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Assigning Shadow Prices to Synthetic Inertia and Frequency Reserves from RES

IEEE Trans. on Sustainable Energy, 2023

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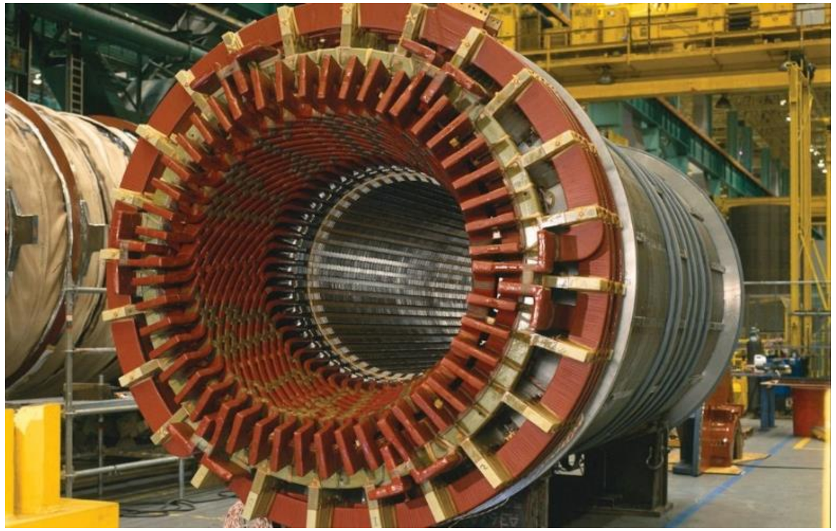
Lower inertia on the road to lower emissions

Thermal generators (nuclear, gas, coal…):



Decarbonisation →

Most renewables: **no inertia**

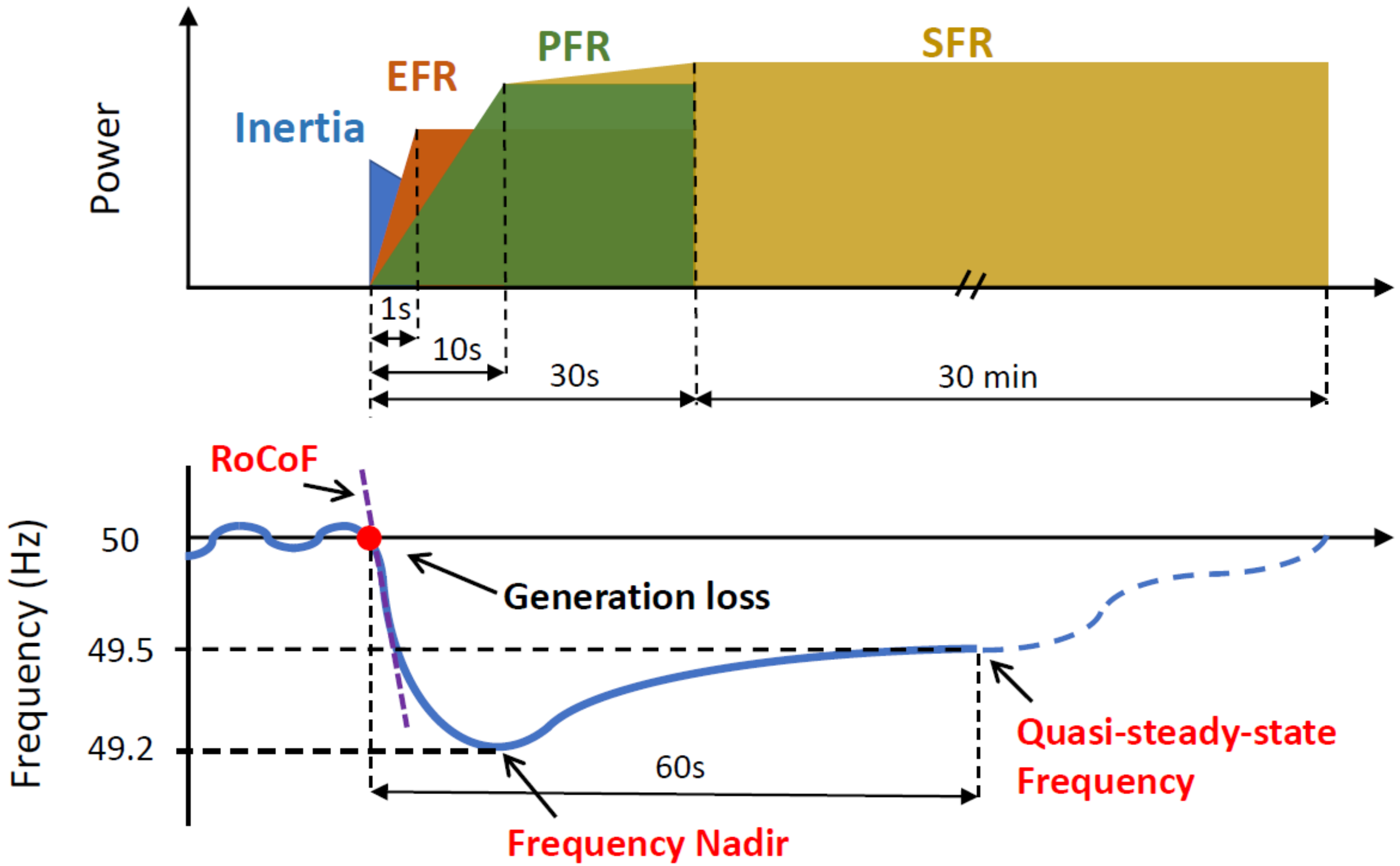
The **risk of instability has increased!**

Inertia stores kinetic energy:

this energy gave us time to contain a sudden generation-demand imbalance

Question we tried to answer

How to create incentives for RES to provide ancillary services?



How to answer this question?

Frequency ancillary services (**'insurance' to prevent blackouts**) → Economic Optimisation (e.g. Unit Commitment)

*Described by **differential equations** (timescale of seconds)*

*Based on **algebraic equations** (timescale of min/hours)*

Swing equation
(reduced-order model for system frequency dynamics):

$$\frac{2H}{f_0} \cdot \frac{\mathrm{d}\Delta f(t)}{\mathrm{d}t} = \mathrm{FR}(t) - P_\mathrm{L}$$

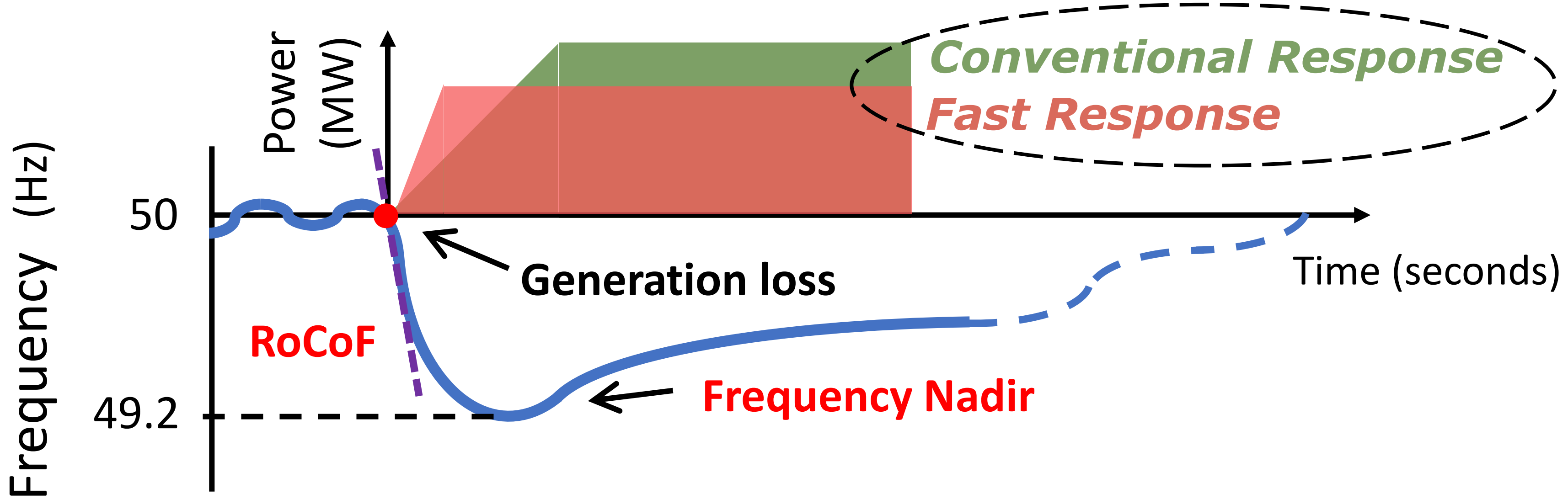
1) *Solve swing equation to obtain the **conditions for maintaining frequency stability***
2) ***Compute shadow prices** from the dual variables of the frequency-security constraints*

Solving the swing equation

Loss of largest power infeed
(N-1 reliability)

$$\frac{2(H_{\text{sync}} + H_{\text{synt}})}{f_0} \cdot \frac{\mathrm{d}\Delta f(t)}{\mathrm{d}t} = \mathrm{FR}(t) - P_{\mathrm{L}} - \mathrm{P}_{\text{rec}}(t)$$

'Recovery effect'
of wind turbines



Solving the swing equation

$$\frac{2(H_{\text{sync}} + H_{\text{synt}})}{f_0} \cdot \frac{\mathrm{d}\Delta f(t)}{\mathrm{d}t} = \mathrm{FR}(t) - P_{\mathrm{L}} - \mathrm{P}_{\text{rec}}(t)$$

Simplifications → **Advantages**

- Uniform frequency model *
- Damping is neglected **
- Ramp approximation for frequency response ***

- Closed form solution
- Convex constraints
- All system magnitudes are decision variables (including 'P_{L}')

Don't like these simplifications? Then you can refer to these alternative papers:

* L. Badesa *et al.*, "Conditions for Regional Frequency Stability in Power System Scheduling" (Parts I and II), IEEE Transactions on Power Systems, 2021

** L. Badesa *et al.*, "Simultaneous Scheduling of Multiple Frequency Services in Stochastic Unit Commitment", IEEE Transactions on Power Systems, 2019

*** M. Paturet *et al.*, "Stochastic Unit Commitment in Low-Inertia Grids", IEEE Transactions on Power Systems, 2020

Clarification on simplifications

The simplifications are **only needed when formulating the market**

Additional advantage → **Simple and clear instructions** to market participants:

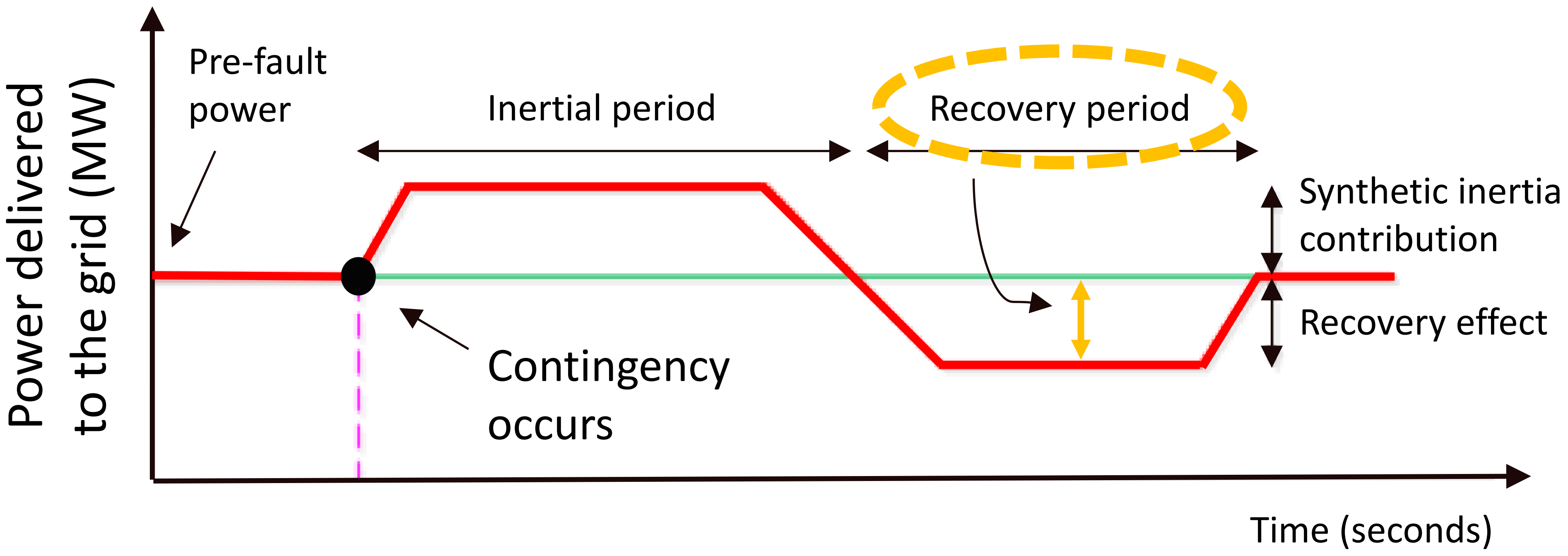
- Comply with a certain ramp requirement for frequency reserves
- Comply with the promised inertia constant

A **full dynamic model** would however be used **for tuning the controllers** of the different devices

'Recovery effect' of synthetic inertia

The **wind turbine decelerates**, so it **deviates from the MPPT**:

- The **power delivered** to the grid by the turbine in the 'post-inertial' period is **lower than the power in the 'pre-fault'** period



Source: NERC Industry Webinar, White Paper: Fast Frequency Response Concepts and Bulk Power System Reliability Needs

Modelling tool: Frequency-secured Unit Commitment

$$\min \sum_{g\in\mathcal{G}} \mathrm{c}_g^{\mathrm{nl}} \cdot y_g + \mathrm{c}_g^{\mathrm{m}} \cdot P_g$$ → **Minimise fuel and commitment costs**

$$\text{s.t.} \sum_{g\in\mathcal{G}} P_g + \sum_{\forall i} \left(\mathrm{P}_i - P_i^{\mathrm{curt}}\right) = \mathrm{P_D}$$ → **Load-balance constraint**

$$y_g \in \{0,1\}$$
$$y_g \cdot \mathrm{P}_g^{\mathrm{msg}} \leq P_g \leq y_g \cdot \mathrm{P}_g^{\mathrm{max}}$$
$$0 \leq R_g \leq y_g \cdot \mathrm{R}_g^{\mathrm{max}}$$
$$0 \leq R_g \leq \mathrm{P}_g^{\mathrm{max}} - P_g$$
$$0 \leq P_i^{\mathrm{curt}} \leq \mathrm{P}_i$$

} **Technical characteristics of generators**

$$0 \leq R_i \leq \mathrm{R}_i^{\mathrm{max}}$$
$$0 \leq R_i \leq P_i^{\mathrm{curt}}$$
Sync. inertia from all g
Synt. inertia from all GFM

} **Ancillary services from generators**

RoCoF constraint
Nadir constraint
q-s-s constraint

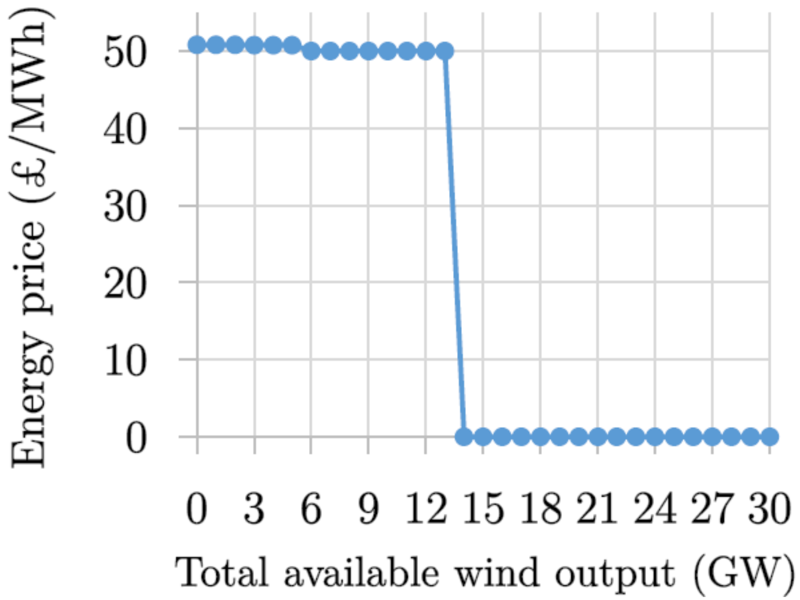
} **Frequency-security constraints**

Results: price for synthetic inertia

Synthetic inertia from wind turbines with grid-forming inverters has the **same price signal as synchronous inertia**, except when the '***recovery effect***' of the wind turbine is too high

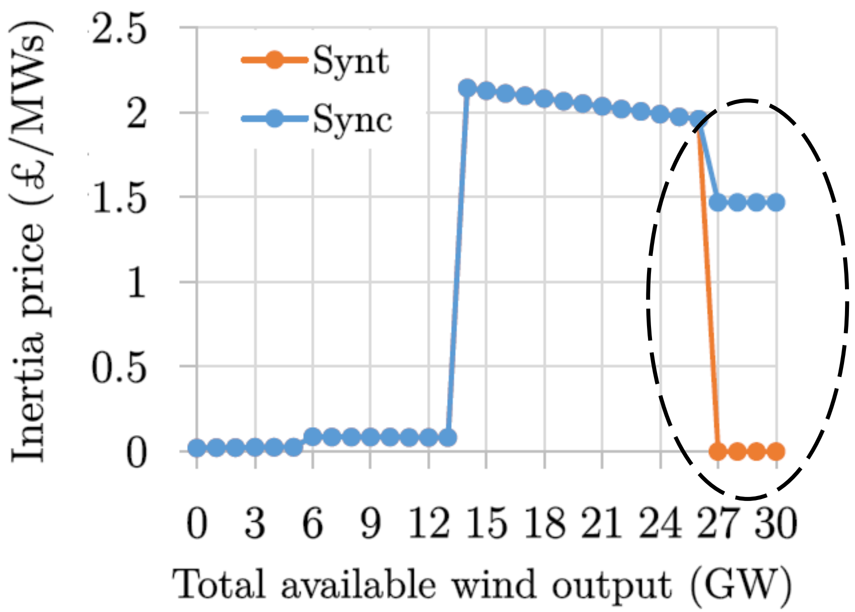
Price for synchronous inertia:

$$\frac{\mu - \lambda_1}{f_0} + 2\lambda_{\text{RoCoF}}$$



Price for synthetic inertia:

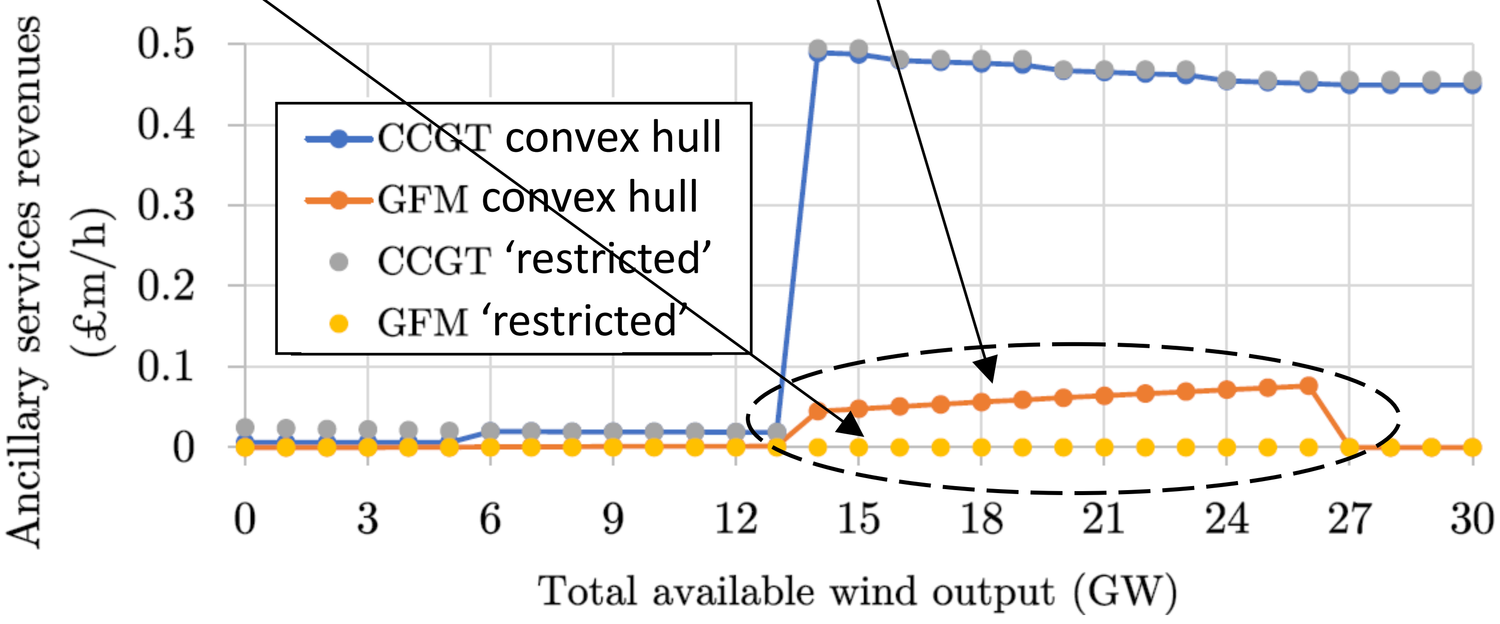
$$\frac{\mu - \lambda_1}{f_0} + 2\lambda_{\text{RoCoF}} - \lambda_{\text{q-s-s}} \cdot k_{\text{rec}}$$



Results: dealing with non-convexities

Challenge: **synchronous inertia** is linked to binary variables (i.e., **non-convexities**)

- ‘**Restricted pricing**’ (i.e. fixing the commitment decision of thermal units) **will not work** for remunerating RES providing frequency services
- **Convex hull pricing** is however **compatible with** remunerating **synthetic inertia**

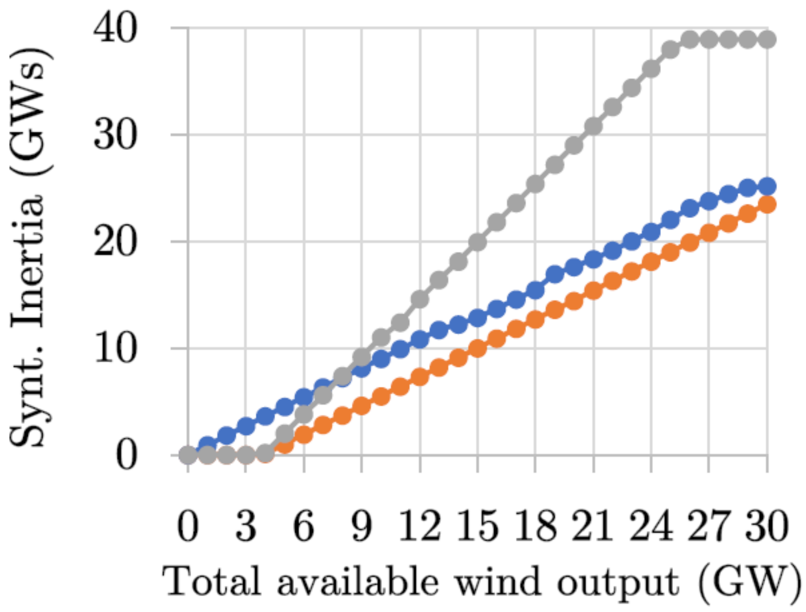


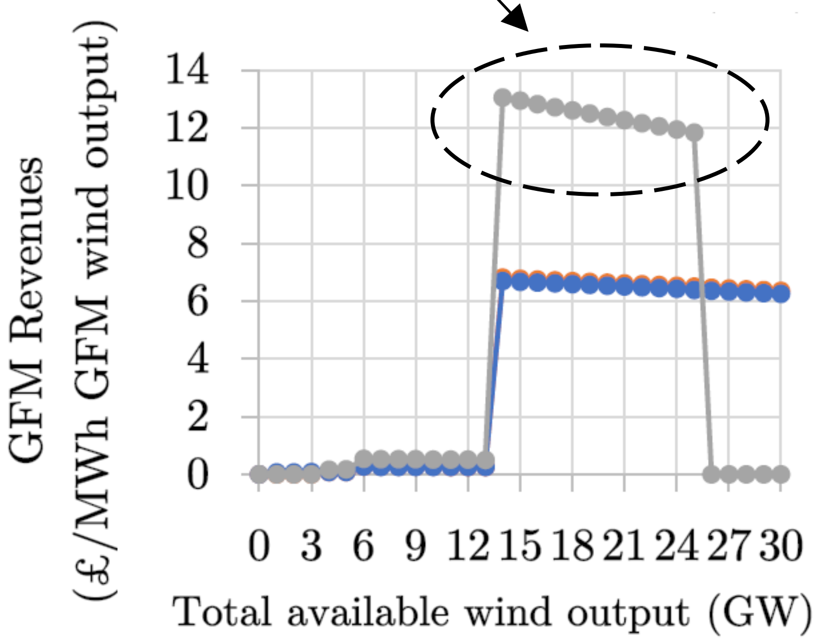
Results: optimising synthetic inertia provision

The synthetic inertia constant is a **control parameter**:

- Synt inertia providers could **increase revenue by optimising** H_{const} hourly
- Requires a **communication network** (investment needed)

Fixed inertia constant   Optimised inertia constant





What's next?

1. The theoretical framework when using **convex hull pricing needs development** (e.g., including AC OPF constraints)

2. Understand **implications** of this market **on other types of stability** (e.g., voltage and transient stability)

3. **Who should pay** for ancillary services?

THANK YOU FOR YOUR ATTENTION!

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