Stochastic models for electricity markets
Lecture 01 - Introduction to power systems

Frontiers in Stochastic Modelling for Finance
Winter School - Università degli Studi di Padova

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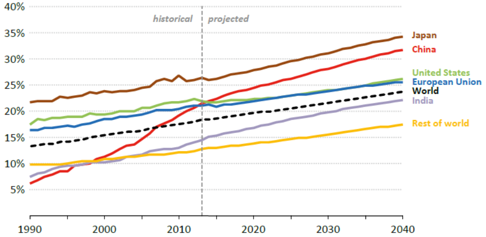
The electricity in the economy

According to the International Energy Agency in her World Energy Outlook 2015 edition

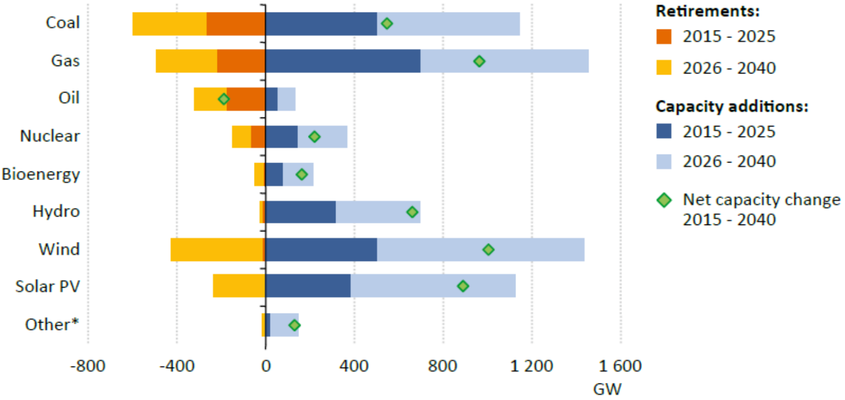
- world electricity demand should grow on average by 2.3% per year between 2013 to 2040, from 20,150 TWh to 34,500 TWh.
- Most of the growth will come from non-OECD countries.
- The increase of electricity demand in China between 2000 and 2040 is almost equivalent to the total demand of all OECD countries in 2000.

Figure 8.2 ▷ **Share of electricity in total final consumption by region in the New Policies Scenario**



An increasing share of renewables in world energy mix

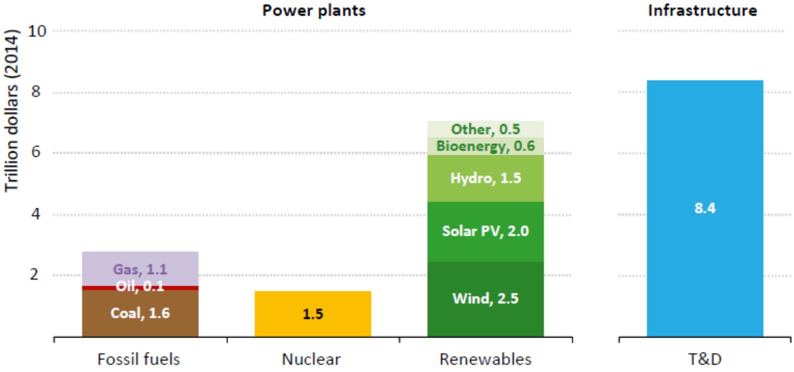
Figure 8.5 ▷ Global power generation capacity retirements and additions in the New Policies Scenario, 2015-2040



* Other includes geothermal, concentrating solar power and marine.

A huge amount of capital investment required

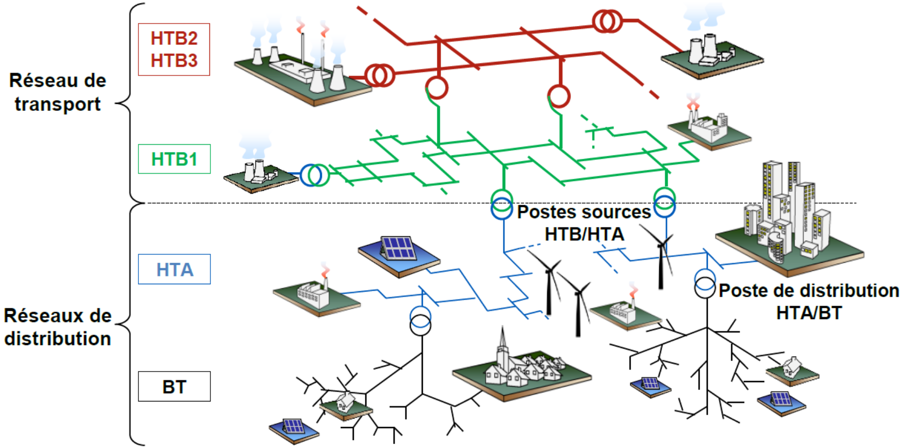
Figure 8.8 ▷ Global cumulative investment in the power sector by type in the New Policies Scenario, 2015-2040



Units

- Tension: Volt (V), measure electricity concentration. Compare to pressure in water flow.
- Intensity: Ampere (A), measures the debit of electricity.
- Power: Watt (W), measure the quantity of electricity transmitted instantaneously.Usualy, power or capacity is measured in kW (1000 W), MW (1000 kW), GW (1000 MW).
- Energy: Watt $\times \Delta t$: measure the quantity of energy produced or consumed during the interval of time Δt. Usualy, energy is measured in kWh (1000 Wh), MWh (1000 kWh), GWh (1000 MWh) and TWh (1000 GWh).

Production - Transmission - Distribution - Consumption

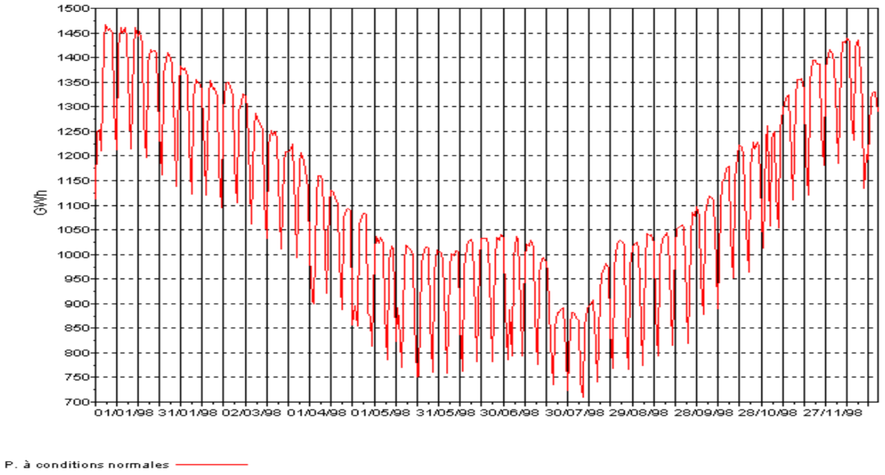


Electricity consumption

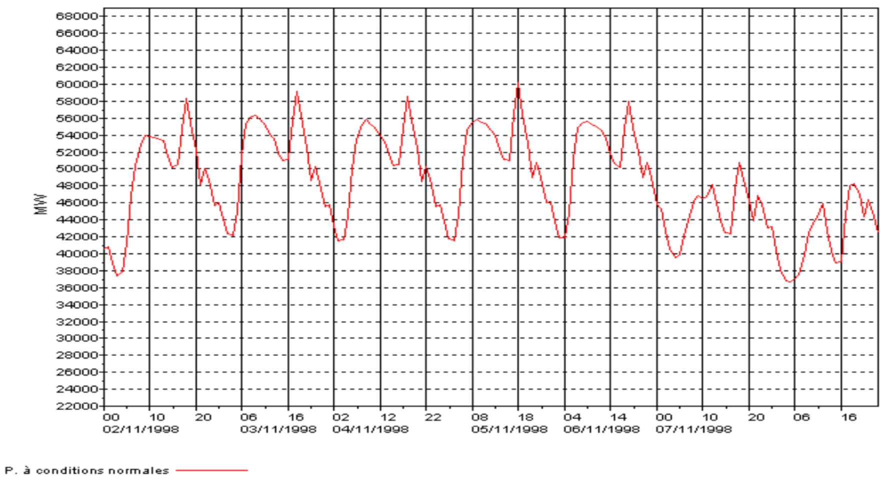
Features

- follows every aspects economic activity (UK tea time, Lady Di funerals, mi-temps final cup,...)
- Exhibits several seasonality patterns: daily, weekly, annualy.
- Sensitive to climate conditions

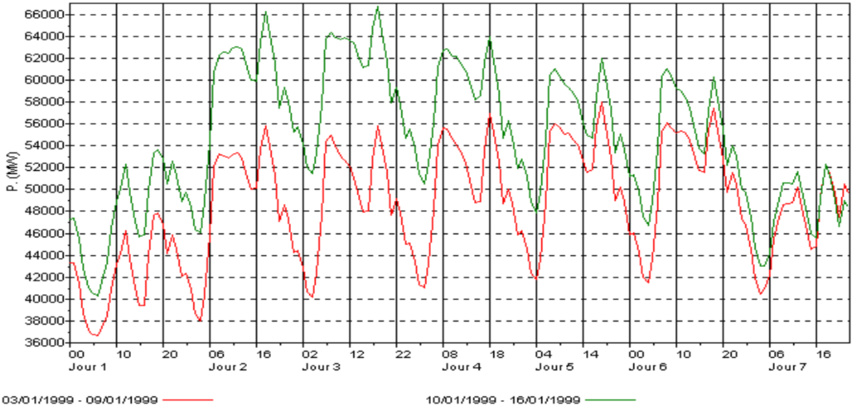
Electricity consumption annual seasonality



Electricity consumption weekly and daily seasonality



Electricity consumption sensitivy to temperature



Electricity consumption

Factor influencing electricity consumption on short-term

- Temperature. France: temperature gradient to cold temperature ≈ 1 GW per degree below a certain threshold.
- Nebulosity. Measured in octa ($1/8$ of the sky).
- Calendar. Ruptures (august, Christmas), special days.

Factor influencing electricity consumption on long-term

- Usages. Electronic devices. Cell phones consume more in France than refrigerators.
- Industrial activity.
- Economic growth.

Main electricity features

A local commodity

- Electricity is non-storable.
- Electricity transmission satisfies specific laws.

Storability

Comments

- Difficult to store large volume of electricity
- Generally, subscribed capacity consumption exceeds installed capacity.
- Example in France: $\approx$ 250 GW of subscribed consumption capacity vs 128 GW installed capacity.
- Many technologies to store power (batteries, air compression).
- Present best way to store large volume of power: hydro-reservoir.
- Limited by pumping rate ≈ 0.74.

Consequences

On short-term (next hours)

- A too long excess of demand compared to production may first resolves in a decrease of frequency,
- ... and if not properly corrected, may lead to dramatic blackouts.
    - July 30th, 2012: India, 670 millions people.
    - August 13th, 2003: Ontario and North America, 50 millions people.
    - November 4th, 2006: UCTE, 15 millions people.
- ⇒ Minute by minute real-time assessment of the equilibrium between consumption and production.
- The Transmission System Operator (TSO) is responsible for the electric system security and reliability.
- He manages the uncertainties on demand and production by a serie of operating reserves.

Question

Value of Loss of Load or energy-unserved

- Give an estimate of the cost of a national black-out in France and deduce and estimate of the value of the energy un-served in €/MWh.

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- Annual electricity gross consumption ≈ 450 TWh.
- Annual GDP 2,200 billions €.
- Value of 1 MWh $\approx \frac{2.2 \cdot 10^{12}}{450 \cdot 10^{6}} \approx$ 4,900 €/MWh

Reserves

Operating reserves

- An operating reserve is a generation that can be mobilised with a short-term notification.
- Operating reserves vary by response time. Three kinds of reserve:
  - primary reserve: response time $\leq$ 20s. Automatic devices. $\approx$ 500 MW in France.
  - secondary reserve: response time $\leq$ 3mn. Automatic. $\approx$ 600 MW in France.
  - tertiary reserve: response time $\leq$ 15mn. Manuel. $\approx$ 1,500 MW in France.
- The volume of each reserve may vary depending on the nature of the uncertainties on a particular electric system.
- They tend to grow in $\sqrt{T}$, where T is the time to mobilisation.

Consequences

On mid-term basis

- Reliability assessment analysis: is there enough capacity to fullfill demand in the next months within a certain default probability?
- Means: changing planned outtage schedule, buy on the market, demand-side management policy
- Extreme way: load shedding.

On long-term basis

- Build new capacity to allow enough excess capacity.
- Demand-side management policy.
- Sound tarification.

Transmission

Comments

- The transmission of electricity satisfies Kirchhoff's laws.
- The intensity at each node should be zero and the tension in each loop should be also zero.

Consequences

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

Interference between commercial flows and physical flows

Situation

A power producer G1 has client in node C whose consumption is 180 MW, while a power producer G2 has also a client in node C whose consumption is 90 MW. Each producer holds enough generation capacity and no production cost advantage.

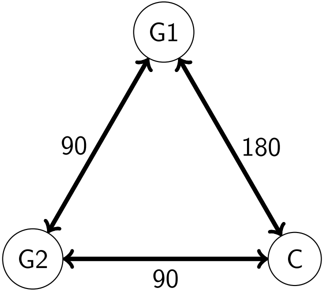


Figure: Network physical capacity limits.

Interference between commercial flows and physical flows

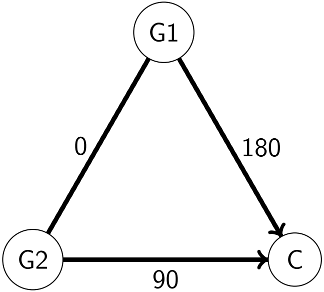


Figure: Desired commercial flows.

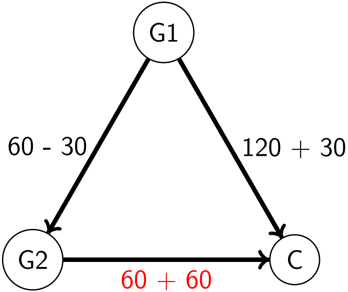


Figure: Physical flows. Congestion

Transmission consequences on trading

Consequences

- ⇒ Cross-border trading opportunities.
- Transfert capacities available for trading between countries need some generation hypothesis.
- In Europe, the available net transfert capacity (NTC) are managed and published by the ENTSO (European Network System Operator)
- Publicly available in her transparency platform (www.entso.net).
- New method for interconnexion allocation: flow-based.

A large panel of technologies to produce electricity

Main generation technologies

- Gas: Combined Cycle, gas turbine
- Coal: Conventional, Advanced, Gasification
- Nuclear: Light Water, Pressurised Water, Boiling Water, Gen3+ (EPR)
- Hydroelectricity: run of the river, or gravitational
- Diesel
- Wind: onshore or offshore
- Photovoltaic: distributed or centralized, solar to electricity or heat concentration
- Biomass
- Marine (getting energy from the tides or the waves)

Cost structure

International Energy Agency, Projected Costs of Generating Electricity – 2005 Edition.

	Investment	O&M	TTB	Lifetime	Load Factor	Efficiency
Gas	400-800	20-40	1-2	20-30	-	0.5
Coal	1000-1500	30-60	4-6	40	-	0.3
Nuclear	1000-2500	45-100	5-9	40	85	0.3
Wind onshore	1000-2000	15-30	1	20-40	15-35	0.3
Wind offshore	1500-2500	40-60	1-2	20-40	35-45	-
Solar PV	2700-10000	10-50	1-3	20-40	9-25	-

Investment cost in USD05/KWe; O&M, operation and maintenance cost in USD05/KWe/year; Contruction time in years; Load factor in percentage.

Heat rate

heat rate

- Fuel price p_f in €/unit ; energy content e_f of the fuel in MWh-heat/unit ; power plant efficiency ρ in MWhe/MWh-heat
- Fuel cost of the power plant $= p_f \times \underbrace{\frac{1}{e_f \times \rho}}_{\text{heat-rate}}$

From fuel price to fuel cost - example of a coal fired plant

- Coal price is $P_c = 40$ in USD/tonne
- The energy content of 1 metric tonne of coal is 29.3 GJ.
- The efficiency of my current coal fired plant in my garden is 0.32
- What is the fuel cost of my coal fired plant in €/MWh?
- Data: 1GJ $=$ 0.28 MWh-heat ; change USD/EURO 0.915.

Heat rate — answer

From fuel price to fuel cost - example of a coal fired plant

- $P_c = 40 \times 0.915$ €/tonne $= 36.6$ €/tonne
- 29.3 GJ $= 0.28 \times 29.3$ MWh $= 8.2$ MWh.
- Fuel cost $= \frac{36.6}{0.32 \times 8.2} = 36.6 \times 0.38 = 14$ €/MWh.

Technical constraints

Order of magnitude for dynamical constraints of thermal generation plant - source: author

	Startup cost kUSD	Pmin MWe	MST hour	MRT hour	RC MWe/h	MNS
Gas	0		38		∞	-
Coal	50	500	4-8	8	200	-
Oil	50	300	2-6	6-8	200	-
Nuclear	-	300	24	72	∞	30-40

Pmin: minimun technical power for a 1000 MW installed capacity plant; MST: minimum stoping time; MRT: minimun running time; RC: ramping capacity; MNS: maximum number of start-up and shut-down per year.

More data con be found in chapter 9 of *Expansion Planning Electricity Generating System*, TRS 241 from NEA, 1984.

Unit commitment

Example

- For the next hour, the demand is equal to 290 MW.
- No reserve constraint. No production uncertainty. No dynamic constraints.
- Available plants with their cost structure

	Investment cost	O&M cost	Fuel cost	Capacity
Plant A	1000	50	50	100
Plant B	1500	30	20	100
Plant C	2500	100	0	100
Plant D	500	5	80	100
Plant E	2500	60	10	100

- You have to satisfy the demand. What plants do you choose?

Unit commitment

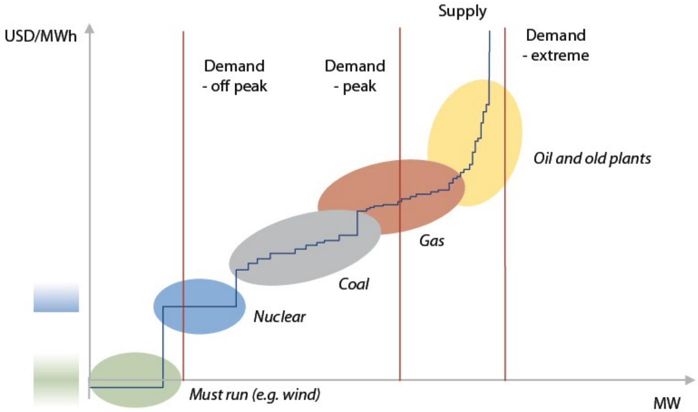
Example

- Investment cost and operating cost have no effect on the scheduling decision.
- Plants are choosen according to their fuel cost.
- Merit order $= C, E, B, A, D$.
- Generation plan $= \{C = 100, E = 100, B = 90\}$.

Remark

- Most expensive plant running is B with fuel cost 20 €/MWh.
- Marginal cost of the system = cost to satisfy one more MWh of demand = 20 €/MWh.

Generation technologies merit order



Effect of a constraint of reserve

Example

- For the next hour, the demand is equal to 290 MW.
- No production uncertainty. No dynamic constraints. But there is a reserve constraint of 30 MW and plants have a minimum production constraint.
- Available plants with their cost structure

	Fuel cost	Capacity	Min Production
Plant A	50	100	20
Plant B	20	100	20
Plant C	0	100	20
Plant D	80	100	20
Plant E	10	100	20

- You have to satisfy the demand and the reserve constraint. What plants do you choose?
- What is the marginal cost of the system?

Effect of a constraint of reserve

Scheduling

- Minimun production constraint compels to start plant A.
- Least cost choice is to set plant A at minimun level, 20 MW.
- Generation plan $= \{C = 100, E = 100, B = 70, A = 20\}$.

Remark

- Most expensive plant running is now A with fuel cost 50 €/MWh.
- Marginal cost of the system = cost to satisfy one more MWh of demand = 20 €/MWh.

Effect of a dynamic constraint

Example

- For the next 3 hours, the demand is equal to be $D_1 = 50$, $D_2 = 19$, $D_3 = 50$. You have to satisfy the demands.
- No production uncertainty or reserve constraint. But now, there is a fixed start-up cost and a minimum production constraint.
- We have two power plants:

	Fuel cost	Capacity	Min Production	Start-up cost
Plant B	10	100	20	1.000
Plant C	20	100	0	0

Effect of a dynamic constraint

Questions

- What plants do you choose?
- What is the marginal cost of the system at time 2?

Scheduling

- Demand is not high enough at time two to start plant B.
- Generation plan is now:
  - Time 1: $\{C = 50\}$.
  - Time 2: $\{C = 19\}$.
  - Time 3: $\{C = 50\}$.
- Total Generation cost = 2.380 €.

Effect of a dynamic constraint

Remark

- Increasing demand by 1 MW at time 2 would allow to start plan B.
- New optimal scheduling would be:
  - Time 1: $\{C = 0, B = 50\}$.
  - Time 2: $\{C = 0, B = 19\}$.
  - Time 3: $\{C = 0, B = 50\}$.
- With total generation cost $= 2.200$ €.
- Increasing demand leads to a decrease of the cost
- Marginal cost at time 2 is negative.
- You should be ready to pay up to 180 €for a demand increase at time 2.

The case of water

The value of stored water

- Releasing the water stored in dams has no cost.
- Nevertheless, the fact that there is a limited amount of water gives it a value (option value, usage value...)
- It should be used at the best possible moments, i.e. when it produces the maximun of economony of the generation cost.
- Optimal scheduling of water reservoir is performed using dynamic programming.
- Close connection to the optionality value of American options.

Conclusion

- Economic dispatch relies on a small set of concepts (merit order, marginal cost, opportunity or option value)
- But, it requires optimisation models to compute the generation plan in realistic cases.