A Multi-Regional Model to Optimize Power System Flexibility under Residual Demand

Théotime Coudray[1] and Sandrine Michel[1]

[1]Université de Montpellier, UMR 5281 ART-Dev

Italian Association of Energy Economists (IAEE)
Symposium 2025 – Sapienza University, Rome

Motivation: Why Regional Flexibility, Why Now?

- Energy transitions are long co-adaptation processes between technologies and institutions.
- Variable Renewable Energy (VRE) reshapes *instantaneous* supply–demand balance:
  - more variability, more locality, more uncertainty.
- Flexibility emerges in the literature as :
  - A set of tools: demand response, storage, inter-regional exchanges, ramping capabilities.
  - An organization principle for power systems
- Yet the relevant **spatial scale** of flexibility governance remains unclear:
  - national vs. local (microgrids, communities) vs. **intermediate regional** layer.

Research Statement and Contributions

Research Question

Does power system flexibility induce a more decentralized structure of operational coordination?

This Paper

- Proposes a **multi-regional MILP** balancing residual demand across four French regions.
- Co-optimizes dispatch, storage, DR and inter-regional exchanges.
- Derives regional nodal prices and flexibility metrics to assess ramping adequacy.

Multi-Regional MILP: Overview

- Decision variables (per region r and time t):
  - Generation $g^k_{r,t}$ and unit commitment $u^k_{r,t}$.
  - Storage charging/discharging $c^s_{r,t}$, $d^s_{r,t}$.
  - Demand response activation $DR_{r,t}$.
  - Inter-regional flows $f_{r \to r',t}$ and slack variables.
- Objective: minimize total system cost under technical constraints.

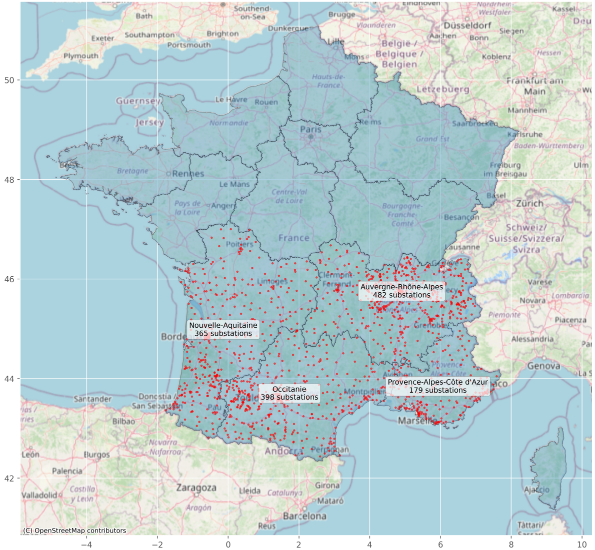
$$\min \sum_{r,t} \left[\underbrace{\sum_k \left(C^r_k g^{r,t}_k + C^{\text{fixed}}_k u^{r,t}_k + C^{\text{start}}_k s^{r,t}_k \right)}_{\text{dispatchable generation}} + \underbrace{\sum_s \left(C^{\text{ch}}_s c^{r,t}_s + C^{\text{dis}}_s d^{r,t}_s \right)}_{\text{storage}} + \underbrace{C^{\text{DR}}\, dr^{r,t}}_{\text{demand response}} + \underbrace{\sum_{r' \neq r} C^{\text{flow}}_{r \to r'}\, f^{r \to r',t}}_{\text{inter-regional exchanges}} + \underbrace{P^{\text{slack}} \left(slack^{r,t}_+ + slack^{r,t}_- \right)}_{\text{adjustment terms}} \right]$$

Objective function

Case Study and Data

- **Residual demand** as an input:
  - Net load $\mathrm{RL}_{r,t}$ after injecting regional solar and wind profiles.
  - Half-hourly resolution for 2022.
- **Geographical scope**:
  - Four interconnected French regions with limited interconnection capacities.
- **Data sources**:
  - Demand and VRE profiles from ODRÉ platform.
  - Installed capacities and techno-economic parameters from RTE and planning reports.

Regional Distribution of Source Substations in France



Result 1: Hydro-Driven Residual Supply Mix

- After VRE injection, the residual demand is covered by a **very low-carbon** mix:
  - Hydropower: **73.4%** of delivered electricity.
  - Nuclear: **26.0%**.
  - Gas: only **0.5%**.

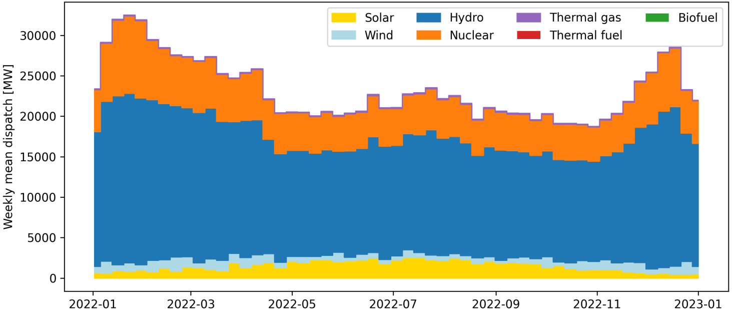


Figure: Weekly mean residual generation stack of the whole system (4 regions) in REGIONALFLEX for the year 2022.

Result 2: Demand Response Provides More Flexibility than Storage

- Demand-Response accounts for **1.1%** of flexible energy while storage accounts only for **0.02%**.

Why is storage used much less?

- Narrow price spreads between charge and discharge hours, plus round-trip losses and cycling costs.
- DR, with a constant marginal cost c_{DR}, competes directly with peaking units and imports.

Result 3: Limited but Valuable Regional Exchanges

- Inter-regional exchanges represent only **5.9%** of total flexible energy.

Interconnection	Congestion rent (M€)
ARA $\rightarrow$ PACA	148.9
NAQ $\rightarrow$ PACA	22.3
ARA $\rightarrow$ OCC	4.3
PACA $\rightarrow$ NAQ	0.2
OCC $\rightarrow$ ARA	0.1
Total	**171.0**

Table: Annual congestion rents by interconnection (in million €).

Result 4: Ramping Adequacy and Probabilistic Flexibility Metrics

- Following Abdin and Zio (2018, 2019), we use:
  - **Insufficient Ramping Resource Expectation (IRRE)**: frequency of ramping shortages.
  - **Expected Flexibility Shortfall (EFS)**: conditional average magnitude of shortages.

Region	IRRE^{+} (%)	IRRE^{-} (%)	EFS^{+} (MW)	EFS^{-} (MW)
ARA	12.34	12.93	188.4	179.8
NAQ	24.68	24.28	92.7	94.3
OCC	20.92	20.58	100.1	101.8
PACA	31.29	29.30	86.4	92.3
System aggregate	**28.87**	**32.67**	**316.3**	**279.7**

Table: Frequency (IRRE) and conditional magnitude (EFS) of ramping shortages in RegionalFlex, computed from time-varying ramping headrooms

Conclusions

Key Messages

- A regional coordination layer can **coherently mobilize** hydro, DR, storage and exchanges to balance residual demand with very low carbon intensity.
- Under current techno-economic assumptions, **demand response dominates** storage as a source of downward flexibility.
- Inter-regional exchanges deliver **limited volumes** but **high economic value** through congestion rents, revealing the spatial value of flexibility.
- However probabilistic metrics (IRRE, EFS) highlight **non-negligible ramping stress**.

Outlook

- Extend to climate-stressed and high-VRE scenarios.
- Explore alternative DR and storage cost structures and policy designs.
- Use regional nodal prices and flexibility metrics to inform governance debates on decentralization and planning.

Thank you for your attention!

coudray.theotime@gmail.com

Key Constraints: Energy Balance and Flexibility

Energy balance in each region r and time step t:

$$\sum_k g_{r,t}^k + \sum_s d_{r,t}^s + \sum_{r' \neq r} (1 - \ell_{r' \to r}) f_{r' \to r,t} = \mathrm{RL}_{r,t} + \sum_s c_{r,t}^s - DR_{r,t} + slack_{r,t}^+ - slack_{r,t}^-.$$

Flexibility-related constraints:

- *Unit commitment & ramping*
  - Capacity limits and on/off status linkage.
  - Ramping limits $|g_{r,t}^k - g_{r,t-1}^k| \leq \rho_k G_k^r$.
- *Storage dynamics*
  - Inter-temporal SOC update with round-trip efficiency and self-discharge.
- *Demand response potential*

$$0 \leq DR_{r,t} \leq \alpha_r \mathrm{RL}_{r,t}.$$

- *Inter-regional exchanges*

$$0 \leq f_{r \to r',t} \leq F_{r \to r'}^{\max}.$$

Congestion rents Calculation

Congestion Rent Definition

$$CR_{i\to j}(t) = F_{i\to j}(t)\left(P_j(t) - P_i(t)\right), \quad CR_{\text{tot}} = \sum_{t,i,j} CR_{i\to j}(t)\,\Delta t.$$

- Regional nodal prices $P_r(t)$ are duals of regional balance constraints.
- Congestion rents quantify the spatial value of flexibility provided by the network.