Dancing with the wind: economic modeling of flexibility in low-carbon power systems

Ange BLANCHARD

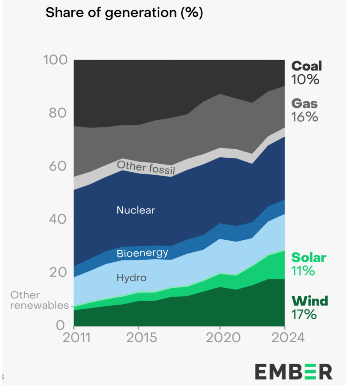
Supervisors: Olivier MASSOL, Sébastien LEPAUL

CentraleSupelec, Climate Economics Chair

October 7, 2025

Context: A rapid growth of PV and Wind production

- Between 2007 and 2023, emissions from the EU power sector halved (-50%)



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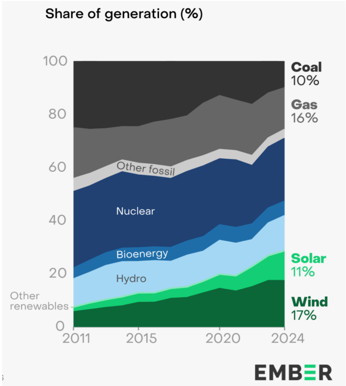

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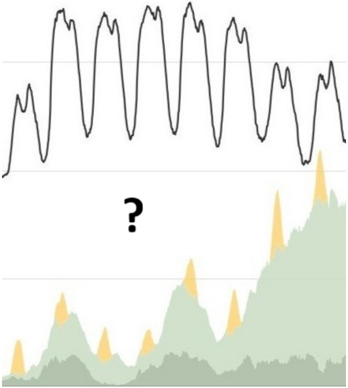
- *"What if the sun doesn't shine and the wind doesn't blow?"*



Flexibility: a definition

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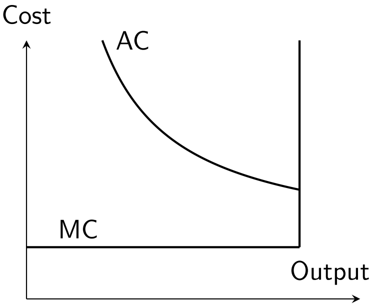

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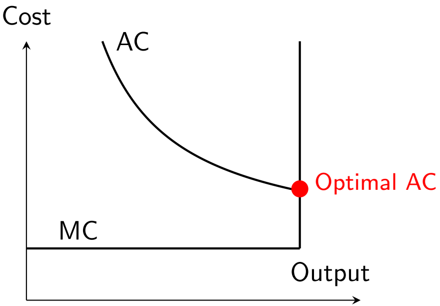

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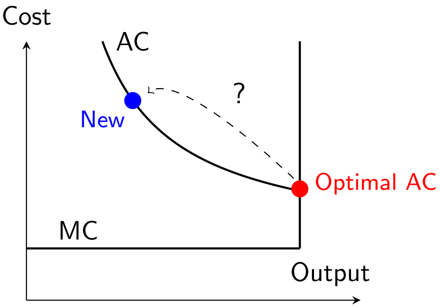

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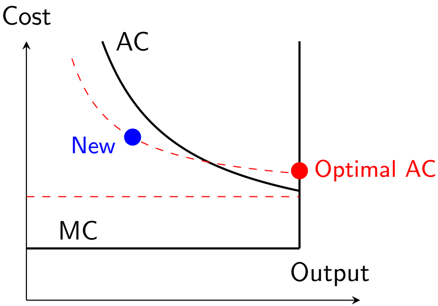

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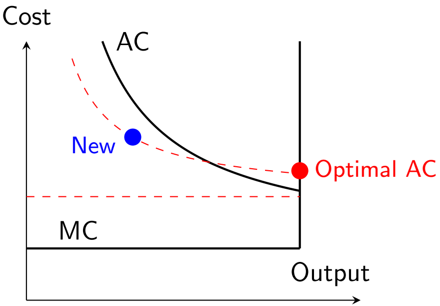
- More Renewables ⇒ higher flexibility needs



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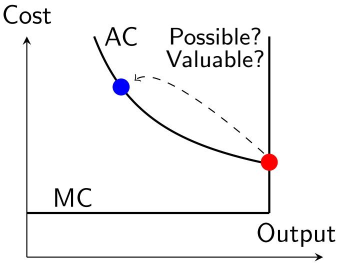
3. Are batteries and hydrogen complements or substitutes in future low-carbon energy systems?
4. What investment strategy to make the hydrogen economy more resilient to foreign dependency?

Chapter 1

The Value of Nuclear Power Plants' Flexibility: A Multistage Stochastic Dynamic Programming Approach

Co-authored with: Olivier MASSOL

Published in: *European Journal of Operational Research*, 2025



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- Renewables and nuclear can coexist **if nuclear is flexible enough** (Green and Léautier 2015)

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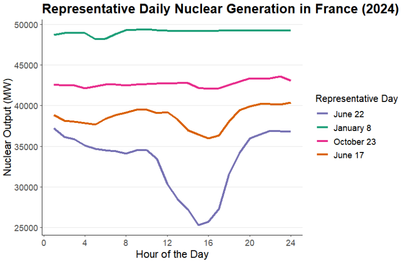

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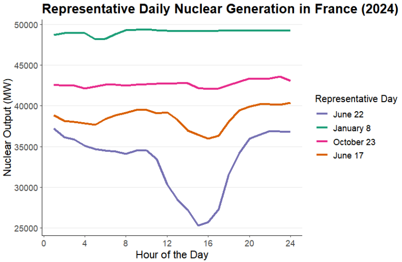

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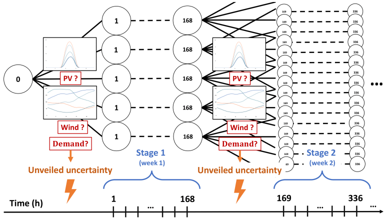
Contribution

New modeling of nuclear flexibility: a scarce stock to be dispatched optimally under uncertainty.

Numerical implementation

Stochastic Dynamic Programming: one-year horizon, 52 stages w. Remaining nuclear flexibility l_w, nuclear output q_w, and uncertainty ξ_w. The stage cost is $C_w(l_{w-1}, q_w, \xi_w)$.



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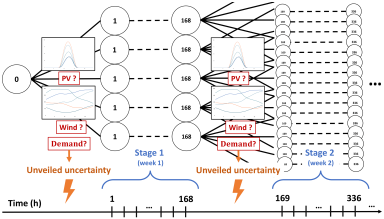

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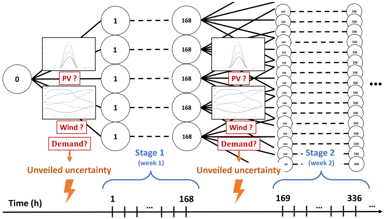
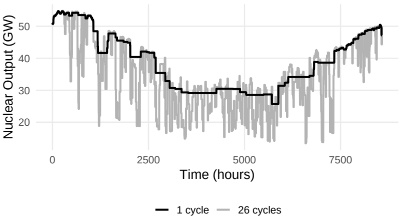


- Stochastic Dual Dynamic Programming algorithm ▸ SDDP
- Application on the French system in 2035
- Different scenarios of nuclear flexibility

Results

French power system in 2035: Nuclear, VREs, Hydro, Gas, Biomass. Current nuclear flexibility = **26 cycles/year**



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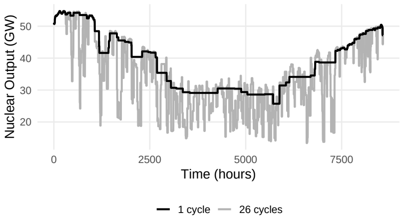
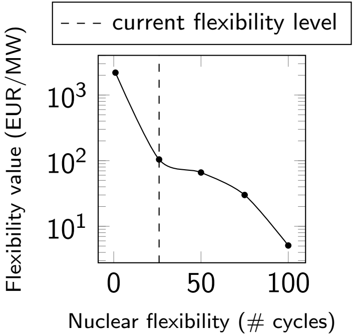
Marginal value of flexibility: μ (scarcity)

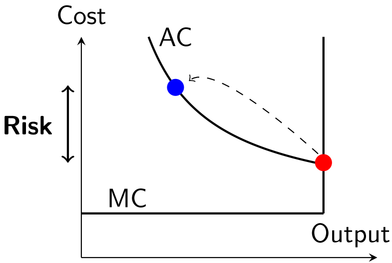




Chapter 2

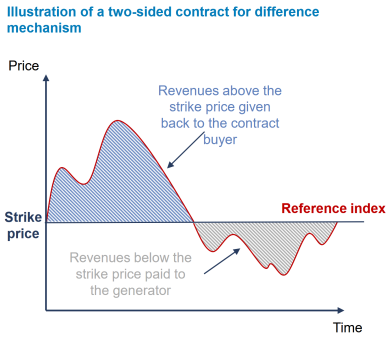
Contracts-for-Difference and Nuclear Flexibility: A Path to Complementing Renewables

Co-authored with: Ramteen SIOSHANSI



Motivation: from Econ 101 to Econ 102

- Nuclear energy can be a sound option. Still, it doesn't develop.
- Market failures (Dimanchev et al. 2024) $\Rightarrow$ public support (CfDs?)



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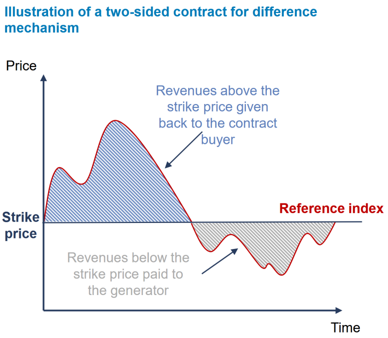

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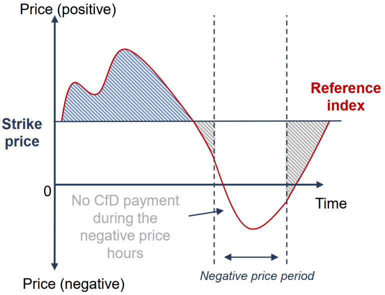
- Other designs exist, are they better suited? (Newbery 2023).

Contribution

First study on nuclear CfDs, a topical issue (Hinkley Point C, Dukovany 5, EPR2)

Illustration of a two-sided contract for difference mechanism with negative-price interruption



Model & Intuitions

- **Equilibrium model:** A nuclear monopolist maximizes profits, anticipating competitors' behavior. MPEC
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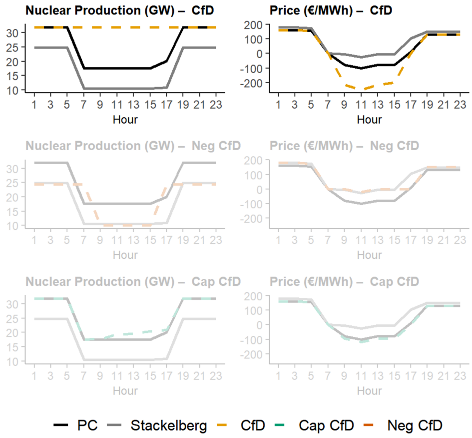
Classical CfD	Negative-price CfD	Capability CfD
Strike price for actual production: $s \cdot q_t$	No payment when negative market price: $\mathbf{1}_{p_t \geq 0} \cdot s \cdot q_t$	Non-production based: $s \cdot Q$

Results



Nuclear Dispatch and prices for different CfD designs

- Classical CfD: Oversupply ⇒ yearly price average -30% compared to optimum

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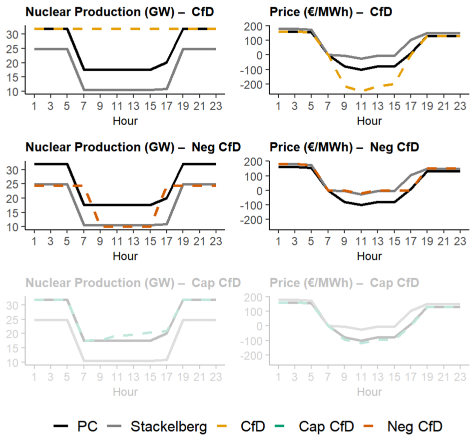

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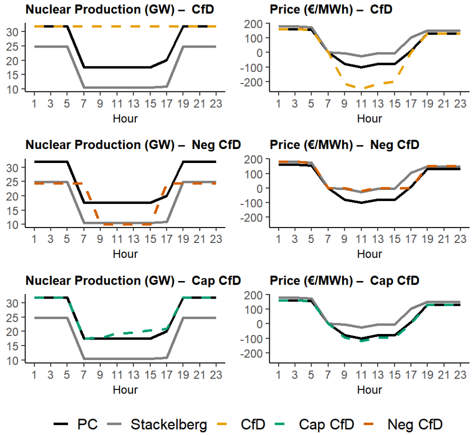

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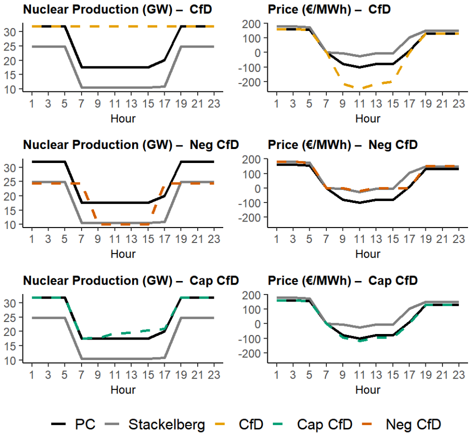

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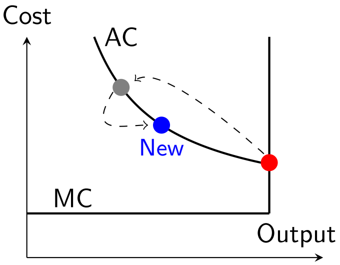
Policy Implications

Design nuclear support as **capacity payments** rather than energy-based to preserve dispatch efficiency.

Chapter 3

Battery and Hydrogen Storage: Complements or Substitutes? A German 2035 Case Study

Co-authored with: Camille MEGY



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- Different storage options for different needs (Dowling et al. 2020)

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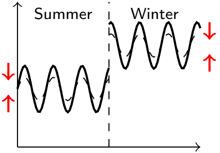

BESS ↓ daily spread

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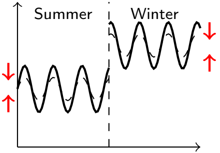

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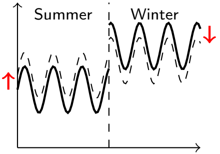

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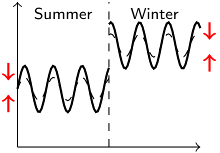
- **UHS** (Hydrogen): Energy cost: ↓, Power cost: ↑ (Petkov and Gabrielli 2020)
- Complements (Virah-Sawmy, Beck, and Sturmberg 2025), or not ? (Loschan, Auer, and Lettner 2024)



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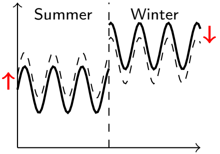
Research gap

Are BESS and UHS complements or substitutes? What is their elasticity of substitution?



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The Morishima Elasticity of Substitution

2 inputs can be used to produce "flexibility": UHS and BESS.
Morishima elasticity of substitution:

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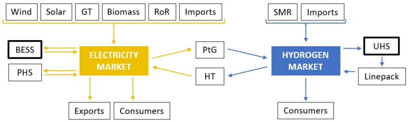

- Numerical modeling of the German energy system

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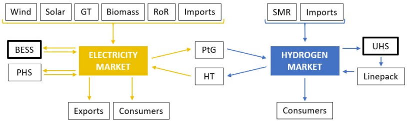

- Numerical modeling of the German energy system
- BESS and UHS investment for different cost assumptions
- Regression: log-capacity against log-cost ratios ▸ Regression

Results

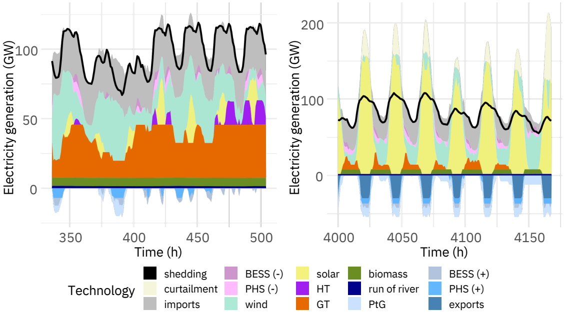

Figure: Electric generation for a typical winter week (left) and summer week (right)

- The two options substitute each other: $\sigma > 0$

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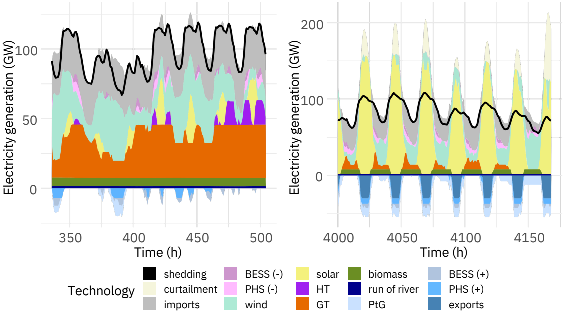

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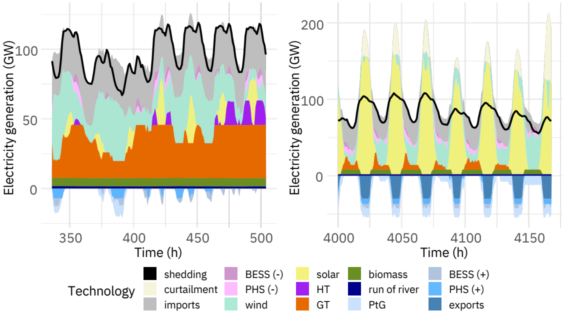

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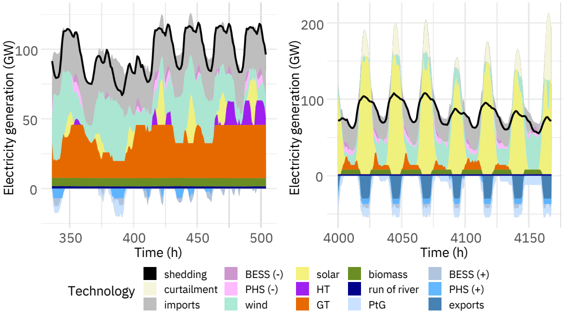

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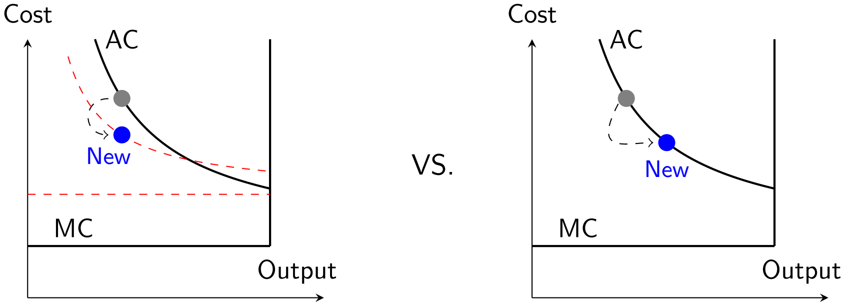
- New challenge for H_2: competition from BESS

Chapter 4

Strategic Investments: Electrolysis vs. Storage for Europe's Energy Security in the Hydrogen Era

Solo-authored

Published in: *Energy Policy*



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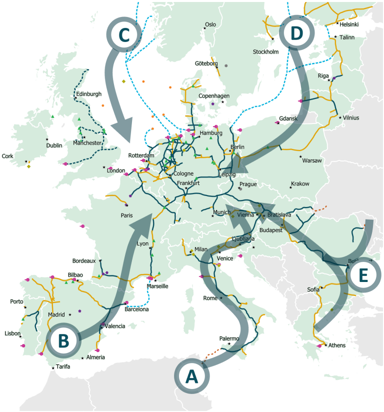

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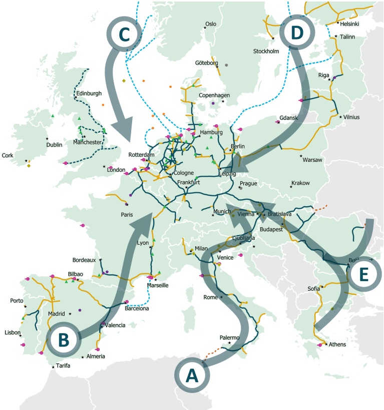
- Historical practice for Oil & Gas: stockpilling. (Chao and Manne 1983) Would it be relevant for H_2?



Motivation

- The EU to import a large part of its H_2 consumption (Dejonghe, Van de Graaf, and Belmans 2023)
- Hydrogen imports to take over the current dependence on gas imports (Carlson, Pickford, and Nyga-Łukaszewska 2023)
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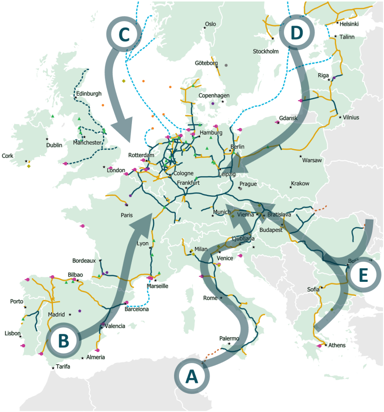
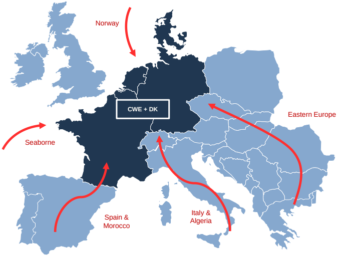


Research question

What optimal hedging strategy for the European H_2 import dependency?

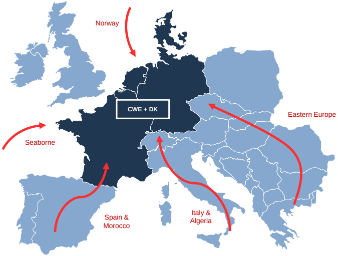
Numerical Model

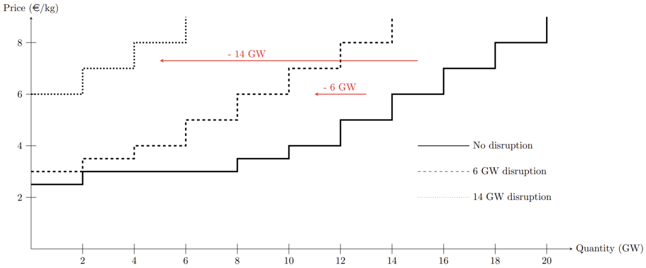
- SDDP algorithm, Central Western Europe, One-year horizon, hourly dispatch
- Endogenous PtG (electrolysis) and UHS (H_2 storage) investment



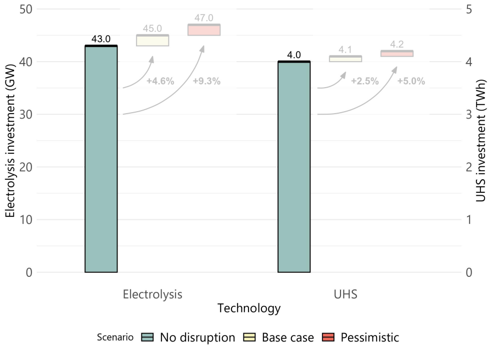
Numerical Model

- SDDP algorithm, Central Western Europe, One-year horizon, hourly dispatch
- Endogenous PtG (electrolysis) and UHS (H_2 storage) investment
- Markov chain: 3 states of the world with transition probabilities



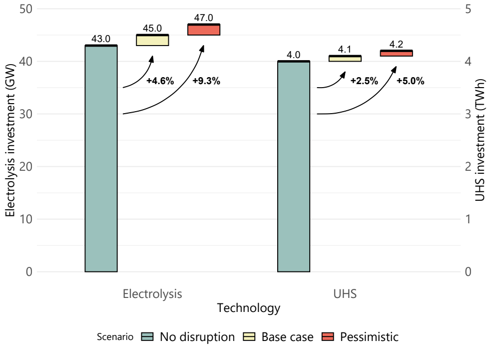


Results



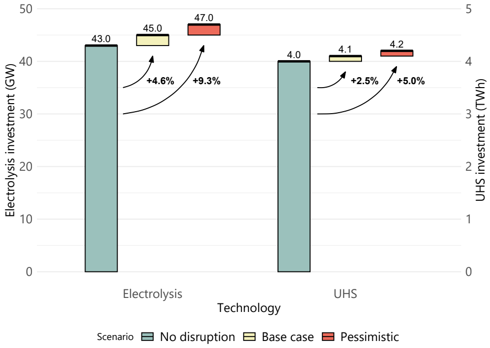
50
40
30
20
10
0
5
4
3
2
1
0
43.0
45.0
47.0
4.0
4.1
4.2
+4.6%
+9.3%
+2.5%
+5.0%
Electrolysis investment (GW)
UHS investment (TWh)
Electrolysis
UHS
Technology
Scenario
No disruption
Base case
Pessimistic

Results



- **Both UHS and electrolysis are helpful:** Complementarity between the two
- **Electrolysis is more efficient:** Twice as much strategic investment as UHS, 95% of the budget

Results



- **Both UHS and electrolysis are helpful:** Complementarity between the two
- **Electrolysis is more efficient:** Twice as much strategic investment as UHS, 95% of the budget
- **Public support:** Private investments will undershoot optimal investment levels (energy security as a public good). Electrolysis should be the priority.

Conclusions

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- Flexibility used to be an abundant by-product of power generation – decarbonization makes it a scarce resource

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- Flexibility used to be an abundant by-product of power generation – decarbonization makes it a scarce resource
- Market flaws become more prevalent
- Old and new modeling approaches (Micro, IO, Markov chains, SDDP, MPEC)
- Key insights:
  1. Nuclear flexibility has value
  2. Incentives matter today more than ever
  3. Electricity can be (partially) stored, challenging peaking plants
  4. Energy security can be (partially) treated with domestic resources

Policy Implications & caveats

Strike the right balance between risk hedging and incentives.

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Grids

How to get flexibility signals at the grid level? (nodal/zonal)

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Demand

How can flexibility foster electrification? (V2G, HP)

Policy Implications & caveats

Strike the right balance between risk hedging and incentives.

Grids

How to get flexibility signals at the grid level? (nodal/zonal)

Demand

How can flexibility foster electrification? (V2G, HP)

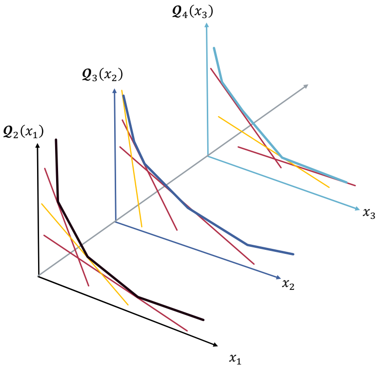
Market design

Can an efficient market design be enough? (entry barriers, modularity, transaction costs)

Thank you

Questions from the Jury

Appendix: SDDP



Each iteration of forward/backward pass adds a Benders cut to the “policy” function, and the approximation of the true cost-to-go function ameliorates.

▸ Main slide

Appendix: MPEC

$$\max_{q_t^{nuc}} \quad \Pi(q_t^{nuc})$$

$$\text{s.t.} \quad q_{min}^{nuc} \leq q_t^{nuc} \leq Q_{nuc} \quad \forall t \tag{1}$$

$$\sum_t |q_{t+1}^n - q_t^n| \leq L \tag{2}$$

Market clearing

$$0 \leq -a_t + bd_t + p_t \perp d_t \geq 0 \quad \forall t \tag{3}$$

$$d_t - q_t^g - q_t^{PV} - q_t^{wind} - q_t^n - q_t^{hydro,bio} = 0, \; p_t \text{ free}, \quad \forall t \tag{4}$$

PV, Wind, and Gas

$$0 \leq e + fq_t^g - p_t + \mu_t^g \perp q_t^g \geq 0 \quad \forall t \tag{5}$$

$$0 \leq -q_t^g + q_{max}^g \perp \mu_t^g \geq 0, \quad \forall t \tag{6}$$

$$0 \leq -q_t^{PV} + q_{max}^{PV} \perp \mu_t^{PV} \geq 0, \quad \forall t \tag{7}$$

$$0 \leq -q_t^{wind} + q_{max}^{wind} \perp \bar{\mu}_t^{wind} \geq 0, \quad \forall t \tag{8}$$

$$0 \leq q_t^{PV} - q_{min}^{PV} \perp \rho_t^{PV} \geq 0, \quad \forall t \tag{9}$$

$$0 \leq q_t^{wind} - q_{min}^{wind} \perp \rho_t^{wind} \geq 0, \quad \forall t \tag{10}$$

$$0 \leq -p_t + \mu_t^{PV} - \rho_t^{PV} \perp q_t^{PV} \geq 0 \quad \forall t \tag{11}$$

$$0 \leq -p_t + \mu_t^{wind} - \rho_t^{wind} \perp q_t^{wind} \geq 0 \quad \forall t \tag{12}$$

Storage

$$0 \leq \nu_{t-1} - \nu_t + \mu_{s,t} \perp S_t \geq 0, \quad \forall t > 1 \tag{13}$$

$$0 \leq c_s + p_t - \eta\nu_t + \mu_t^{stor,+} \perp q_t^{stor,+} \geq 0, \quad \forall t \tag{14}$$

$$0 \leq c_s - p_t + \nu_t + \mu_t^{stor,-} \perp q_t^{stor,-} \geq 0, \quad \forall t \tag{15}$$

$$S_{t+1} - S_t - \eta q_t^{stor,+} + q_t^{stor,-} = 0, \nu_t \text{ free} \quad \forall t < T \tag{16}$$

$$0 \leq -S_t + S_{max} \perp \mu_t^s \geq 0, \quad \forall t \tag{17}$$

$$0 \leq -q_t^{stor,+} + q_{max}^{stor,+} \perp \mu_t^{stor,+} \geq 0, \quad \forall t \tag{18}$$

$$0 \leq -q_t^{stor,-} + q_{max}^{stor,-} \perp \mu_t^{stor,-} \geq 0, \quad \forall t \tag{19}$$

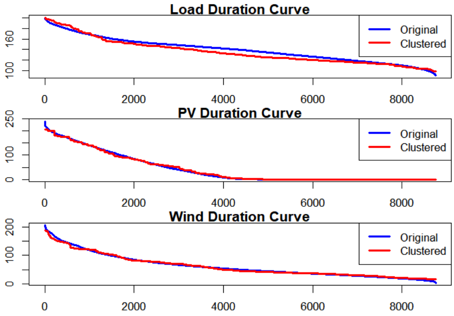
Upper-level: the nuclear operator maximizes profit.
Lower-level: the competitive market clears (Social welfare is maximized).
Lower-level problem (convex quadratic) is replaced by KKT conditions.

Main slide

Appendix: Profit functions

- Perfect Competition:
  $\Pi_{\mathrm{PC}} = \sum_t (p_t - c) q_t$
- Nuclear monopoly:
  $\Pi_{\mathrm{S}} = \sum_t (a_t - b q_t - c) q_t$
- Classical CfD:
  $\Pi_{\mathrm{CfD}} = \sum_t (s - c) q_t$
- Negative Price CfD:
  $\Pi_{Neg} = \sum_t (p_t - c) q_t + \mathbf{1}_{p_t \geq 0} \sum_t (s - p_t) q_t$
- Capability CfD:
  $\Pi_{\mathrm{Cap}} = \sum_t (p_t - c) q_t + (s - p_t) Q$

Appendix: Temporal aggregation

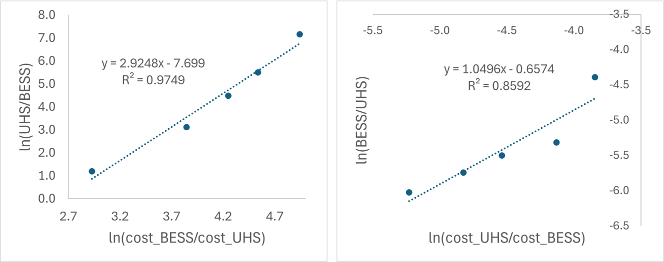


10 representative days extracted from historical data, using a clustering approach (k-medoïds)

Main slide

Appendix: Dispatch

Main slide



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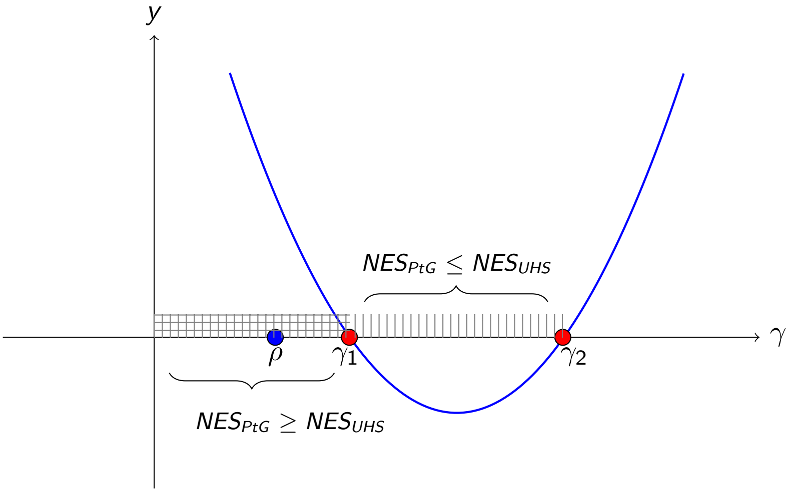

Figure: Graphical representation of the analytical result: PtG is more cost-efficient than UHS for hedging.