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

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01

# Introduction

Nuclear power and flexibility

# Motivation

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- 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 ?***





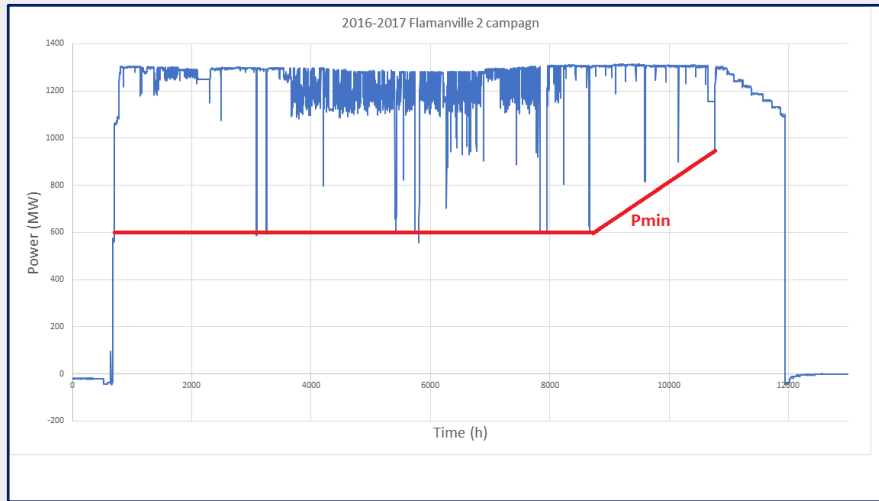


02

# 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

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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 !**



03

# Modelling *approach*

SDDP for modelling opportunity costs



# SDDP literature

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The Stochastic Dual Dynamic Programming algorithm, originally developed by Pereira & Pinto (1991) for **hydropower** scheduling 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.



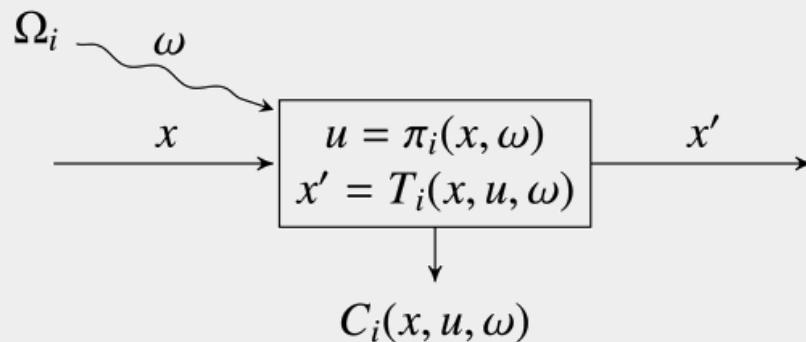
# How to use a stock optimally ?

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

$$V_i^\pi(x, \omega) = \min_{x, x', u} C_i(x, u, \omega) + \mathbb{E}_{j \in i^+, \phi \in \Omega_j}(V_j(x', \phi))$$

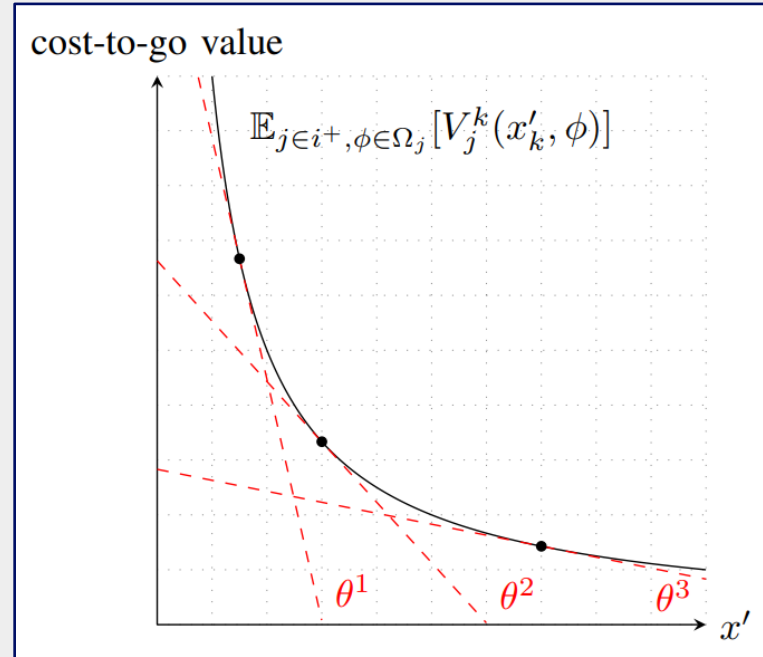
subject to

$$x' = T_i(x, u, \omega),$$
$$u = \pi_i(x, \omega) \in U_i(x, \omega)$$



# How to use a stock optimally ?

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



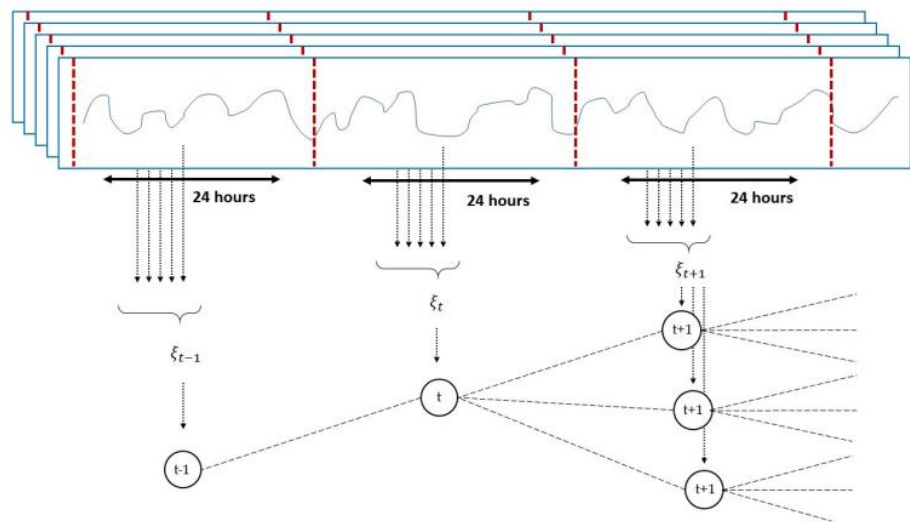


# *Application* 04

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



# French electric system



365  
nodes

Day ahead modelling  
for uncertainty

9  
technologies

One cluster for nuclear,  
solar and wind  
exogenous

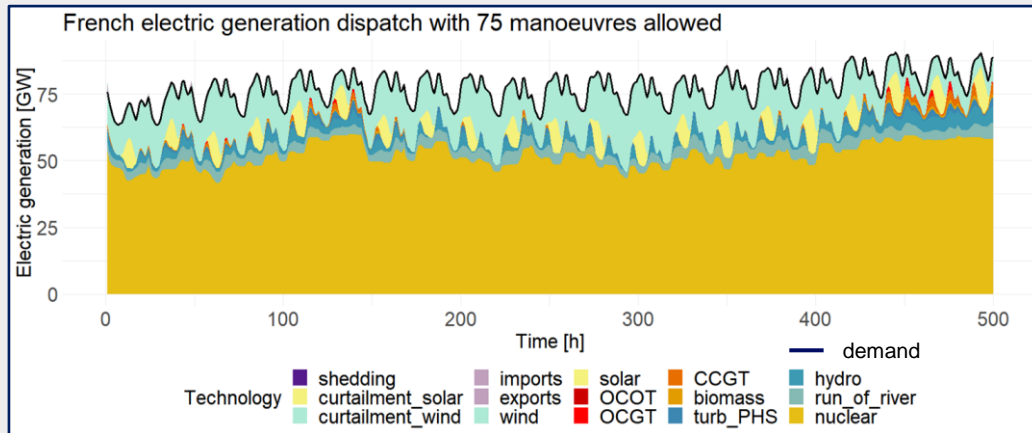
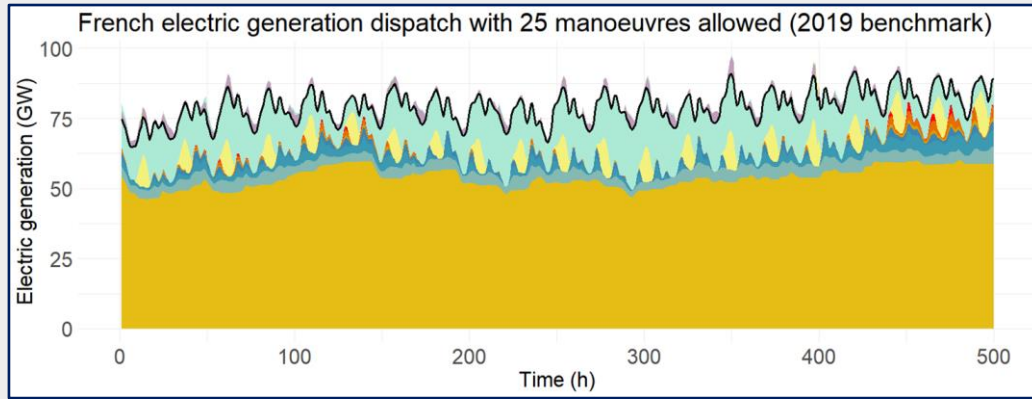
8760  
Time steps

Within a day, hourly  
resolution

5  
Possible profiles

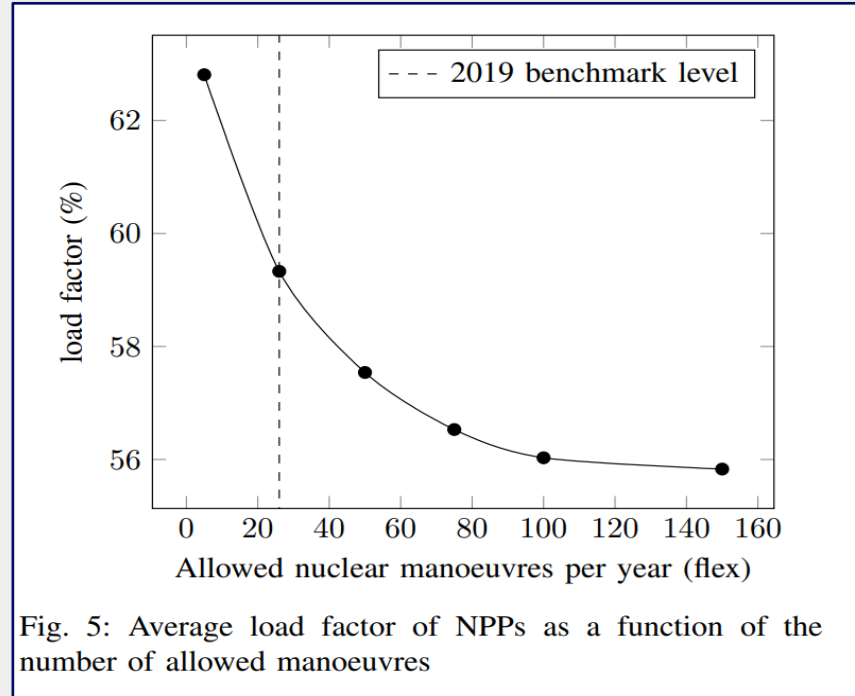
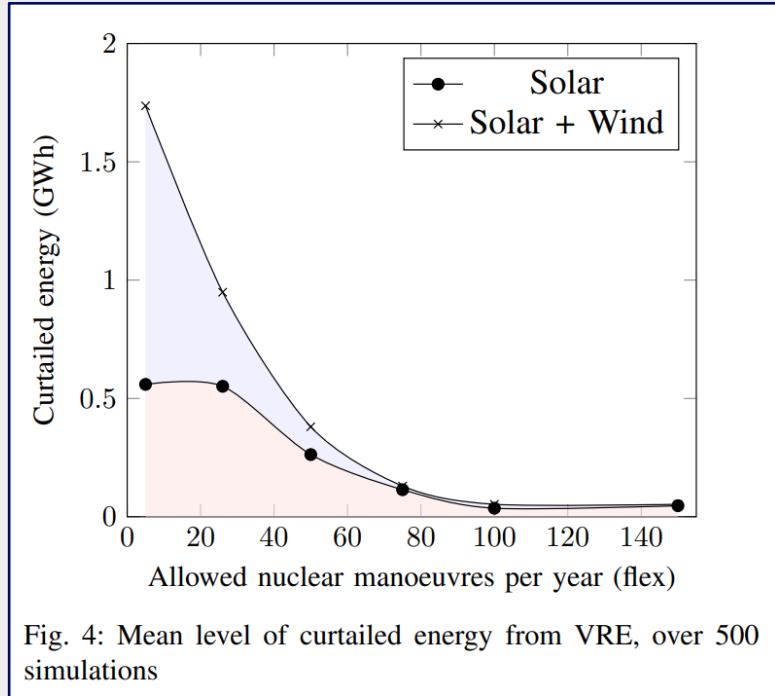
Each day, we pick out  
time series from a set of  
5 renewables profiles

# Power dispatch



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

# Main results



# Main results

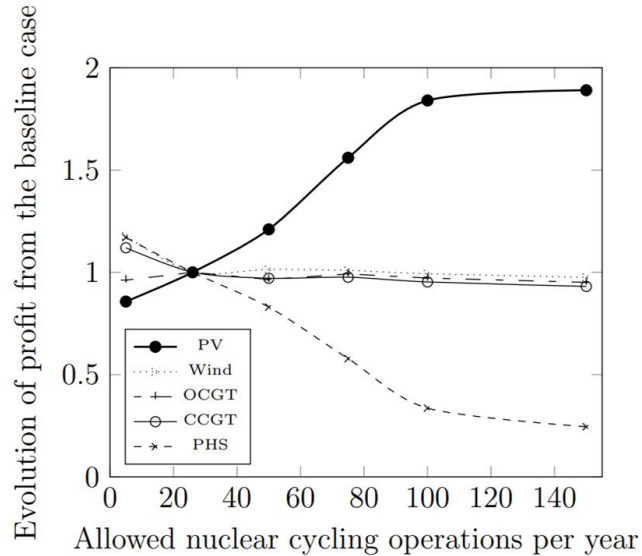
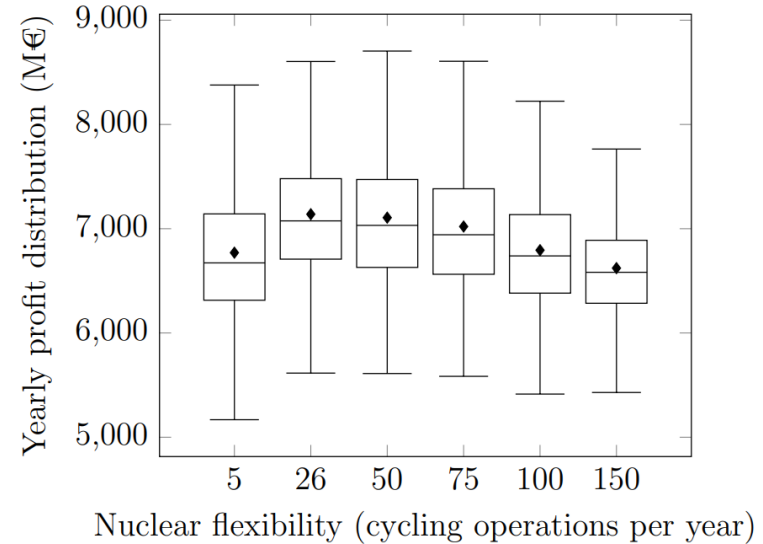


Figure 8: Mean level of profit for different technologies, over 500 simulations

Figure 9: NPPs profit distribution for different cycling constraints





A landscape photograph with a blue color overlay. In the background, a hill is topped with several wind turbines. The foreground shows a body of water reflecting the sky. A white vertical line is on the left side, and a white horizontal line is near the bottom.

# *Conclusion*

& further work

# 06

# French nuclear flexibility by 2035

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## Technically feasible

- No need for more than 100 cycles per 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

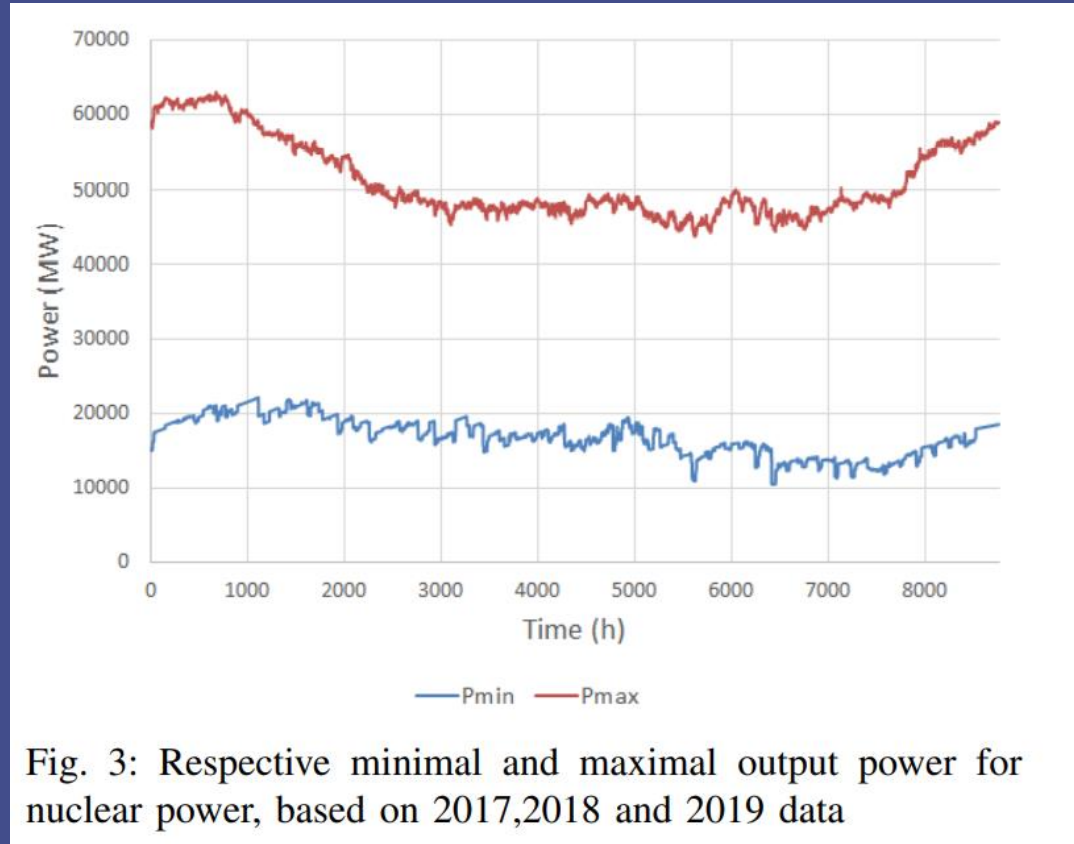


# Thanks

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Questions ?

# Further material





## Further material

Technology	Capacity (GW)	Derating factor	Variable cost (€/MWh)
Solar	50	∅	0
Wind	50	∅	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	∅	∅	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