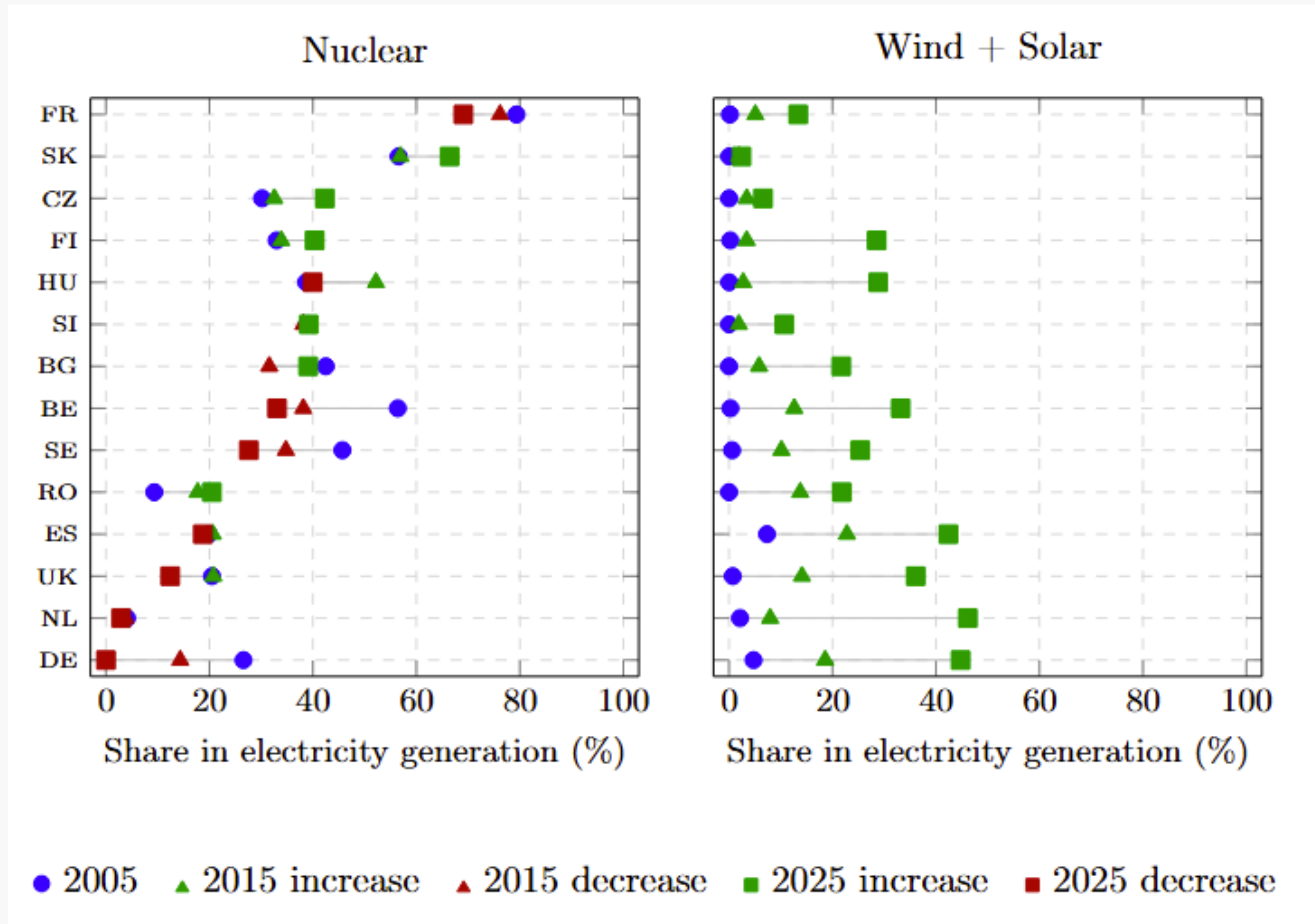


Supply (in-)flexibility in the transition toward climate-neutral power systems

Natalia Goryashchenko, Julia Grübel, Jonas Egerer

20th ENERDAY Conference, March 27, 2026, Dresden

Nuclear and RES in European countries



Nuclear fleet in EU (2025):

- 97 GW of installed capacity;
- 9% of total installed capacity;
- 23% in total electricity generation.

source: <https://ember-energy.org/>

Motivation

Europe's path to climate neutrality implies:

- Rising costs for fossil-fired power generation;
- Increasing capacity of Wind and PV;
- Increasing periods of very low electricity spot market.



Need for flexibility

Research questions:

How do assumptions on the flexibility of nuclear power plants in the low-carbon transformation of the energy system affect:

- the **supply and storage composition** and **market outcomes** in the electricity system?
- the **economics** of **existing nuclear** power plants?

Literature Review

Nuclear modelling approaches:

- **Total flexibility:**
 - Göke, Wimmers, von Hirschhausen (2025)
 - Kan, Hedenus and Reichenberg (2020)
- **Total inflexibility:**
 - Fattahi et al (2023)
 - Aunedi et al (2023)
- **Flexibility is limited by ramping constrains:**
 - Loisel et al 2018
 - Shirizadeh et al (2021)
 - Jenkins et al (2018)
- **Flexibility is limited by the fuel cycle:**
 - Lynch et al (2022)

Our contribution:

Extend **market model**

(investments + market outcomes)

with **detailed nuclear**

representation and exogenous

size of fleet

Nuclear modelling approach

Compare **two approaches** on **flexibility** for **existing nuclear fleets**:

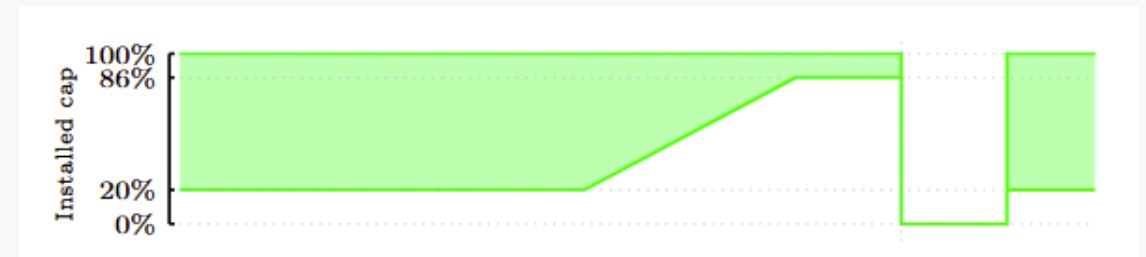
Non-flexible (baseload):

- Output variable: **90–100%**
- Shutdowns only for **refueling/maintenance**



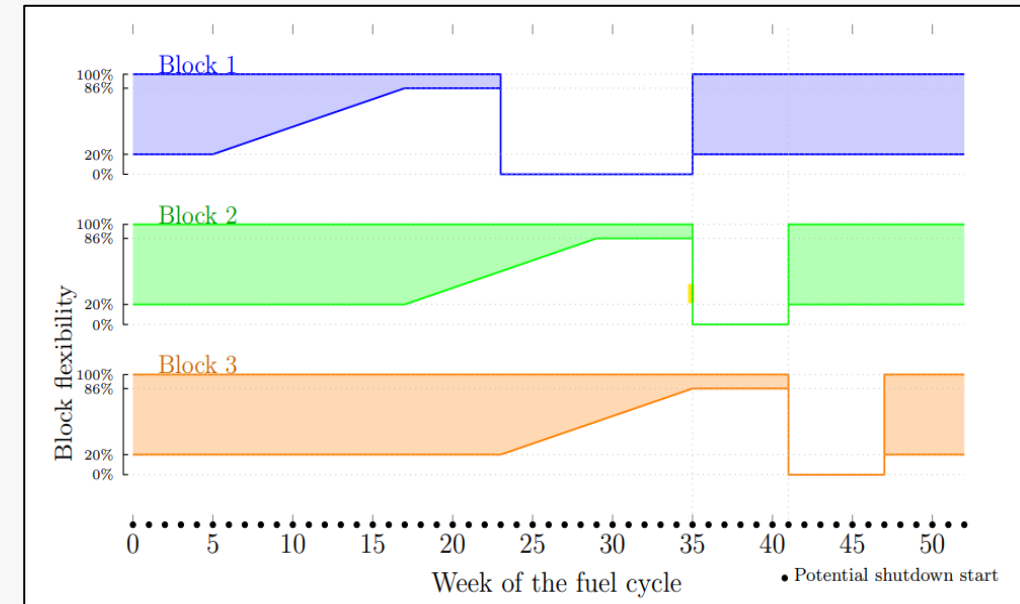
Partly flexible:

- Output variable: **20–100%**
- Shutdowns only for **refueling/maintenance**



Methodology:

- **3-year fuel cycle:** 3 x 12-month → Each power plant has 3 blocks
- Year 1: **2 months** maintenance and refueling
- Year 2 & 3: **2 weeks** refueling
- Consecutive refueling schedule for blocks 2 & 3
- **Model decision** → start week for maintenance block 1



Model framework

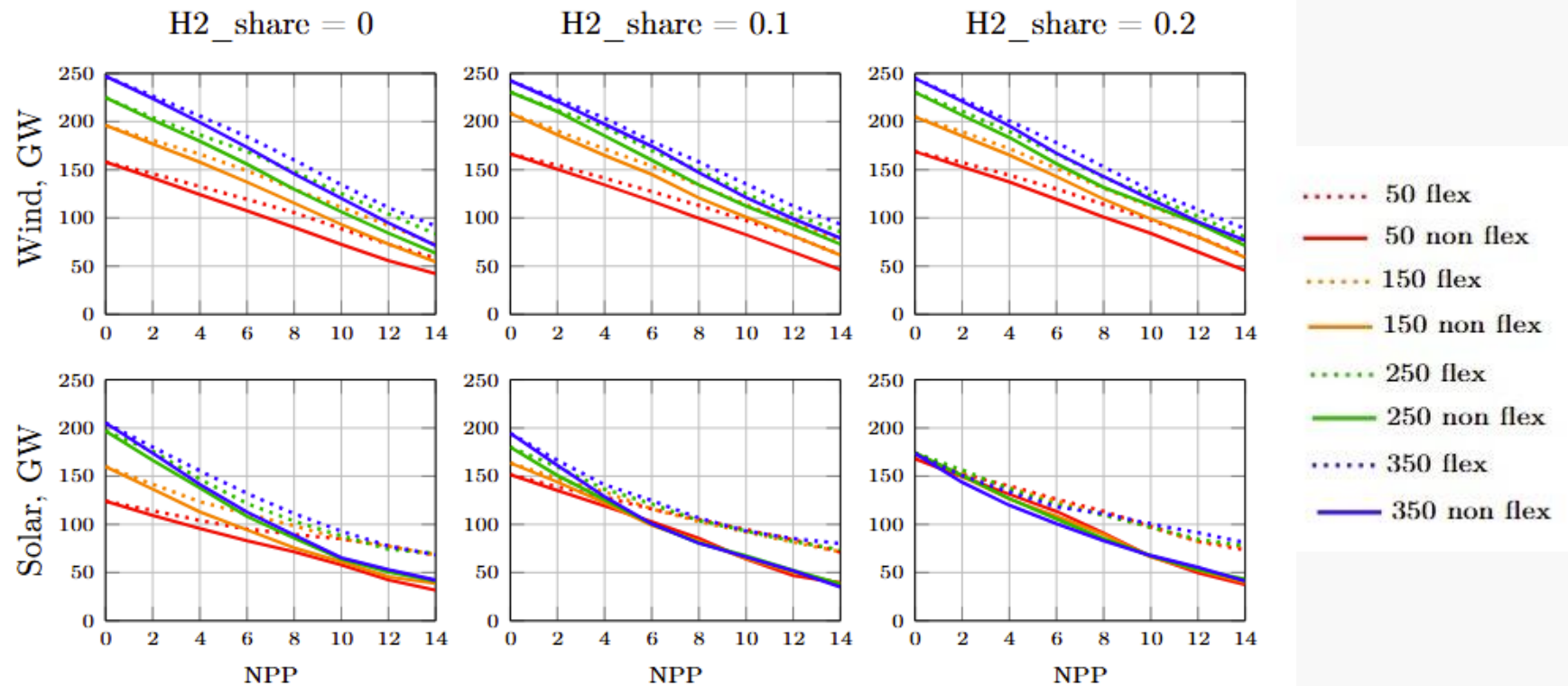
- Mixed-Integer Linear Optimization (MILP) model:
 - Binary variables: optimal weekly decision on revision/fuel cycle determine hourly on/off for nuclear
- Temporal resolution: one year with 8760 hours
- Spatial resolution: single bidding zone → no cross-border trade!
- Technologies: nuclear, wind, PV, gas turbine, battery, electrolyzer, H2 storage, H2 power plant
- TYNDP data for France (ENTSO-E, 2022): Hourly time series on demand and wind / PV availability

Key parameters for sensitivity analysis:

- **Nuclear power plants** 0 to 14 power plants with 3 blocks each (max. ~ 55 GW)
(corresponding to the share in total electricity demand: 0% to ~80%)
- **EU-ETS CO₂ price:** 50 €/t, 150 €/t, 250 €/t, 350 €/t
- **Hydrogen demand share:** 0%, 10%, 20%

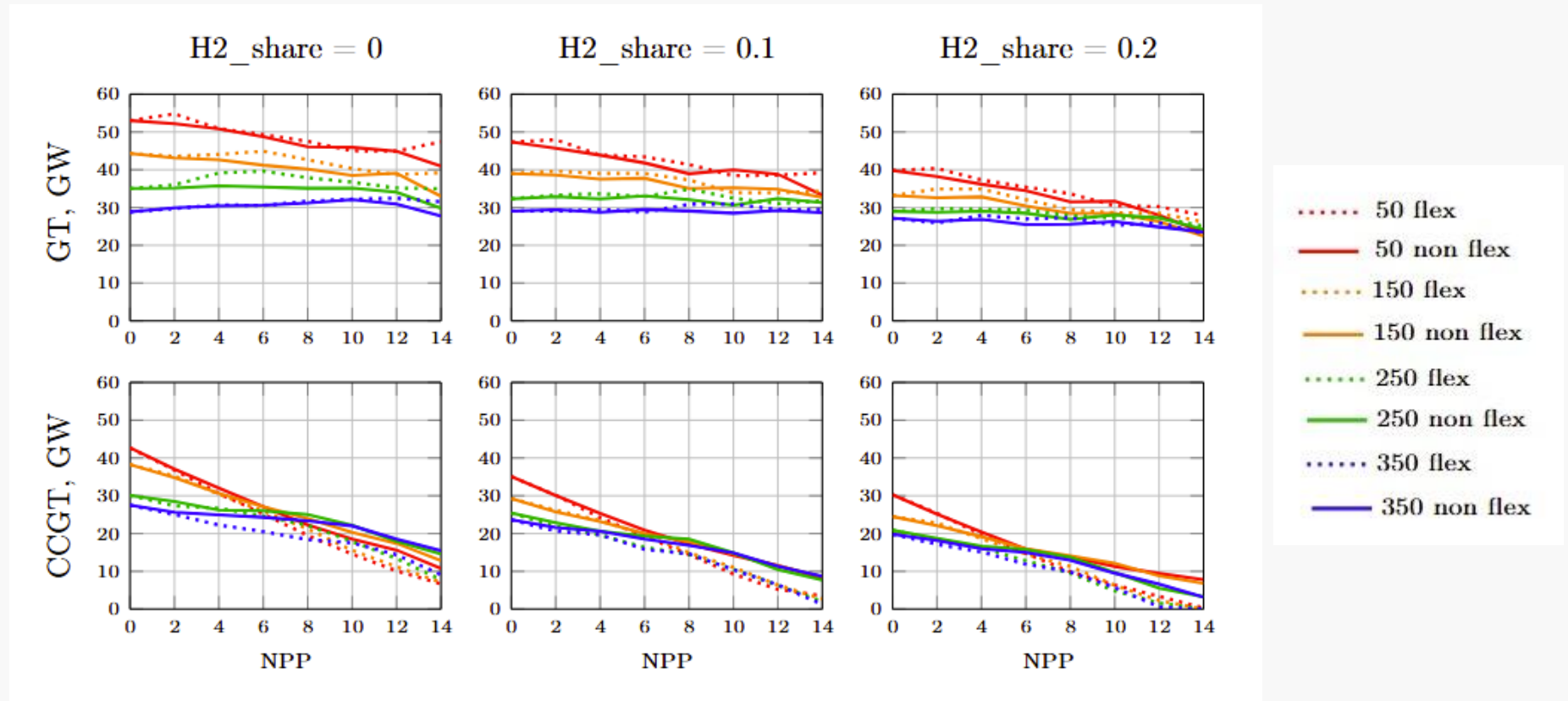
Result 1: Electricity system – installed capacity

Wind and Solar



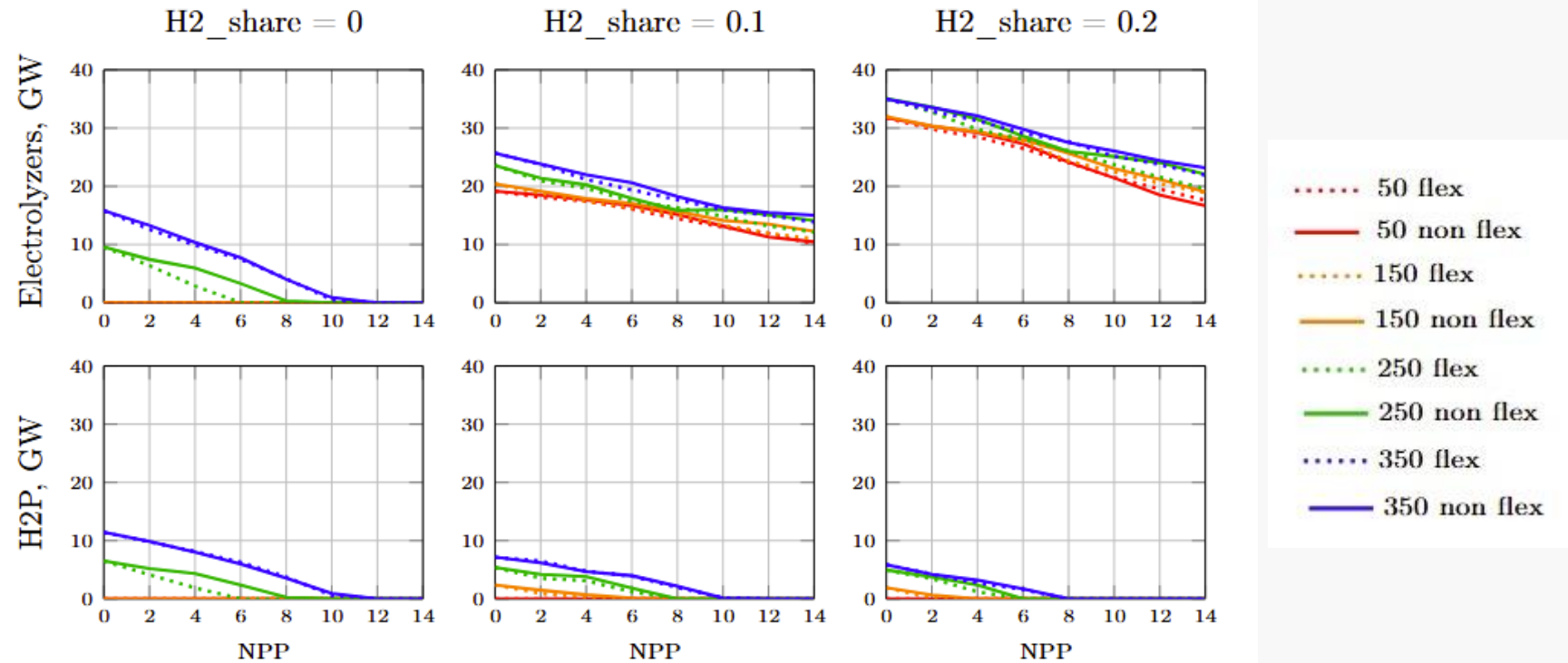
- RES capacity increases with flexibility; effect increasing with nuclear share;
- Solar profits more from nuclear flexibility;
- Solar not longer sensitive to CO₂ price with increasing nuclear and with hydrogen demand.

GT and CCGT



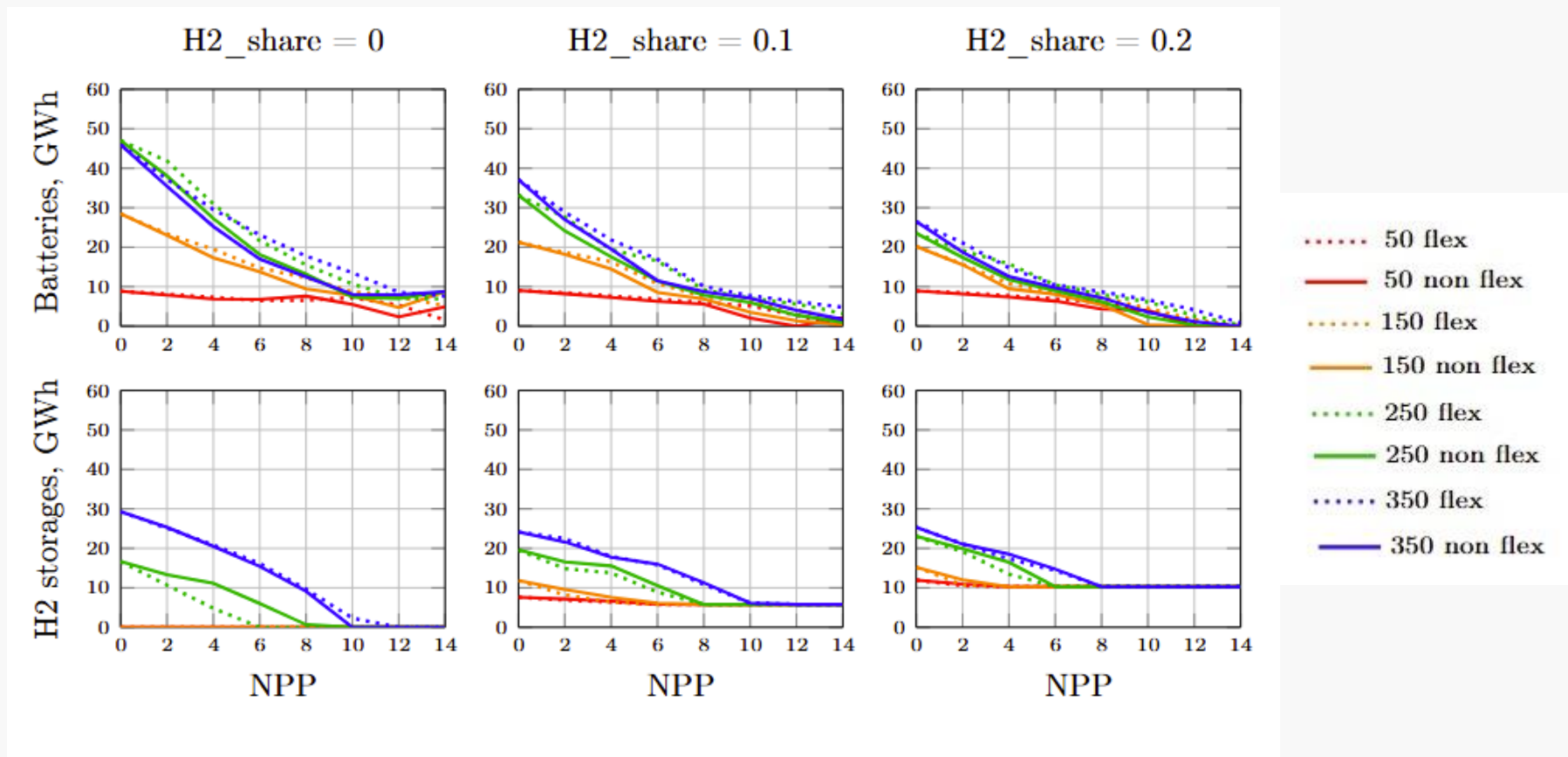
- Flexible nuclear can increase GT and decrease CCGT capacity;
- High share of nuclear requires less CCGT capacity, low effect on gas turbines;
- Higher CO₂ prices decrease mainly GT capacity.

Hydrogen-electricity conversion



- No hydrogen demand → hydrogen is needed only if CO₂ price is high and number of nuclear is low;
- There is hydrogen demand → system needs more electrolyzers and less H₂ power plants;
- Flexible nuclear can decrease investment in hydrogen cycle.

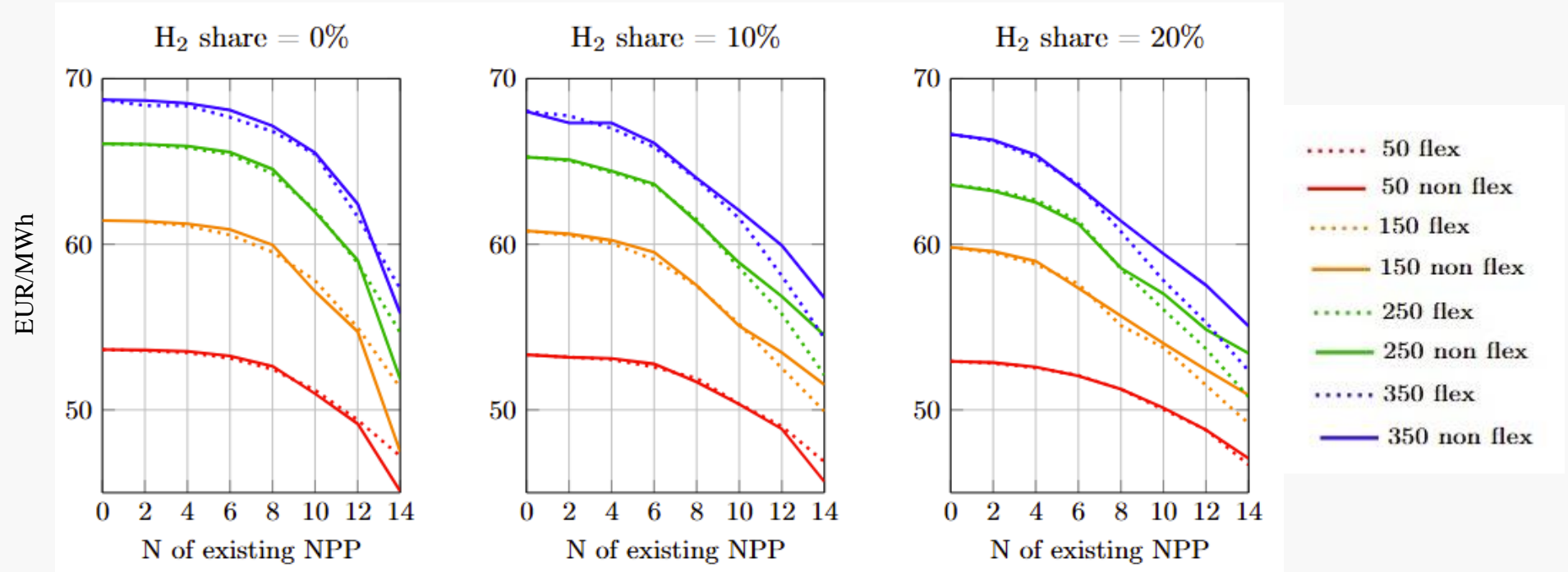
Storages



- Battery capacity lower for high nuclear capacity;
- Flexible nuclear can increase battery and decrease H₂ storage capacity.

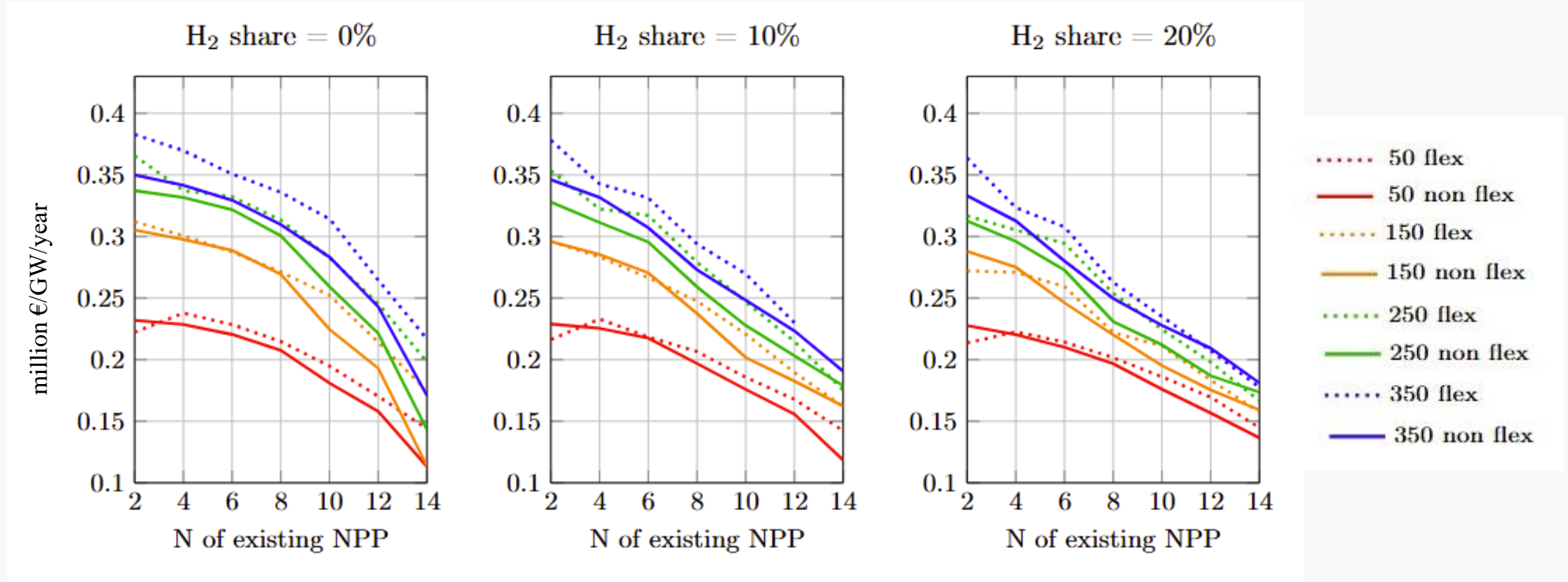
Result 2: Nuclear market rents

Electricity prices



- If nuclear fleet is limited, flexibility doesn't influence electricity price;
- If nuclear fleet is high, CO₂ price is low and there is no hydrogen demand, flexibility results in higher electricity prices;
- If the CO₂ price is high and there demand for hydrogen, flexibility leads to lower prices.

Market payments to nuclear (above variable generation costs)



- Flexible nuclear increases market payments per capacity (in most cases!);
- H₂ demand = 0: increasing reduction with number of nuclear power plants;
- H₂ demand > 0: linear reduction with payments lower (low nuclear-medium) and higher (very high nuclear).

Summary

- Model representation of nuclear power plants (partly flexible, not flexible) has an effect on system composition and market results;
- Flexible operation allows more RES investment but has limited effect on electricity prices (except for very high nuclear shares);
- Market payments with increasing nuclear capacity:
 - Decreases faster with hydrogen demand
 - Additional payments from flexible operation
- Possible extensions:
 - Economic: More flexibility of nuclear power plants with endogenous temporal shut-downs to omit losses during longer zero price periods (high computation cost)
 - Technical: costs of accelerated material wear due to varying loads (how to measure?)

Thank you for your attention!

Methodology: Objective function

$$\begin{aligned}
 & \sum_{x \in X} \sum_{b \in B} \sum_{t \in T} \left[(1 - z_{x,b,t}^{\text{down}}) c_{x,b}^{\text{run}} \bar{y}_x + z_{x,b,t}^{\text{down}} c_{x,b}^{\text{down}} \bar{y}_x \right] \\
 & + \sum_{x \in X} \sum_{b \in B} \sum_{t \in T} c_{x,b}^{\text{var}} y_{x,b,t} \\
 & + \sum_{p \in P} c_p^{\text{fix}} \bar{y}_p + \sum_{p \in P} \sum_{t \in T} c_p^{\text{var}} y_{p,t} + \sum_{x \in X} \sum_{b \in B} c_{x,b}^{\text{fix}} \bar{y}_x \\
 & + \sum_{s \in S} c_s^{\text{fix}} \bar{l}_s + \sum_{e \in E} c_e^{\text{fix}} \bar{y}_e + \sum_{f \in F} c_f^{\text{fix}} \bar{y}_f \\
 & + \sum_{t \in T} \left(M d_t^{\text{unmet}} + M^{\text{H}_2} d_t^{\text{H}_2, \text{unmet}} \right)
 \end{aligned}$$

← Fixed O&M costs nuclear plants

← Variable costs (fuel & CO₂):

- (x,b) nuclear plants
- (p) fossil-fired power plants

← Investment and fixed O&M costs:

- (x,b) nuclear plants
- (p) Fossil-fired power plants and RES
- (s) Battery and H₂ Storage
- (e) Electrolyzers
- (f) H₂ power plants

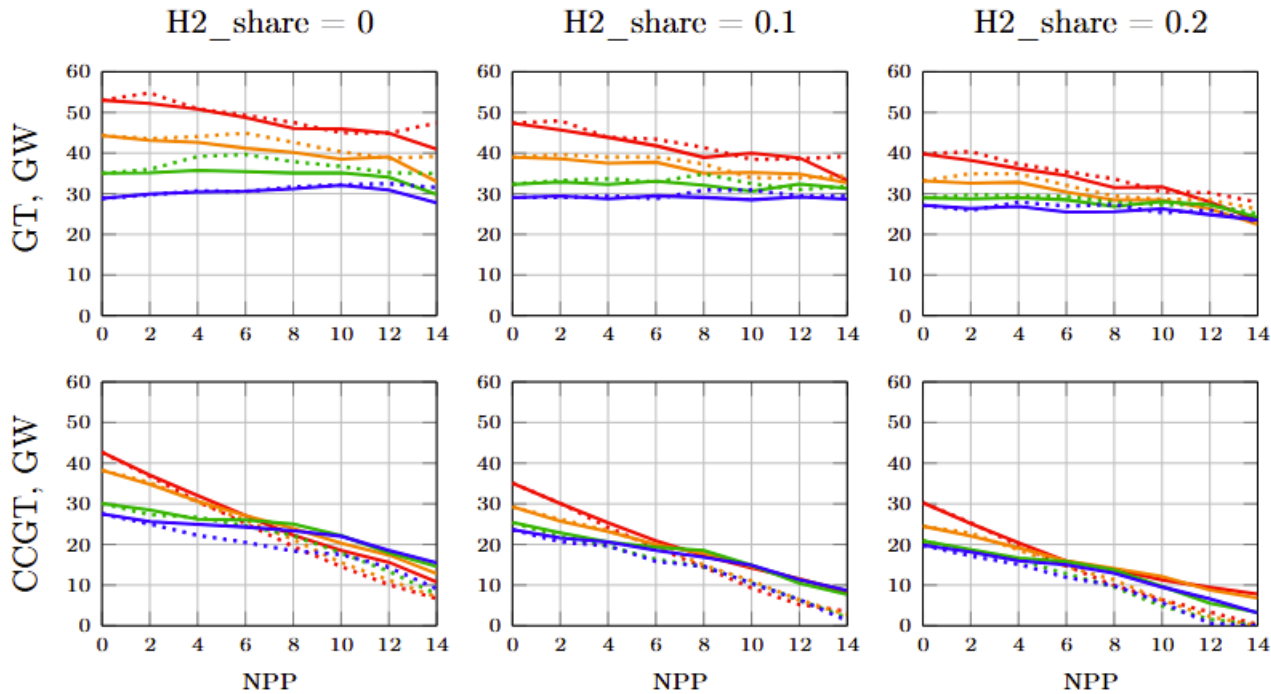
← penalties for unserved load

Methodology: electricity balance

$$\begin{aligned}
 d_t + l_{s^{\text{BAT}},t}^{\text{in}} + \sum_{e \in E} d_{e,t} = & \leftarrow \text{electricity demand} + \text{storage charging} + \text{electrolyzer demand} \\
 \sum_{x \in X} \sum_{b \in B} y_{x,b,t} & \leftarrow \text{nuclear generation} \\
 + \sum_{p \in P} y_{p,t} & \leftarrow \text{RES and conventional generation} \\
 + l_{s^{\text{BAT}},t}^{\text{out}} & \leftarrow \text{storage discharging} \\
 + \sum_{f \in F} y_{f,t} & \leftarrow \text{electricity produced by hydrogen-fueled power generation} \\
 + d_t^{\text{unmet}}, & \leftarrow \text{unmet demand} \\
 \text{for all } t \in T. &
 \end{aligned}$$

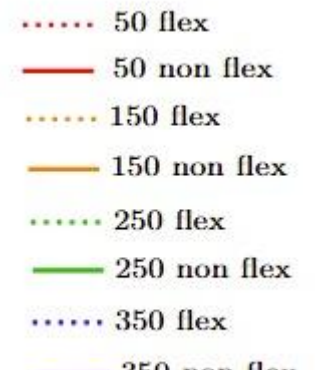
Methodology: hydrogen balance

$$\begin{aligned}
 d_t^{\text{H}_2} + l_{s\text{H}_2,t}^{\text{in}} + \sum_{f \in F} d_{f,t} &= \leftarrow \text{H}_2 \text{ demand} + \text{H}_2 \text{ storage charging} + \text{H}_2 \text{ demand of H-to-power facilities} \\
 \sum_{e \in E} y_{e,t} &\leftarrow \text{H}_2 \text{ production from electrolyzer} \\
 + l_{s\text{H}_2,t}^{\text{out}} &\leftarrow \text{H}_2 \text{ storage discharging} \\
 + d_t^{\text{H}_2, \text{unmet}}, &\leftarrow \text{unmet H}_2 \text{ demand} \\
 \text{for all } t \in T. &
 \end{aligned}$$

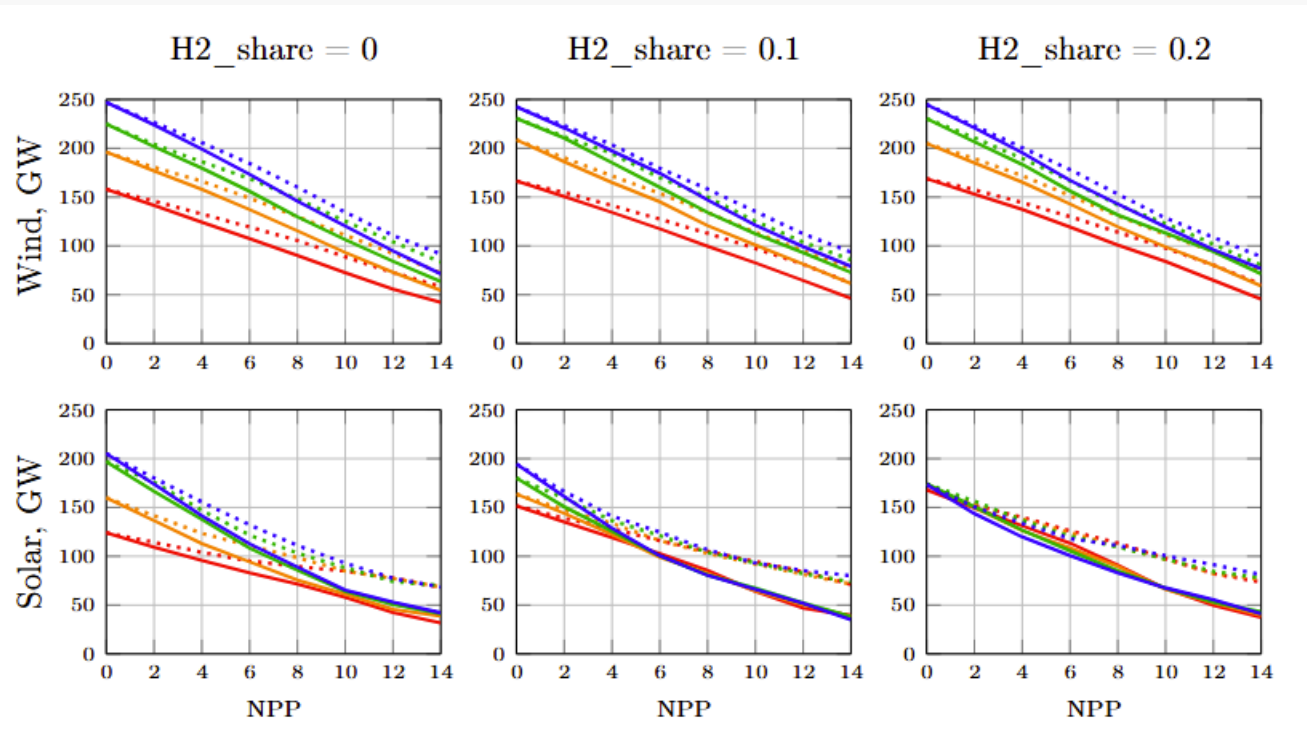


- As nuclear capacity increases, combined-cycle gas turbines (CCGT) gradually lose competitiveness relative to open-cycle gas turbines (GT), especially at higher CO2 prices.
- A system dominated by nuclear baseload requires less efficient med-merit generation and instead values fast-ramping peaking capacity for residual balancing.
- Rising carbon prices reinforce this shift by penalizing fossil generation more strongly.

- High share of nuclear requires less gas capacity, especially CCGT
- CCGT capacity decreases with higher CO₂ prices and Hydrogen demand

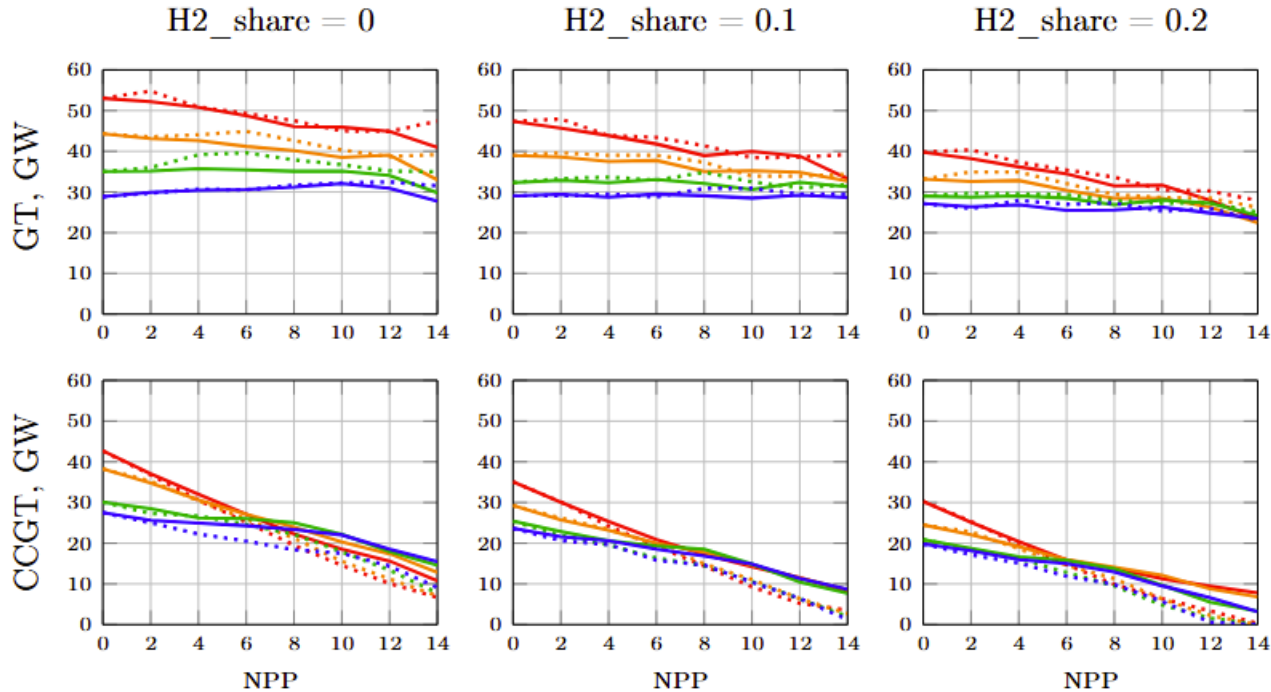


Wind and Solar



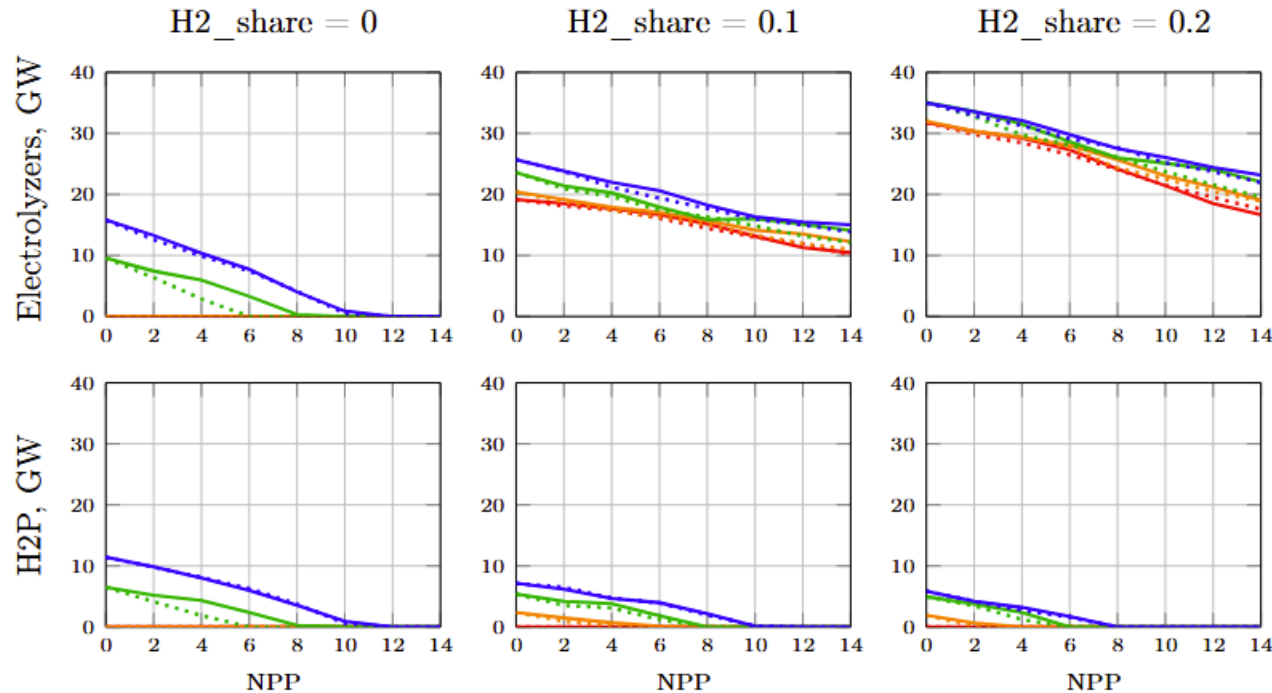
- Nuclear flexibility facilitates higher RES deployment.
- In the flexible regime, wind and solar capacity expand relative to the non-flexible case, as flexible nuclear operation reduces crowding-out effects.
- The effect is particularly pronounced for solar PV, whose concentrated intraday production profile benefits more strongly from flexible nuclear output adjustments.

GT and CCGT



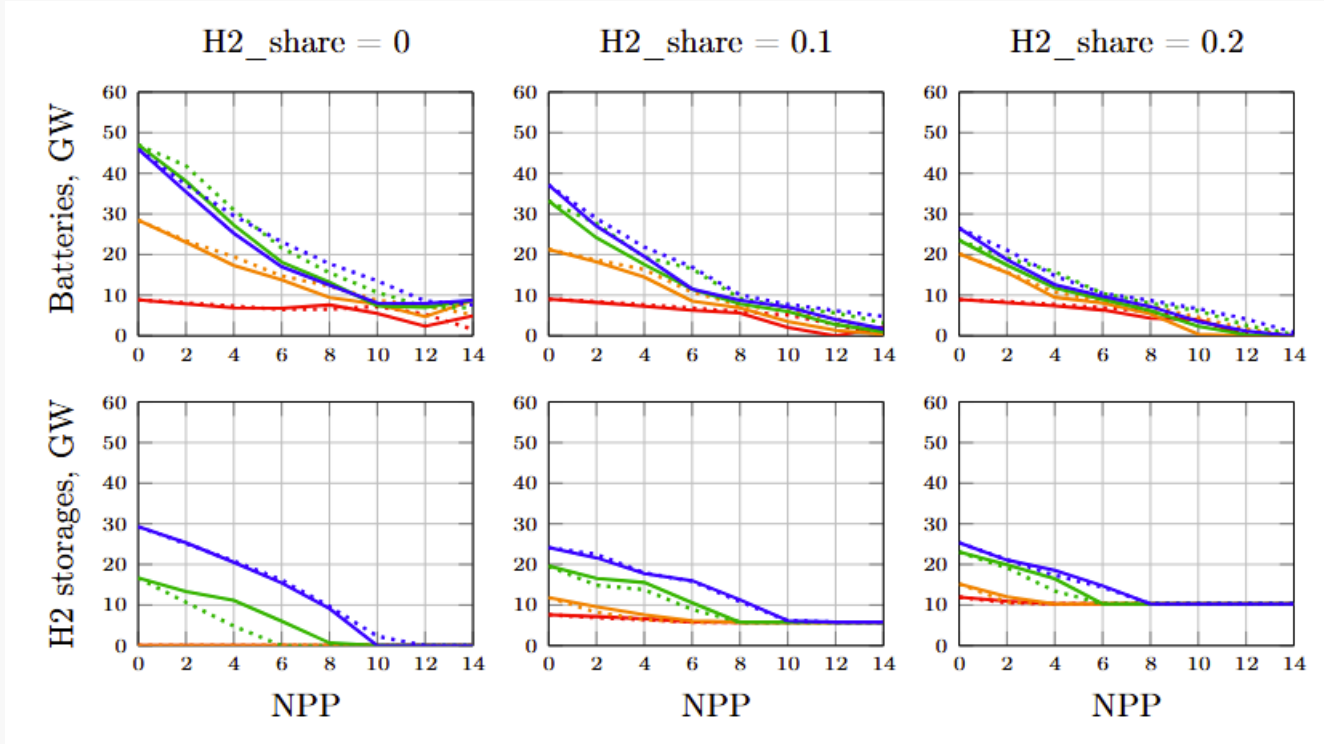
- As nuclear capacity increases, combined-cycle gas turbines (CCGT) gradually lose competitiveness relative to open-cycle gas turbines (GT), especially at higher CO2 prices.
- A system dominated by nuclear baseload requires less efficient mid-merit generation and instead values fast-ramping peaking capacity for residual balancing.
- Rising carbon prices reinforce this shift by penalizing fossil generation more strongly.

Hydrogen conversion



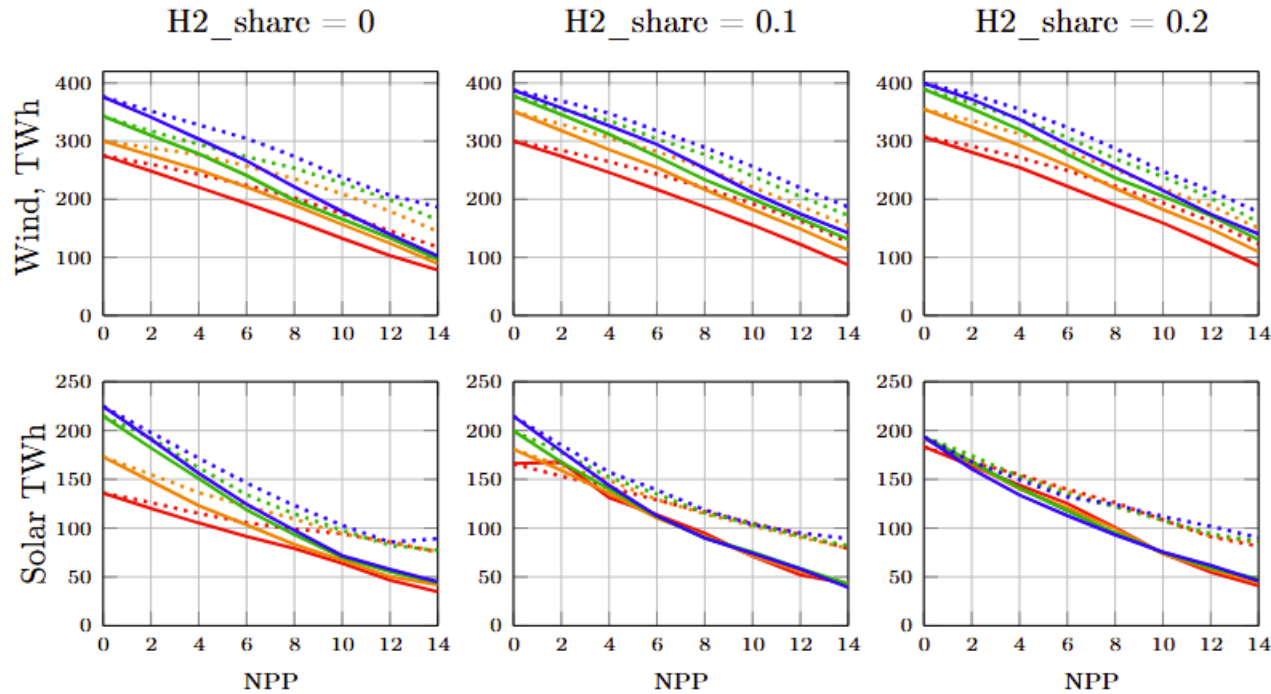
- Hydrogen-based technologies emerge only under high CO₂ price levels, reflecting their relatively high cost.
- In the flexible nuclear regime, hydrogen deployment is systematically lower than in the non-flexible case, as part of the system's balancing requirement is absorbed by nuclear load-following.
- Hydrogen capacity declines as nuclear capacity increases, indicating that long-duration flexibility options become less necessary in systems with a large low-carbon baseload.

Storage



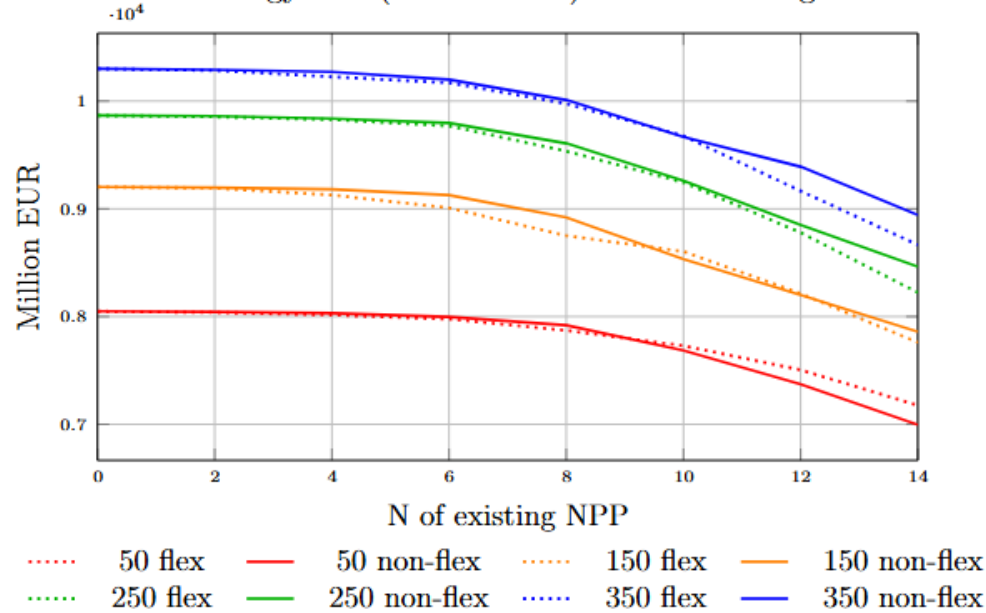
- Battery deployment decreases with increasing nuclear capacity.
- Batteries primarily complement variable renewables, especially solar PV.
- When nuclear capacity expands – or when flexibility is provided internally by nuclear load-following – the need for short-term balancing through batteries diminishes.

Results: RES electricity production

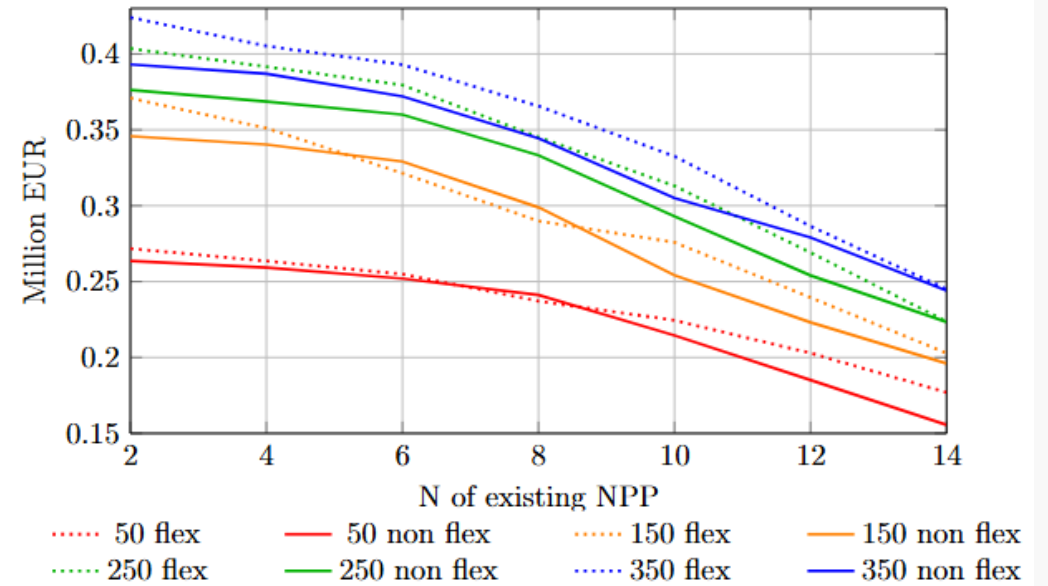


- Allowing nuclear power plants to operate flexibly is associated with higher generation from both wind and solar technologies relative to the inflexible case.
- The gap between flexible and inflexible nuclear operation is more pronounced at low hydrogen demand.
- Nuclear flexibility becomes progressively more valuable for integrating wind generation
- Wind generation tends to increase with hydrogen demand, while solar - decrease

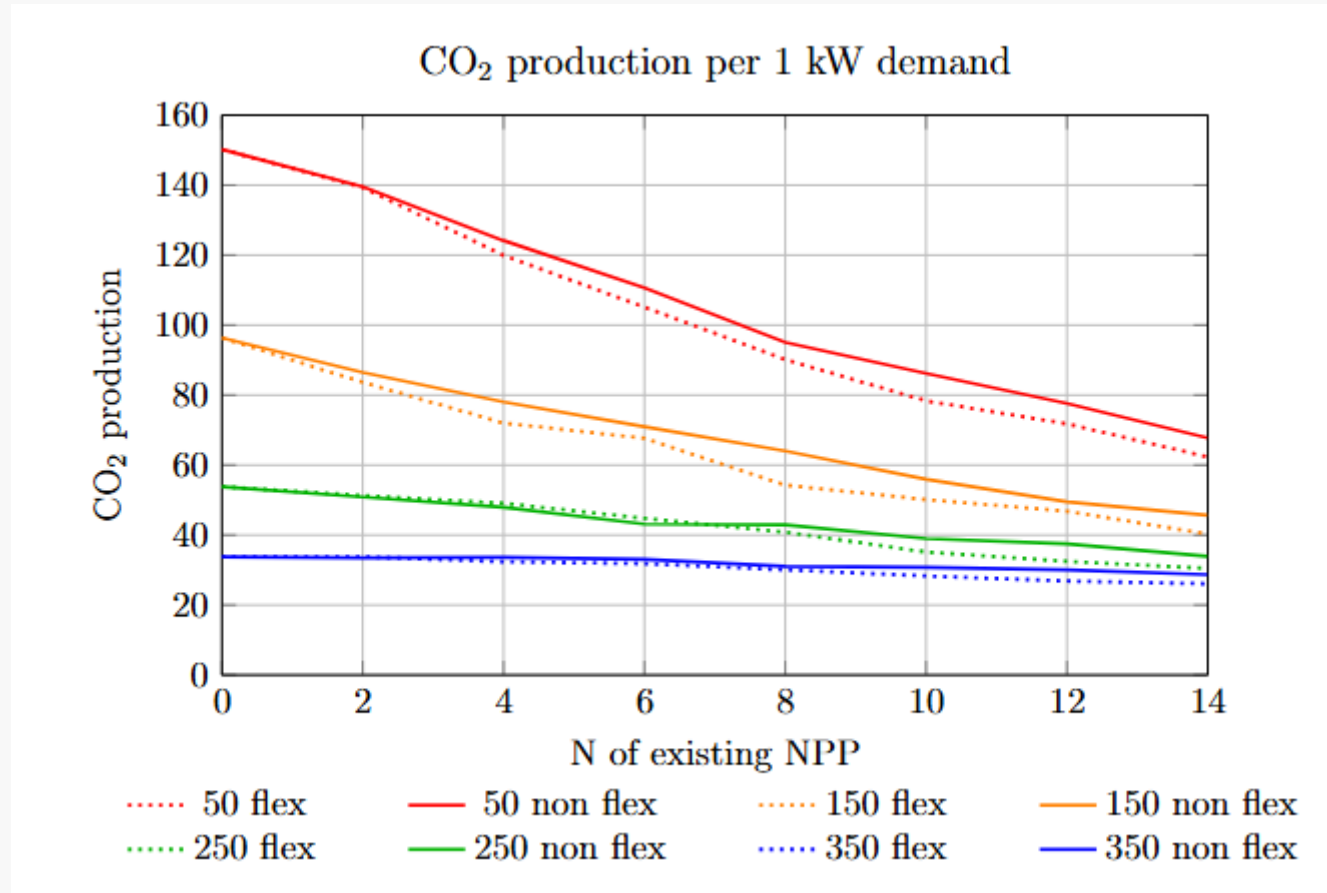
Total energy cost (million EUR) vs N of existing NPP



Nuc profit per MW installed cap, million EUR



- At high nuclear penetration (>10 units), operating mode affects consumer payments.
- At high CO₂ prices (250–350 €/tCO₂), flexible nuclear lowers total consumer payments by reducing reliance on expensive and/or carbon-intensive marginal technologies during imbalance periods.
- As the CO₂ price decreases, this advantage of flexible operation diminishes.
- At low CO₂ prices (≈50 €/tCO₂), inflexible nuclear becomes cheaper for consumers, as the system shifts toward a simpler, less capital-intensive mix with lower flexibility needs.



Parameters: Existing nuclear power plants

Parameter	Value
Variable O&M cost	7 €/MWh
Fuel costs	3.6 €/MWh
Efficiency	33%

Parameters: VRES

Constraints: generation is limited by the invested capacity and availability

$$y_{p,t} \leq \alpha_{p,t} \cdot \bar{y}_p, \quad \text{for all } p \in P, t \in T.$$

	Wind	Solar
CapEx,	1137 €/MW	395 €/MW
Lifetime	30 years	40 years
Fixed OpEx	3 %/yr	3 %/yr
Variable OpEx	1.0 €/MWh	0.1 €/MWh

Parameters: natural gas power plants

Constraints: generation is limited by the invested capacity and availability

	Natural Gas GT	Natural Gas CCGT
CapEx	468 €/MW	900 €/MW
Lifetime	30 years	30 years
Fixed OpEx	3 %/yr	3 %/yr
Variable OpEx	3 €/MWh	4 €/MWh
Fuel cost	26 €/MWh	26 €/MWh
Efficiency	0.42	0.58
Emission factor	0.202 tCO ₂ /MWh	0.202 tCO ₂ /MWh
Availability	85%	85%

Parameters: hydrogen

Constraints:

- Electricity generation from hydrogen is limited by the installed capacities and efficiencies;
- Hydrogen generation by electrolyzer is limited by the installed capacities and efficiencies.

	Electrolyzer (electricity → H₂)	Hydrogen-to-power conversion
CapEx	1200 €/MW	800 €/MW
Lifetime	20 years	30 years
Fixed OpEx	3 %/yr	3 %/yr
Efficiency	0.7	0.39
Variable OpEx	2.0 €/MWh	3.0 €/MWh



Parameters: battery storages

Constraints:

- Can charge and discharge energy only within the installed capacity;
- **Storage Capacity** is assumed to be **four times** greater than the maximum **charging and discharging capacity**;
- Storage **level** = level in the previous period + charged electricity - discharged electricity (taking into account the loss of energy during an hour of storage);
- Storage level at the **first** hour = the level at the last hour.

	Batteries
CapEx	340 €/MW
Lifetime	20 years
Fixed OpEx	3 %/yr
Efficiency (round-trip)	0.85
Losses	0.001% per time step

Parameters: hydrogen storages

Constraints:

- Can charge and discharge energy only within the installed capacity;
- **Storage Capacity** is assumed to be **four times** greater than the maximum **charging and discharging capacity**;
- Storage **level** = level in the previous period + charged electricity - discharged electricity (taking into account the loss of energy during an hour of storage);
- Storage level at the **first** hour = the level at the last hour.

	Batteries
CapEx	91 €/MW (0.33 €/MWh)
Lifetime	20 years
Fixed OpEx	3 %/yr
Efficiency (round-trip)	0.85
Losses	0.001% per time step



Discussion

Shapes renewable integration:

- Flexible nuclear → higher wind (and some PV) penetration.
- Non-flexible nuclear → decreases RES capacity

Interplay with CO₂ prices:

- At 130 EUR/MWh → gas power plants relevant for peak load hours
- At high prices → Hardly any gas capacity, flexibility of nuclear (and storage) becomes crucial

Fleet size matters:

- Flexibility is less of an issue with fewer reactors
- With 10–14 units (60-80%), operational mode decisively changes the mix

Economic & policy implications:

- System planning must account for (in-)flexibility of nuclear, not just installed capacity
- Policy relevance: existing nuclear fleets can act as enablers (or barriers) for renewables, depending on their flexibility



Literature Review

- **Country case studies (France, Sweden, UK, NL):** Nuclear's value is highly context-dependent; in some systems, renewables alone achieve decarbonization at similar costs, while others show complementary roles;
 - **Shirizadeh & Quirion (2020, France)** → existing nuclear remains but renewables dominate by 2050.
 - **Fattahi et al. (2023, Netherlands)** → nuclear complements renewables but is value sensitive to capital cost & trade assumptions.
- **Modeling focus:** Many studies misrepresent nuclear as rigid baseload; more realistic modeling of load-following shows trade-offs between plant profitability and system benefits;
 - **Bistline et al. (2023)** → standard models misrepresent nuclear; need realistic flexibility representation.
 - **Lynch et al. (2022)** → nuclear fleet flexibility crucial under high-RES systems; system-level optimization shows importance of min-load & scheduling.

Literature Review

- **Modelling focus**

- **Loisel et al (2018):**

- different flexibility cycles are modeled;
- In which EU regions is NPP's flexibility necessary?

- **Jackins et al (2018):**

- flexible, partly flexible, and non-flexible operation modes are modeled;
- How does NPP's operation mode influence total system costs and VRES outcome?

- **Lynch et al. (2022):**

- NPP flexibility modelling based on physical aspects of the fuel cycle;
- Influence of nuclear flexibility with systems with different VRES penetration

**No
literature
on how
nuclear
flexibility
affects
investment
decisions**