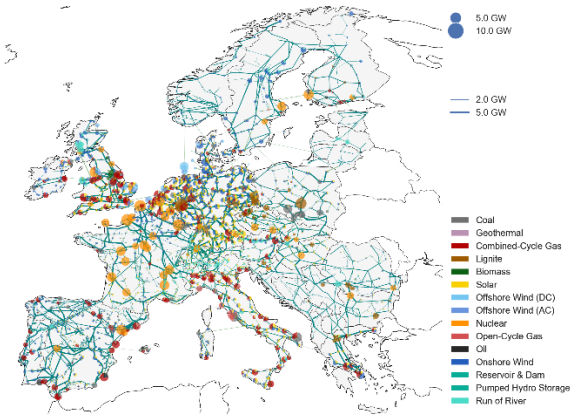
Energy System Modeling with Python



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Chair for Control and Integration of Grids

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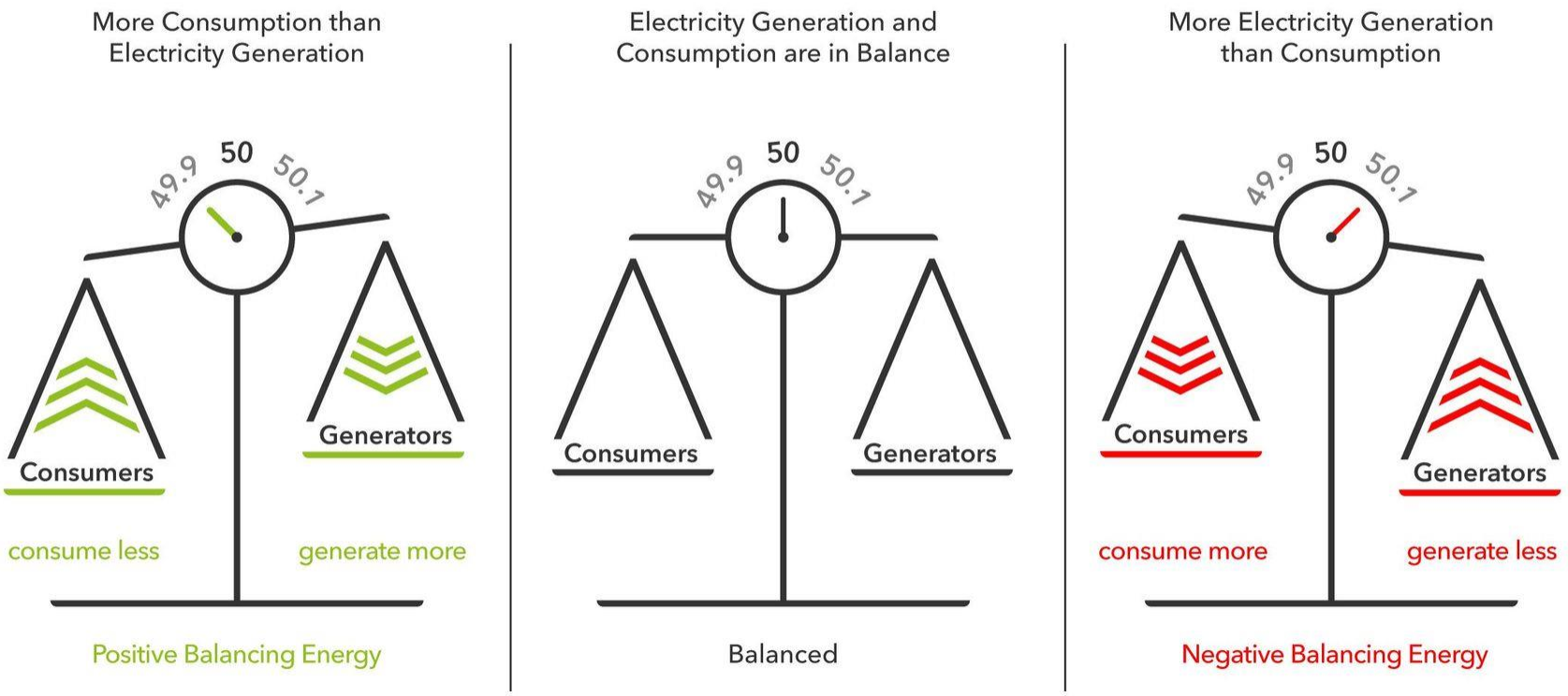
Why Keep System in Balance?

Balance between electricity generation and electricity consumption



Balancing Markets: The Grid's Real-Time Safety Net

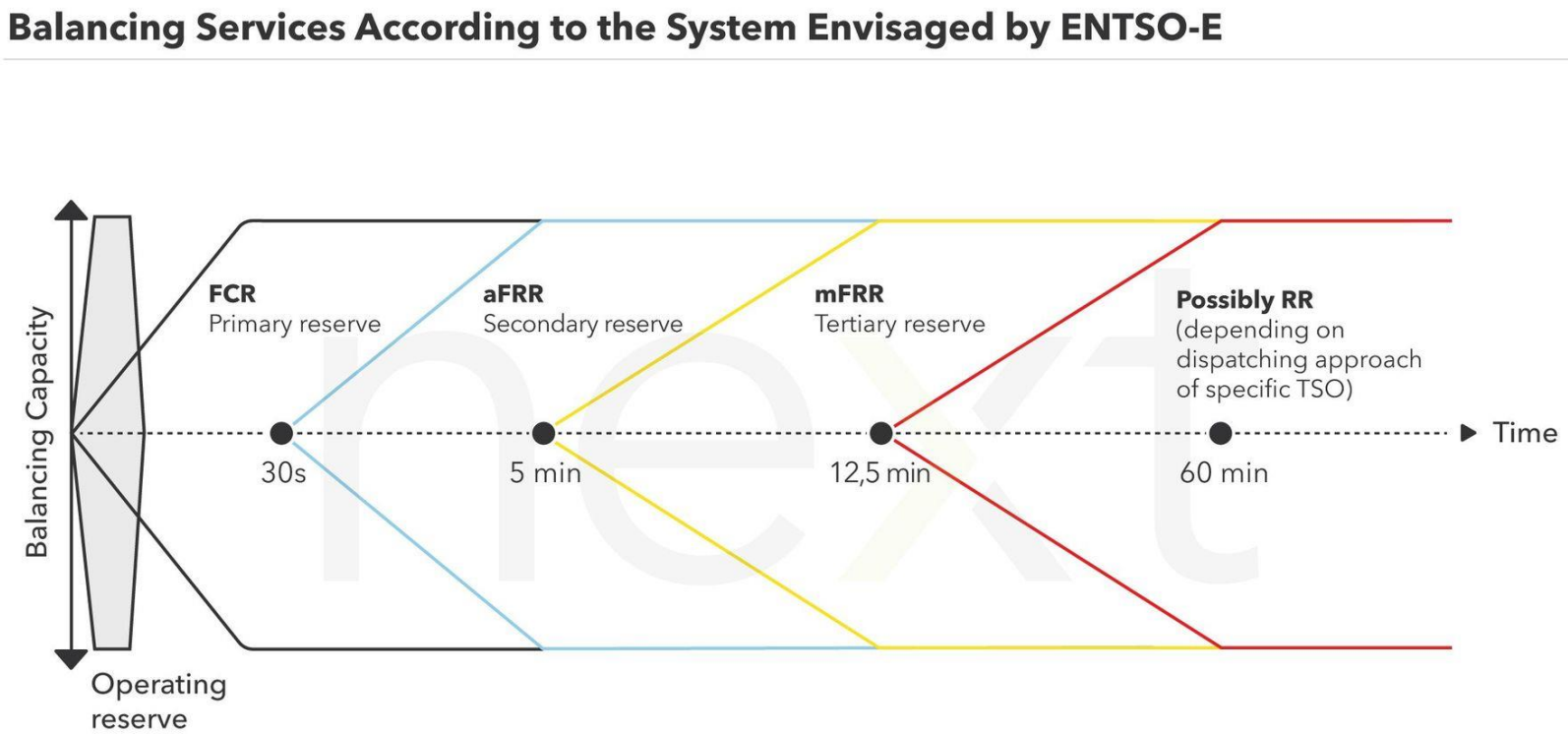
- **Definition & role** – Balancing services are short-term, reactive tools TSOs deploy to correct frequency deviations and avoid black-outs; they comprise both *balancing capacity* (reserve held) and *balancing energy* (energy activated).

- **Frequency safeguard** – If the grid drifts beyond ±0.2 Hz from its nominal 50/60 Hz, TSOs activate reserves to restore balance.

- **Market mechanism** – Reserves are procured through national or common auctions; Europe is progressively harmonising rules to enable cross-border exchange and broader participation.

- **Main ENTSO-E products**
  - **FCR** (primary, < 30 s)
  - **aFRR** (secondary, ≤ 5 min)
  - **mFRR** (tertiary, ≤ 12.5 min)
  - **RR** (replacement)

FCR, aFRR and mFRR: What is the Difference?



Automatic Frequency Restoration Reserve (aFRR)

- **What it is** – Secondary reserve automatically triggered by TSOs; BSPs must deliver the instructed power within **5 minutes (FAT)**. After 30 s it takes over from FCR; after 12.5 min it is supported or replaced by mFRR.

- **Bid directions** – *Positive aFRR* (increase generation / reduce load) vs. *Negative aFRR* (decrease generation / increase load).

- **Remuneration** – Two-part payment:
  - *Capacity price* for keeping flexible MW available
  - *Energy price* for the activated MWh

- **Typical providers** – Pumped-storage plants, gas turbines and, increasingly, aggregated “virtual power plants”.

Why aFRR Price Formation Matters for TSOs & Policy

- **1. Reduce Balancing Costs**
  - Smarter volume sizing and activation timing
  - Avoid costly last-minute interventions

- **2. Enable Better Flexibility Incentives**
  - Clear signals attract storage & demand response
  - Supports market-based procurement

- **3. Inform Targeted Policy Design**
  - Data-driven adjustments to auction rules, bid caps
  - Align gate closures & penalties with real needs

Capstone Project: “Explaining aFRR Price Formation”

Goal: Develop your hypothesis and workflow to explain price formation in the aFRR market using real-world data.

Step-by-step instructions:

- **Form teams** of 2–4 students
- **Brainstorm key influencing factors** of positive & negative aFRR prices
  - Technical (e.g. PV, wind, load, storage)
  - Market-based (e.g. Day-Ahead price, bidding patterns)
- **Define your workflow:** Which methods from Lectures 7 & 8 will you use?
- **Present:** Each team presents their proposed **problem framing and analysis plan**
  - Hypotheses on influencing factors
  - Planned data workflow and models
  - Challenges and open questions