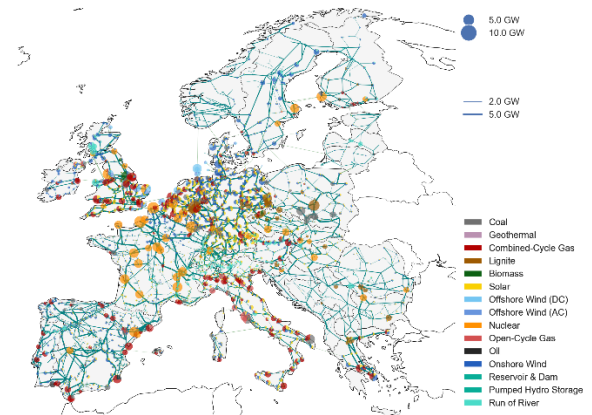


# Energy System Modeling with Python

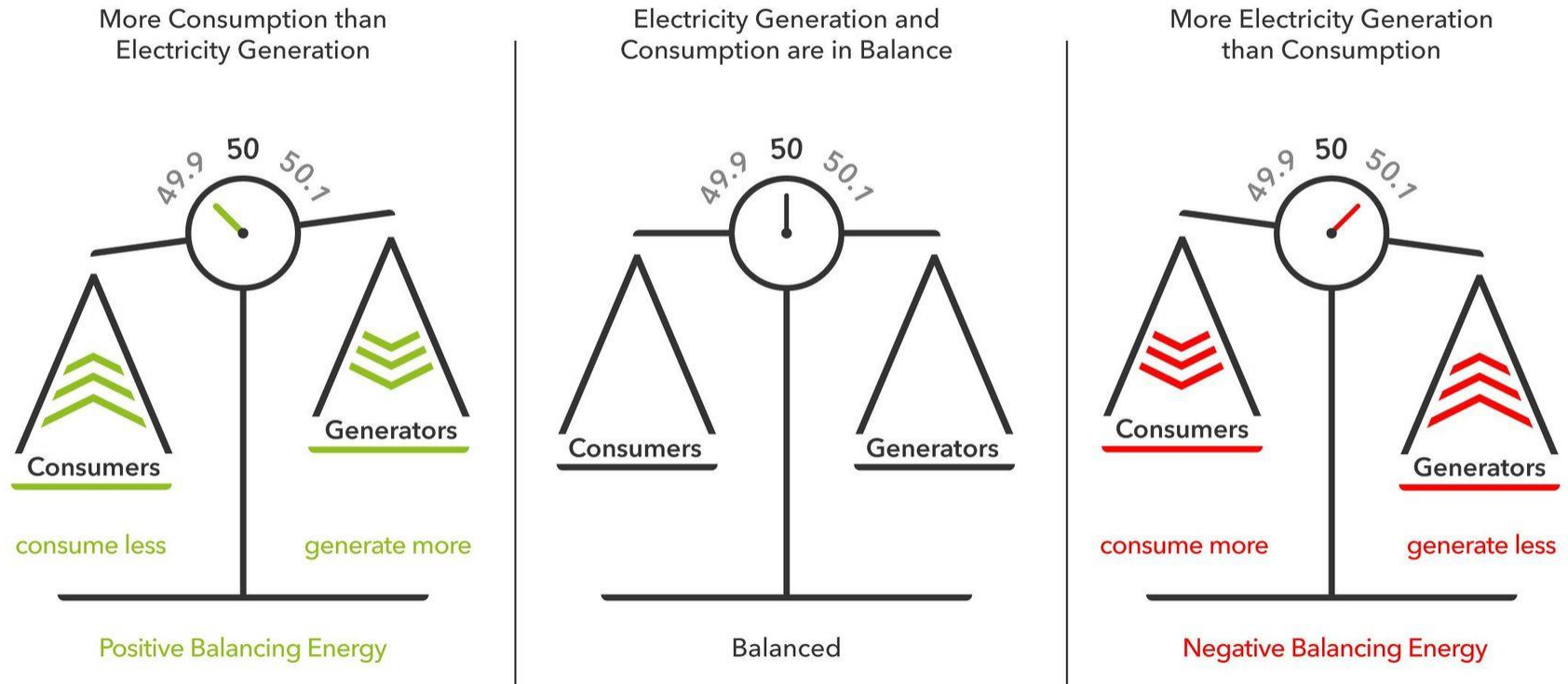
University of Freiburg (Germany) | Faculty of Engineering  
Department of Sustainable Systems Engineering | INATECH  
**Chair for Control and Integration of Grids**

Tuesday, 3. June 2025



# Why Keep System in Balance?

## Balance between electricity generation and electricity consumption



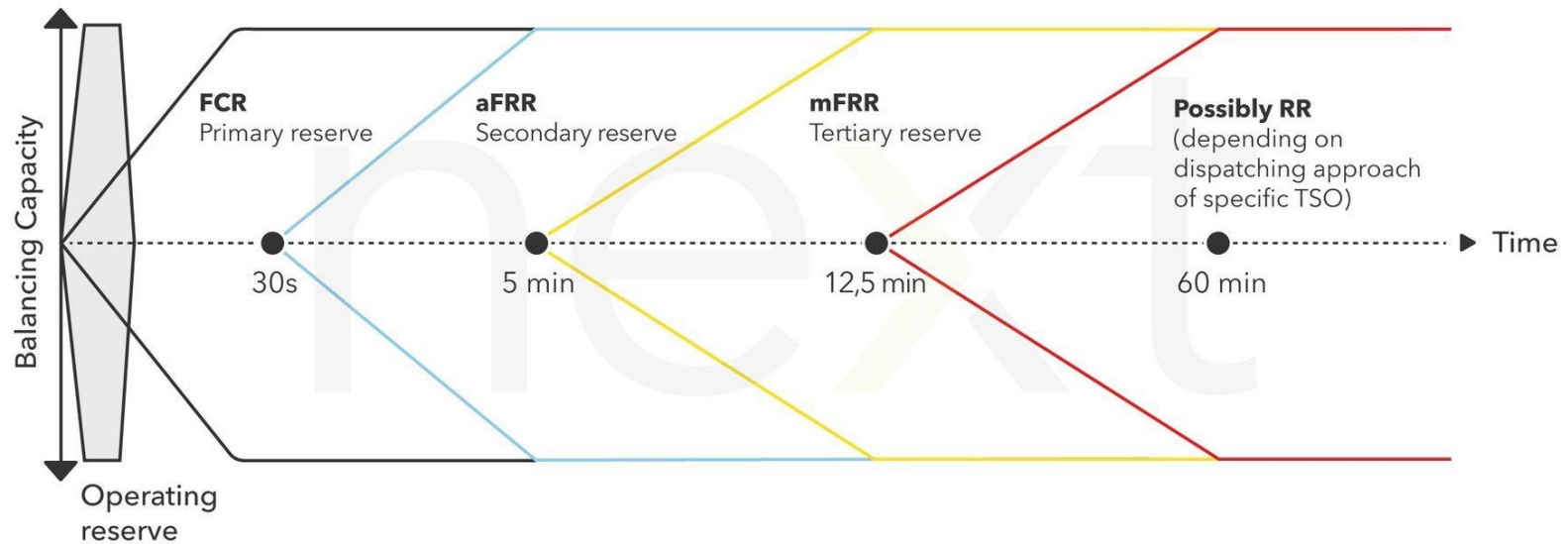
# Balancing Markets: The Grid's Real-Time Safety Net

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- **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  $\pm 0.2$  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,  $\leq 5$  min)
  - **mFRR** (tertiary,  $\leq 12.5$  min)
  - **RR** (replacement)

# FCR, aFRR and mFRR: What is the Difference?

## Balancing Services According to the System Envisaged by ENTSO-E



# Automatic Frequency Restoration Reserve (aFRR)

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- **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”.

# aFRR Market Design & Price Structure

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## ■ Product Design

Market is organized in **4-hour blocks** (e.g., 00–04, 04–08, etc.)

Bidders submit separate offers for each time block

TSOs procure **capacity** (MW) and later activate **energy** (MWh) as needed

## ■ Clearing Mechanism

**Pay-as-Bid** auction: each accepted bid is paid at its offered price

No uniform market clearing price – instead:

- **Min price** – lowest accepted bid
- **Max price** – highest accepted bid
- **Average price** – volume-weighted average

## ■ Implications for Analysis

Prices may vary significantly **within the same day**

Interpretation must consider the time-block structure

Each 4-hour period is a separate market with its own price range

# Why aFRR Price Formation Matters for TSOs & Policy

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- **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”

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*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