Modelling Flexible Nuclear Generation in Low-Carbon Power Systems: *A Stochastic Dual Dynamic Programming approach*

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Introduction

Nuclear power and flexibility

Motivation

- With rising share of Renewables, **flexibility is needed**

- Nuclear is a low-carbon and dispatchable energy source… but it comes with **specific technical constraints**.

- Some nuclear intensive systems already use nuclear to dampen variations of supply and/or demand (France). ***To what extent ?***

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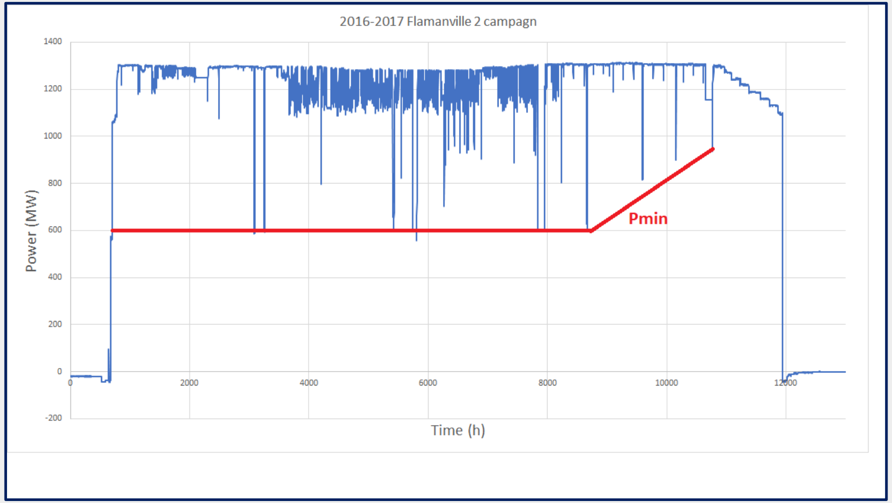
Nuclear Power plants

Specific constraints on flexibility

Constraints



Nuclear is submitted to several constraints narrowing its flexibility potential, mainly **Mechanical stress** & **Atomic considerations (Xenon effect)**.

Number of cycling operations limited to **200 per year**, 5 per week and 2 per day (IAEA).

Constraints are enounced as limitation on virtual **stocks**

Relevant *literature*

Previous works on Nuclear flexibility generally use MILP to model cycling operations in a deterministic framework.

- In Loisel *et al.* (2018), the number of cycles is limited and the whole European system is depicted.
- In Jenkins *et al.* (2018), ramping constraints and moments of imposed stable power are modelled.
- In Cany *et al.* (2016), different scenarios of energy production are compared and nuclear flexibility is modelled through ramping rates only.
- Lynch *et al.* (2022) accounts for the change in flexibility for each reactor induced by atomic considerations.

No stochasticity involved !

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Modelling *approach*

SDDP for modelling opportunity costs

SDDP *literature*

The Stochastic Dual Dynamic Programming algorithm, originally developped by Pereira & Pinto (1991) for **hydropower** schedulling purposes.

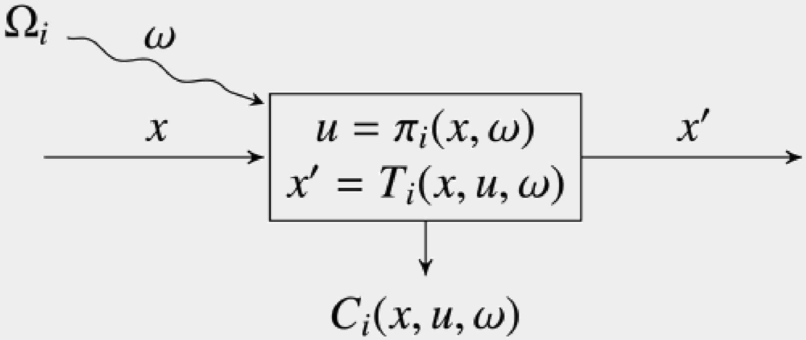
Benders cut to fasten SDP algorithms, suited for **storage management** (water, batteries… a stock of nuclear cycling operations ?)

Recent application: Papavasiliou et al. (2018) for real-time storage dispatch under Renewable supply uncertainty.

How to use a stock *optimally* ?

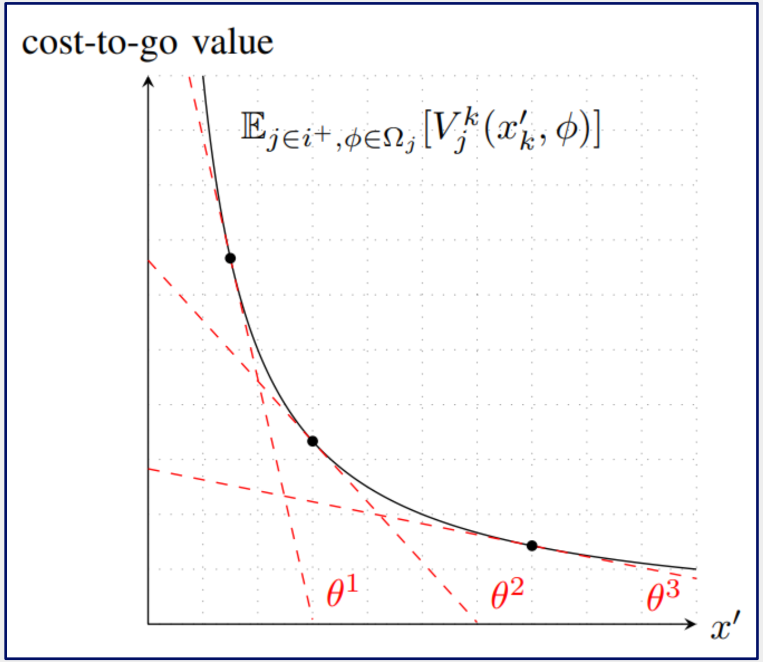
$$\underset{\pi}{\text{minimize}} \quad \mathbb{E}_{i\in\mathbb{R}^+,\omega\in\Omega_i}(V_i^\pi(x_0,\omega))$$

$$\begin{aligned} V_i^\pi(x,\omega) = \min_{x,x',u} \quad & C_i(x,u,\omega) + \mathbb{E}_{j\in i^+,\phi\in\Omega_j}(V_j(x',\phi)) \\ \text{subject to} \quad & x' = T_i(x,u,\omega), \\ & u = \pi_i(x,\omega) \in U_i(x,\omega) \end{aligned}$$



How to use a stock *optimally* ?

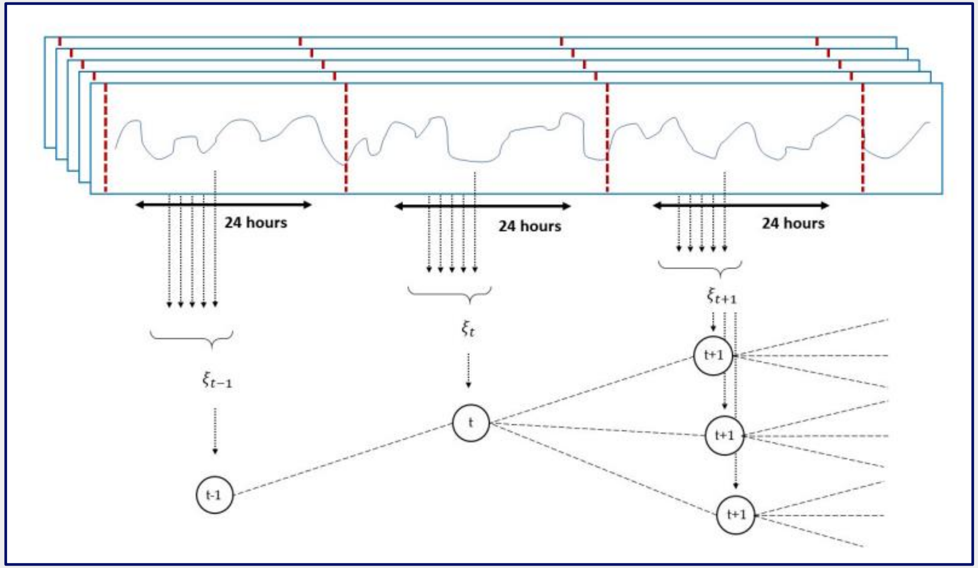
- Approximation of the cost-to-go term with **Benders cuts**
- Back & Forth iterations for building the **convex enveloppe** of the function
- Once training ends, we get a « **policy** » to be run over hundreads of simulations



Application 04

What benefits from an increased nuclear flexibility of French reactors in 2035 ?

French electric *system*



365 nodes

Day ahead modelling for uncertainty

8760 Time steps

Within a day, hourly resolution

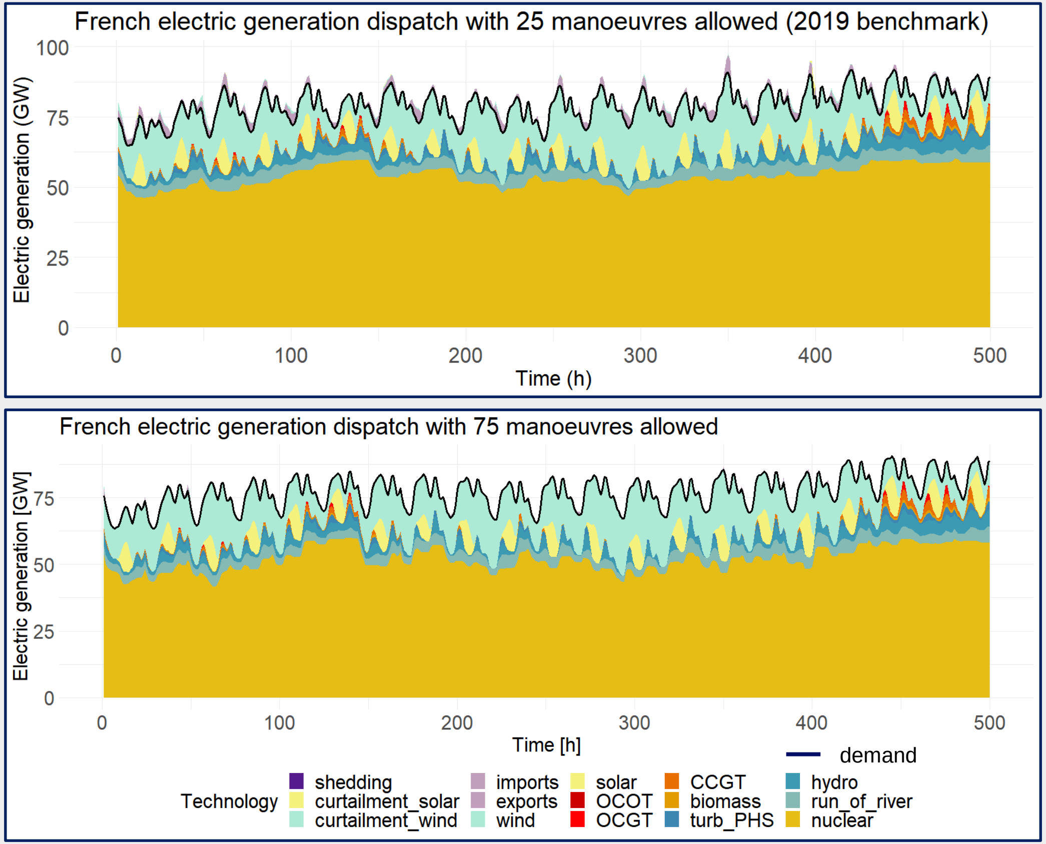
9 technologies

One cluster for nuclear, solar and wind exogenous

5 Possible profiles

Each day, we pick out time series from a set of 5 renewables profiles

Power *dispatch*



- **2035**, French TSO projections
- Curtailment is clearly **reduced**
- With 75 manœuvres, nuclear **dampens solar variations**

Main *results*

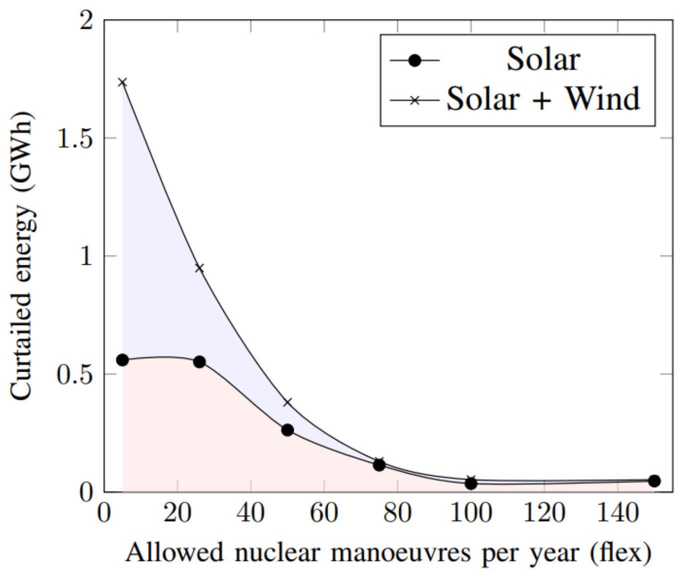
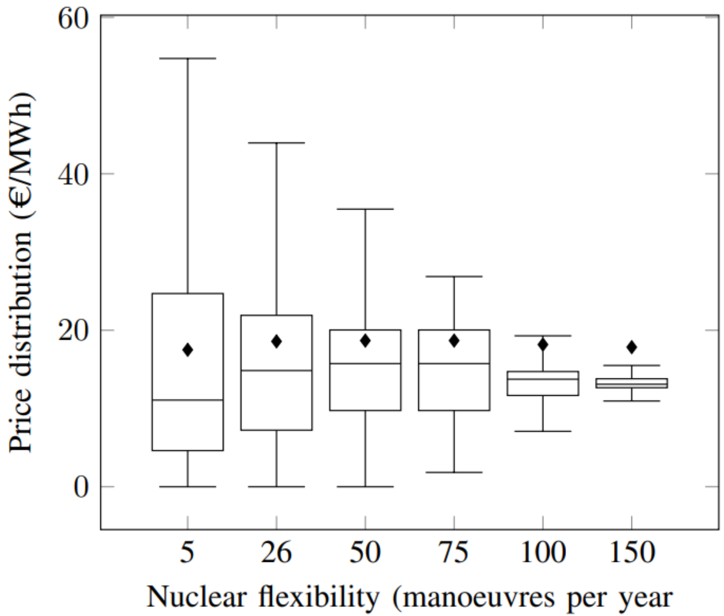


Fig. 4: Mean level of curtailed energy from VRE, over 500 simulations



For the sake of readability, extreme values are not displayed

Main *results*

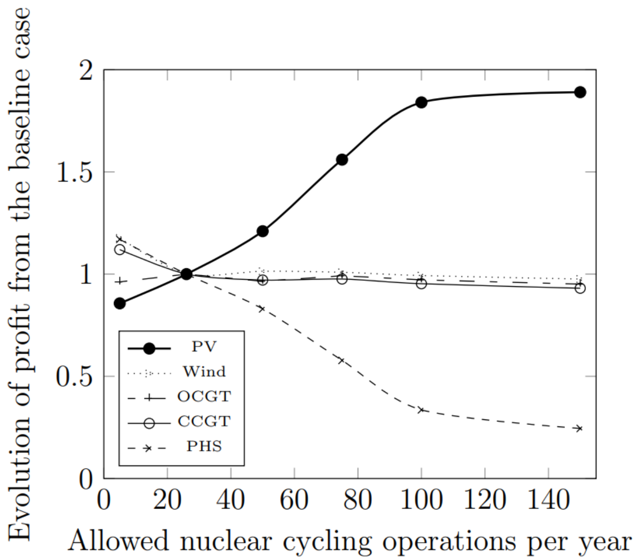
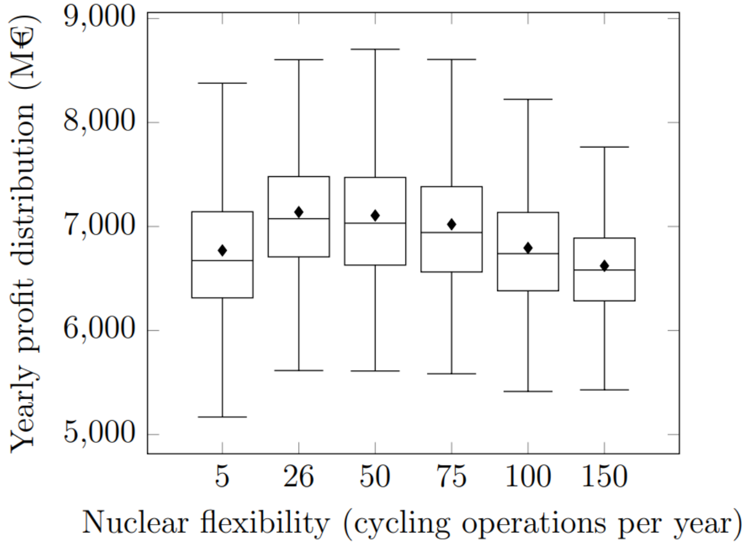


Figure 8: Mean level of profit for different technologies, over 500 simulations

Figure 9: NPPs profit distribution for different cycling constraints



Conclusion

& further work

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French nuclear flexibility by 2035

Technically feasible

- The need in cycling would be no more than **80-100/year**
- SDDP can be used for dispatching the cycling operations

Economically viable

- Nuclear profits plateau between **26-50 cycles**
- Solar profits **x1,5** for the same cycling range


Thanks
Questions ?

Further material

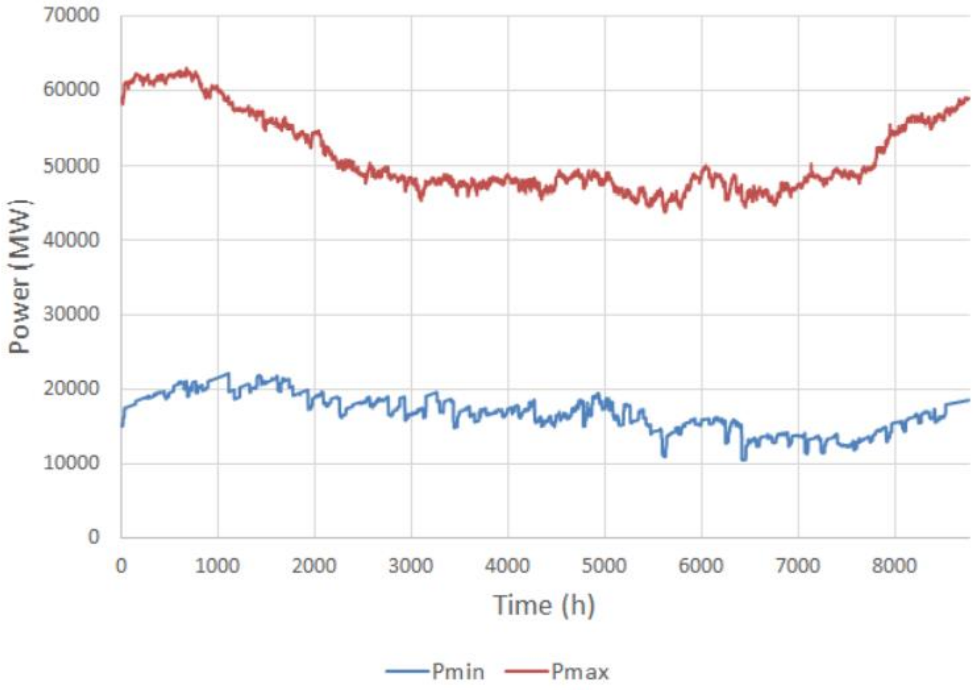

Fig. 3: Respective minimal and maximal output power for nuclear power, based on 2017,2018 and 2019 data

Further material

Technology	Capacity (GW)	Derating factor	Variable cost (€/MWh)
Solar	50	Ø	0
Wind	50	Ø	0
Hydro reservoir	8	0.86	0
PHS	7	0.54	0
Nuclear	63	$f(t)$	14
Biomass	2	0.9	99
CCGT	6.6	0.88	100
OCGT	4.7	0.94	151
OCOT	1	0.94	258
Imports	25	0.5	268
VoLL	Ø	Ø	10,000

TABLE II: Generation capacity installed in France in 2035, by technology

Further material

Scenario	Lower bound (G€)	Mean objective value (G€)	discrepancy
flex = 5	4.85	4.87	0.41%
flex = 26	4.54	4.55	0.29%
flex = 50	4.40	4.40	0.10%
flex = 75	4.31	4.33	0.38%
flex = 100	4.28	4.29	0.12%
flex = 150	4.27	4.27	-0.19%

TABLE III: Convergence data for different flexibility levels

Further material

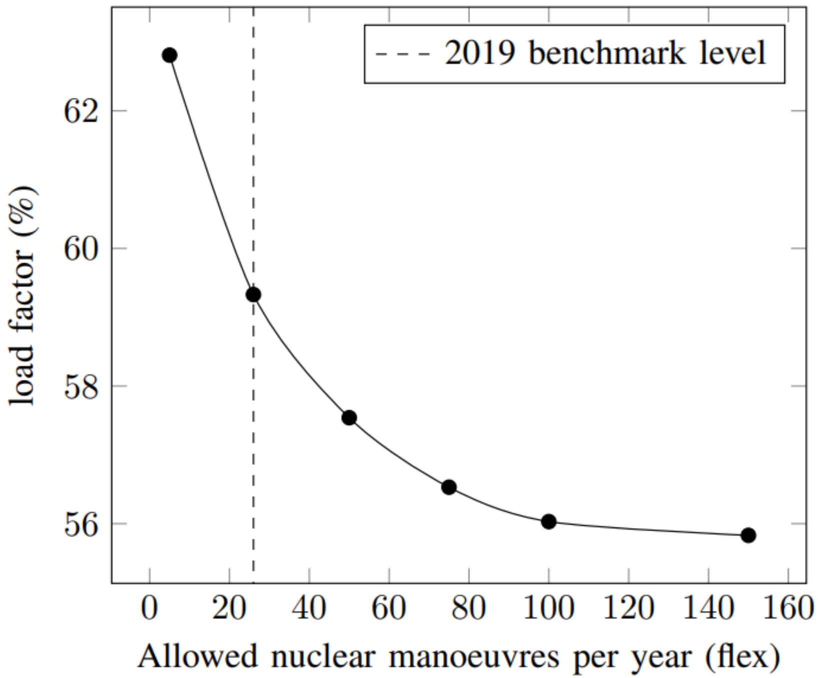

Fig. 5: Average load factor of NPPs as a function of the number of allowed manoeuvres