PhD-Hours - Hamza Benabbes-Taarji

RESILIENCE SCENARIOS OF THE FRENCH ELECTRICITY MIX IN 2035 INTEGRATING THE EFFECTIVE MANEUVERABILITY OF NUCLEAR POWER PLANTS

PhD Director: Muriel FALLOT[1]
SUPERVISORS : Jean-Michel DO[2] et Nicolas THIOLLIERE[1]

[1] Subatech, IMTA-IN2P3/CNRS-Université, 44307 Nantes, France
[2] DES/ISAS/DM2S/SERMA, CEA Saclay – Université Paris-Saclay

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CONTEXT

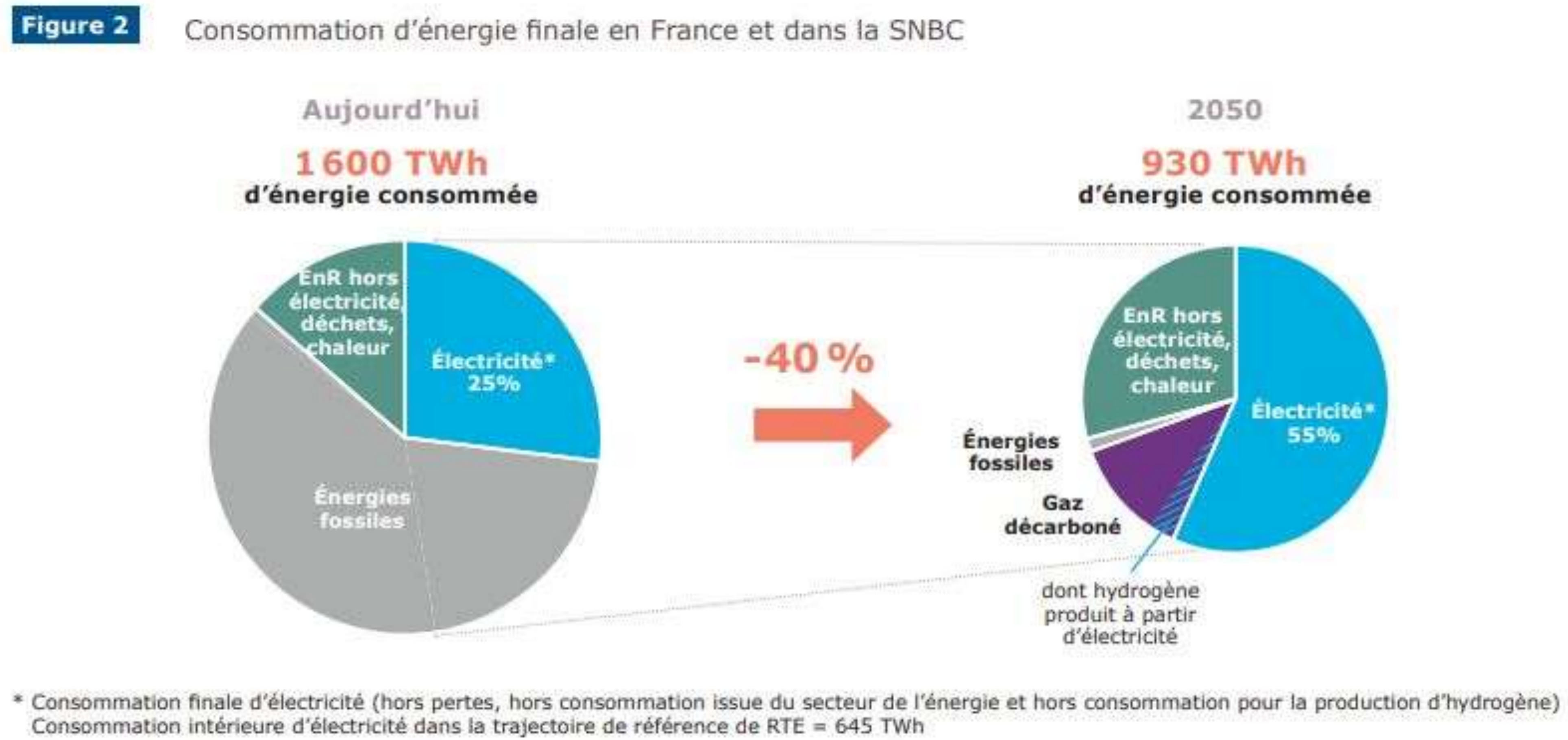
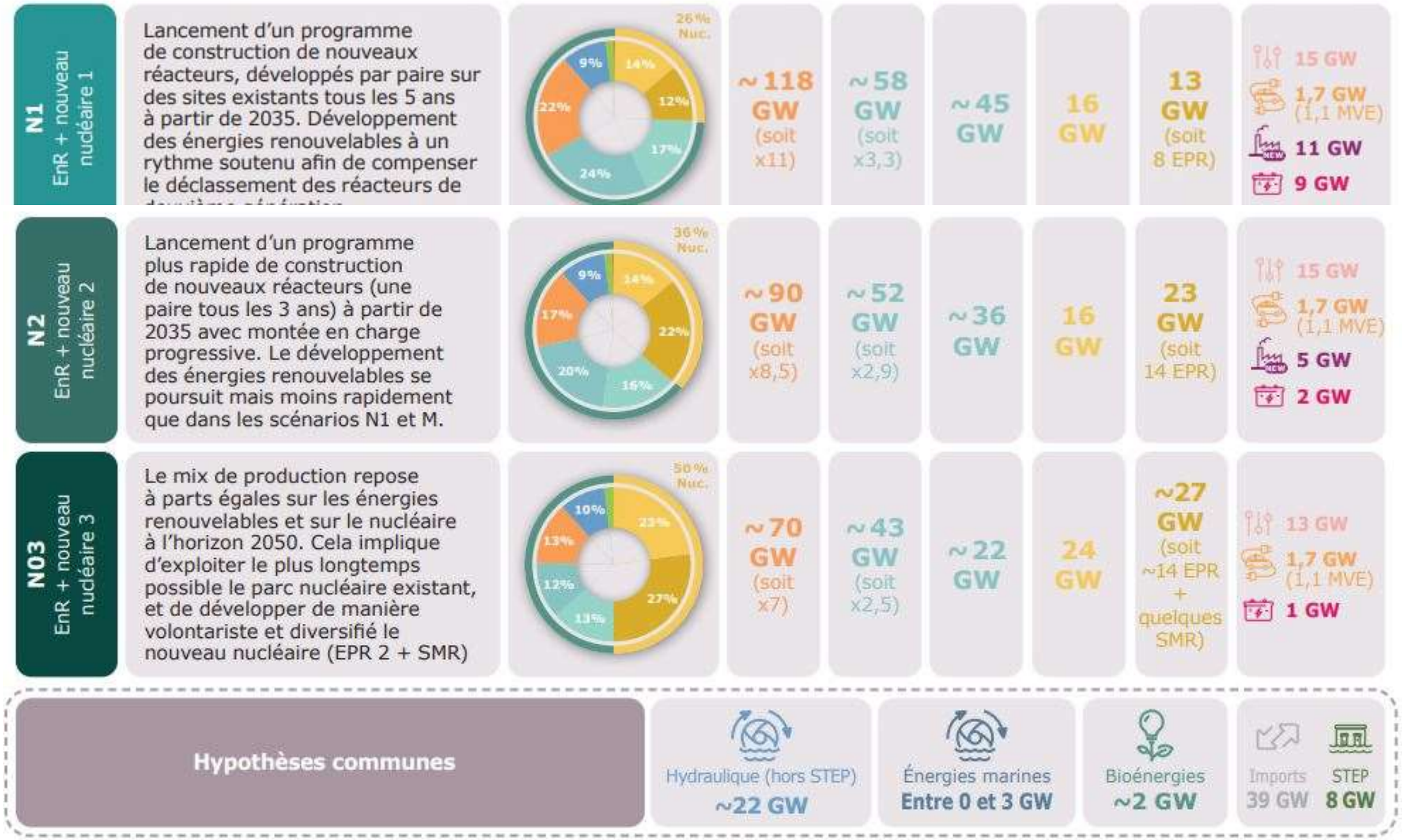


Figure 2
Consommation d'énergie finale en France et dans la SNBC
Aujourd'hui
1 600 TWh
d'énergie consommée
EnR hors électricité, déchets, chaleur
Électricité*
25%
Énergies fossiles
-40 %
2050
930 TWh
d'énergie consommée
EnR hors électricité, déchets, chaleur
Électricité*
55%
Énergies fossiles
Gaz décarboné
dont hydrogène produit à partir d'électricité
* Consommation finale d'électricité (hors pertes, hors consommation issue du secteur de l'énergie et hors consommation pour la production d'hydrogène)
Consommation intérieure d'électricité dans la trajectoire de référence de RTE = 645 TWh

CONTEXT

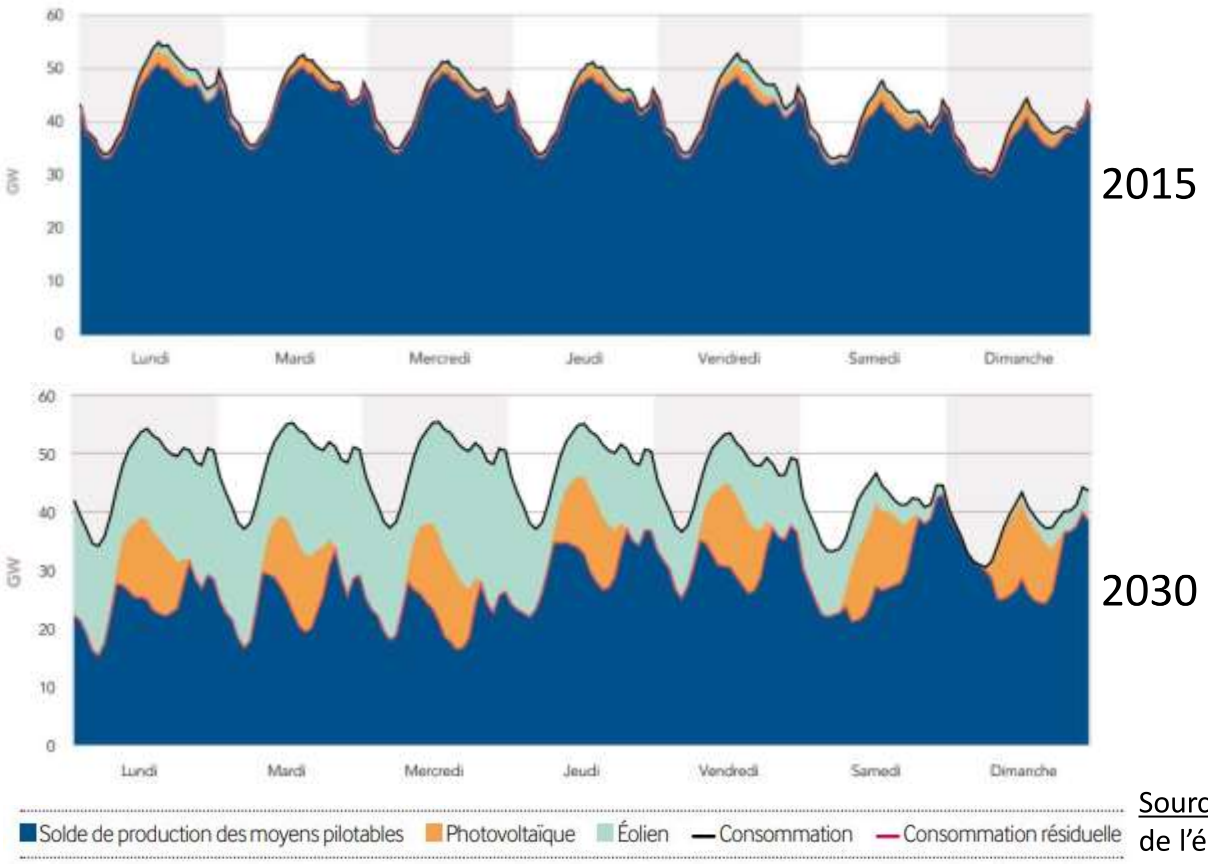
RTE Futures énergétiques 2050 (scenarios with nuclear power):



THE SHARE OF NUCLEAR POWER GETS LOWER IN ALL SCENARIOS

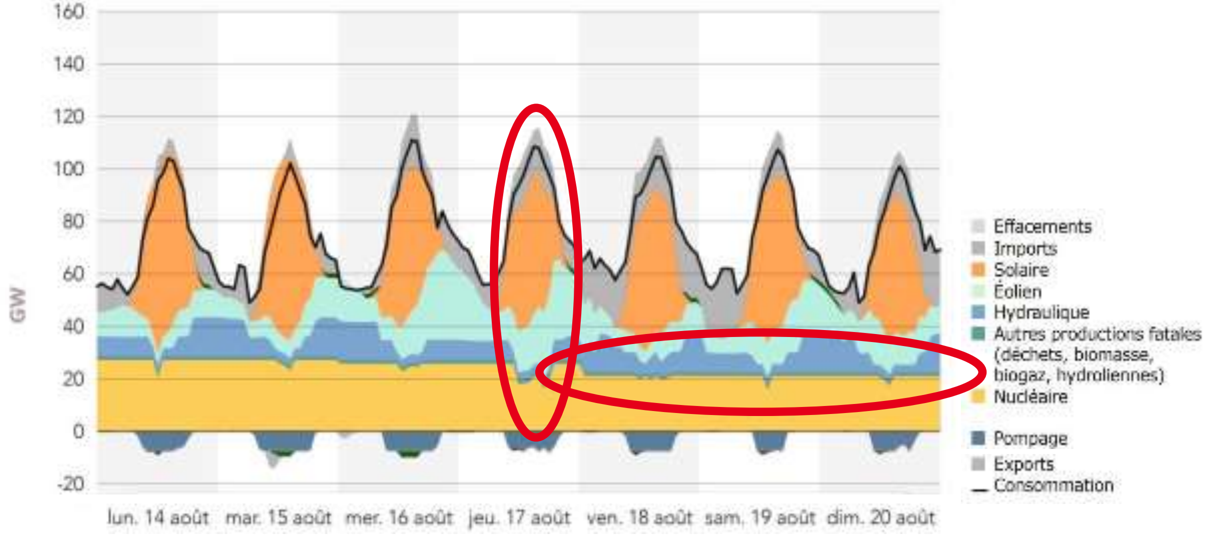
CONTEXT

In this context, the need for flexibility of Nuclear Power Plants (NPPs) increases.



Source: RTE : Bilan prévisionnel de l'équilibre offre-demande d'électricité en France (2015)

Mix électrique simulé lors d'une canicule avec un faible vent dans le scénario N2 en 2050



Source: RTE : *Futurs énergétiques 2050 – climat et système électrique* (2022)

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WHY IS THE MANEUVERABILITY OF NPPs A POSSIBLE ISSUE?

There are some technical constraints when it comes to load-follow operation in NPPs…

- **Limit of deviation from the reference temperature (material integrity, etc.)**
- **Limits on tritium releases, as well as FP and PA from primary circuit effluents**
- **Limit of deviation from the reference axial offset (risk of Xenon oscillations, hot spot factor, PCI risk)**
- **Limits on vessel fluence**
- **Maximum time limit for prolonged operation at intermediate power**
- **Limits on maximum power ramps**
- **Limits on minimum and maximum power (evolves over the cycle)**
- **Limits on minimum time at shutdown and in operation**
- **Limits on cold source heating**
- **Limit on the fatigue of rod mechanisms**
- **Need to comply with scheduled shutdown, maintenance, and periodic testing calendars**
- **Difficulty in maintaining hot shutdownsLimits on minimum durations at power plateaus**
- **… Many more**

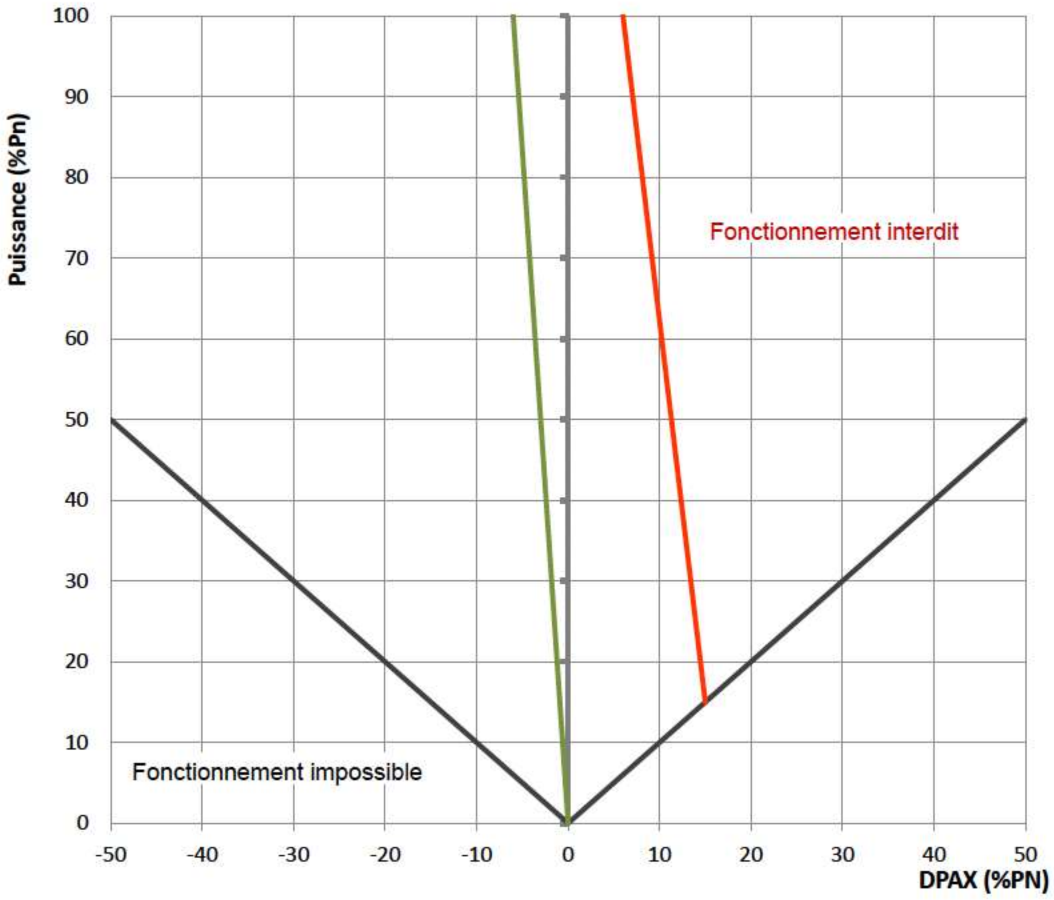
WHY IS THE MANEUVERABILITY OF NPPs A POSSIBLE ISSUE?

AO:

$$AO = \frac{P_H - P_B}{P_H + P_B}$$

DPAX:

$$\Delta I = \frac{P_H - P_B}{P_{nom}} = AO * P_r$$



WHY IS THE MANEUVERABILITY OF NPPs A POSSIBLE ISSUE?

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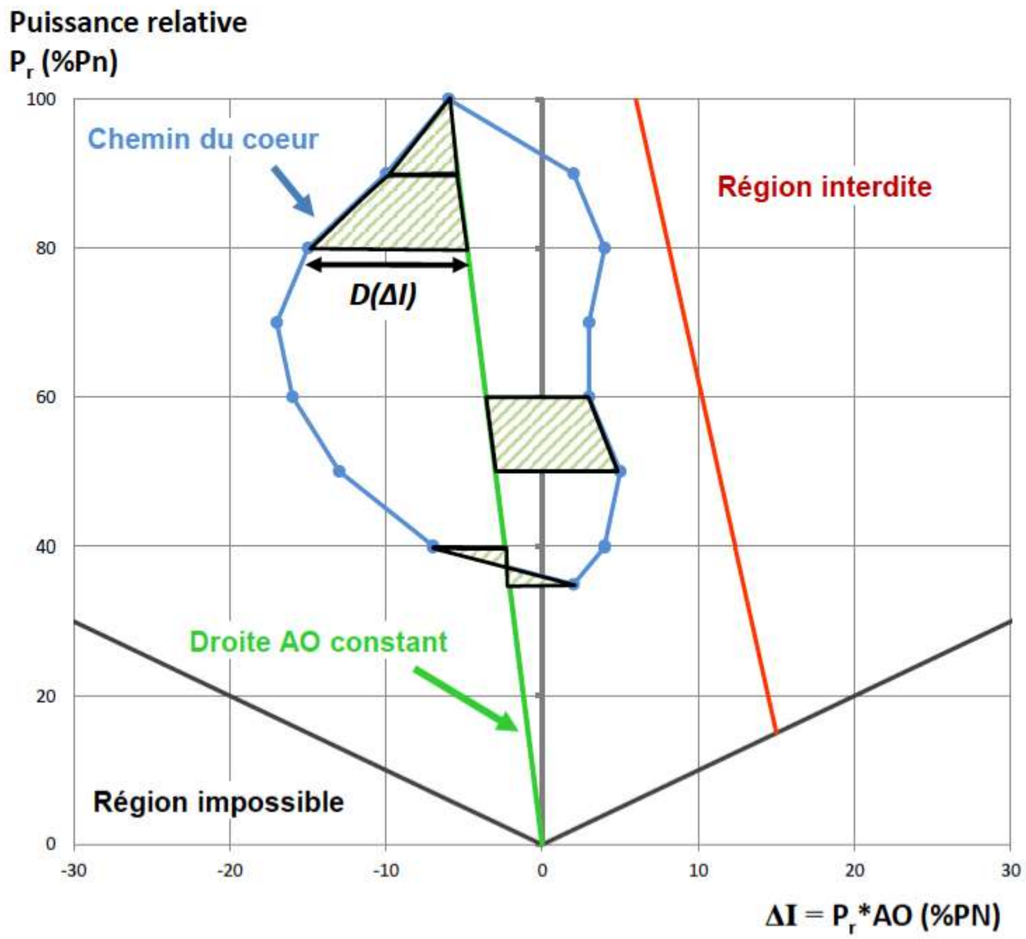

Source: Mathieu Muniglia. Optimisation du pilotage d'un REP dans le cadre de la transition énergétique à l'aide d'algorithmes évolutionnaires. 2017.

MEMORY EFFECT!

cea cnrs Subatech

WHY IS THE MANEUVERABILITY OF NPPs A POSSIBLE ISSUE?

We will also monitor **the volume of effluent** due to Tritium discharge limits into the environment. Tritium is contained in the effluents generated when changing the boron concentration—a powerful neutron poison whose control is necessary for operating a PWR—in the primary circuit.

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OUR WORK IN REACTOR PHYSICS

We base our work on the **ALGO NPP load-follow simulator** developed by three phd students before me (and still being developed). It is based on the **APOLLO3®** neutronics code developed at the SERMA laboratory of CEA where I work.

ALGO couples the neutronics simulations to the thermal-hydraulics of the secondary and tertiary circuits of an NPP to provide us with accurate estimate of the axial offset and of the effluent volumes.

It models the **G-mode** of load-following that allows some french PWRs to be some of the most maneuverable NPPs. The G-mode is based on **independant groups of control rods** (for adjusting the power and the temperature in the core independently) as well as on **diluted boric acid**.

The insertion and removal of control rods tends to increase/decrease the axial offset.

The use of boric acid increases the effluent volume.

→ It is therefore hard to optimize load-following at the same time for both the axial offset and the effluent volume.

OUR WORK IN REACTOR PHYSICS

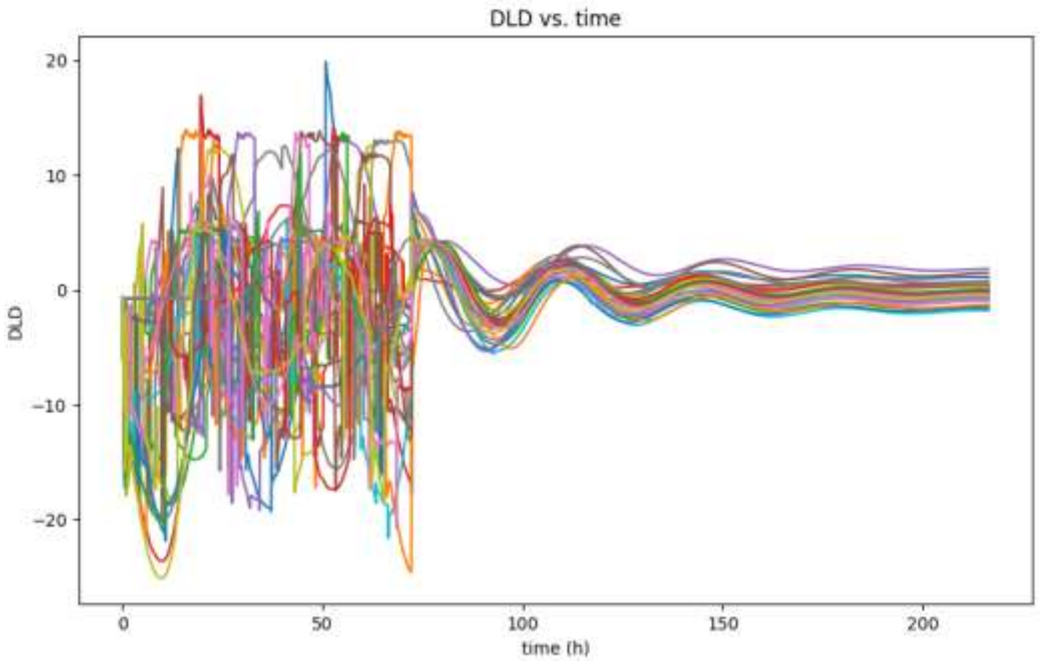
The problem with ALGO is that it is very slow (roughly 90min of calculation for 24h simulated).

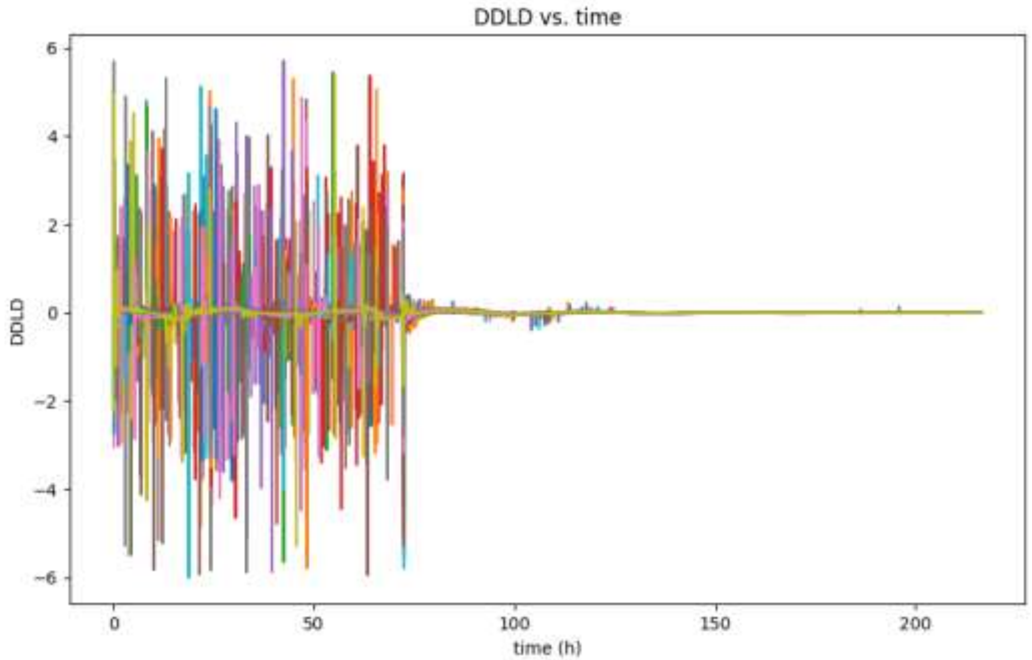
It is quite constraining when it comes to black box optimization of a rather irregular function if there are more than a few thousand points in the search space.

We therefore developed meta-models of ALGO to tackle optimization problems with a cost-function that we can evaluate much faster.

OUR WORK IN REACTOR PHYSICS

The outputs of our meta-models cannot directly be the two observables of interest due to the memory effects and the constraint to have a limited fixed input size:



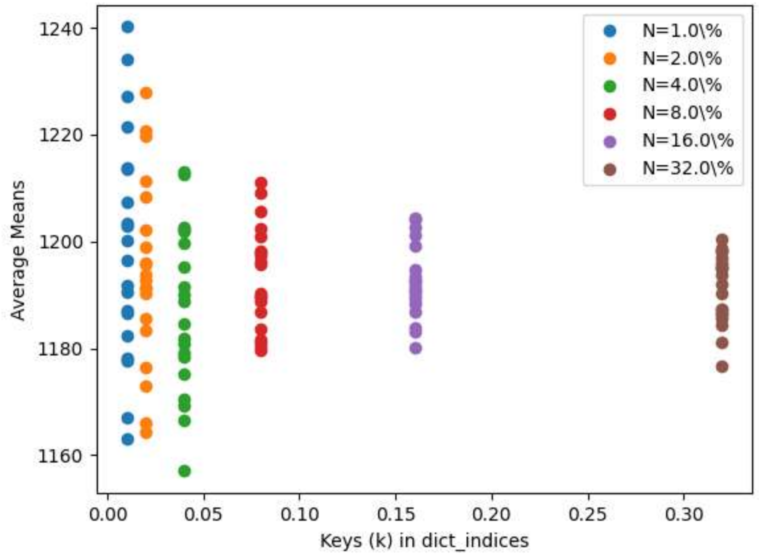


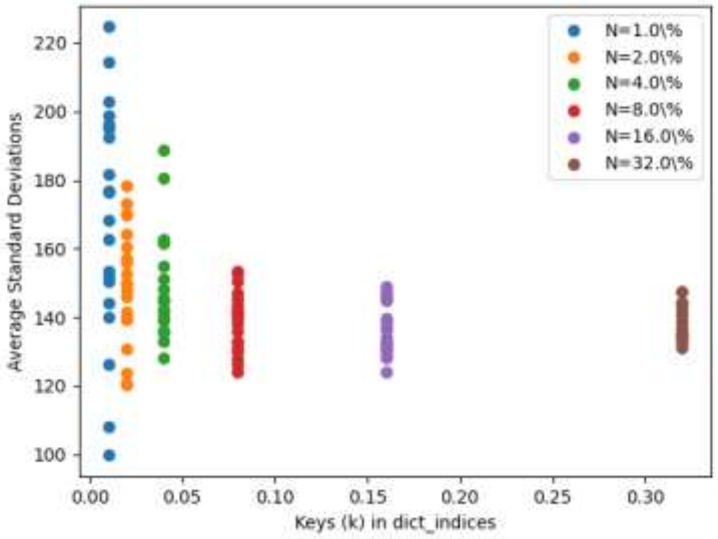
We choose to take as input to our meta-model, the values of the electrical power every hour in the last 53h of operation

OUR WORK IN REACTOR PHYSICS

Since we want to meta-modelize ALGO, the outputs of ALGO simulations will be our base truth.

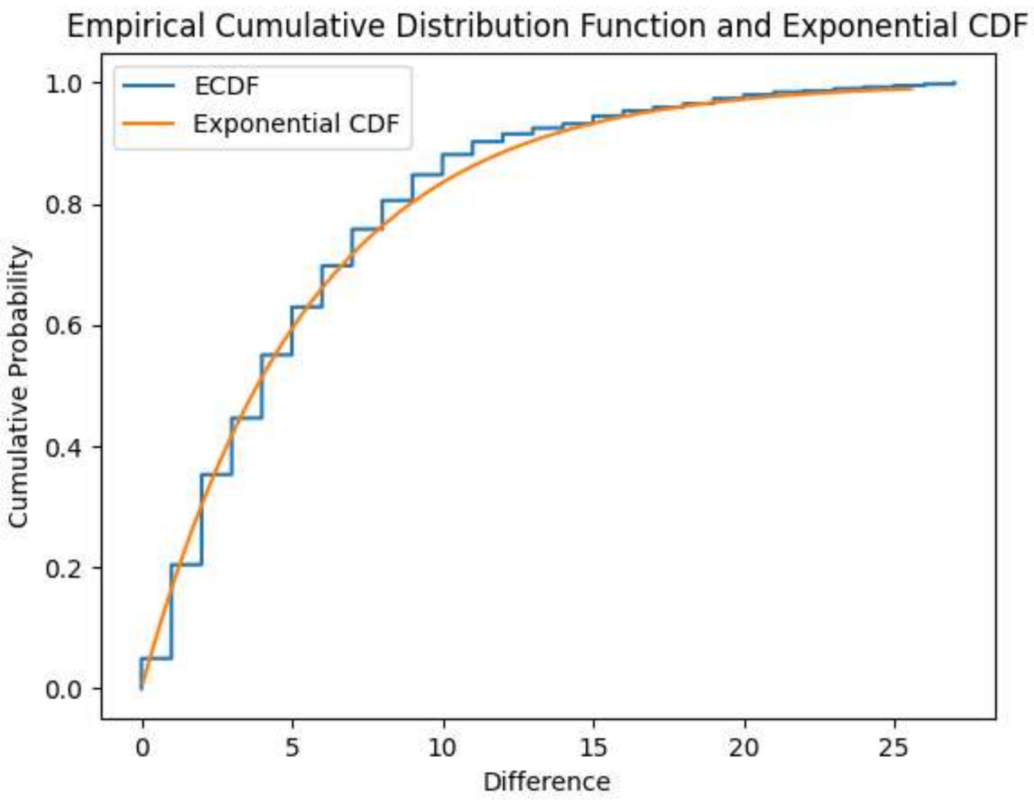
As for the inputs chosen for the ALGO simulations to create the training and testing database, it is usually suggested in such cases to take real load-following data, however it seems difficult to do this while keeping a relatively small simulation time and a large enough share of the data that are not just power plateaus:

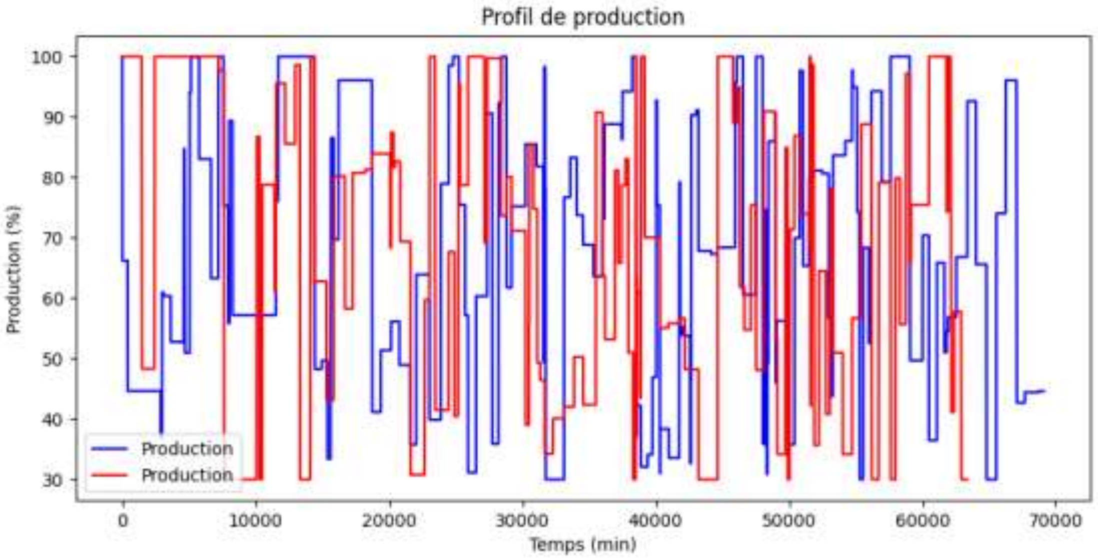




OUR WORK IN REACTOR PHYSICS

So instead we sample the inputs of our training and testing dataset from relevant distributions:





As we will see later, there is a bias associated with this way of generating the data

OUR WORK IN REACTOR PHYSICS

The results of our meta-modelizing efforts seem encouraging as our best model ends up having relative errors below 2% for each observable of interest while alloying speed-ups of ALGO of the order of x10^8 !

Model	RMSE	MAE	Mean Absolute Relative Error(%)
LSTM	0.060	0.025	7.6
GRU	0.056	0.025	6.6
CNN	0.028	0.017	4.0
HistGradBoost	**0.012**±0.001	**0.0076**±0.0003	**1.78**±0.29
RandomForest	0.015	0.009	1.9
MLP	0.042	0.024	5.4

→ **The Histogram-base gradient boosted tree model performs the best for us.**

Its performances are quite satisfactory given that we have a lower bound on the best possible performance: RMSE =0.004, MAE = 0.003, and MARE = 0.6%.

OUR WORK IN REACTOR PHYSICS

We can now use our meta-model to help us in a useful optimization problem.

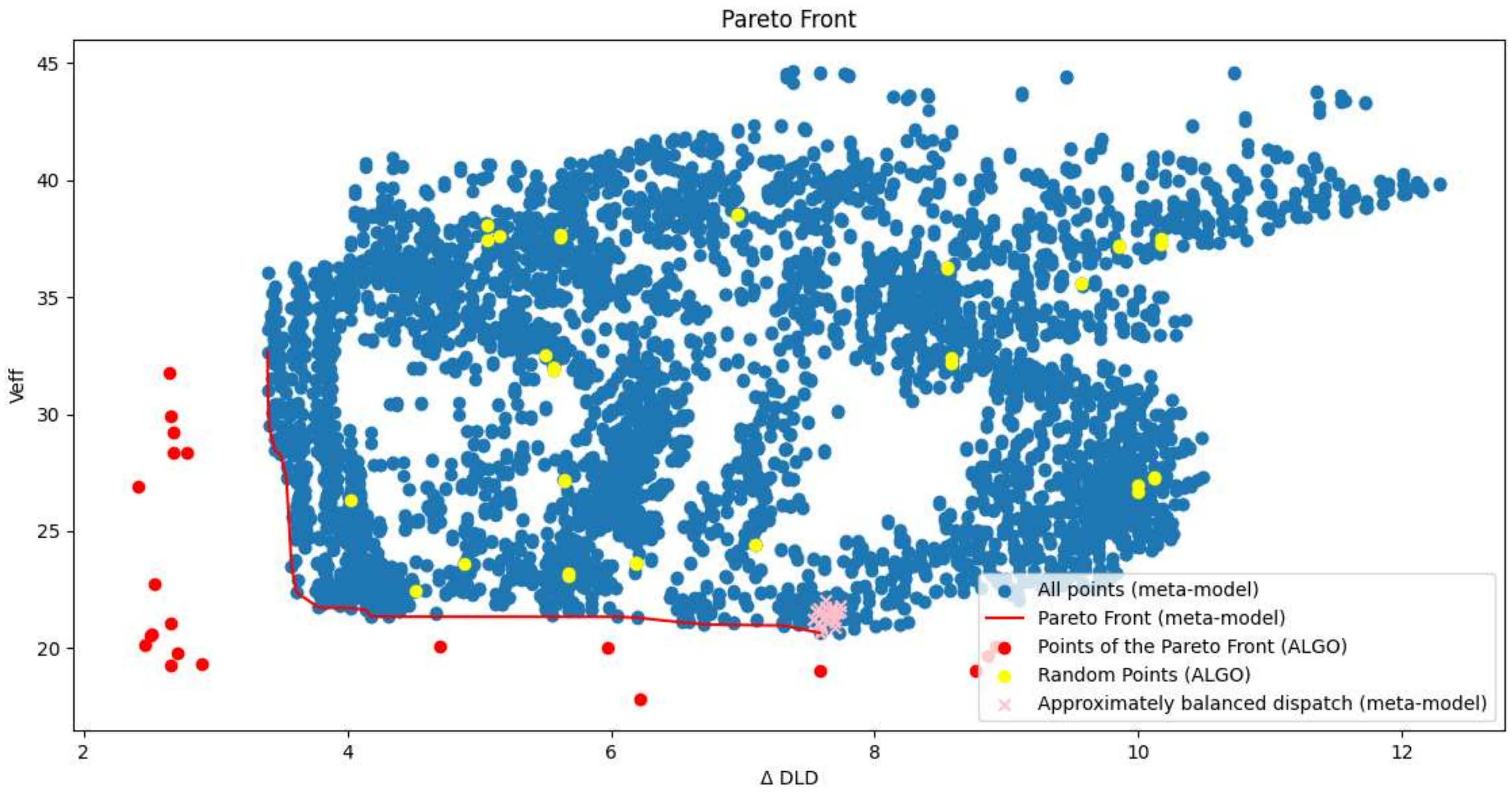
Goal: Dispatching a variable load among multiple reactors

Cost-functions for the optimization: the time derivatives of the effluent volume and of the distance to the right-side limit on the maneuvering diagram.

These two observables are negatively correlated, so there is a need to resort to a pareto front

Pareto front = The set of all points for which there are not other points performing better on both observables.

OUR WORK IN REACTOR PHYSICS

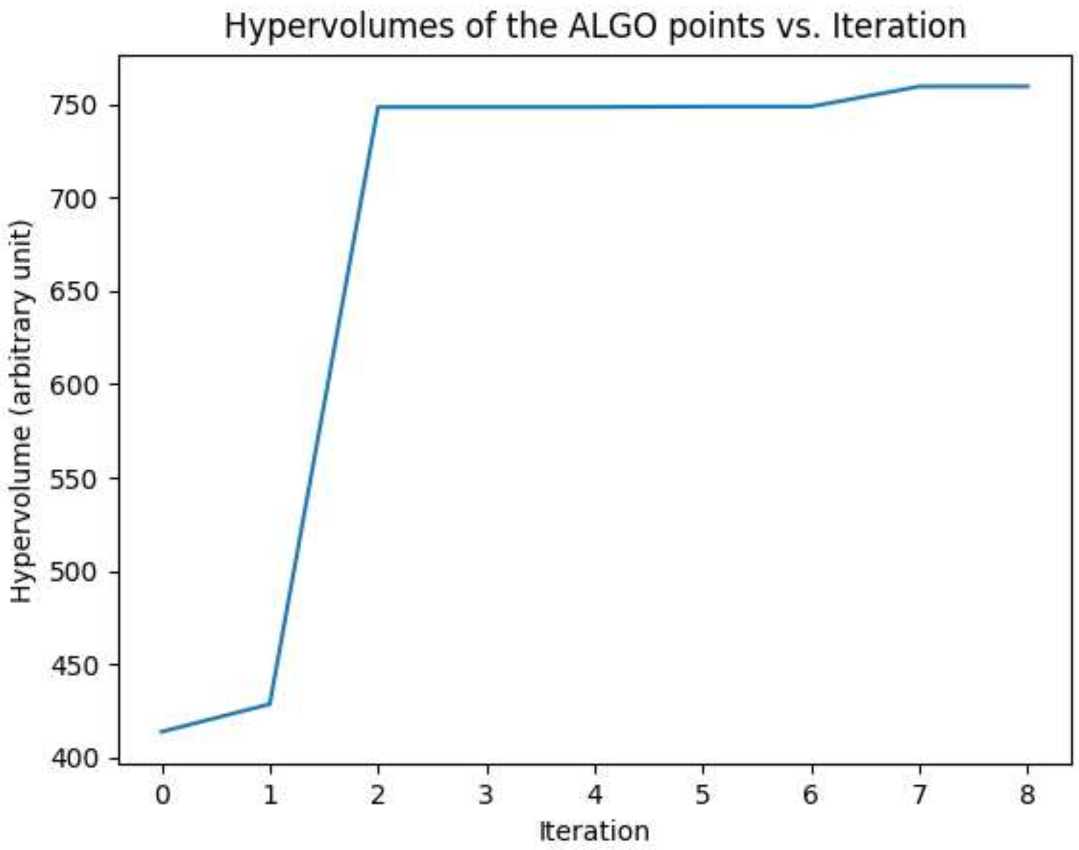


- 2-reactor and 3-reactor dispatch problems easily solved to match 72h of average daily load (with a grid-search with a discretization step of 1% on the electrical power)
- The shape of the Pareto front is conserved
- Conservative solution (in so far as the front re-calculated by ALGO dominates the front of the meta-model)
- In this specific case, the problem is partially solved for any number of reactors
- Improvable results despite due to bias of the training database and possibly due to the iregularity of ALGO

→ Need for coupled optimization

OUR WORK IN REACTOR PHYSICS

The coupled optimization helps improving the results:



We are still in the process of comparing these solutions to the ones created by previously existing method.

However, no other optimizationmethod should perform better than ours for more than 4 or 5 reactors, given that the search space becomes exponentially big.

OUR WORK IN REACTOR PHYSICS

Some other notable things we worked on in the reactor physics part of the PhD:

- **We co-developed and contributed to the ALGO load-follow simulation code**
- **We improved the quality of the input data of our neutronics core calculation with lattice calculation for MOX fuel with environment (this also allowed us to account for Tritium)**
- **We developed a model of the primary effluent treatment circuits, to be able to identify: a filled effluent tank, and the amount of Tritium in the tanks.**
- **We developed a 1D-model to quickly predict Xenon oscillations in a reactor core.**

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OUR WORK IN ECONOMICS

NOTHING SO FAR …

Our ideas, roughly:

-Robustness study

-Trying to identify possible future bottlenecks for flexibility of NPPs

-Studying cost gains with our improved maneuverability strategies

-Estimating the time and cost of possible adaptations of the nuclear fleet or of the change of maneuvering strategies vs. the cost of doing nothing

…

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WHAT IS NEXT?

- **Finishing comparing our optimization method with previously existing ones**
- **Try to perform the optimization itself with a different alogirthm (e.g. evolutionary algorithm)**
- **Findind a trade-off between accuracy and calculation time to use our meta-model to write the constraints in a MILP algorithm**
- **Further validation of our 1D-model for Xenon Oscillations**
- **Identifying limiting situations in the dispatch problem (e.g. by exploring other parameters like the temperature and mass flow rate of the cold source, high burnup of the fuel…)**
- **Estimating the impact of load-follow on the fluence on the core vessel**
- **Improve our model for the tertiary circuit (especially for the condenser and for cooling towers)**
- **Coming to Nantes to work on the technical economics aspects with Nicolas Thiollière!**

THANK YOU FOR YOUR ATTENTION