MIXOPTIM : a tool for the evaluation and the optimisation of the electrical mix in a territory

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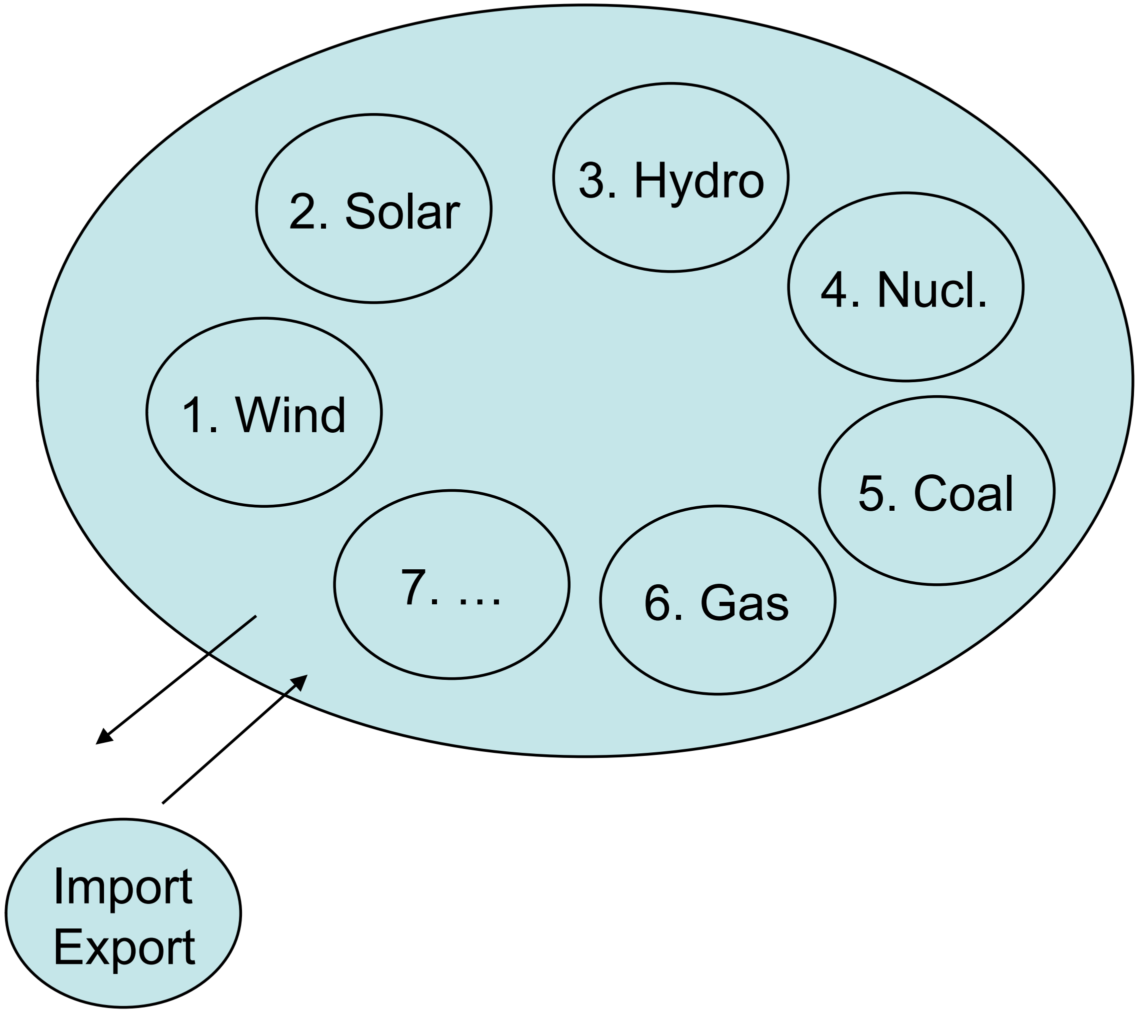
Sources and territory



Installed power

(α1, α2, ...αi, …).

Power effectively produced at time t

(β1, β2, …βi, …)

How much does it cost to satisfy the electrical demand?

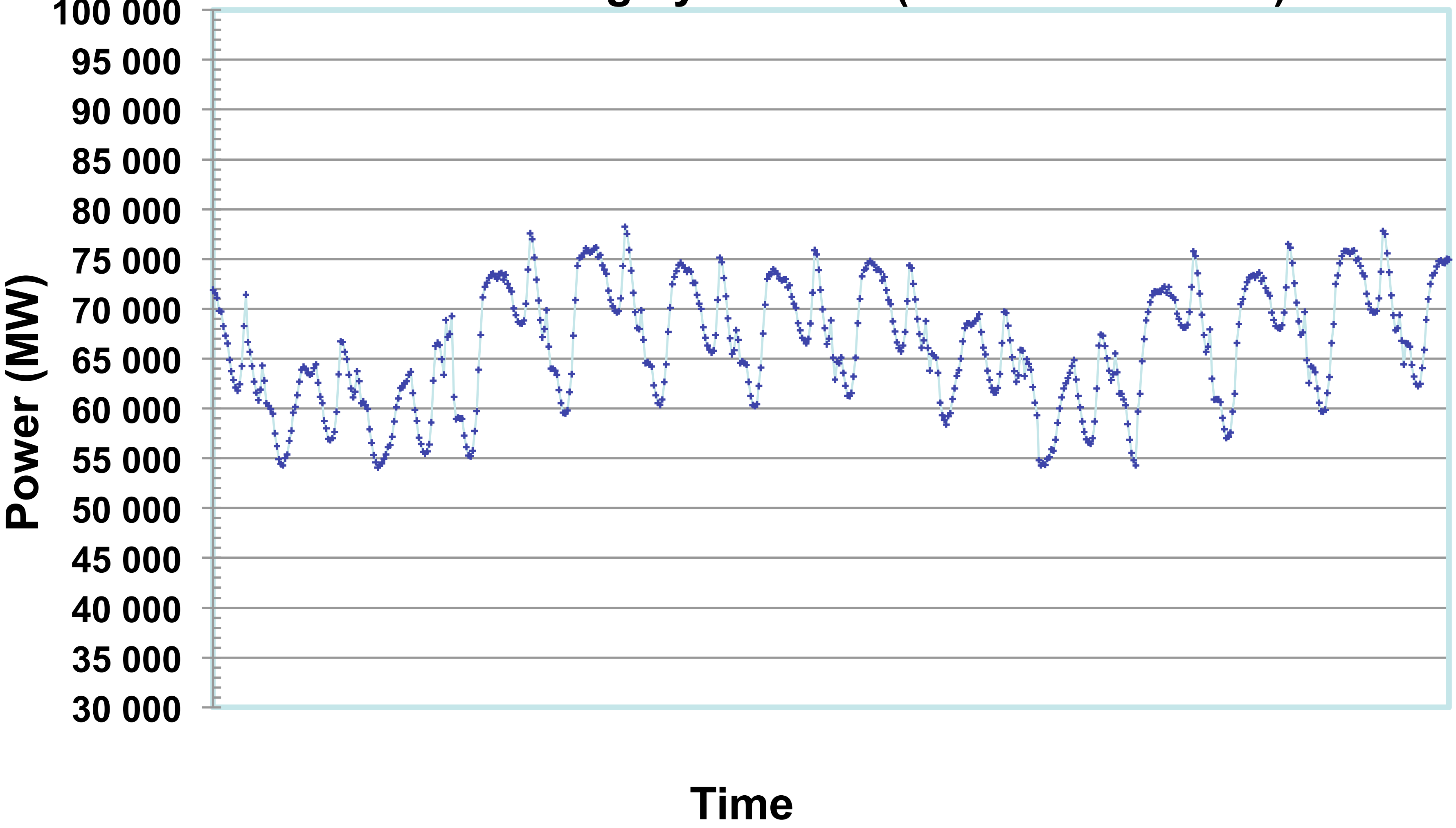
- Demand is fluctuating
- Availability of sources is fluctuating
- Ranking order for the sources

$$D(t) = \sum_i \beta_i \quad ; \quad \beta_i(t) = x_i(t).\alpha_i$$

- Many conditional probabilities
- Difficult to determine average values
- System is non linear

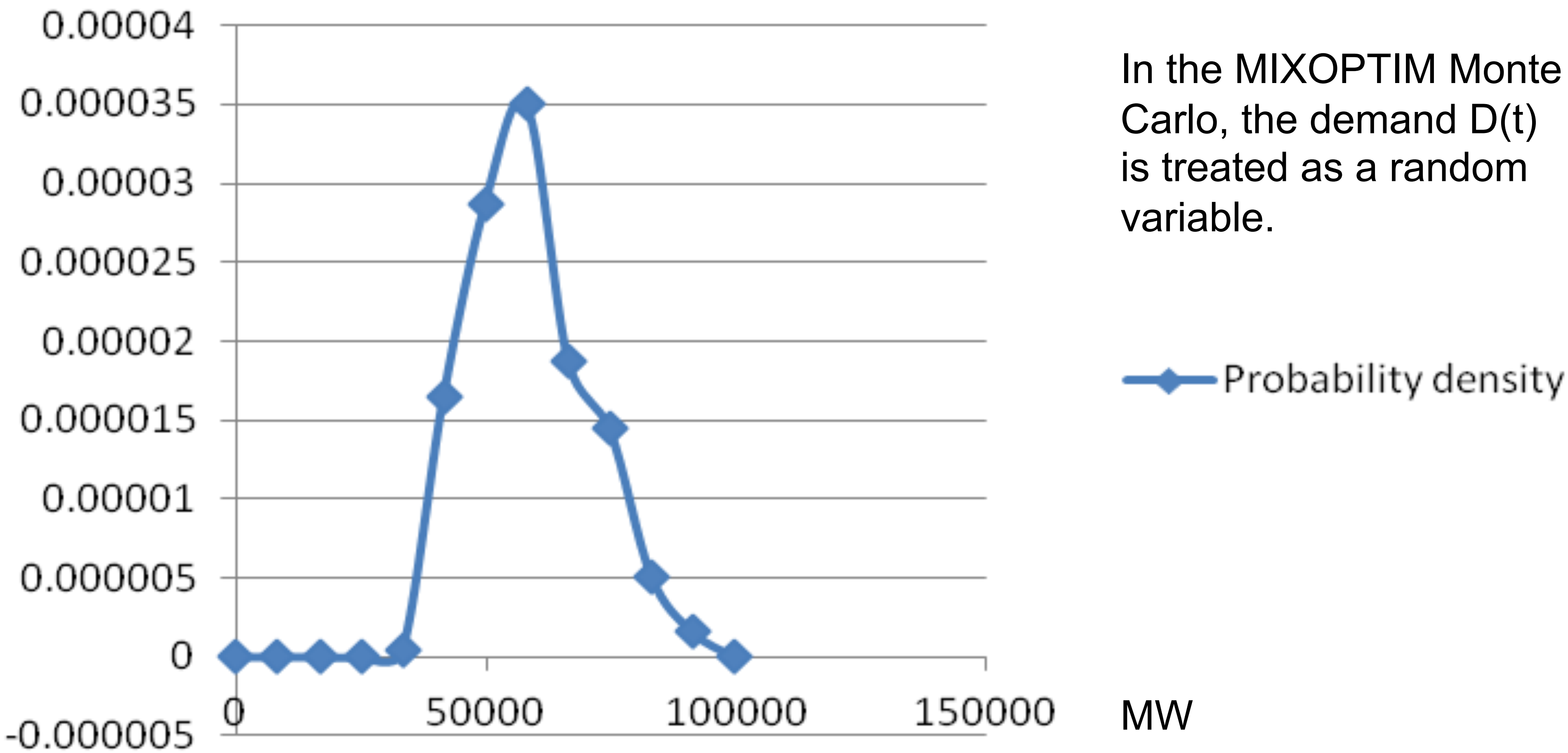
- Monte-Carlo simulation

Demand is highly variable (RTE France 2012)



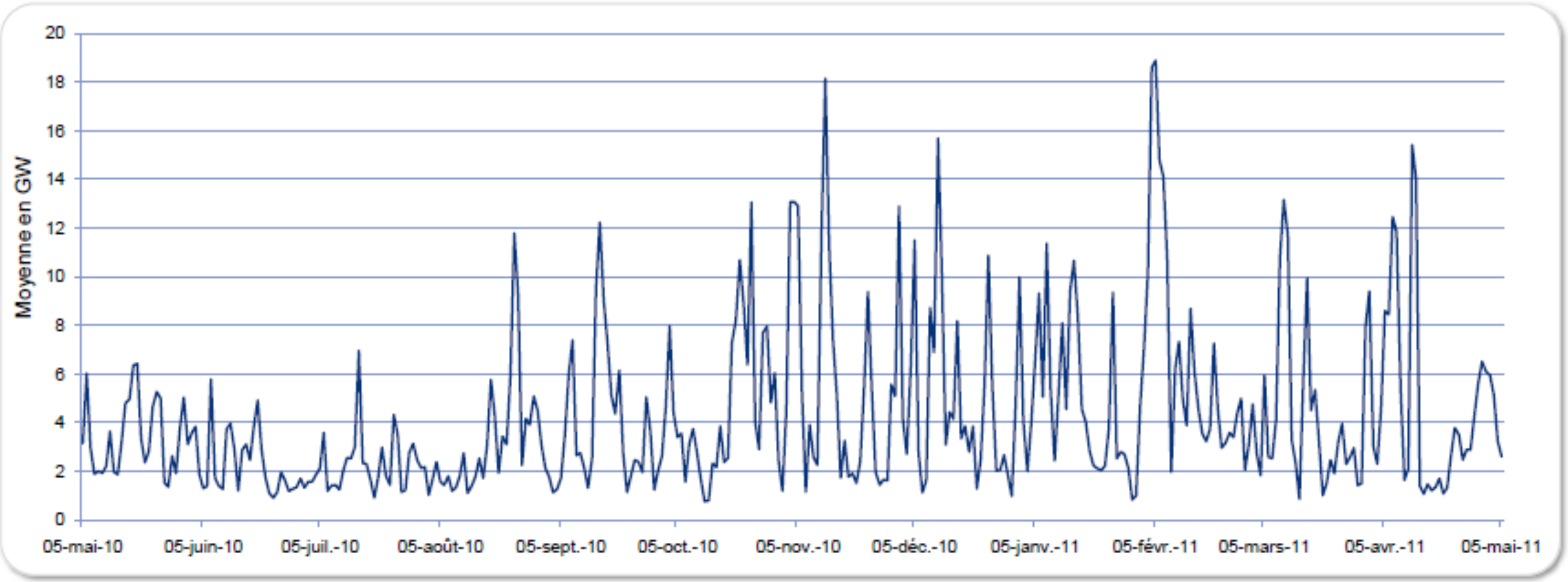
Daily, weekly, yearly variations + weather + football matches,+…

Probability density of the demand



In the MIXOPTIM Monte Carlo, the demand D(t) is treated as a random variable.

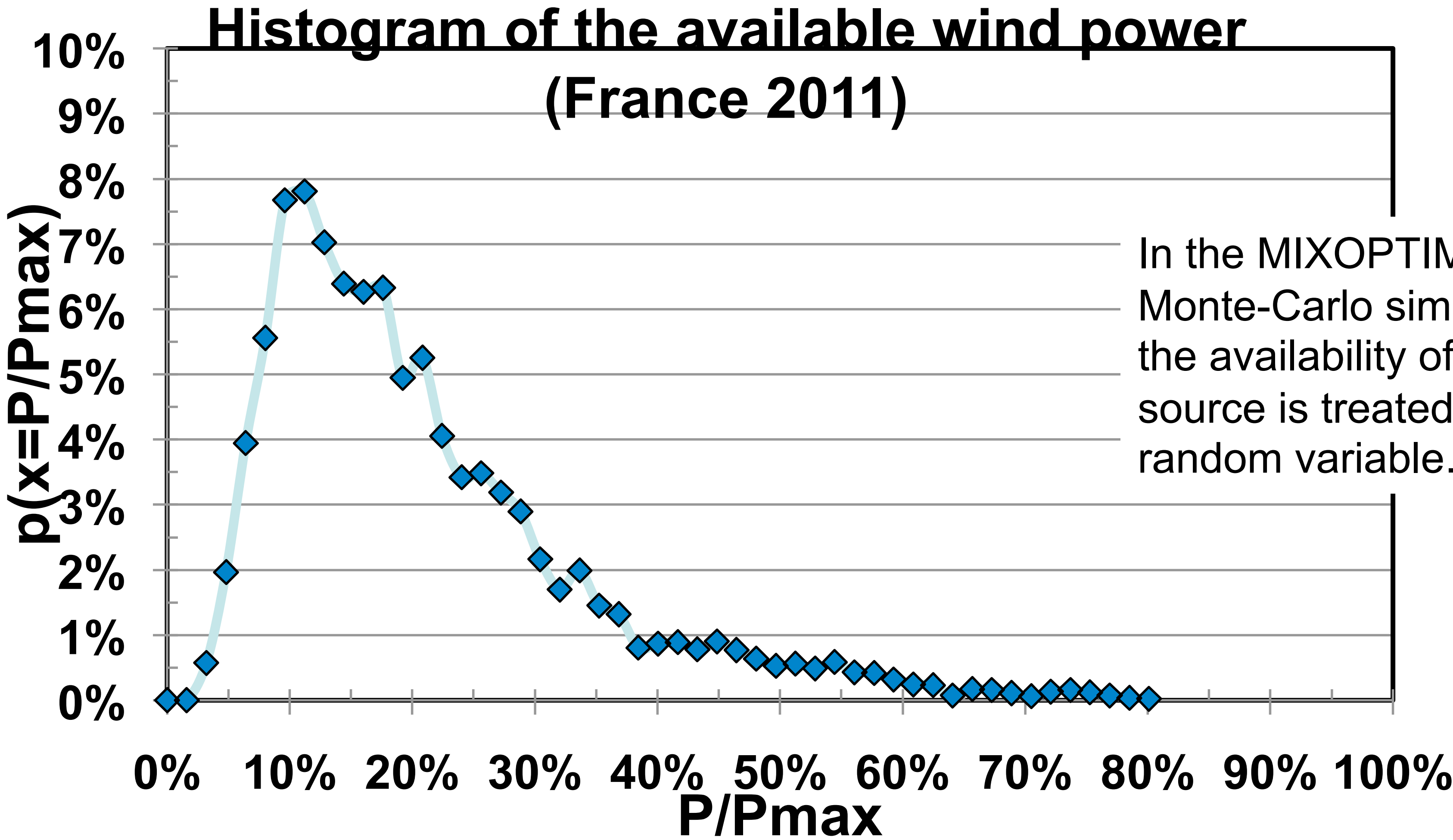
Wind power



Germany 2010-2011

Intermittent sources are well named!

A probability law for the available fraction of the fleet



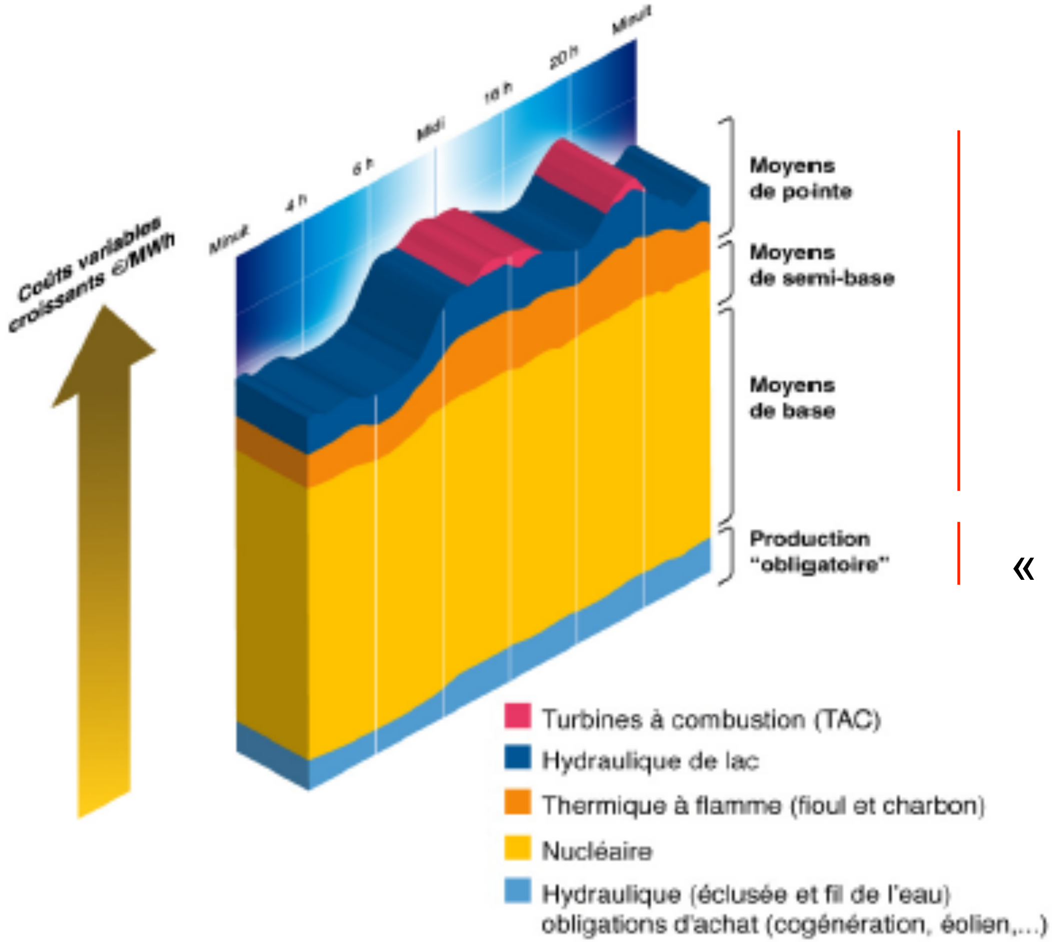
In the MIXOPTIM Monte-Carlo simulation, the availability of each source is treated as a random variable.

Réf : Flocard-Pervès, comm.part.

Ranking of the sources

Sources are solicited with a determined priority order

Exemple d'une journée de forte consommation en hiver



« Controllable »,
or «Dispatchable »

« Mandatory », or « Fatal »

Costs for each source

$$C_i = F_i.\alpha_i + M_i.\beta_i$$

€/h

Fixed cost (investment amortization, …incl. quote part of the grid cost)(€.MW^{-1}.h^{-1})

Installed power (MW)

Variable cost (fuel, …)(€/MWh)

Produced power (MW)

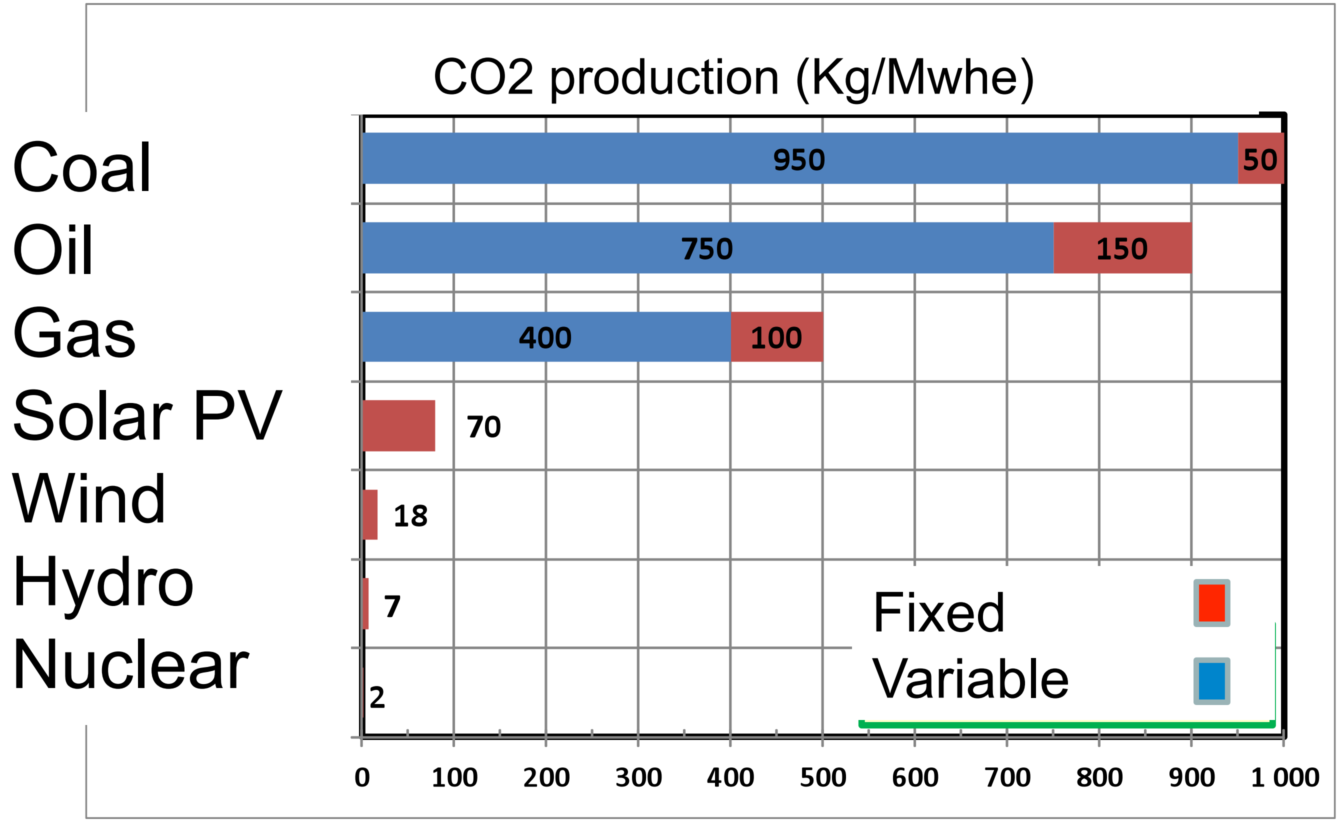
Costs for each source (€/MWh)

	Wind	Solar	Hydro	Hydraulic STEP	Gen II LWR	Gen III LWR	Coal	Other renewables	Gas	Peak power sources (gas turbines)
M	1	1	1	1	10	12	51	54	67	194
F	22	45	35	36	12	53	20	50	13	16

Important to distinguish nuclear Gen II and Gen III, because cost structure is very different. If both are mixed, the interest of keeping Gen II nuclear as long as possible does not appear.

Table 1: The cost of the energy sources (€/MWhe)
Ref : "Projected costs of generating electricity", report OECD/NEA 2010

CO2



Ref. H. Safa, CEA.

Same formalism fixed-variable for CO2 production.

Power imports and exports

- Import and Export are treated like other sources: they contribute negatively and positively to the power and financial balance of the territory. I/E cost is determined by a stock exchange mechanism (MIXOPTIM considers this variable cost as a random variable).
- Availability of this source is limited by the interconnexion capacity of the territory.

The load factor of the sources

$$Kp_i = \frac{\overline{\beta_i}}{\alpha_i} = \overline{x_i}$$

MIXOPTIM **calculates** the load factor of the sources (contrary to most other mix evaluation tools, which **assume** Kp values).

MIXOPTIM calculates three indicators

- Economy

$$P_{economy} = \frac{\overline{C}}{\overline{D}}$$

€/MWh

- Climatic

$$P_{CO2} = \frac{CO2}{\overline{D}}$$

tCO2/MWh

- Security of supply

$$P_{\sup ply1} = \frac{IMPORT}{\overline{D}}$$

$$P_{\sup ply2} = FCUT$$

MIXOPTIM : MC method

- Determine randomly D(t) and Xi(t) (available fraction of sources)
- Deduce the xi(t) (used fraction of s ources)
- Deduce C, CO2, IMPORTC, CUT

→N Monte-Carlo tests

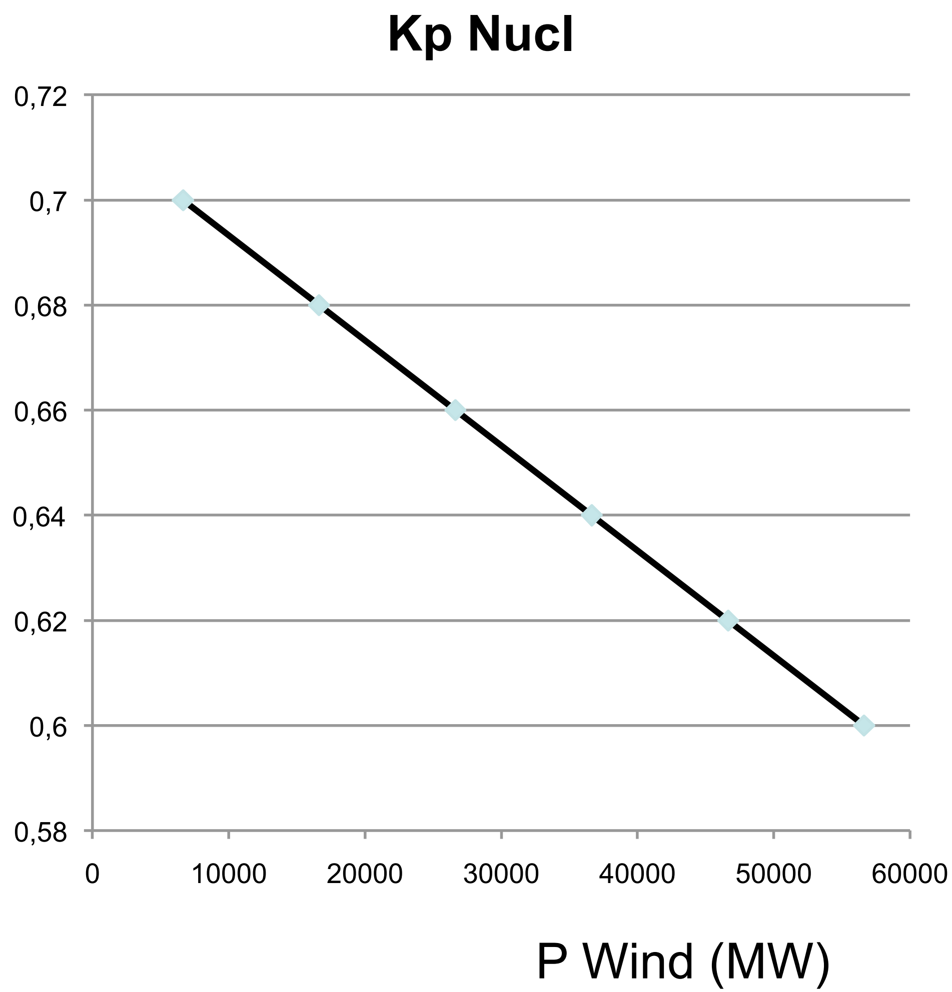
→Average

→Indicators

Validation of MIXOPTIM on the 2012 French mix

	Average demand (MW)	Cost (€/ MWh)	CO2 (Kg/ MWh)	P imported (MW)	P exported (MW)
Observed (2011)	57 740	44.7	56.4	1 630	7 970
Calculated	54720	46.1	60.6	660	11950

Evolution of the load factors Kp as a function of the part of variable renewable energy in the mix



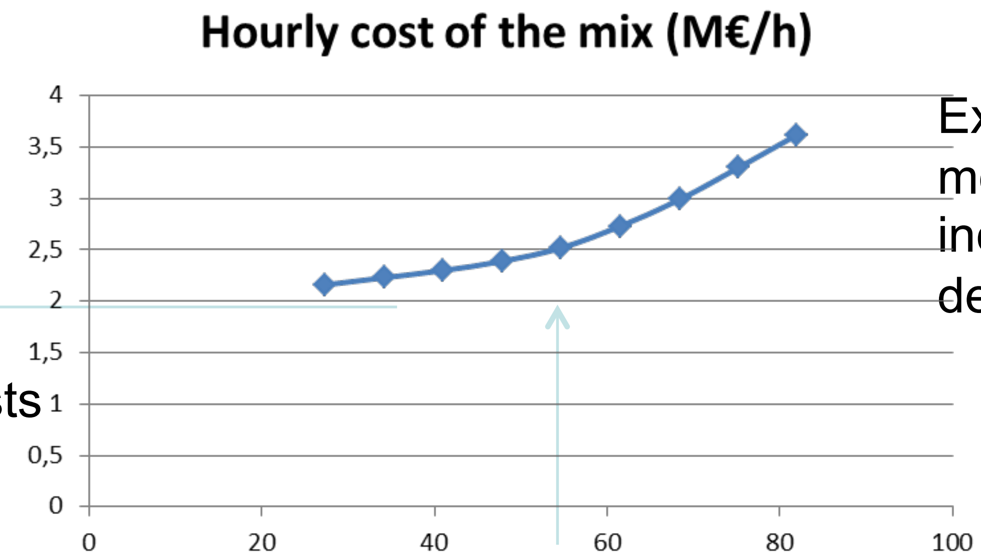
Mutual influence between sources

Validation of MIXOPTIM: Load factors

Kp calculated and observed for the French mix 2011.

	Wind	Sol	Coal	Gas	Nucl
Observed (2011)	0.21	0.11	0.19	0.40	0.79
Calculated	0.21	0.12	0.17	0.30	0.70

Hourly cost of the mix vs average demand



Expensive sources are more solicited with increasing values of the demand

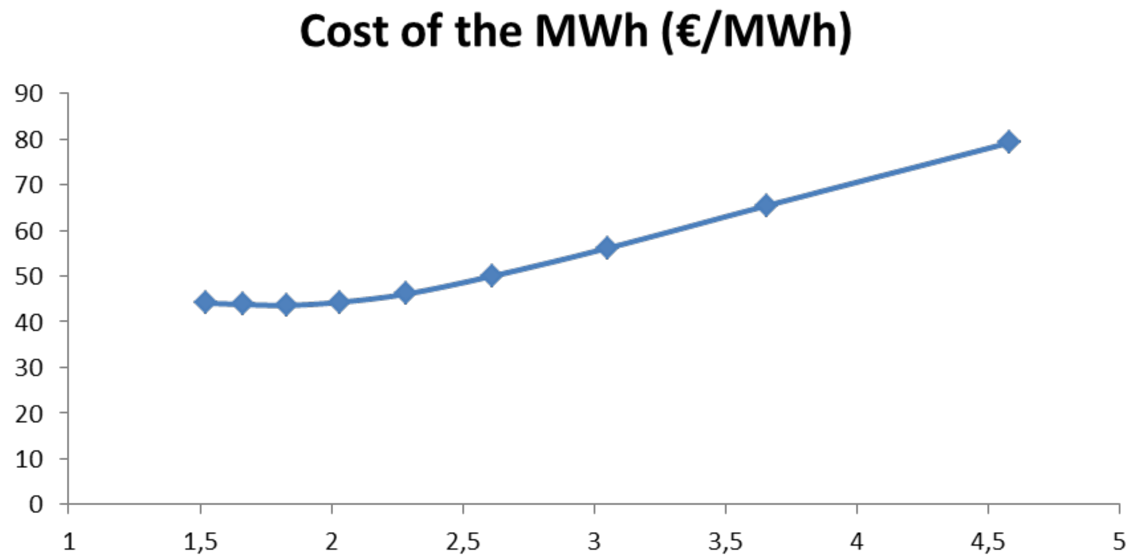
Fixed costs

Average demand (GW)

Average demand (France, 2011)

For a given fleet, the hourly cost is far from proportional to the demand

Optimal sizing of the mix



Mix sizing

(Pinstalled / Average demand)

Undersized mix → need to use expensive sources + risks of power cuts

Oversized mix → high fixed costs

An example of utilisation of MIXOPTIM: Cost of the closure of the Fessenheim plant

	Delta €/MWh	Delta $KgCO_2$/ MWh	Crit. Indep.
2013 French fleet	0	0	1.00
Without Fessenheim, without replacement	0.1	2.5	1.23
Without Fessenheim, with replacement by an EPR	1.2	-0.2	1.00
Without Fessenheim, with replacement by 8 GW Solar PV	5.6	0.5	1.05

Intermittence management and flexibility of the sources

With mixes containing high proportions of variable renewable energies, problems arise:

- Is the studied mix able to follow the imposed fluctuations?
- How much backup power is needed?
- Does one gain something in increasing the fluctuation speed of controlled sources like coal, gas or nuclear?
- How much energy storage is needed?

Intermittence management and time flexibility of sources
Imposed fluctuations, controlled fluctuations

$$D(t) = \sum_{All\,sources} P_i(t)$$

Imposed	Controlled
Fluctuations of the demande D(t)	Variations de puissance des sources pour faire du suivi de charge
Fluctuations of mandatory sources $P_{mandatory}(t)$ (Wind, solar)	$P_{sources\ pilotées}$ (t) (gaz, charbon, nucléaire,…)

$$D(t) - \sum P_{imposed}(t) = \sum P_{controlled}(t)$$

Imposed fluctuations must be compensated by controlled fluctuations

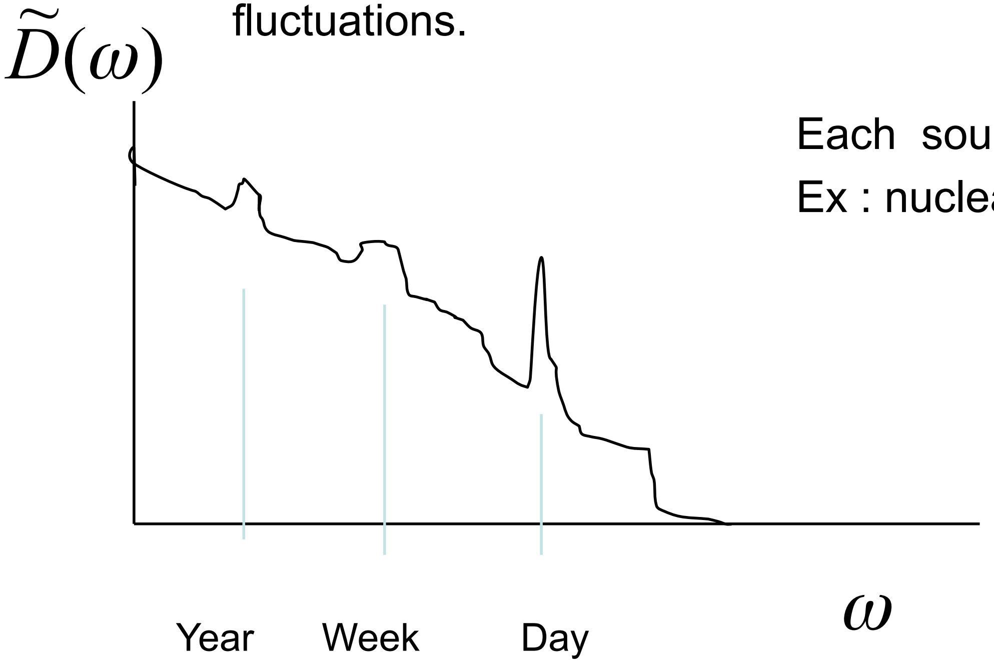
Frequency spectrum of the fluctuations

$$\widetilde{D}(\omega) = \frac{1}{2T}\int_{-T}^{T} D(t).e^{i\omega.t}.dt$$

The Fourier transform of the signal (demand, mandatory sources) gives the amplitude of the power fluctuations at angular frequency omega.

Intermittence management and flexibility of the sources

Controlled sources must be able to respond as rapidly as the imposed fluctuations.



Each source is characterized by a cutoff frequency.

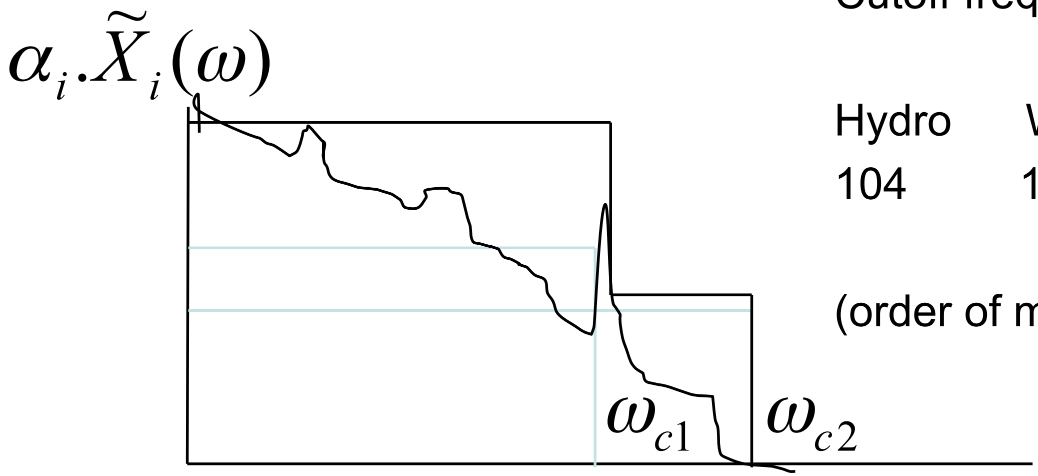
Ex : nuclear → d(ΔP/P)/dt = 2%PN min^{-1} → ω_c=1h^{-1}

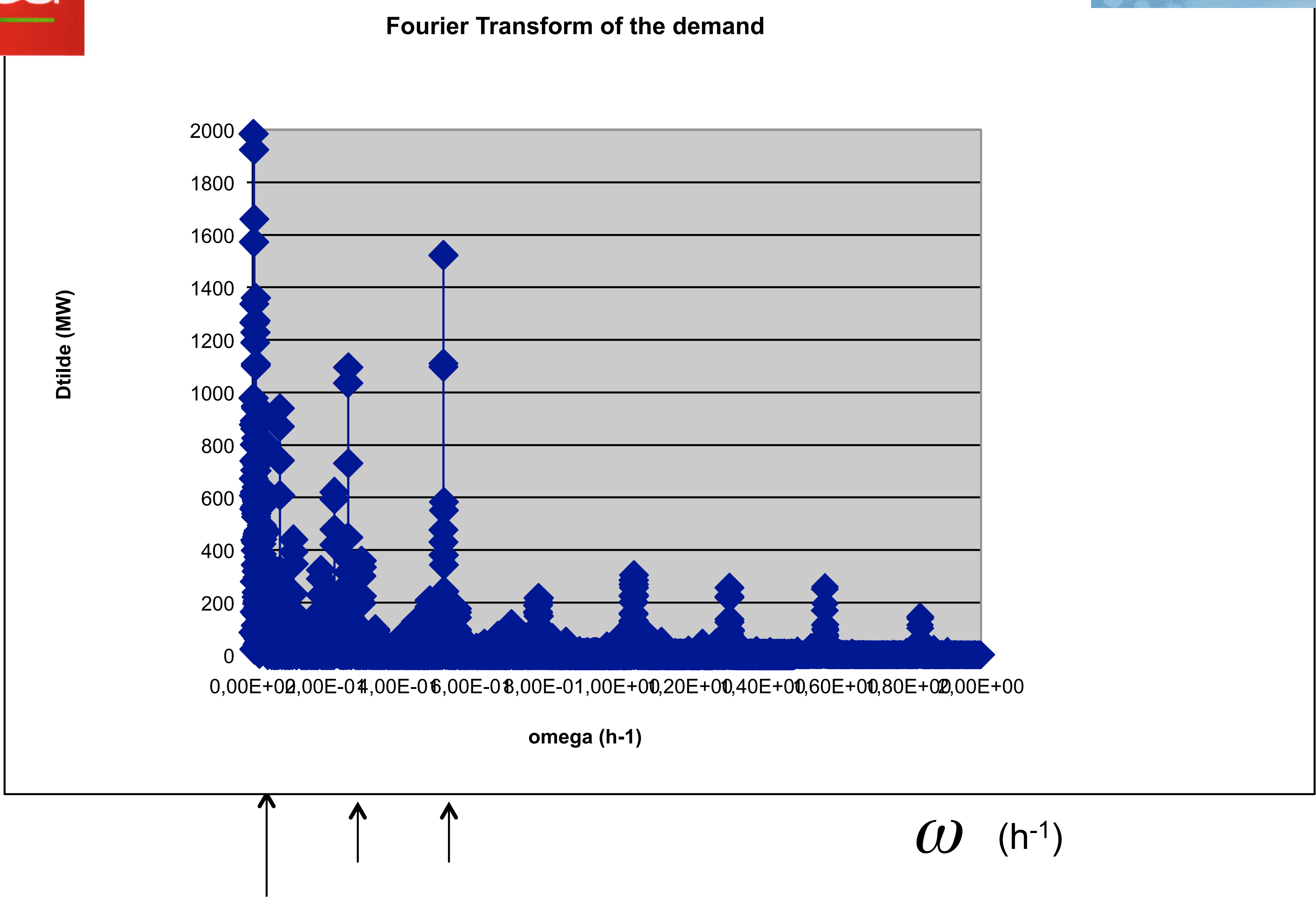
$$\omega_c = \frac{1}{P}.\frac{dP}{dt}$$

Cutoff frequency ω_c of the sources (h^{-1})

Hydro	Wind	Sol	CGT	Nuc	Gas	Coal
104	10	10	10	1	0.5	0.25

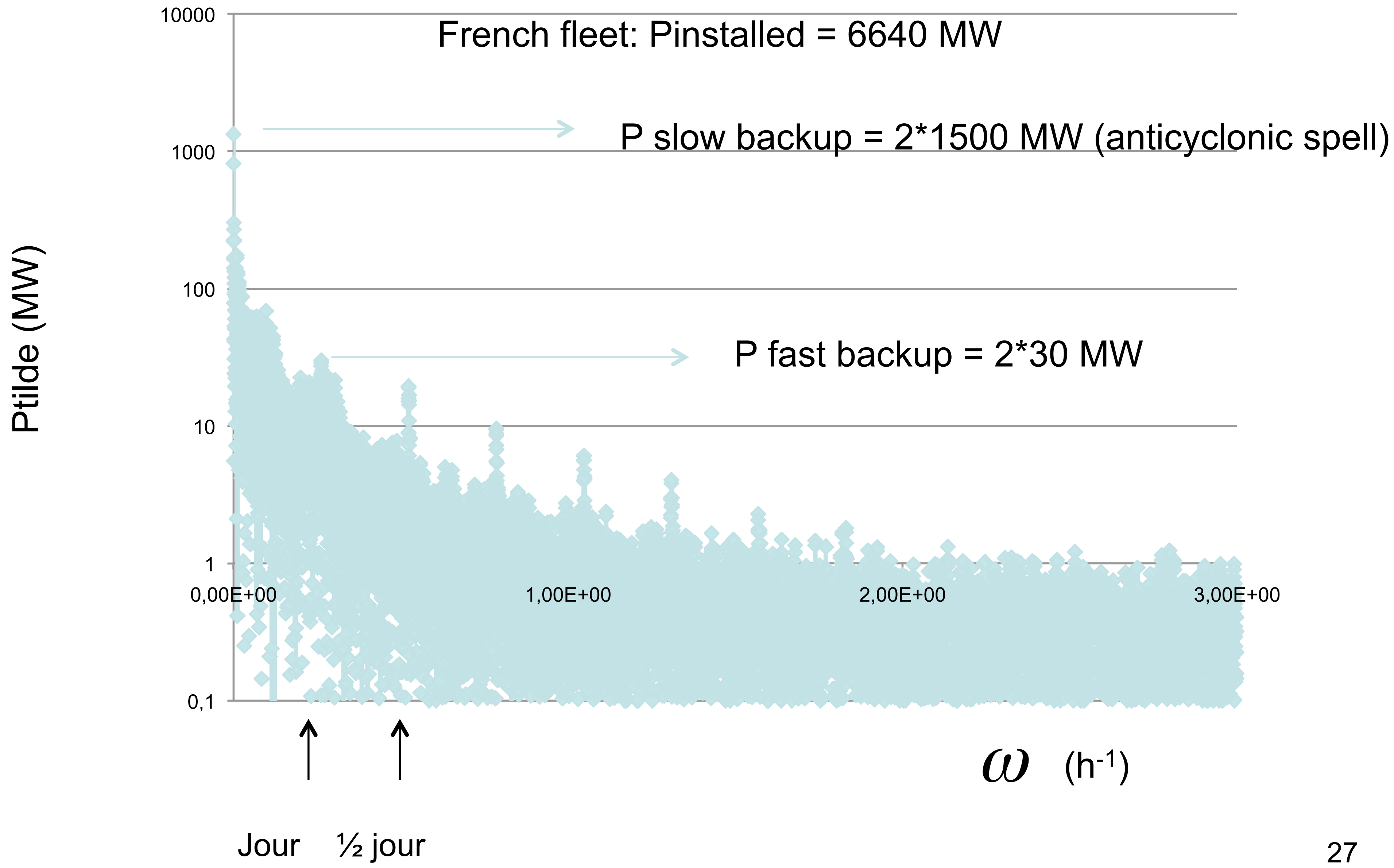
(order of magnitude)





Week Day ½ day

Frequency spectrum of wind production

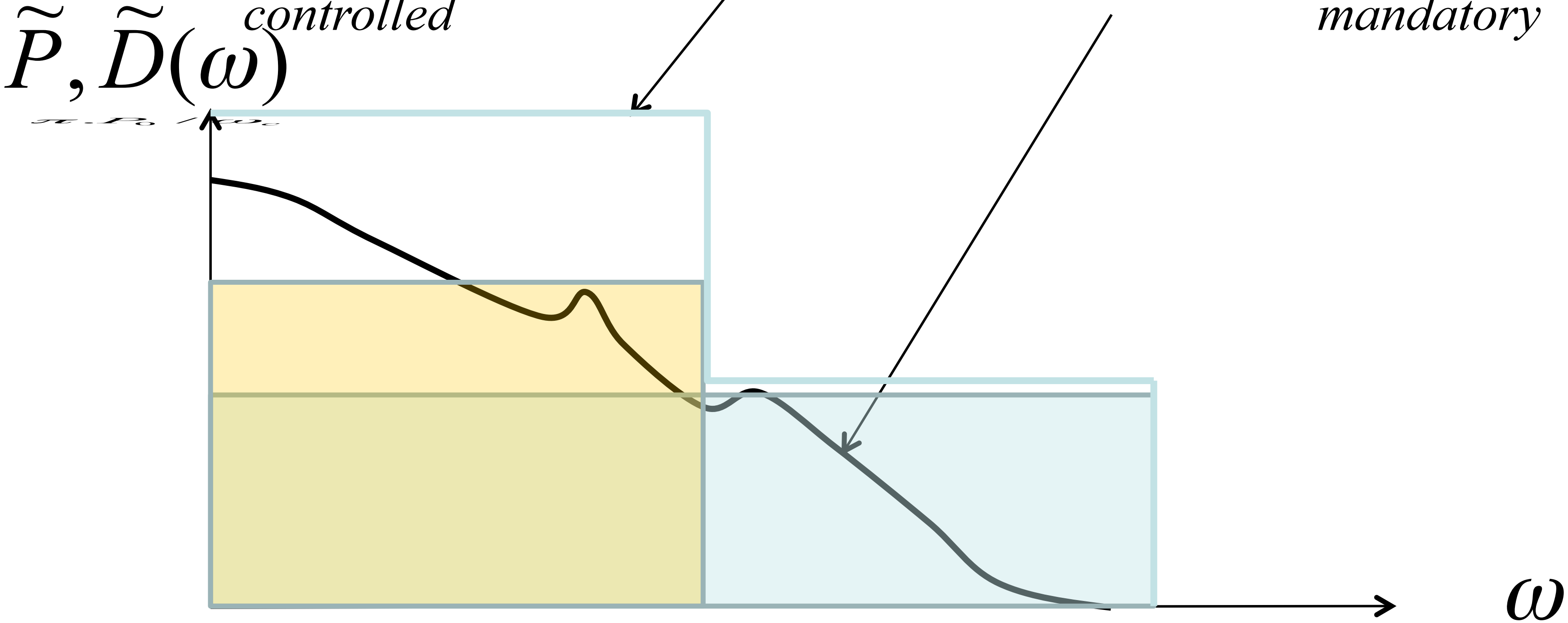


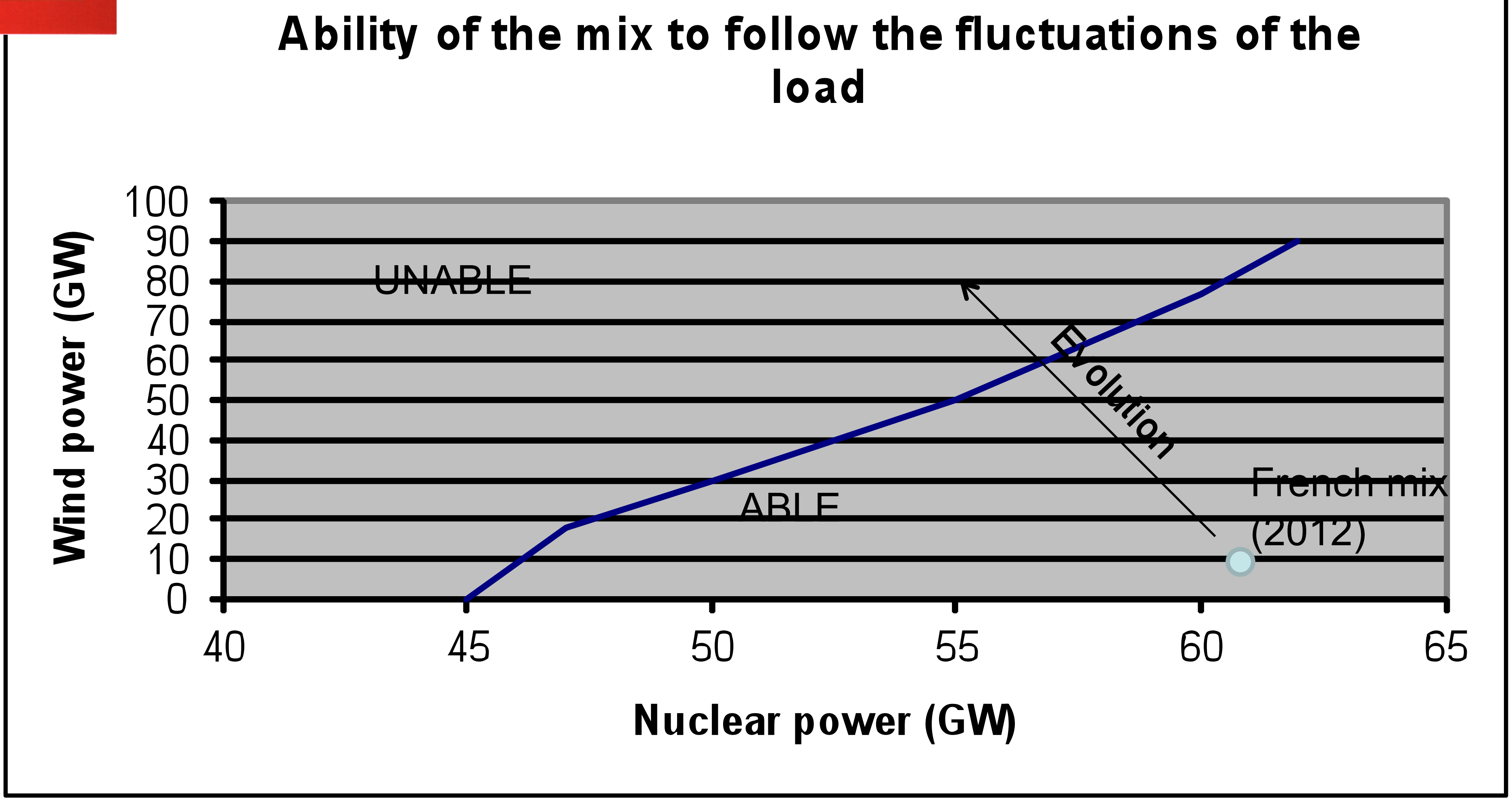
Intermittence management and flexibility of the sources

Conditions for a mix able to satisfy the demand:

$$\sum_{All\,sources} \alpha_i . Kd_i + \alpha_{imp\,\exp} > D_{\max}$$

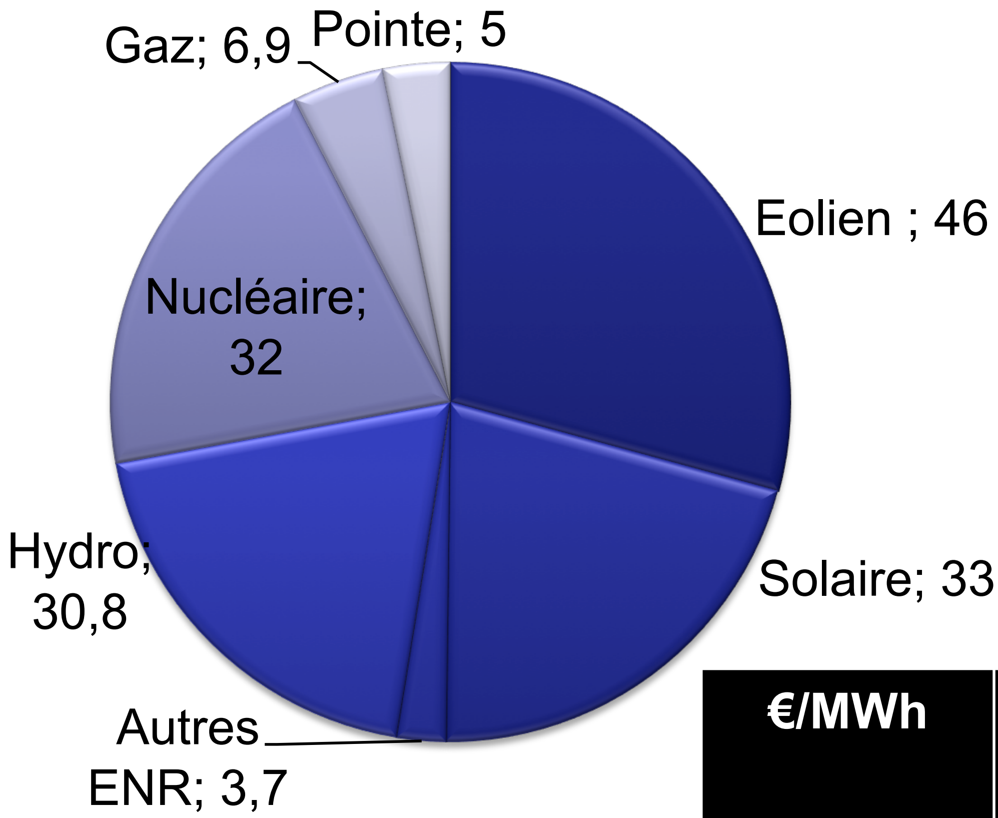
$$\sum_{controlled} \alpha_i . Kd_i . c(\omega_{ci}) > 2\tilde{D}(\omega) + 2 \sum_{mandatory} \tilde{P}_i(\omega)$$





Starting from the French mix 2012, the nuclear and wind power are allowed to vary.

Analyse MIXOPTIM du mix de l'ADEME 2030



€/MWh	KgCO2/MWh	Probabilité de coupure (an-1)
83	40	0

Mix exportateur net

Probabilité de recours à l'import = 4.e-2

Critère de performance global =1.24 soit moins bien que le mix français actuel (=1).

Mixoptim indique que ce mix est inapte au suivi de charge.

Gestion de l'intermittence et flexibilité temporelle des sources

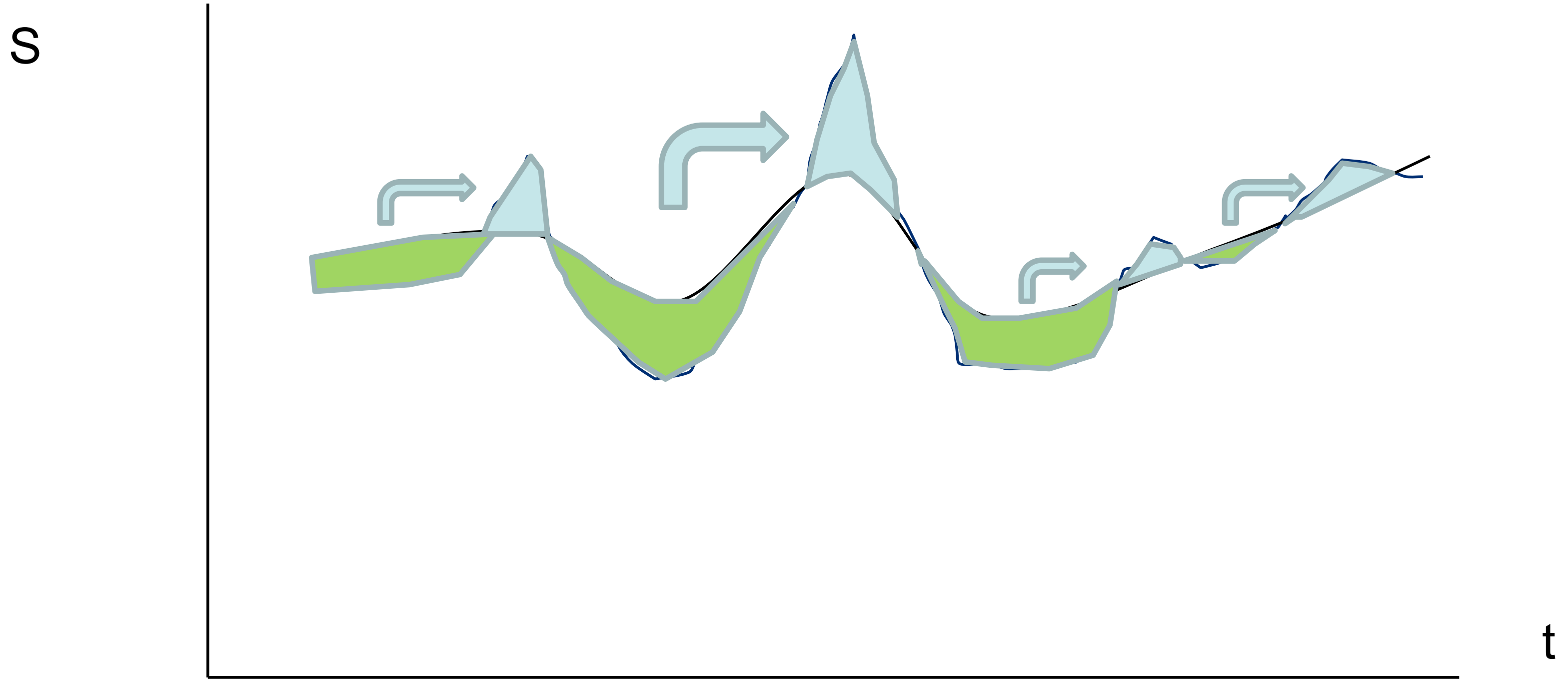
- Avec peu de sources fatales fluctuantes et beaucoup de nucléaire dans le mix, les paramètre sensibles sont l'amplitude des fluctuations de la demande et la fréquence de coupure du nucléaire : ce sont ces deux paramètres qui décident si le mix peut ou non suivre la charge. Le mix français actuel satisfait les critères.

- Avec beaucoup de sources fatales fluctuantes dans le mix, la proportion desdites sources devient aussi un paramètre important.

- C'est ainsi que le mix de l'ADEME 2030 est inapte au suivi de charge car il ne satisfait pas le critère « basse fréquence ».

- The main problem is the follow-up of low frequency fluctuations (eg anticyclonic spell), because they put the largest demand on the power of controllable sources.

(Dé)store electrical power?

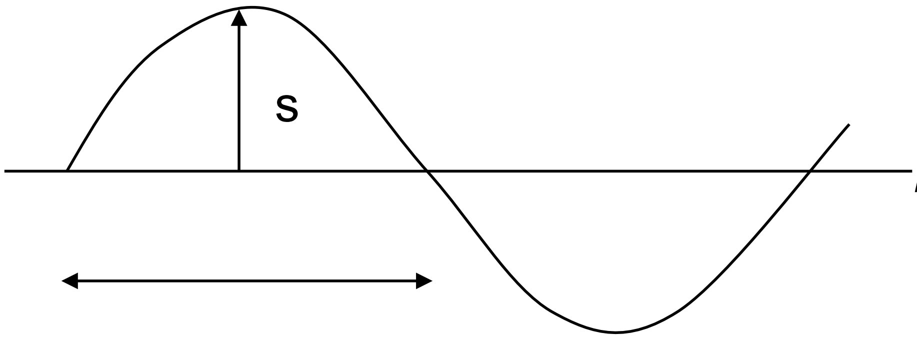


Introducing (de)storage capacities in the mix permits one to smooth the imposed fluctuations: $S_{smoothed} = S * g_{\tau}$

(de) store electrical power

« Imposed » power :

$$S(t) = D(t) - \sum_{fatal} P_i$$



$$\bar{S} + s.\cos \omega t$$

$$\tau = \frac{\pi}{\omega}$$

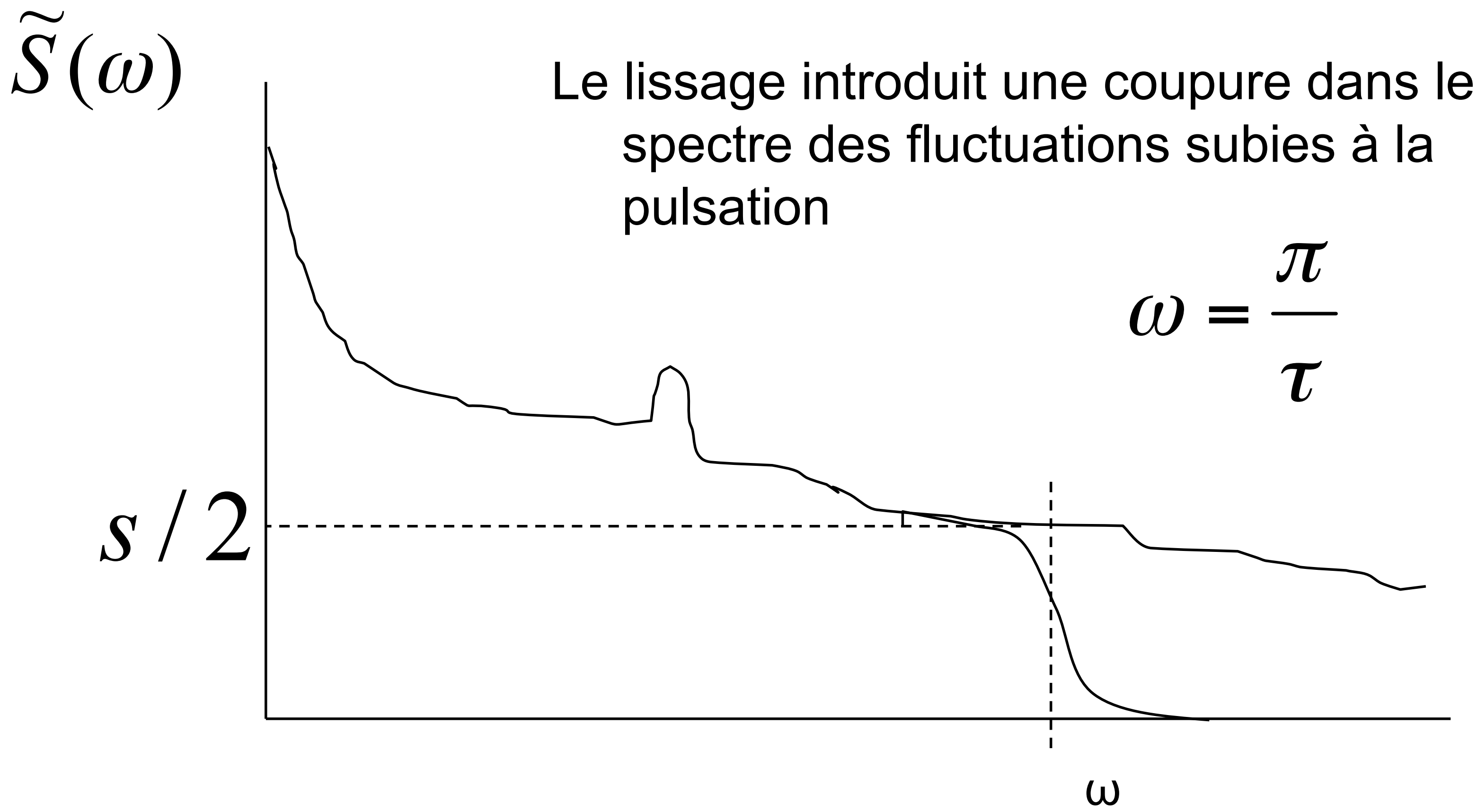
Half-period

Energy to be (de)stored to smooth the imposed power fluctuations at frequency omega:

$$E = 2.s / \omega$$

s is the spectral component of the power fluctuations at frequency omega

(De) store electrical power?



Le lissage introduit une coupure dans le spectre des fluctuations subies à la pulsation

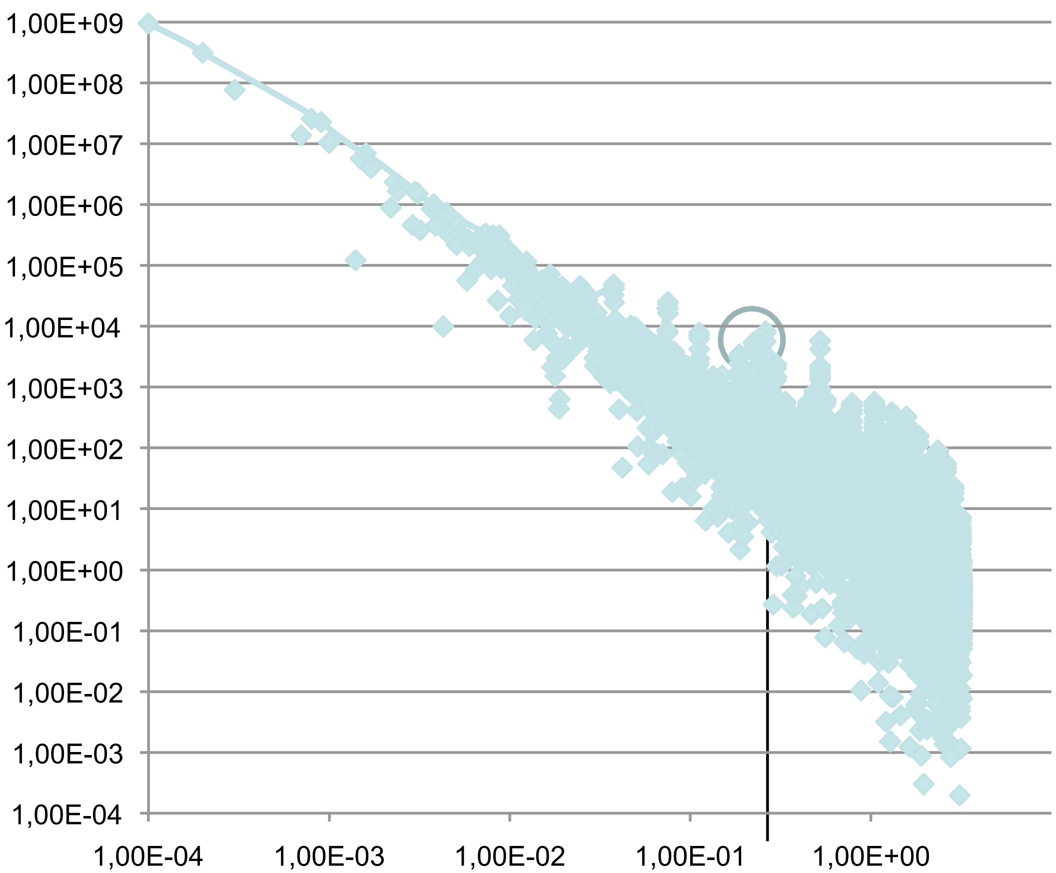
$$\omega = \frac{\pi}{\tau}$$

Pour pouvoir lisser les fluctuations subies S(t) à la pulsation ω, il faut disposer d'une énergie (dé)stockable $4.\widetilde{S}(\omega)/\omega$

(De)store electrical power

E

(MWh)



ω (h^{-1})

To smooth the demand D(t) at frequency $\omega = 0.25h^{-1}$ (1 day), one needs a (de)storable energy $\frac{4.\tilde{D}(\omega)}{\omega}$ 2*10 000 MWh.

Mix'optimisation: simulated annealing

Ref mix $\{\alpha_i\}_{ref}$ is given

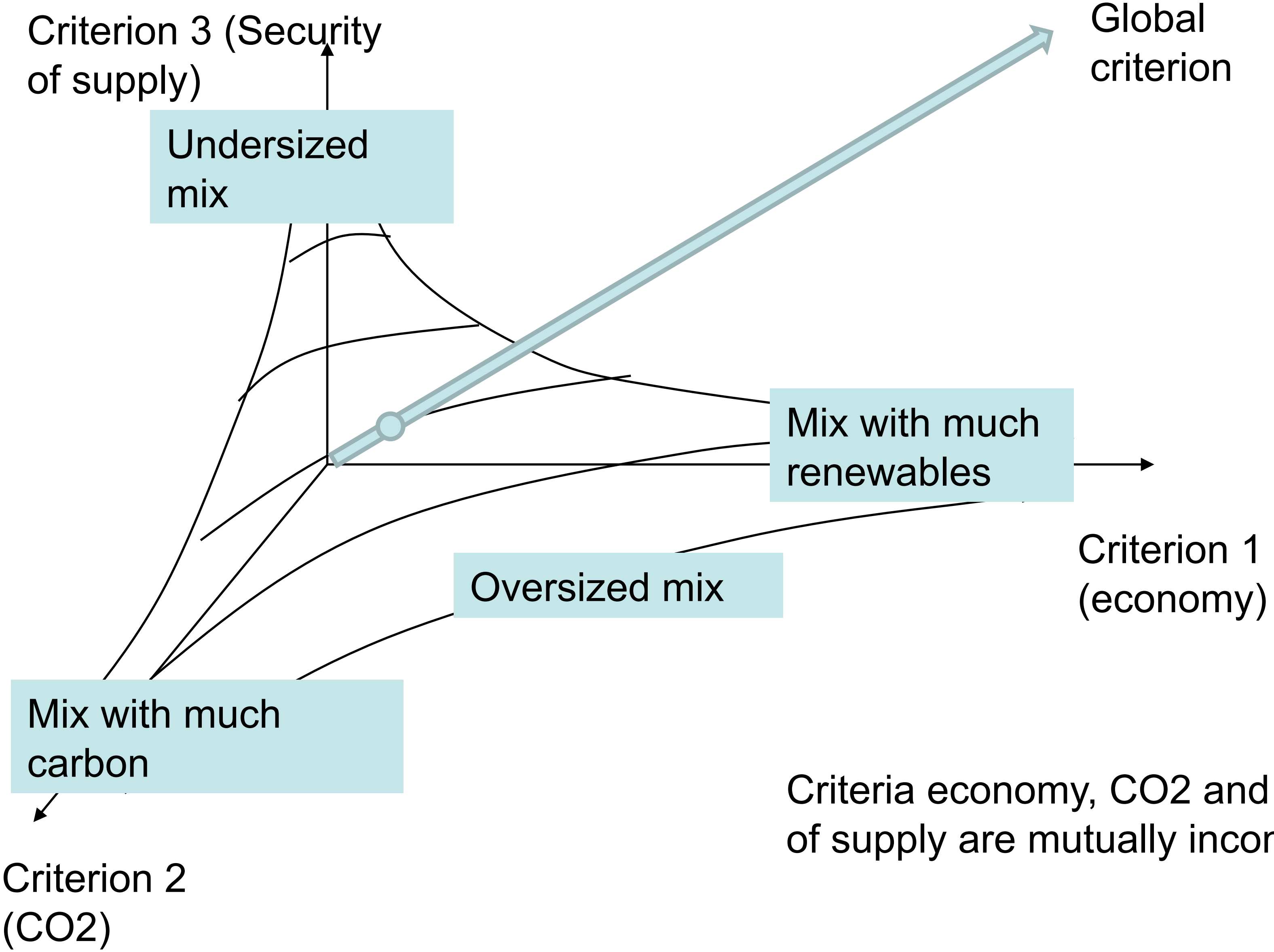
Calculation of $\{criteria\}_{ref}$

$\{\alpha_i\} = \{\alpha_i\}_{ref} + \{\Delta\alpha_i\}$ (randomly determined)

Calculation of {criteria}

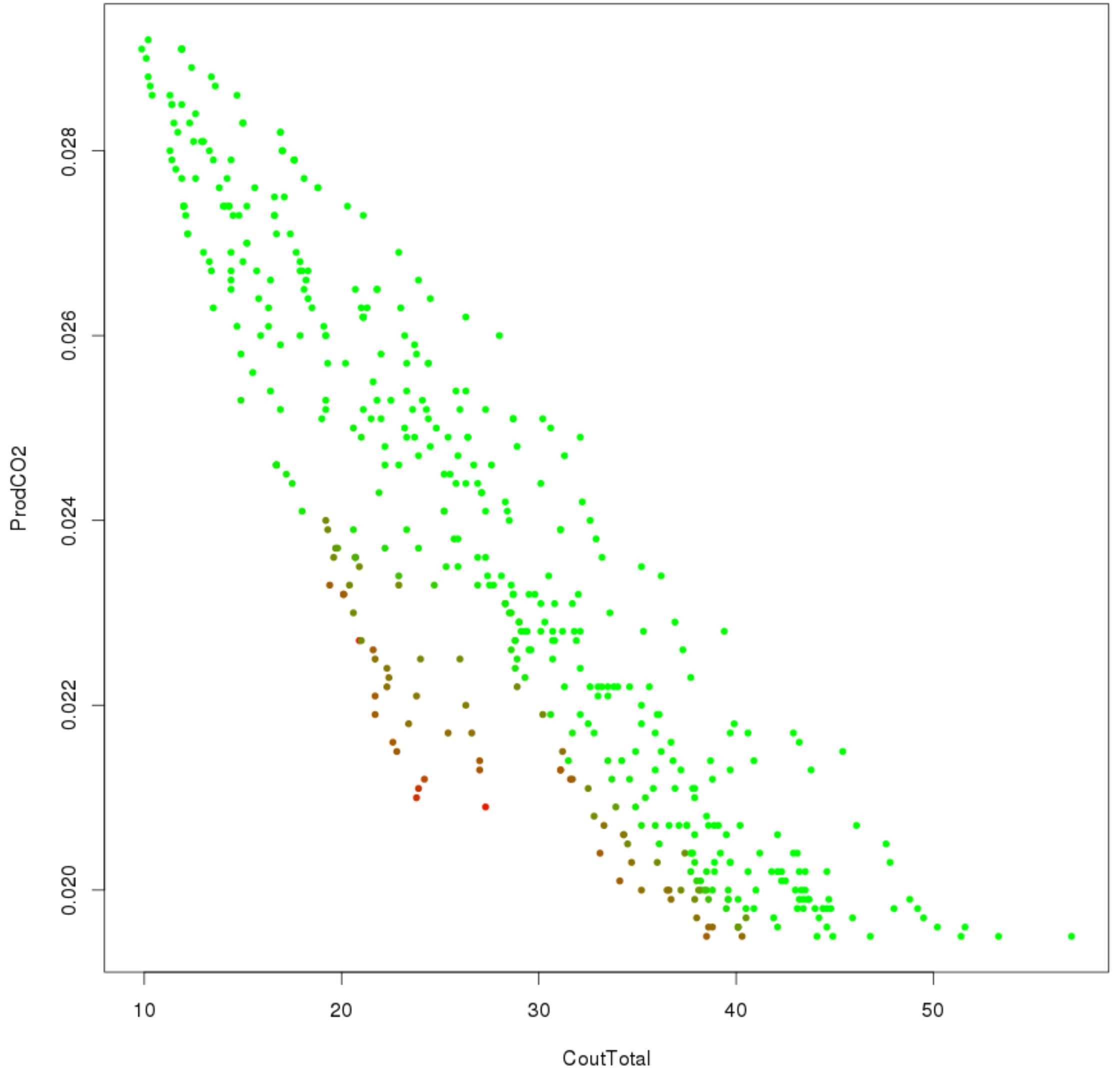
If $\{criteria\} < \{criteria\}_{ref}$, $\{\alpha_i\}_{ref} = \{\alpha_i\}$

Pareto front



Criteria economy, CO2 and security of supply are mutually incompatible

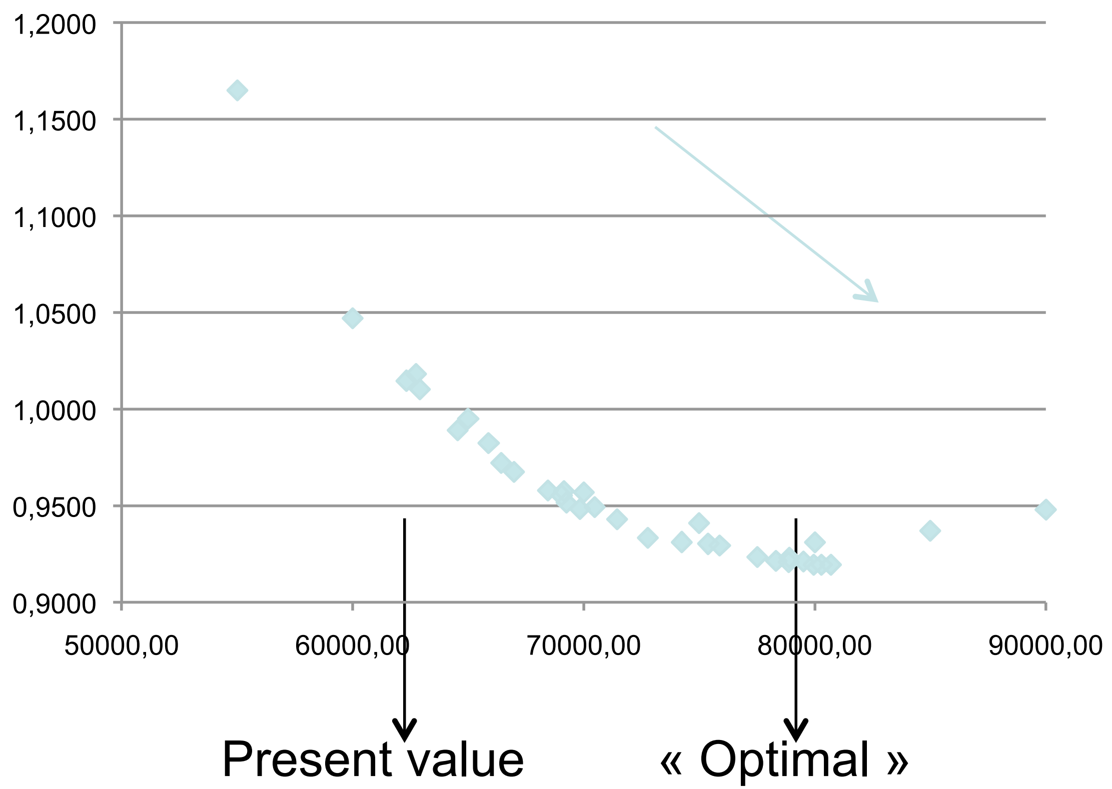
Front de Pareto



Mix'optimisation on a unique criterion

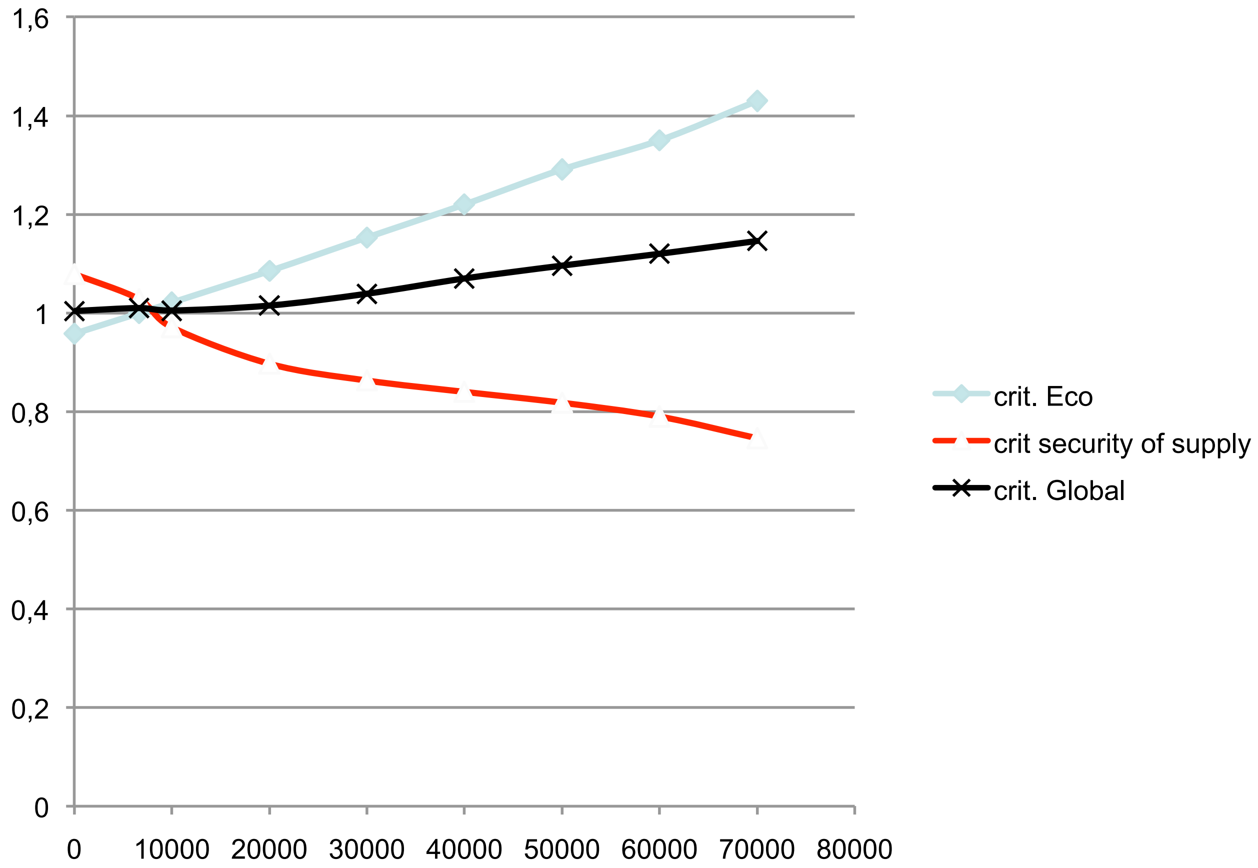
$$P_{global} = 0.4\frac{P_{economy}}{P_{eco\,ref}} + 0.3\frac{P_{environment}}{P_{envt\,ref}} + 0.3\frac{(P_{\sup ply1} + P_{\sup ply2})}{P_{\sup ply\,ref}}$$

Criterion global



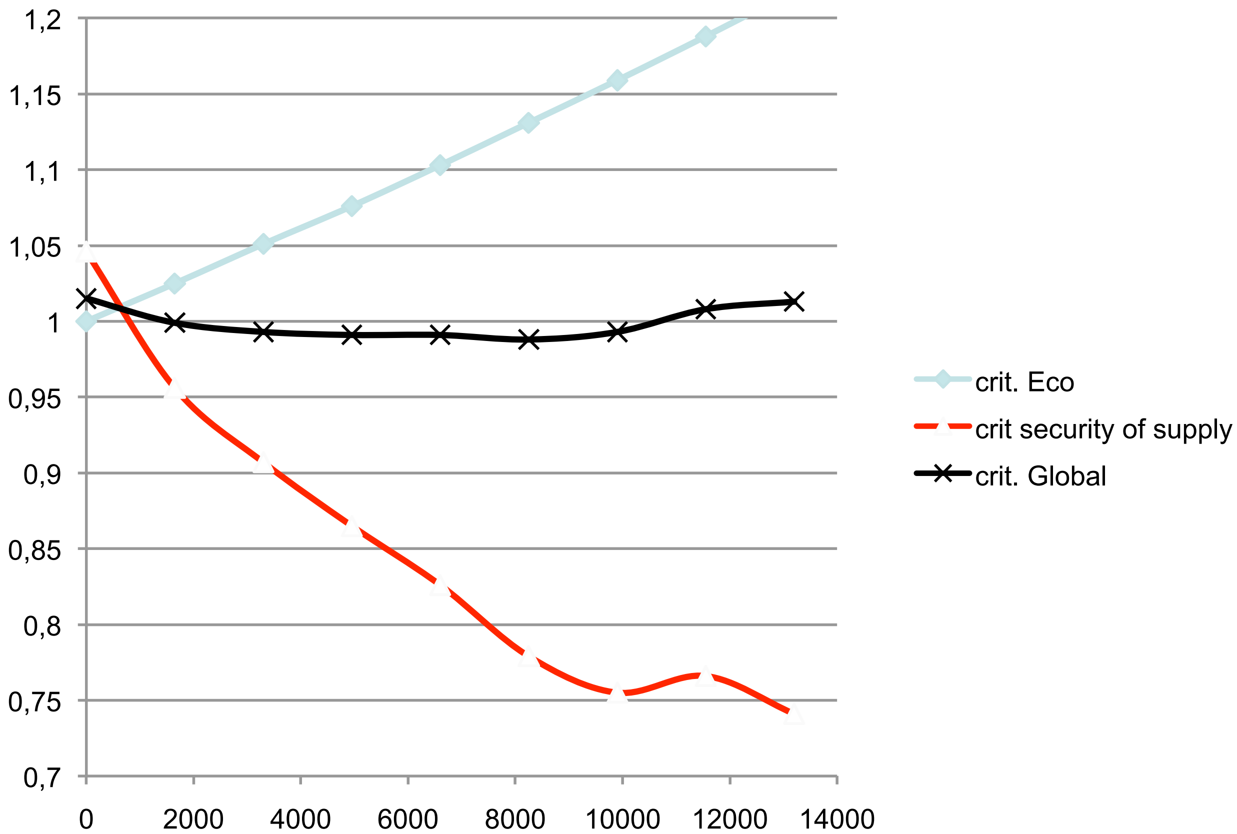
Gen II installed power (MW)

Optimising wind power



On fait varier la puissance éolienne du mix français, toutes choses égales par ailleurs. L'indicateur global ne fait que se dégrader au fur et à mesure que la puissance éolienne croît, principalement à cause du critère « coût du MWh ».

Optimising Gen III nuclear power



On fait varier la puissance « EPR » du mix français, toutes choses égales par ailleurs. L'indicateur global passe par un optimum très plat pour 4 ou 5 tranches.

Global criterion optimisation (French mix)

The « optimal » mix has an installed capacity of 2.3 times the average demand → Do not undersize the installed capacity!

The « optimal » mix keeps much Gen II nuclear power. We are far from the ordonnance of the good doctor Hollande!

The « optimal »mix is strongly export-oriented. Invest in power production, if you can produce it cheap, and if the interconnexion capacity allows the export!

Gen 2 nuclear (amortized) produces power at a cost smaller than the average export price of the MWh . Closing the nuclear plants will reduce this income source.

MIXOPTIM: an open source software, in evolution

Software includes :

•A mix evaluation module, with cost, CO_2 and security of supply criteria as output.
•Two mix'optimisation modules: simulated annealing and genetic algorithm, with the Pareto front and the composition of the optimal mix as output.
•A module of spectral analysis, to test the fluctuation follow-up capabilities of a mix.
•Un module of smoothing the imposed fluctuations, to evaluate the benefits of (de) storage.

•A database for the cost and CO_2 of each source

•A database with typical spectra for mandatory sources.

Work in progress

- MIXOPTIM : an objective method to evaluate a mix, and eventually optimize it.

- Main added value of MIXOPTIM: provide a treatment of intermittence (with determination of the Kp), and quantitative criteria assessing the fluctuation follow-up capacity of the mix.

- Mixoptim is validated on the french mix. Wish to validate it on other European mixes.

- MIXOPTIM is being used to analyse the ANCRE scenarios.

- Publish MIXOPTIM. Already on internet : http://ec2-79-125-24-168.eu-west-1.compute.amazonaws.com/
- Source (Fortran 95!) available on request.