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How to design economic mechanisms for efficient operation of low-inertia power grids

TRANSIT

Luis Badesa

Technical University of Madrid (UPM)
Spain

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IEEE PES Power & Energy Society®

IEEE PES ISGT INNOVATIVE SMART GRID TECHNOLOGIES EUROPE

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UNIVERSITY OF ZAGREB
Faculty of Electrical Engineering and Computing

3 topics covered

1. **Unlocking the support from DER** via risk-constrained optimization

2. From **low-level control** instructions to **system-level optimization** via data-driven methods

3. **Who should pay** for frequency-containment services?

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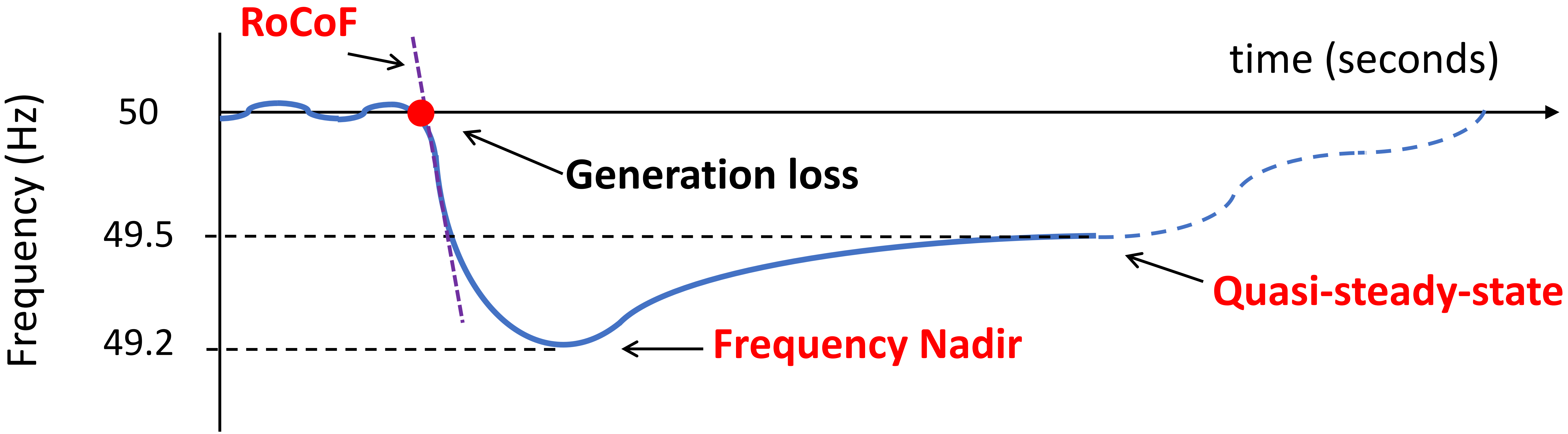
Frequency stability



Key to keep frequency within safe limits to **avoid demand disconnection!**

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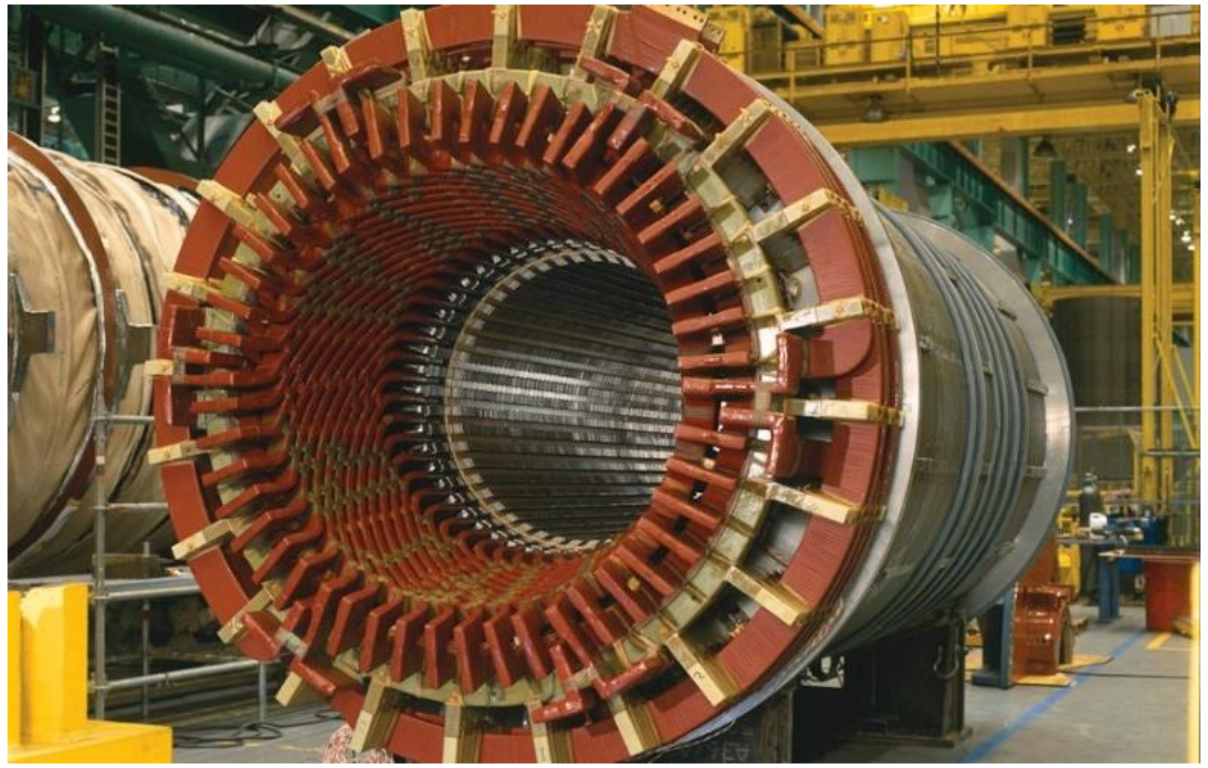
Lower inertia on the road to lower emissions

Thermal generators (nuclear, gas, coal…):



Decarbonization

Most renewables:
no inertia

The **risk of instability has increased!**

Inertia <u>stores kinetic energy</u>:
this energy gave us time to contain a sudden generation-demand imbalance

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Paper:

C. O'Malley, L. Badesa et al., "Frequency Response from Aggregated V2G Chargers With Uncertain EV Connections," ***IEEE Trans. on Power Systems***, 2023

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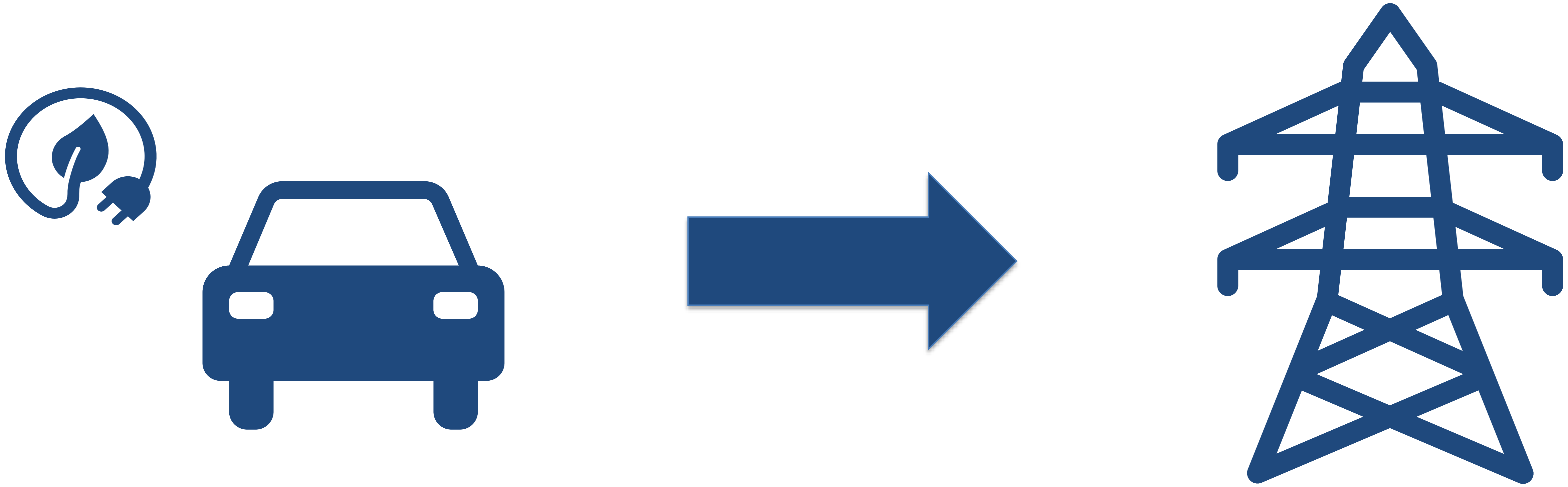
Unlocking support from Distributed Energy Resources

- **DER could be very valuable** to support system stability, but they are **inherently uncertain**
- We focus on **Vehicle-to-Grid (V2G)**: the system operator cannot control when the EV owners plug in their vehicles



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Why is this important?

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Now	→	Future
Stability through **gas plants**		Stability services from **DER**
• **Pros**: certain + reliable		• **Pros**: abundant + **cheap**
• **Cons**: expensive + polluting		• **Cons**: uncertain

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Stability conditions for optimization

What is the **value of V2G** as a countermeasure to low inertia?

Described by
differential equations
(timescale of sub-seconds)

Based on
algebraic equations
(timescale of min/hours)

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Uncertainty within the stability conditions

We propose the use of **chance constraints**:

Probability of complying with **stability limit** $\geq$ 1 - **ϵ**

Uncertainty in
EV plug-in times

Risk appetite
(*e.g.*, 1% chance of
under-delivery)

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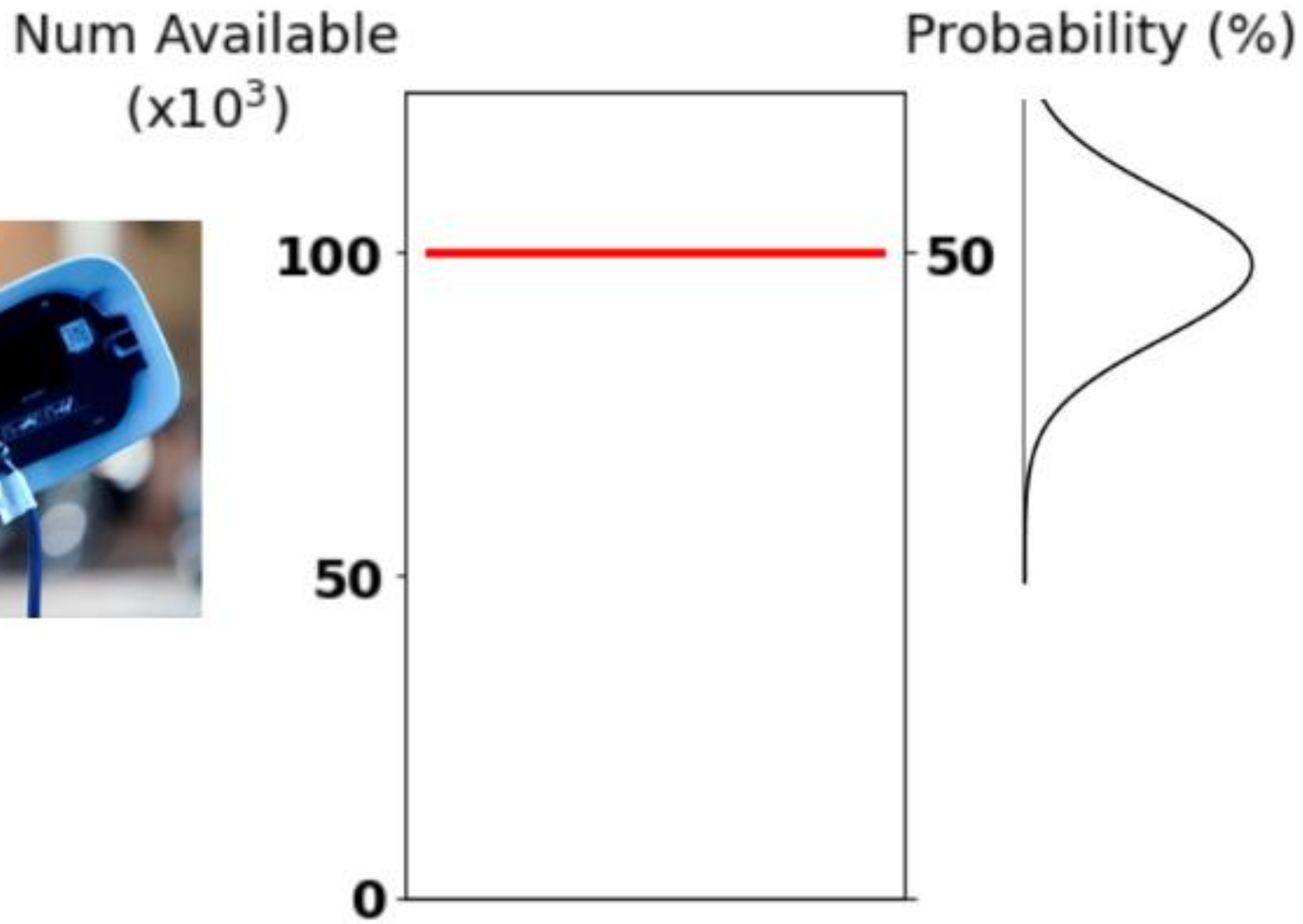
What do we mean by risk?

Probabilistic forecast
for EV connections



Naïve scheduling:

- Use **deterministic forecast** (mean)
- Count on 100k EVs
- 50% chance of having less than expected

Risky!

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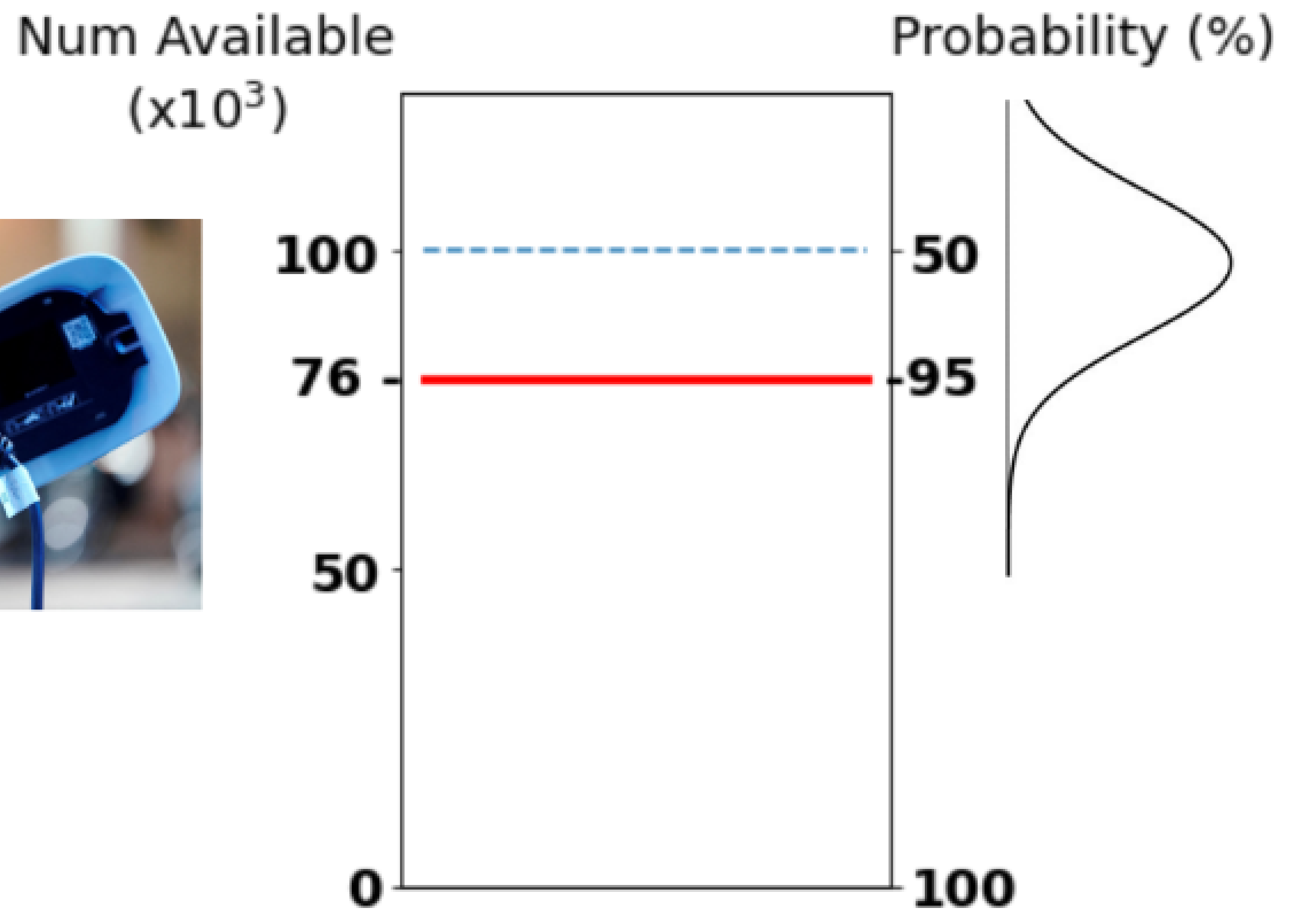
What do we mean by risk?

Probabilistic forecast
for EV connections



Risk-limited scheduling:

- Specify **risk tolerance** (*e.g.*, 5%)
- Count on **76k** EVs

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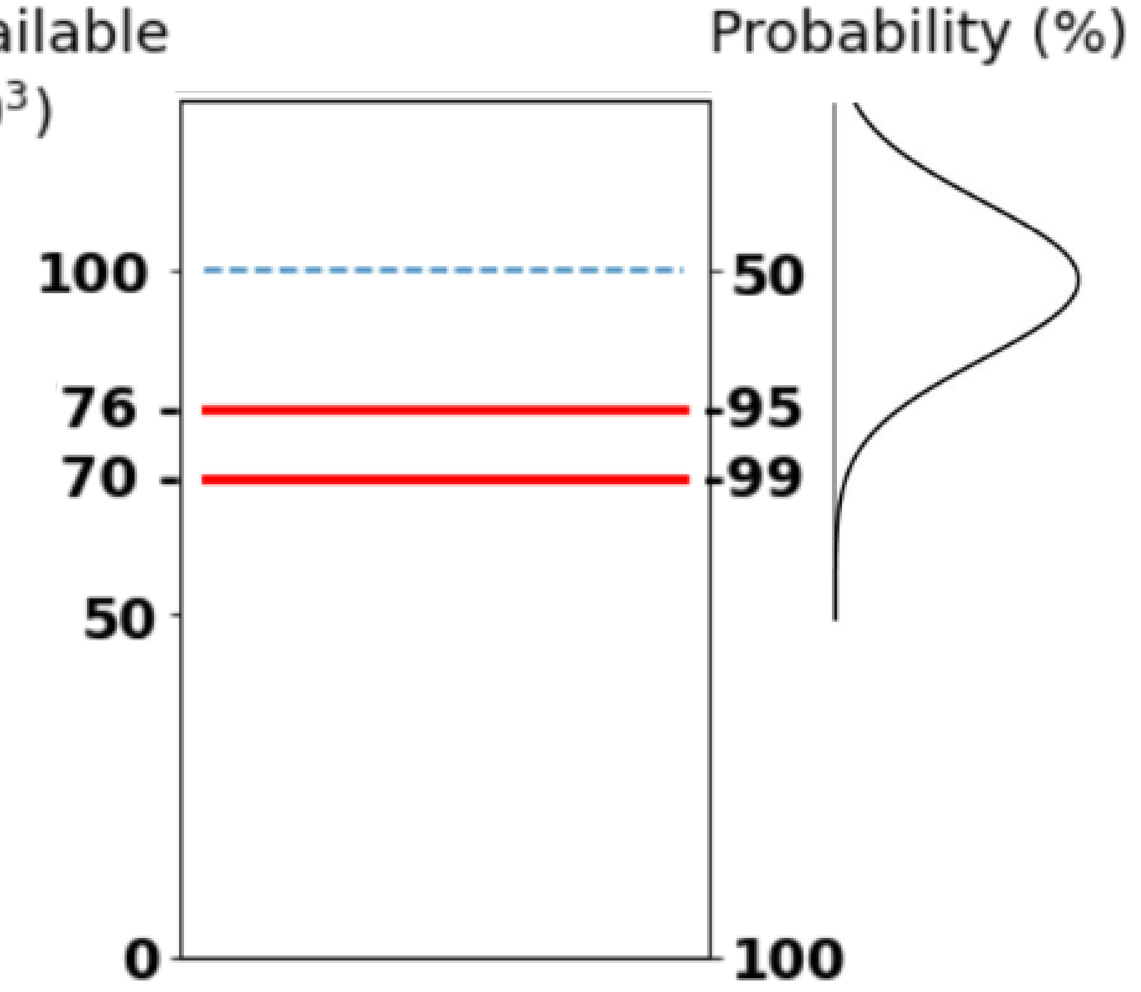
What do we mean by risk?

Probabilistic forecast
for EV connections



Risk-limited scheduling:

- Specify **risk tolerance** (*e.g.*, **1%**)
- Count on **70k** EVs

Lower risk implies <u>less support</u> from EVs considered

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Steps for deducing chance constraints

1. Model system frequency via **single-machine swing equation**:

$$\frac{2H}{f_0}\frac{d\Delta f}{dt} = \boldsymbol{R^{EV}}(t) + \boldsymbol{R^{ND}}(t) + \boldsymbol{R^{G}}(t) - \boldsymbol{PL_{max}}$$

2. **Solve swing equation** to obtain RoCoF and nadir **constraints**:

$$\mathbb{P}\left[\left(\frac{\boldsymbol{H}}{f_0} - \frac{(\boldsymbol{R^{ND}} + \boldsymbol{R^{EV}})\cdot T_1}{4\Delta f_{max}}\right)\frac{\boldsymbol{R^{G}}}{T_2} \geq \left(\frac{\boldsymbol{PL_{max}} - (\boldsymbol{R^{ND}} + \boldsymbol{R^{EV}})}{2\sqrt{\Delta f_{max}}}\right)^2\right] \geq 1-\epsilon$$

3. Use a **convex reformulation** for the non-convex chance constraints

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Convexification of chance constraint

Several options for the **convex reformulation**:

The **more information** available in the forecast,
the **less conservative** the reformulation:

- **Gaussian** uncertainty?
- **Unimodal** distribution? (single peak)
- Only mean and variance known?
  Distributionally-robust formulation (most conservative)

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Results for Great Britain

- **Frequency-secured UC** run for a full year in 2030

- Two **EV fleets** considered:
    - ‘**Domestic** V2G’: 85,000 units, 10 kW chargers
    - ‘**Work** V2G’: 15,000 units, 20 kW chargers

- **Risk** of under-delivery set at **1%**
    - Does **not mean** 1% risk of **violating security**: that risk is extremely small (largest *N*-1 contingency needs to happen too)

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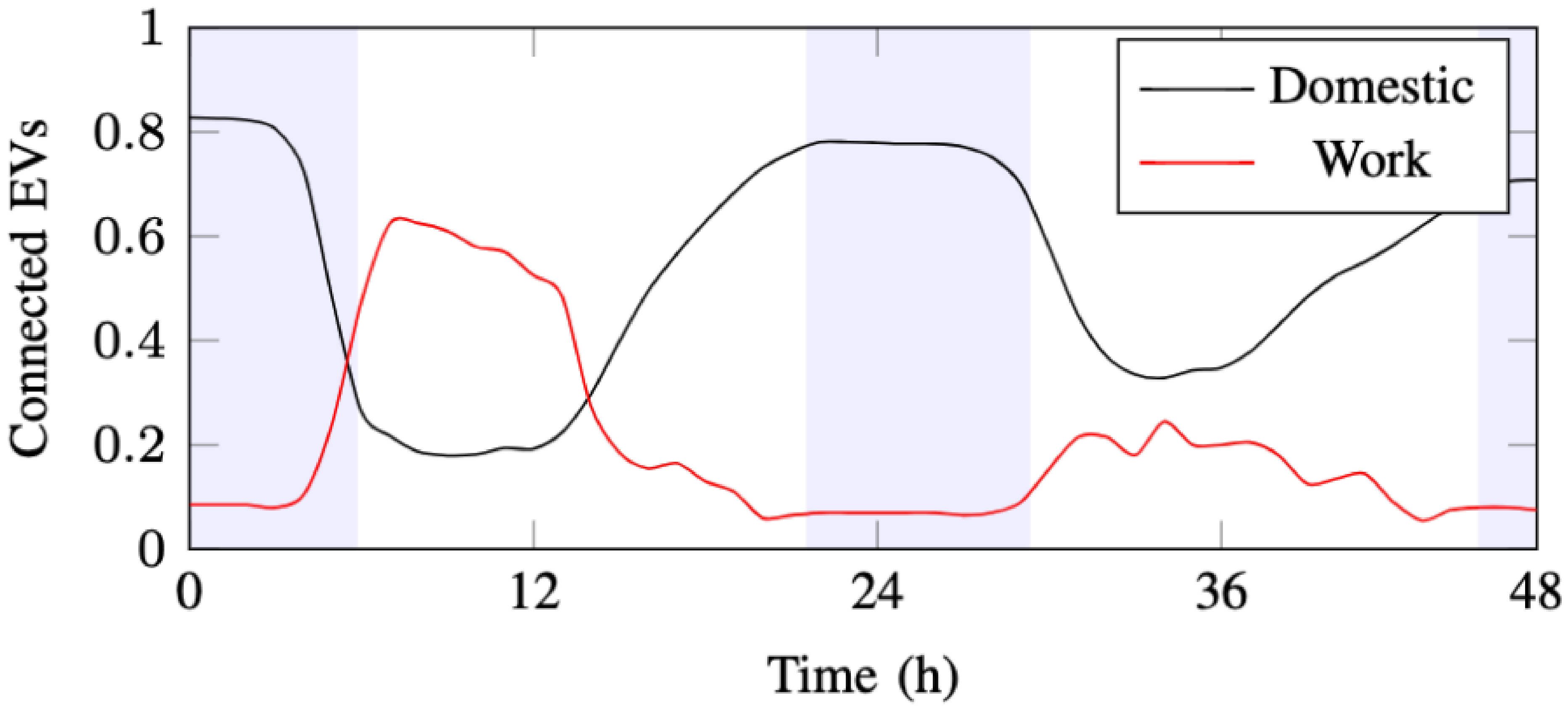
EV connectivity forecasting and data analysis

Data from UK Department of Transport, 2017



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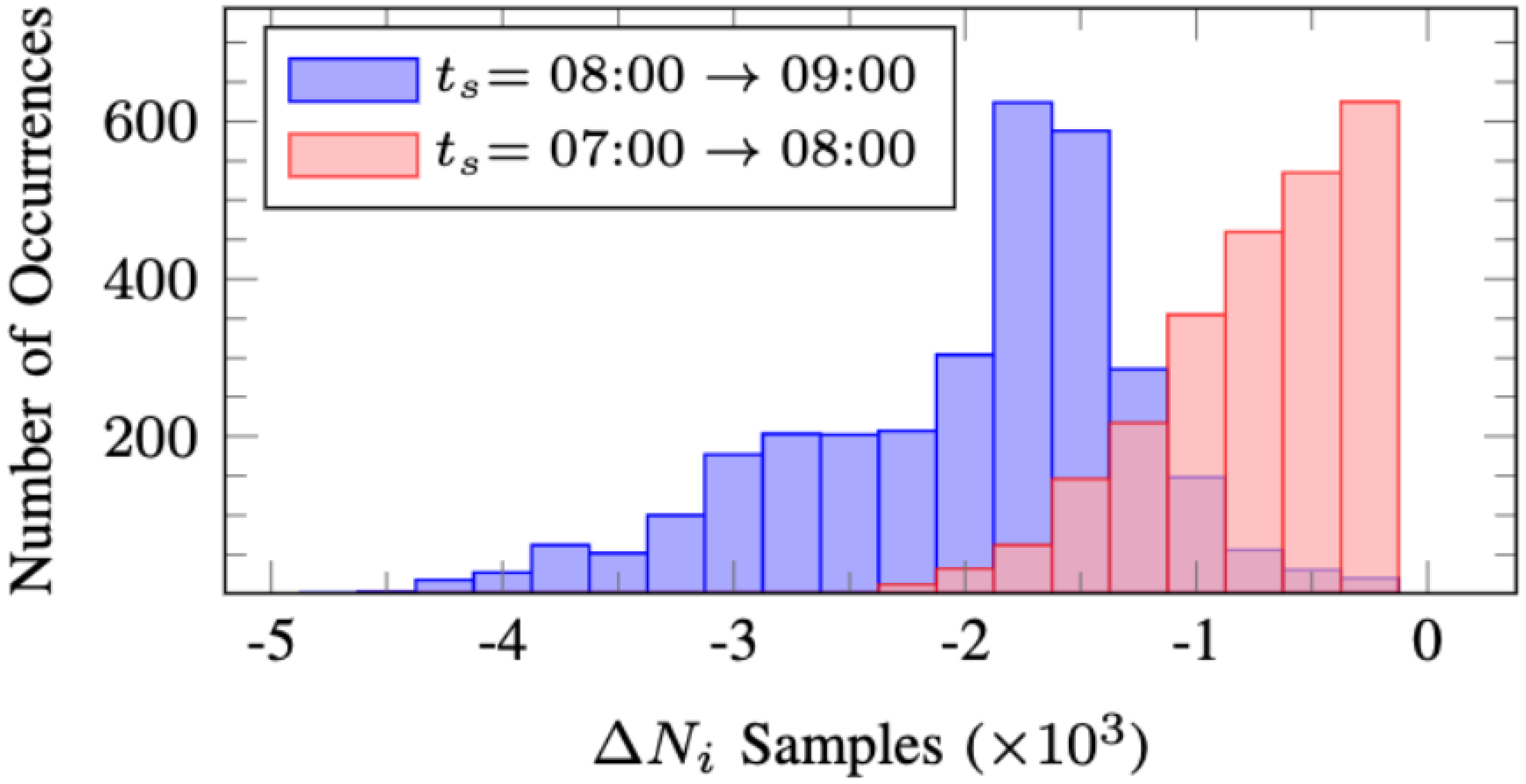
Test for ambiguity set

Domestic fleet disconnections
on weekday



- **Not** Gaussian
- **Unimodal** with high confidence (from Shapiro-Wilk test)

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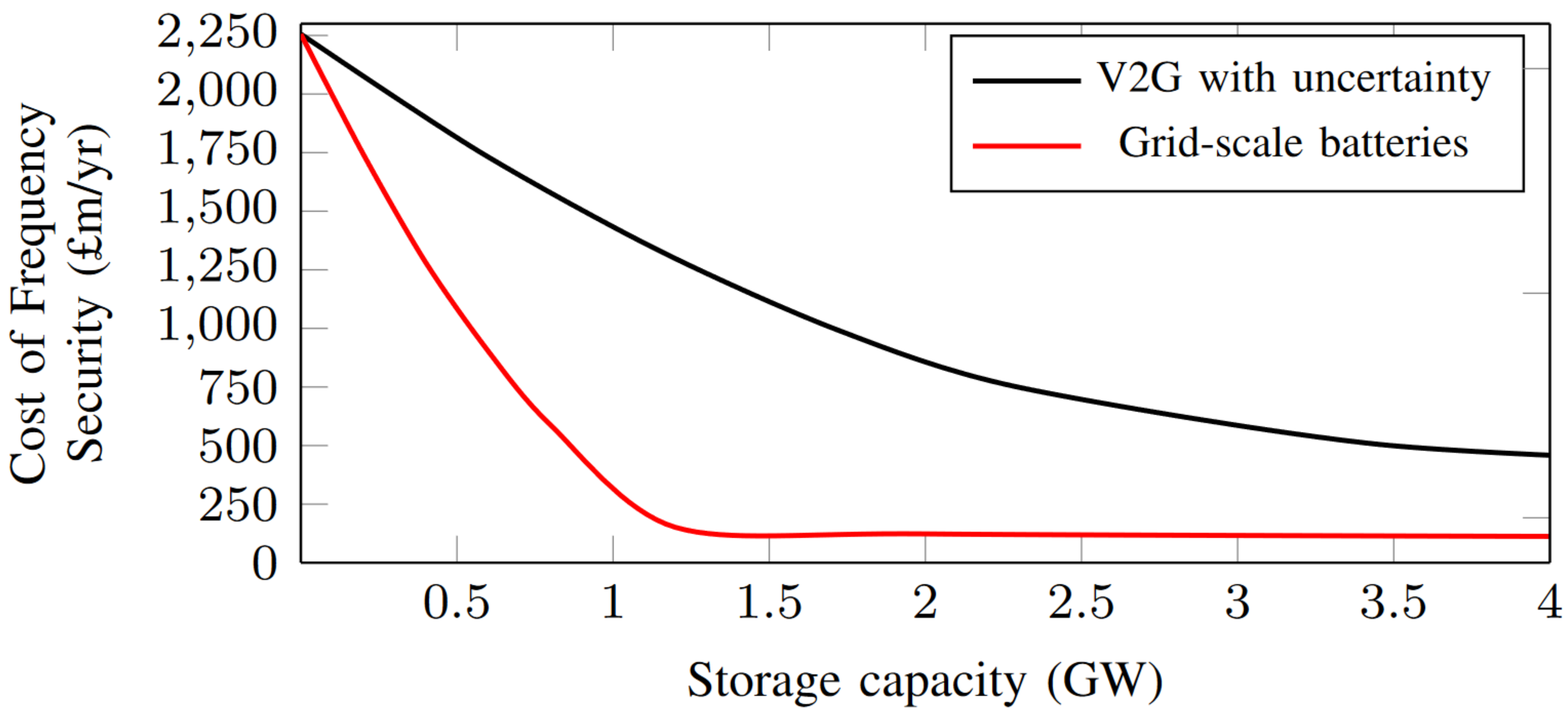
Results: comparison of V2G to BESS

V2G capacity shown to be **one third as valuable** as stationary BESS

- EV chargers only have an **EV connected ~40% of the time**
- EV chargers are subject to **uncertainty**



But EVs have **no additional** investment cost!

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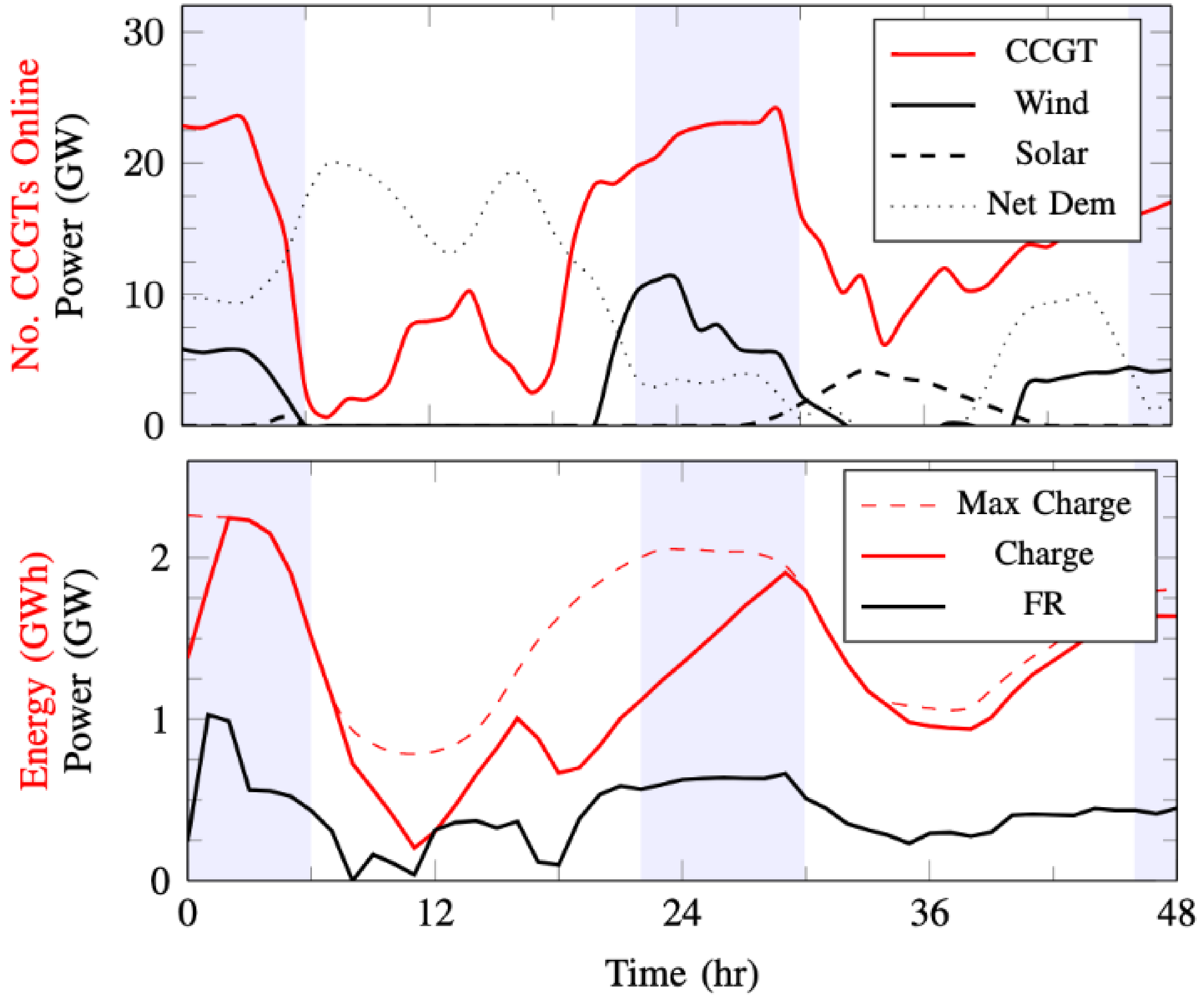
Where does this value come from?



Fewer CCGTs are needed,

thanks to **frequency support** from **EVs**

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3. **Who should pay** for frequency-containment services?

Paper:
Q. Chen, L. Badesa et al., "Adaptive Droop Gain Control for Optimal Kinetic Energy Extraction From Wind Turbines to Support System Frequency," ***IEEE Access***, 2024

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Research question

How to **translate** the **system** optimal **dispatch**

into **specific control gains** for devices?

(not possible with fully analytical methods as the one shown earlier)

Goal:

Optimal kinetic energy extraction from wind turbines depending on **overall system dispatch**

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Approach we used

Data-driven methods allow to compute explicit control instructions

But, **how to choose the classifier?**

- We opt for an **Optimal Classification Tree** (OCT): **simple** structure and **tractable** for incorporating into optimization

Other options:

- Logistic regression and SVM: limited by hyperplane separation (although kernels could be used)
- Neural Networks: problems with tractability due to binary variables

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Adaptive Droop Gain (ADG)

$$\mathrm{ADG}\underbrace{(v_w, \boldsymbol{P_G}, L_D, pl, \Delta P_L}_{\text{System operating condition}}, \omega_r) = \widetilde{K}_{\text{sys}} \cdot \underbrace{(\omega_r^2 - \omega_{r,min}^2)}_{\text{deter over-deceleration}}$$

$$\widetilde{K}_{\text{sys}} = f(v_w, \boldsymbol{P_G}, L_D, pl, \Delta P_L)$$

An **Optimal Classification Tree** (OCT) is used to encode frequency-stability conditions within a system-wide economic dispatch

- The **ADG** is **explicitly incorporated** into the OCT

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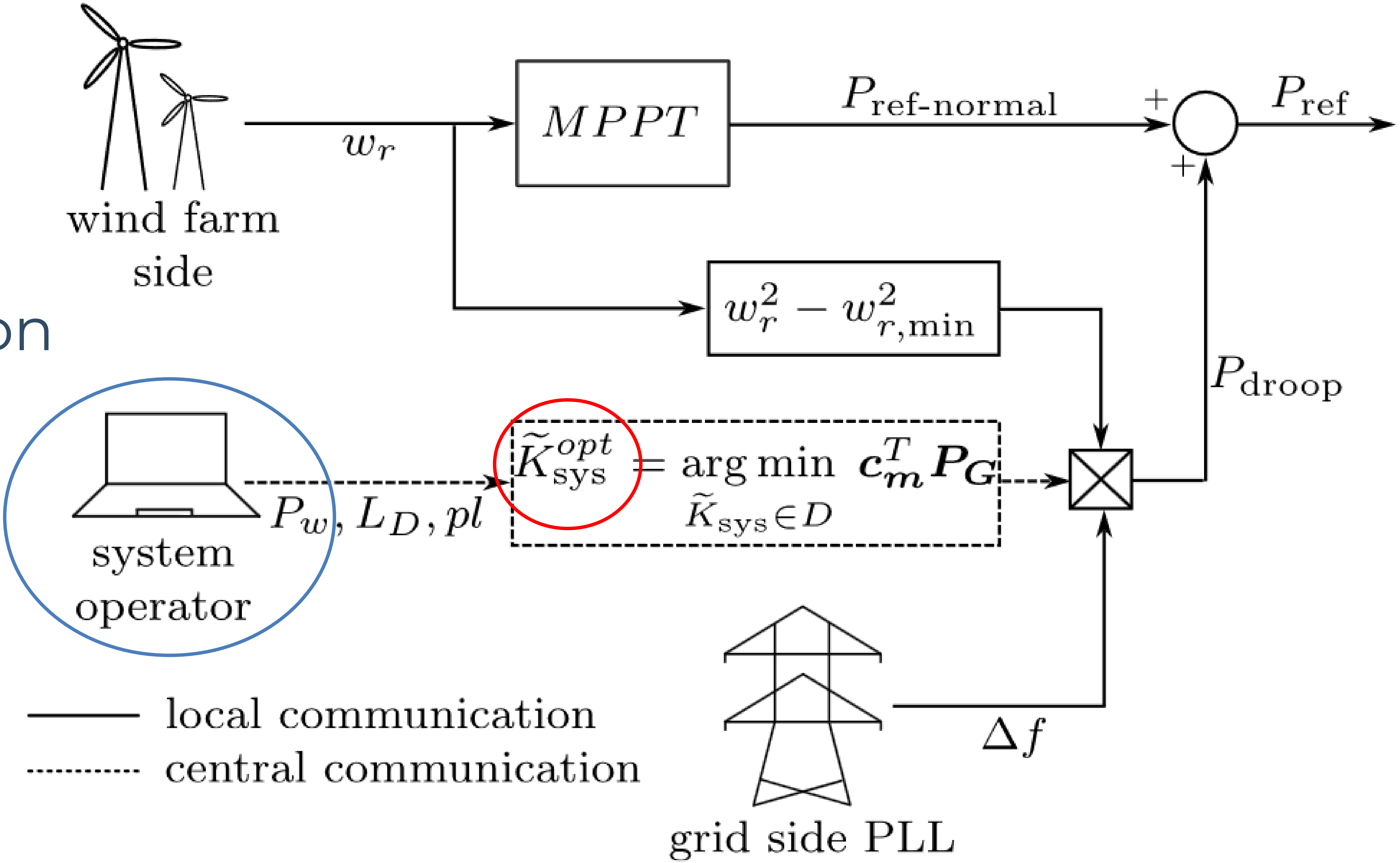
Communication requirements

Hourly communication
with system operator
(rest is local)



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Optimal Classification Tree

Offline training

(outside the Unit Commitment / OPF)

Minimize classification error

Penalize tree depth

$$\min \frac{1}{\hat{\mathcal{L}}} \sum_{t \in \underline{\Omega}^{\mathcal{T}}} l_t + \alpha \sum_{m \in \underline{\Omega}^{B}} d_m$$

$$\text{s.t. } l_t \geq \omega \cdot n_{0t} - \mathcal{M} \cdot (1 - c_t) \quad \forall t \in \underline{\Omega}^{\mathcal{T}}$$

$$l_t \leq \omega \cdot n_{0t} + \mathcal{M} \cdot c_t \quad \forall t \in \underline{\Omega}^{\mathcal{T}}$$

$$l_t \geq n_{1t} - \mathcal{M} \cdot c_t \quad \forall t \in \underline{\Omega}^{\mathcal{T}}$$

$$l_t \leq n_{1t} + \mathcal{M} \cdot (1 - c_t) \quad \forall t \in \underline{\Omega}^{\mathcal{T}}$$

Classification boundaries (linearized via big-M)

Penalize 'false safe' predictions (adjustable parameter)

$$n_{1t} = \sum_{i \in \Omega^{\mathcal{N}}} z_{it} \cdot Y_i \quad \forall t \in \underline{\Omega}^{\mathcal{T}}$$

'Safe' classifications

$$n_{0t} = \sum_{i \in \Omega^{\mathcal{N}}} z_{it} - n_{1t} \quad \forall t \in \underline{\Omega}^{\mathcal{T}}$$

'Unsafe' classifications

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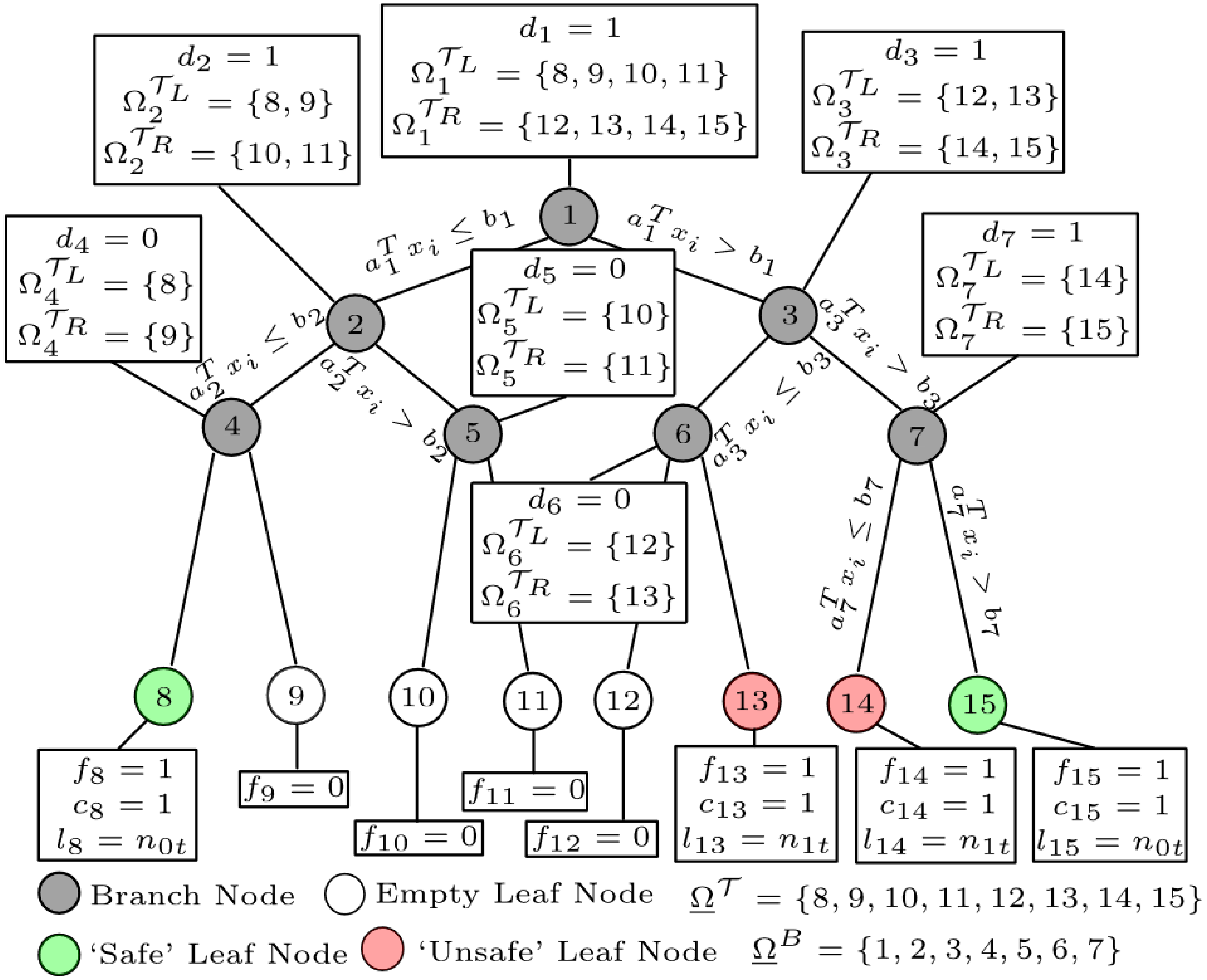
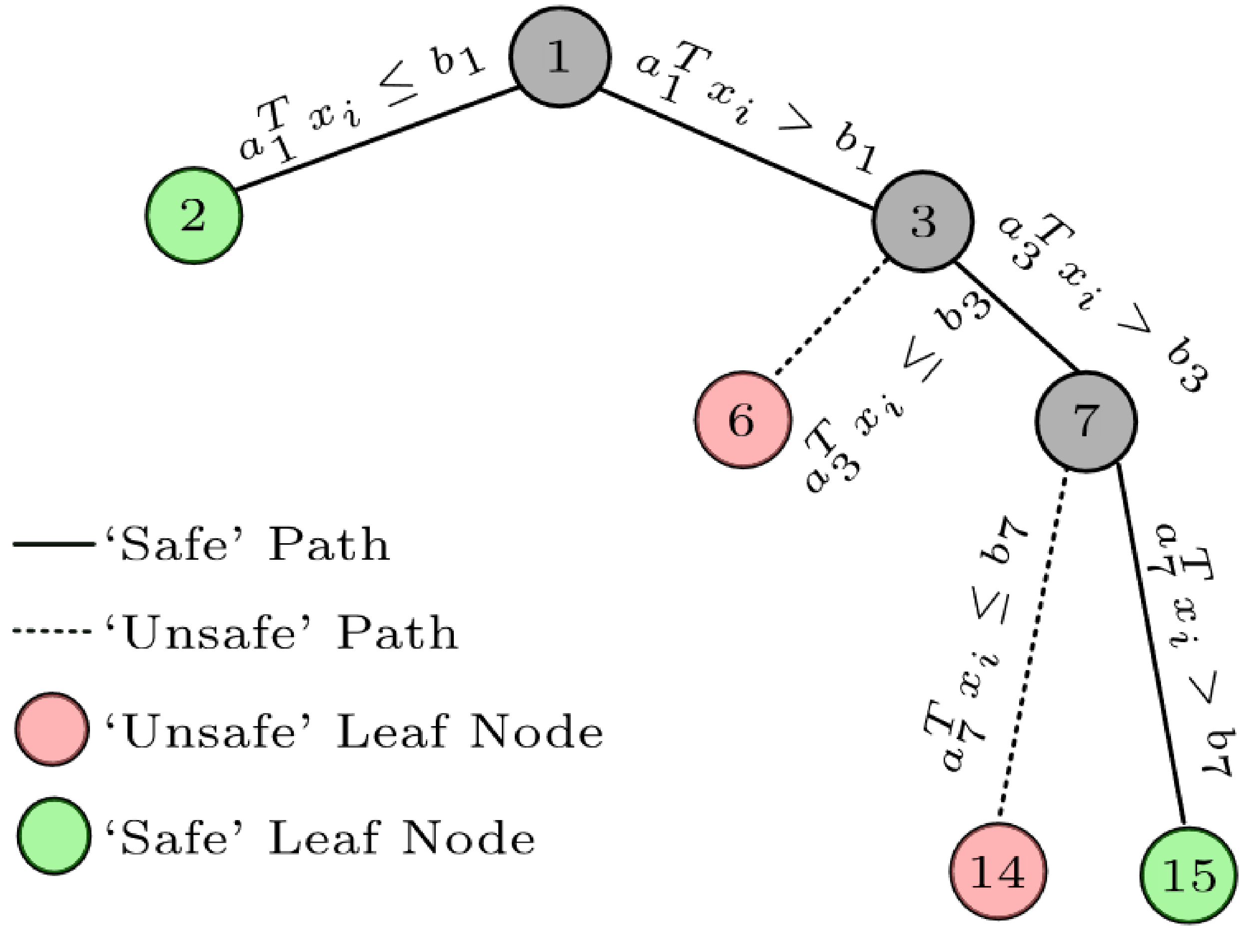
Optimal Classification Tree



Pruning redundancies



This OCT is **integrated into the OPF** as a set of constraints

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Case studies

- **Frequency-secured OPF** run for an IEEE 14-bus network

- 1,500 **labelled samples** from **dynamic simulations** in Simulink
  - ~2 days computing time (on standard laptop)
  - 70% for training, 20% for validation, 10% for testing

- **Training OCT** offline (solving MILP): ~30 min
  - Could be retrained, *e.g.*, daily, using new datasets with updated wind and load forecasts (reduces conservativeness)

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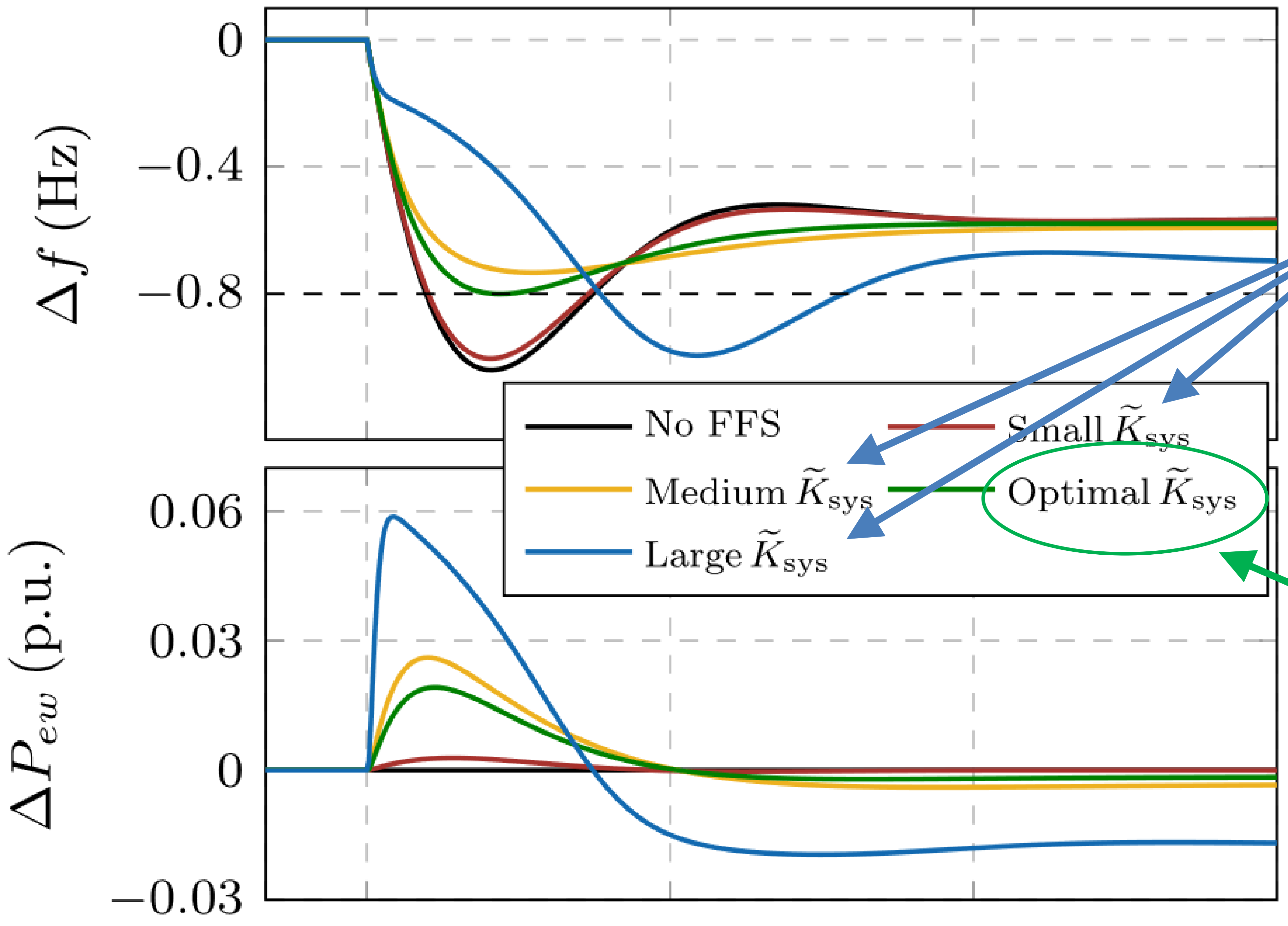
Results



Fixed *a priori*

Optimized for current **operating condition** via the classification tree

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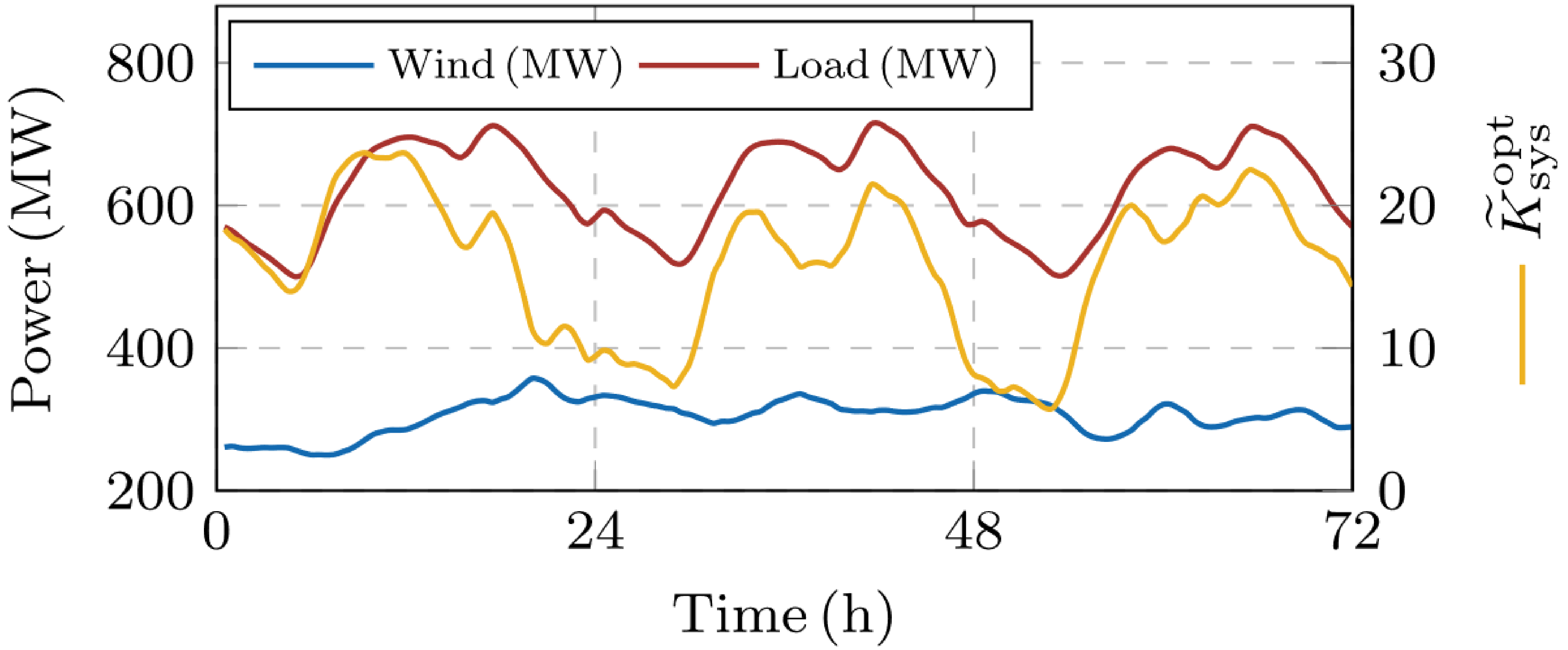
Dispatch solutions

The **optimal** droop gain ***K*$_{sys}$ fluctuates** with the system dispatch: roughly inversely proportional to wind power



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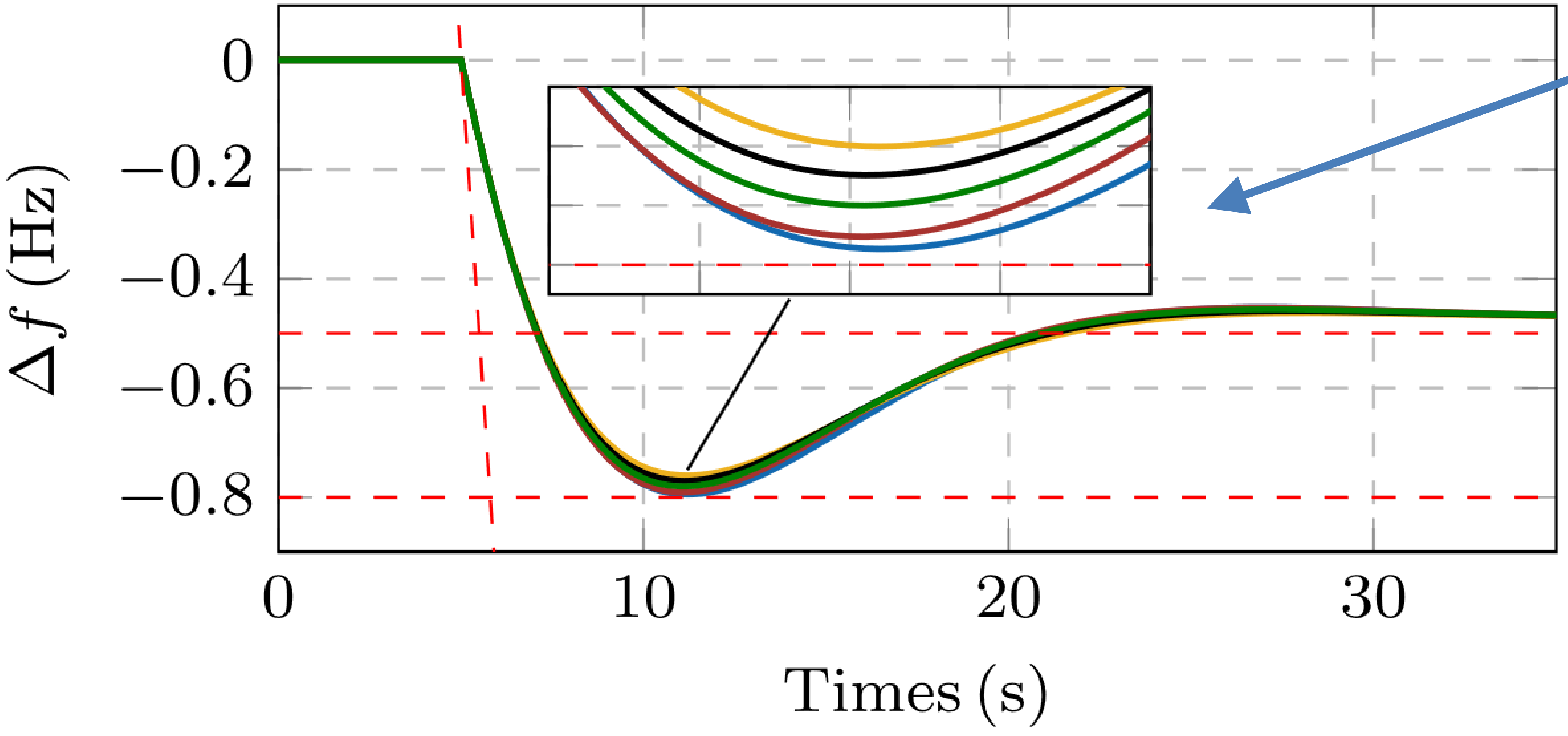
Security boundary

Slight underestimation of nadir due to **conservativeness** in **OCT**



5 different
OPF solutions,
arbitrarily chosen

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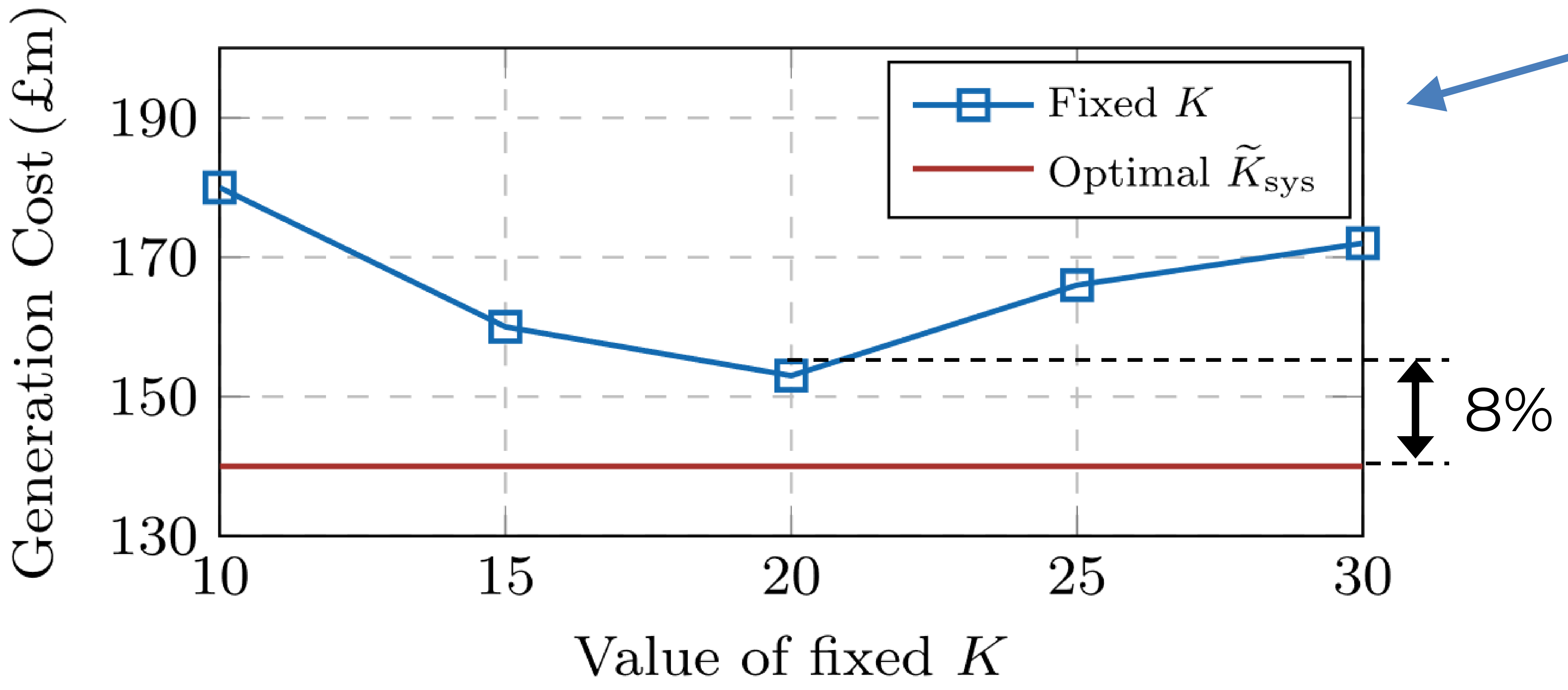
Cost savings

System **savings of** at least **8%** compared to system-unaware controller

Weekly costs for 50% wind penetration



Note that the optimal value of fixed gain (K = 20) can only be computed by system optimization (through the OCT)

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3. **Who should pay** for frequency-containment services?

Paper:
C. Matamala, L. Badesa et al., "Cost Allocation for Inertia and Frequency Response Ancillary Services," ***IEEE Trans. on Energy Markets***, 2024

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Cost allocation for frequency services

We have focused on optimizing the total cost of frequency services, but…

1. **Who should cover this cost?**
   - Generators?
   - Consumers?
   - Only a subset of the former?

2. **How much should each market participant pay?**

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First, why worry about who pays?

- Currently **costs are socialized** in most countries (except Australia)
- **Until recently**, irrelevant who paid (**costs were small** due to high inertia)

Goal of moving towards a **‘causer pays’ framework**:

To create **incentives to ‘do less harm’** to the grid

(in order to **reduce the cost** of frequency services for consumers)

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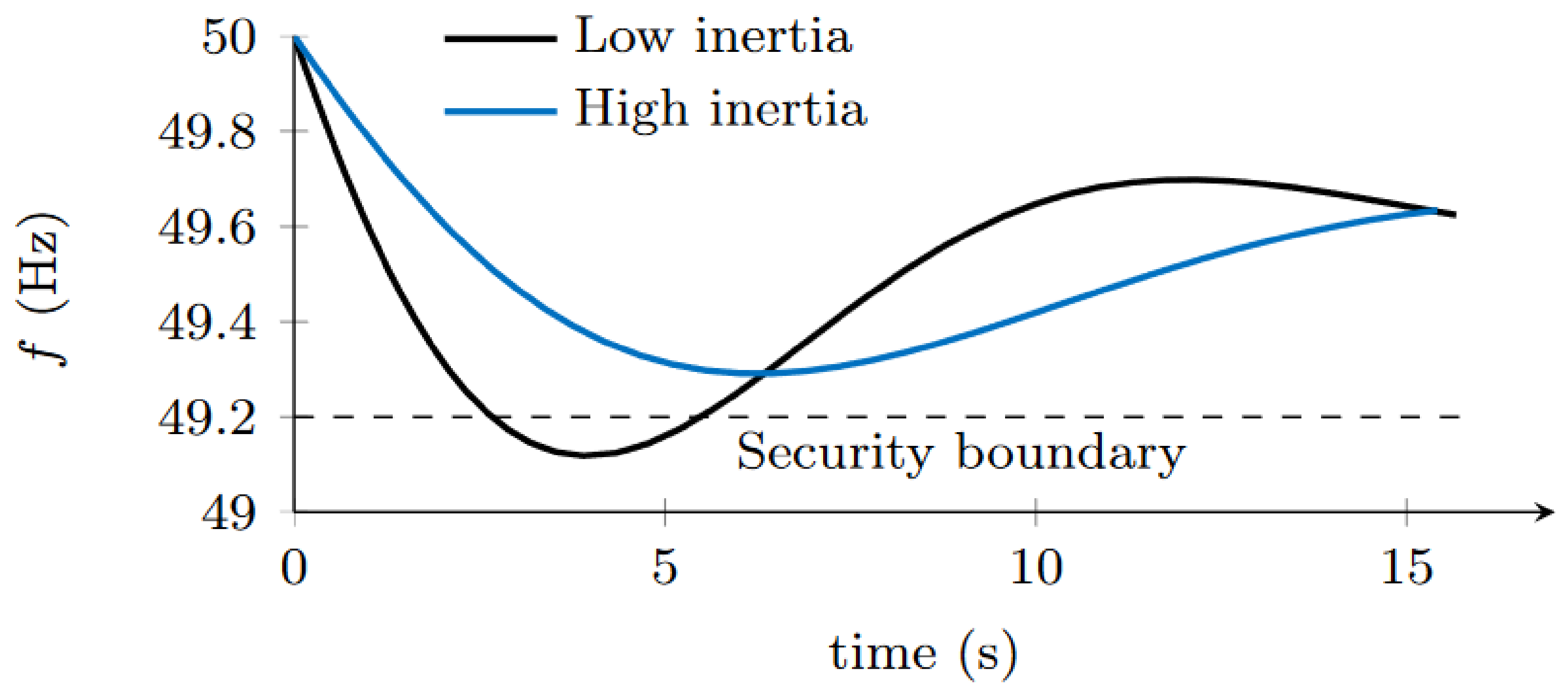
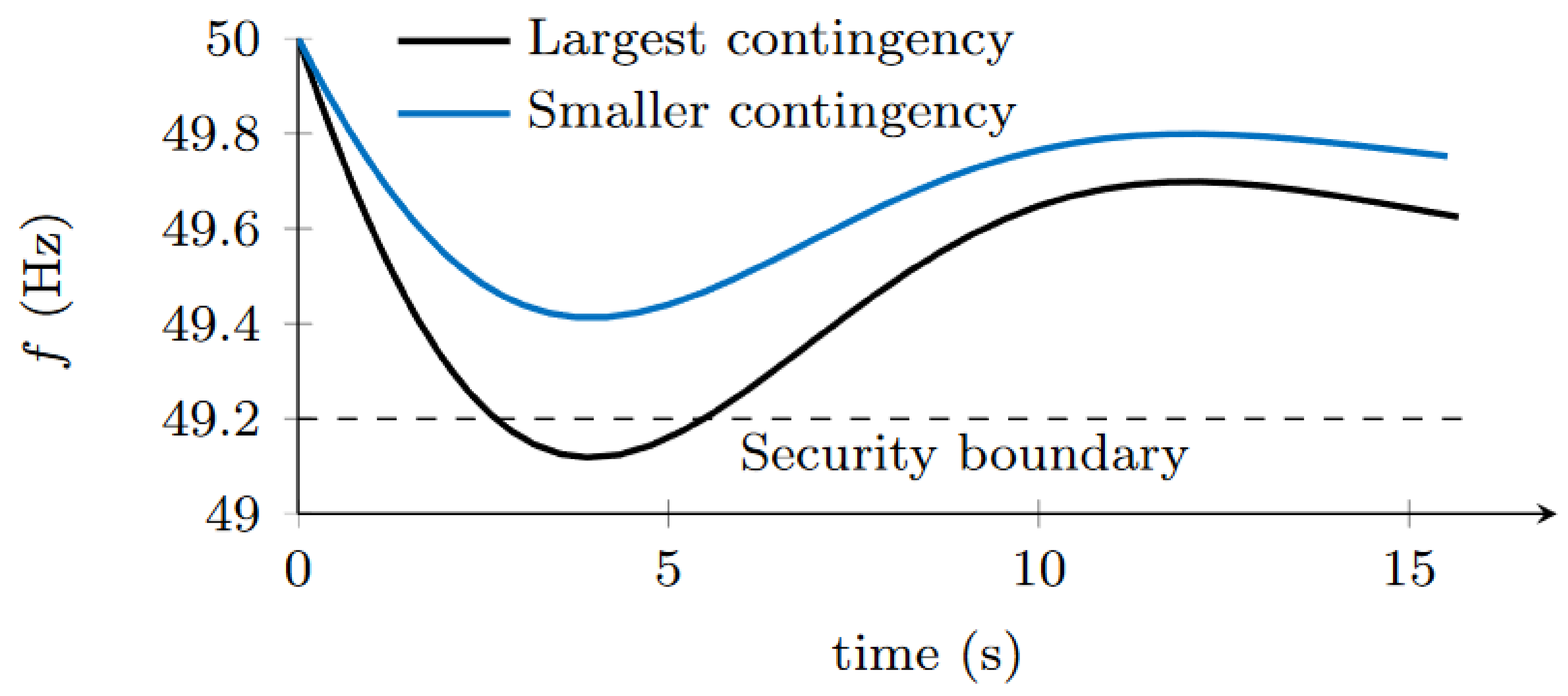
Who causes the need for frequency services?

Large units do: a low-inertia system would do fine if all units were small (there would be no large, sudden power imbalances)



Impact of inertia

under a large contingency



Impact of contingency size

in a low-inertia system

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Who causes the need for frequency services?

Large units do: a low-inertia system would do fine if all units were small (there would be no large, sudden power imbalances)

We **rule out penalizing** the **lack of inertia**

- Inertia is a service, it should be remunerated appropriately
- But lack of inertia is not a problem by itself

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How to split the cost?

Option 1: proportional cost allocation

- ✓ Easy to design: **each unit pays in proportion to its size**
- ✓ Creates **incentive** for large units **to 'do less harm'**
- **Problem**: it **maintains cross-subisidies**

(small units still subsidize large ones)

Option 2: sequential cost allocation (coming next)

- ✓ Advantage: no cross-subsidies

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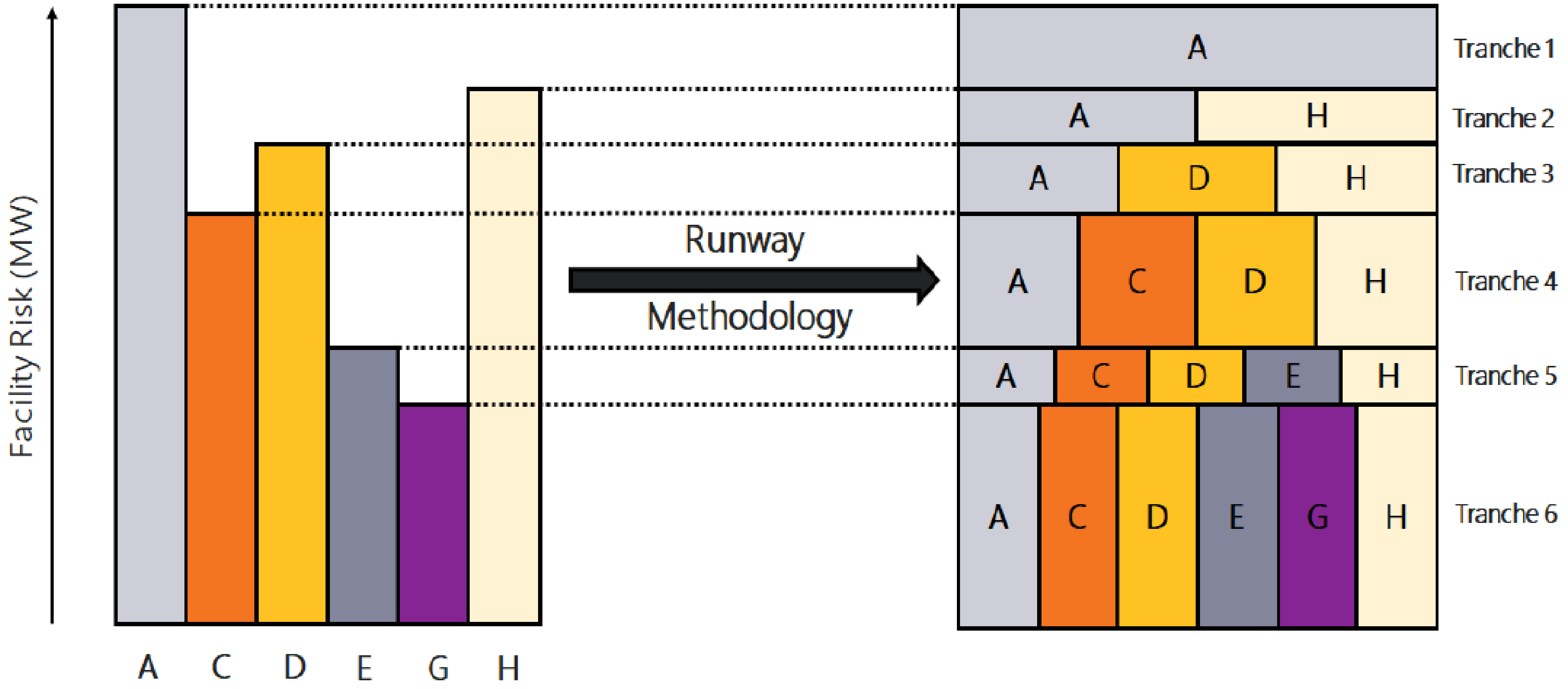
Sequential cost allocation (Shapley value)

Each unit pays for the **additional cost** that it creates



Reference: "A report describing the Wholesale Electricity Market in the South West Interconnected System", Australian Energy Market Operator, September 2023

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Steps

1) Frequency-containment services **market clearing** (driven by largest unit)

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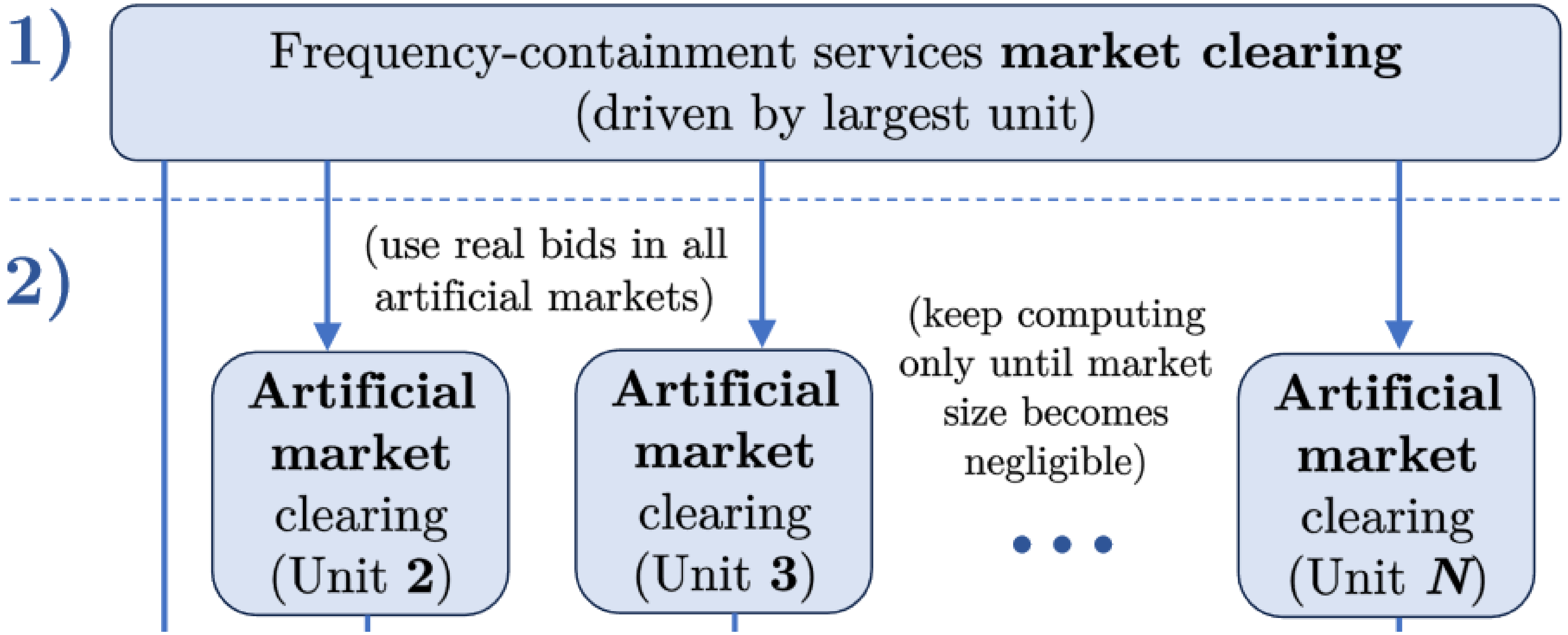
Steps



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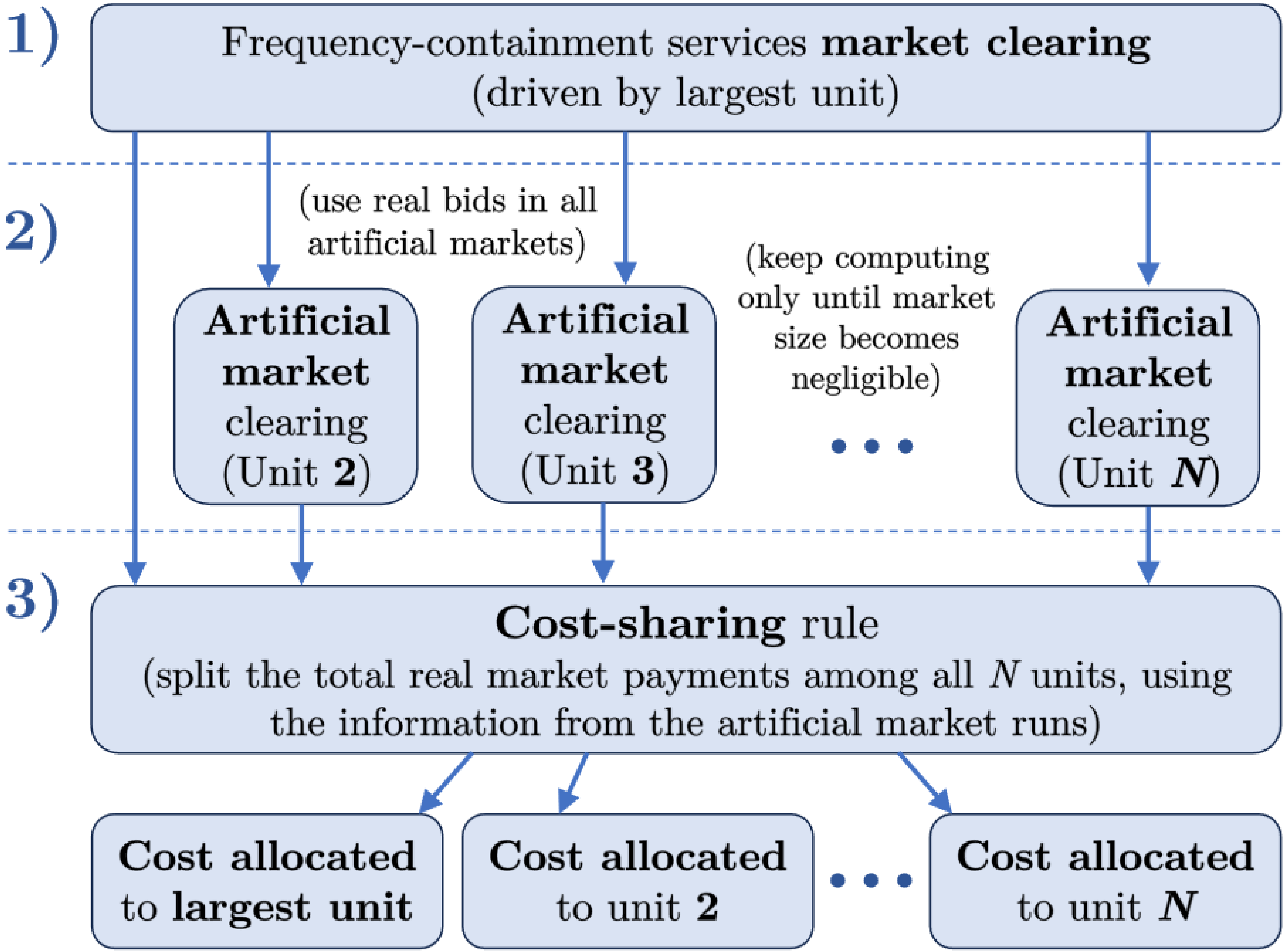
Steps



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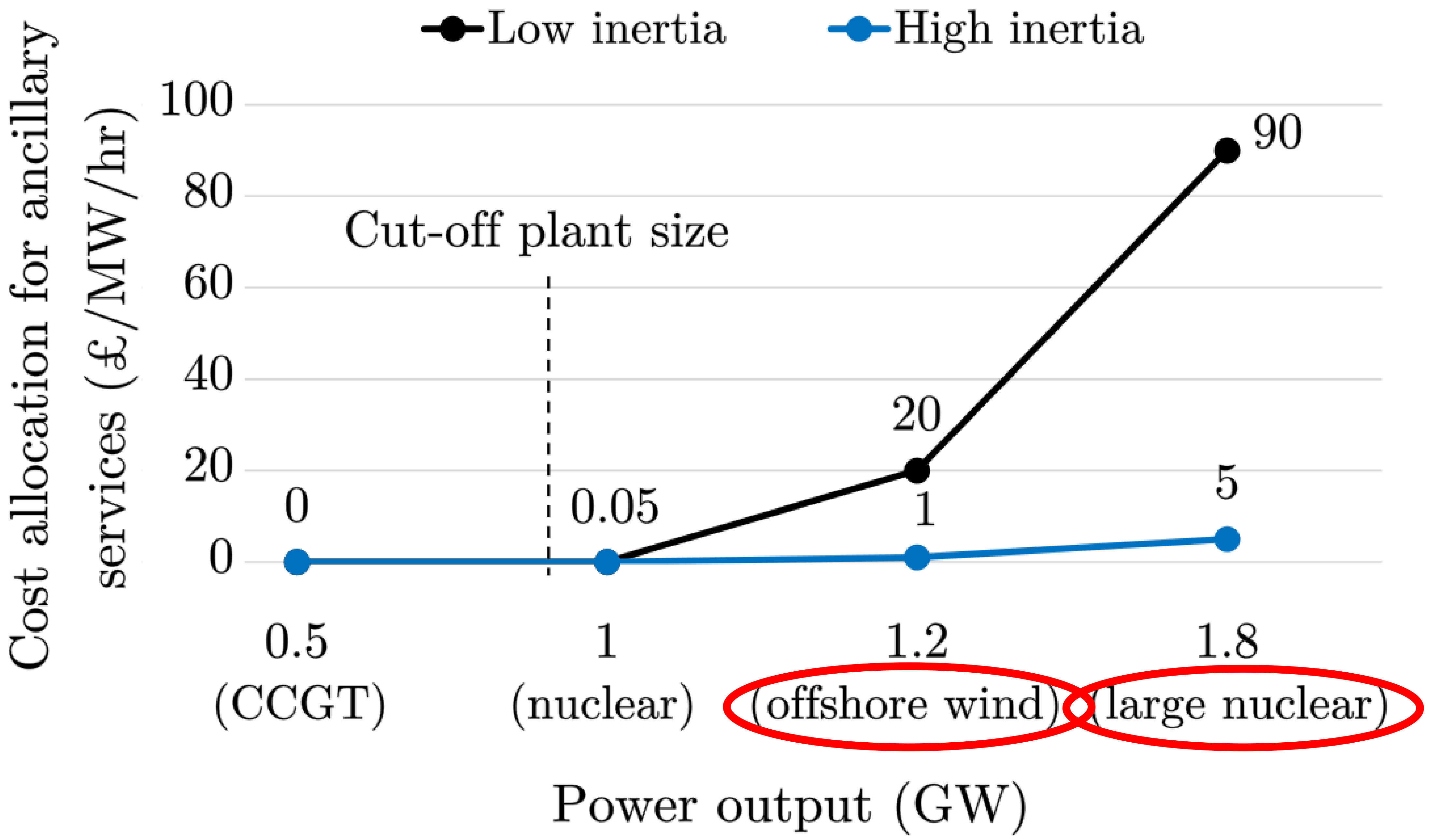
Analysis for Great Britain



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Benefits of the cost allocation

- To create **investment signals**
  - Large units would be **responsible for their system-integration cost** (*e.g.*, nuclear, offshore wind, HVDC)
  - **Costs** would still **trickle down to consumers**, but appropriate economic signals for generation would be in place
- To **incentivize flexibility**
  - Large units can reduce the cost they are allocated by **reducing power output/demand**

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Thank you for your attention!

All papers and some related code on my website:

https://badber.github.io/

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