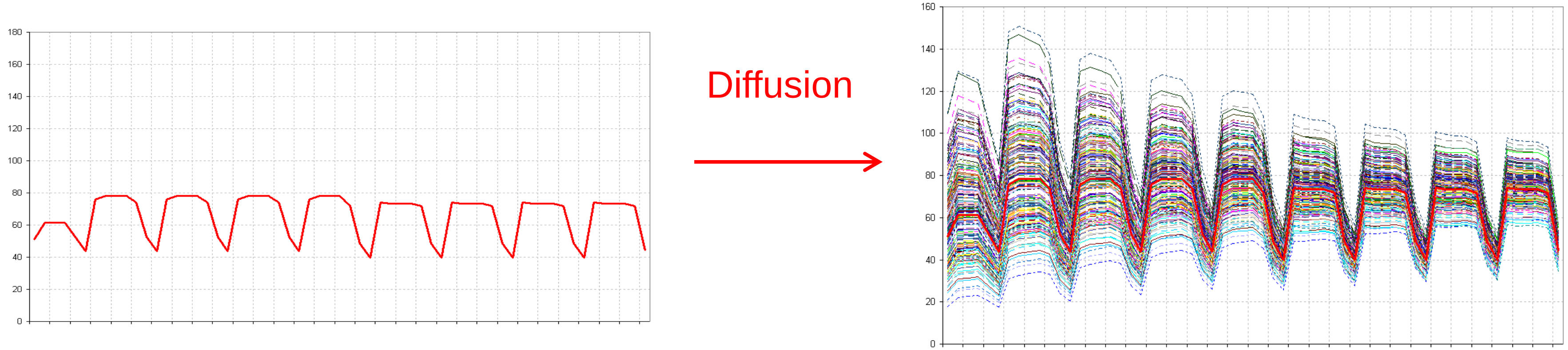
Parameters: $sigma_S$ = 0%, a = 0, $sigma_L$ = 10%, rho = 0

Forward curve modelling by factorial models

Illustration with a two factors model

- Diffusion of the forward curve with a constant LT volatility & weighted ST volatility
  - The impact of the long term volatility is constant, whatever the maturity.
  - The short term volatility is weighted by a mean-reverting coefficient. It has a decreasing impact : high at short term, zero at long term.

- Example with t_0 = 01/12, t = 15/12, forward maturities from 01/01/2011 to 01/03/2011



Parameters: sigma_S = 100%, a = 10, sigma_L = 10%, rho = 0