UNIVERSIDAD POLITÉCNICA DE MADRID

Imperial College London

Probabilistic Scheduling of Under-Frequency Load Shedding to Secure Credible Contingencies in Low Inertia Systems

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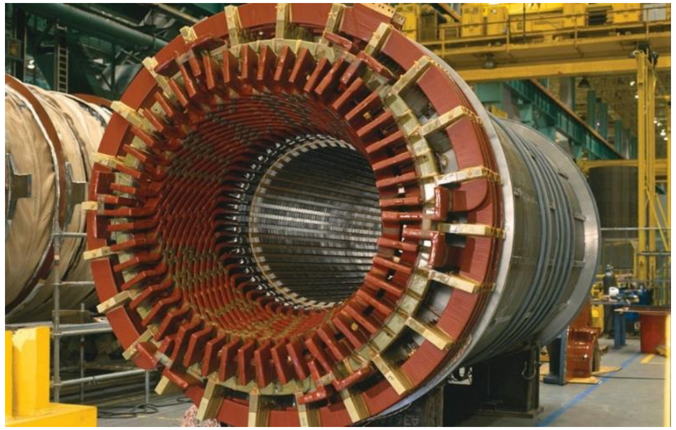
Cormac O'Malley, <u>Luis Badesa</u>, Fei Teng and Goran Strbac

Motivation: Lower inertia on the road to lower emissions

Thermal generators (nuclear, gas, coal…):

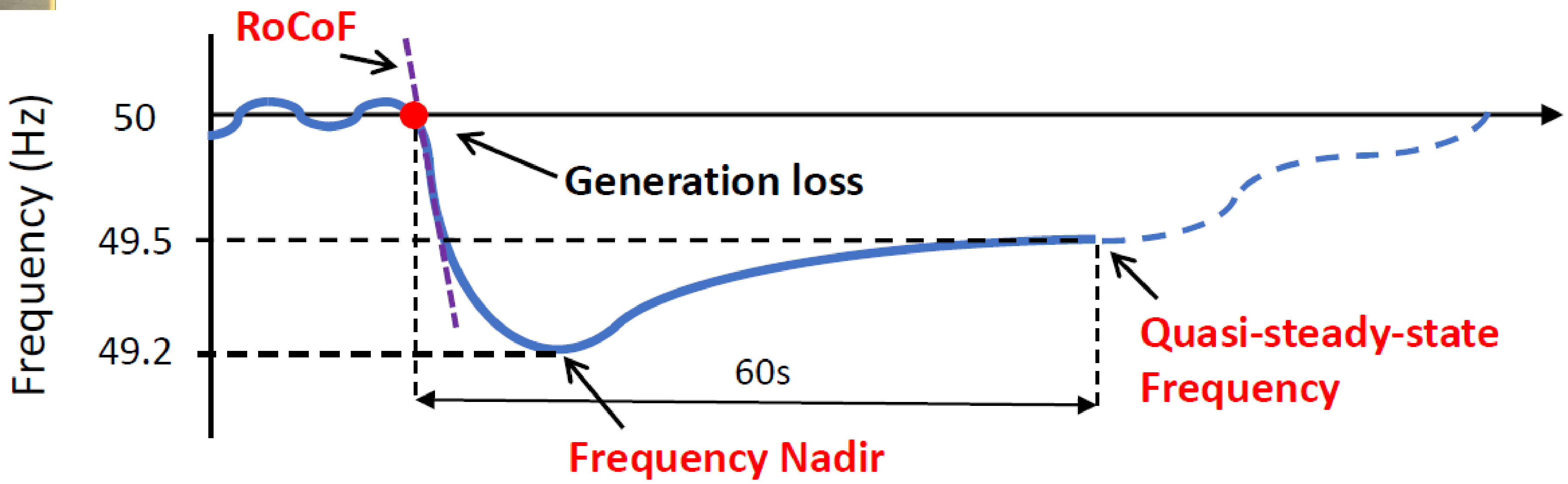


Decarbonisation

Most renewables: **no inertia**

Inertia is <u>no longer a by-product of energy</u>:

It is now **<u>more expensive</u> to keep the system stable**



Question we tried to answer:

How <u>valuable is it to accept some UFLS</u> after big outages?

How to answer this question?

Frequency-secured Unit Commitment

$$\min \quad \sum_{g\in\mathcal{G}} \mathrm{c}_g^{\mathrm{nl}} \cdot y_g + \mathrm{c}_g^{\mathrm{m}} \cdot P_g \longrightarrow$$

Minimise fuel and commitment costs

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

Load-balance constraint

$$\left.\begin{array}{l}\text{RoCoF constraint}\\ \text{Nadir constraint}\\ \text{q-s-s constraint}\end{array}\right\} \text{Frequency-security constraints}$$

(plus other typical UC constraints)

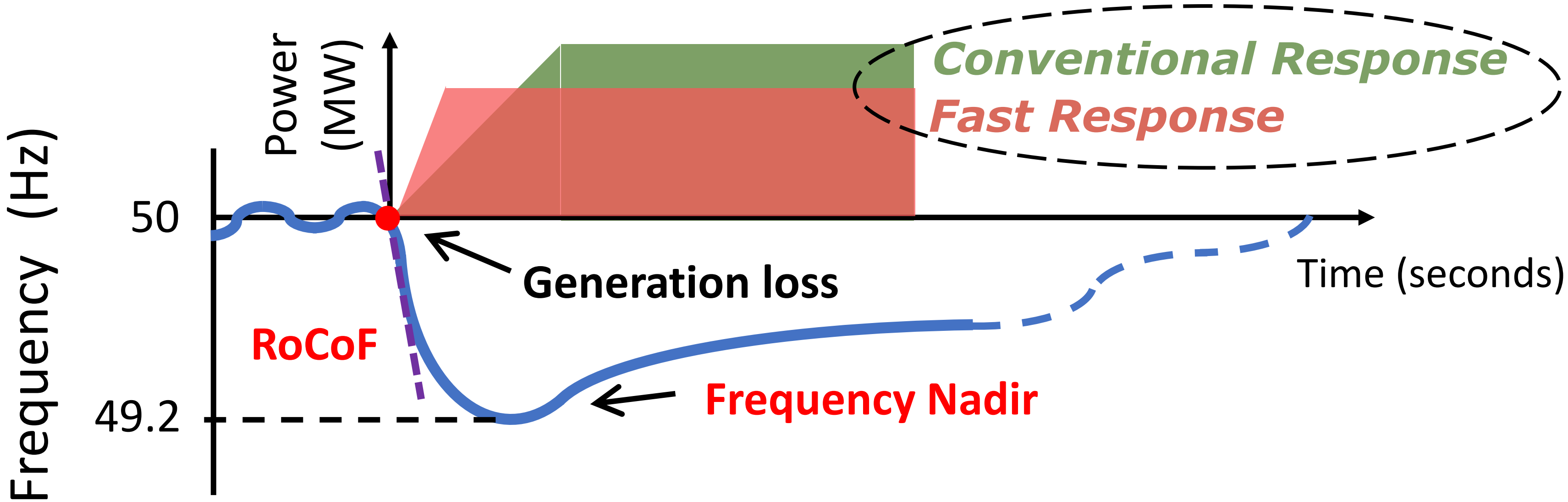
Main contribution: We **incorporate UFLS as a decision variable** within the frequency-security constraints

Frequency-security constraints

Solving the swing equation

Loss of largest power infeed
(*N*-1 reliability)

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



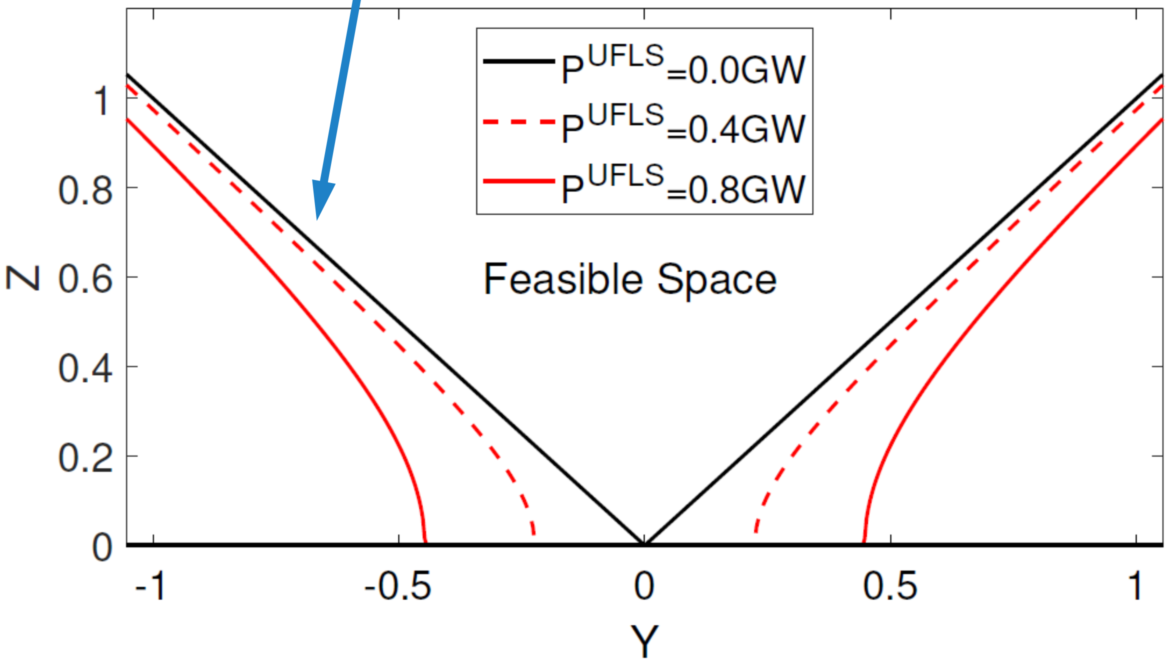
Triggered once frequency reaches the **UFLS activation threshold**

(this time depends on the system inertia and frequency response)

Nadir constraint: non-convex due to UFLS

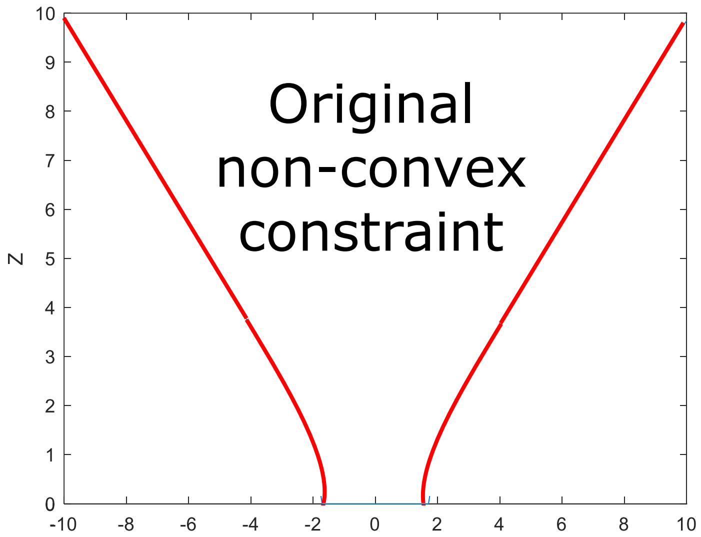
$$\underbrace{\left(\frac{H}{f_0}-\frac{R_1\cdot T_1}{4\Delta f_{trig}}\right)}_{=\,z}\underbrace{\frac{R_2}{T_2}}_{=\,x}\geq\underbrace{\left(\frac{PL_{max}-R_1}{2\sqrt{\Delta f_{trig}}}\right)}_{=\,y}^{2}-\underbrace{\left(\frac{P^{UFLS}}{2\sqrt{\Delta f_{trig}}}\right)}_{=\,u}^{2}$$

Second-Order Cone

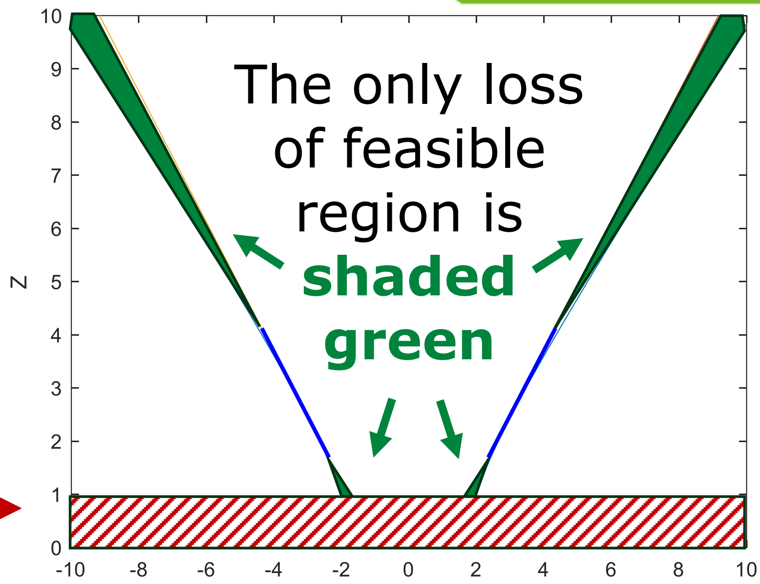


A higher volume of UFLS moves the constraint further away from convexity

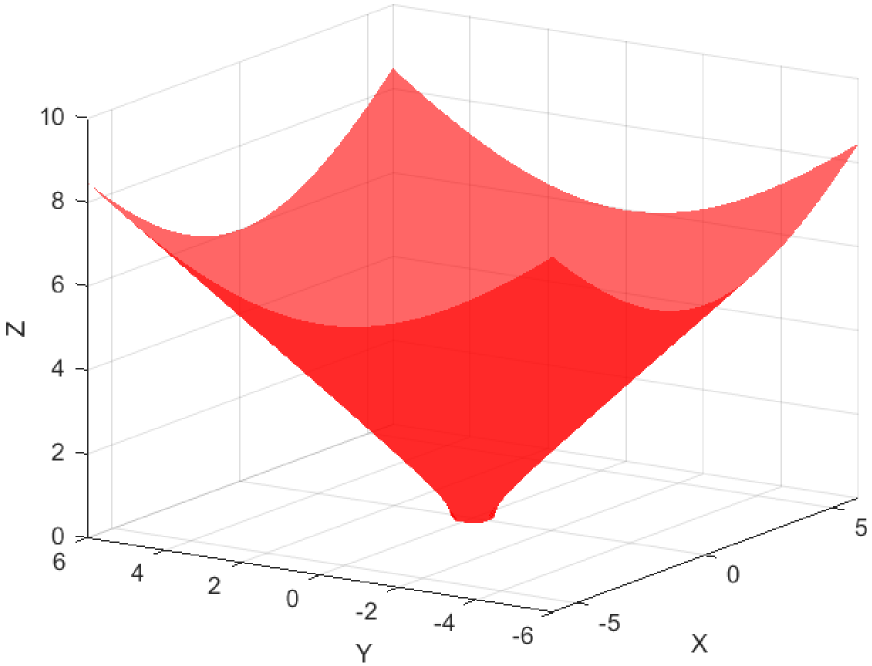
Nadir constraint: convex approximation

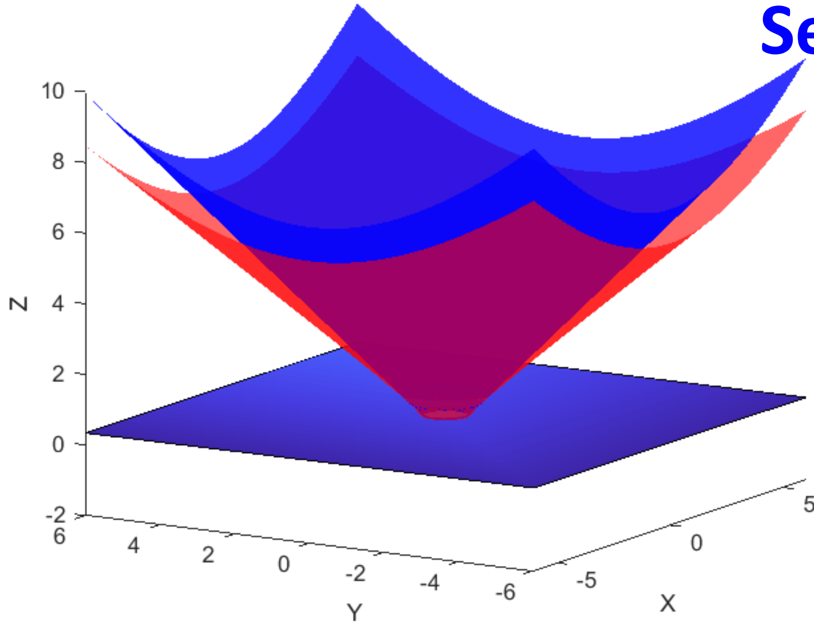


We compute the **least conservative approximation possible**



Not feasible due to other power system constraints



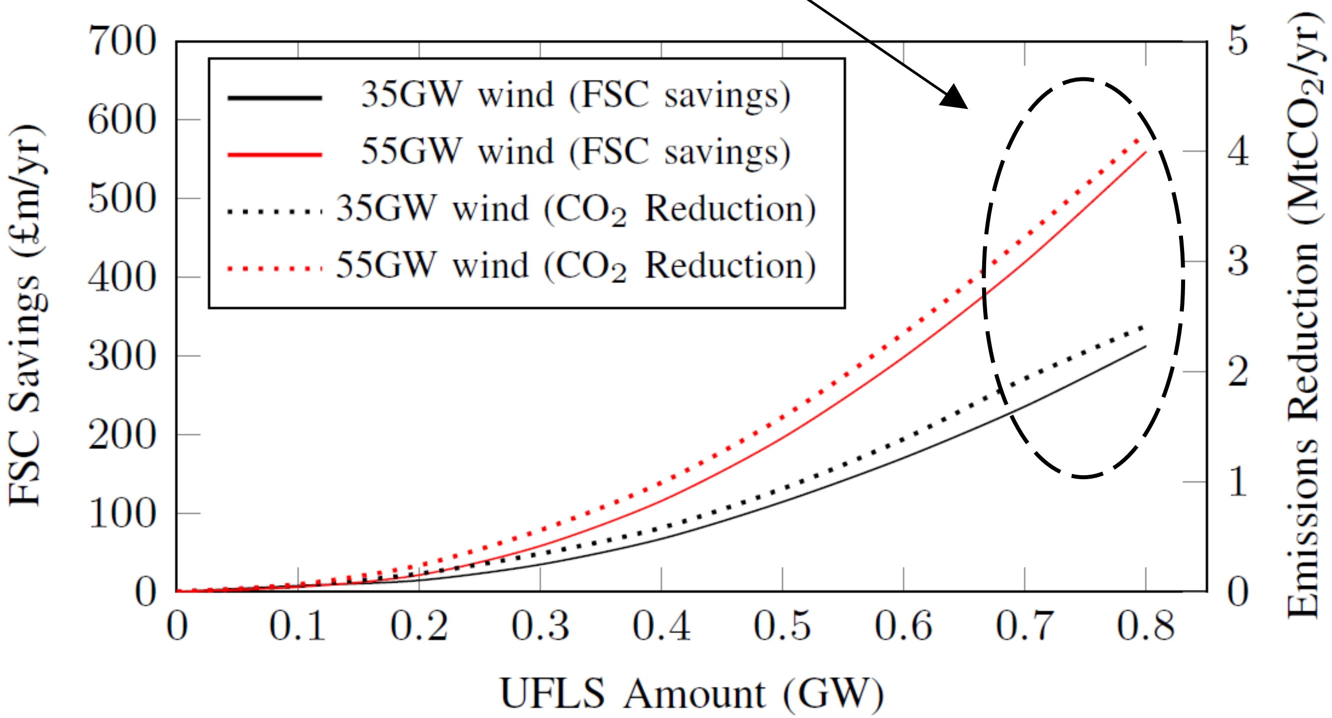


Second-Order Cone

Results: value of UFLS for largest loss

UFLS is **penalised at the Value of Lost Load** in the objective function of the UC

Savings of hundreds of million £ per year in Great Britain



Cost of activating UFLS for largest loss

$$\min \sum_{g\in\mathcal{G}} c_g^{\mathrm{nl}} \cdot y_g + c_g^{\mathrm{m}} \cdot P_g + \overbrace{\underbrace{\pi_{\mathrm{UFLS}}}_{\text{Probability of largest loss occurring}} \cdot \underbrace{P_{\mathrm{UFLS}}}_{\text{Volume of UFLS needed (decision variable)}} \cdot \mathrm{VoLL}}^{\text{Cost of activating UFLS for largest loss}}$$

Probability of largest loss occurring

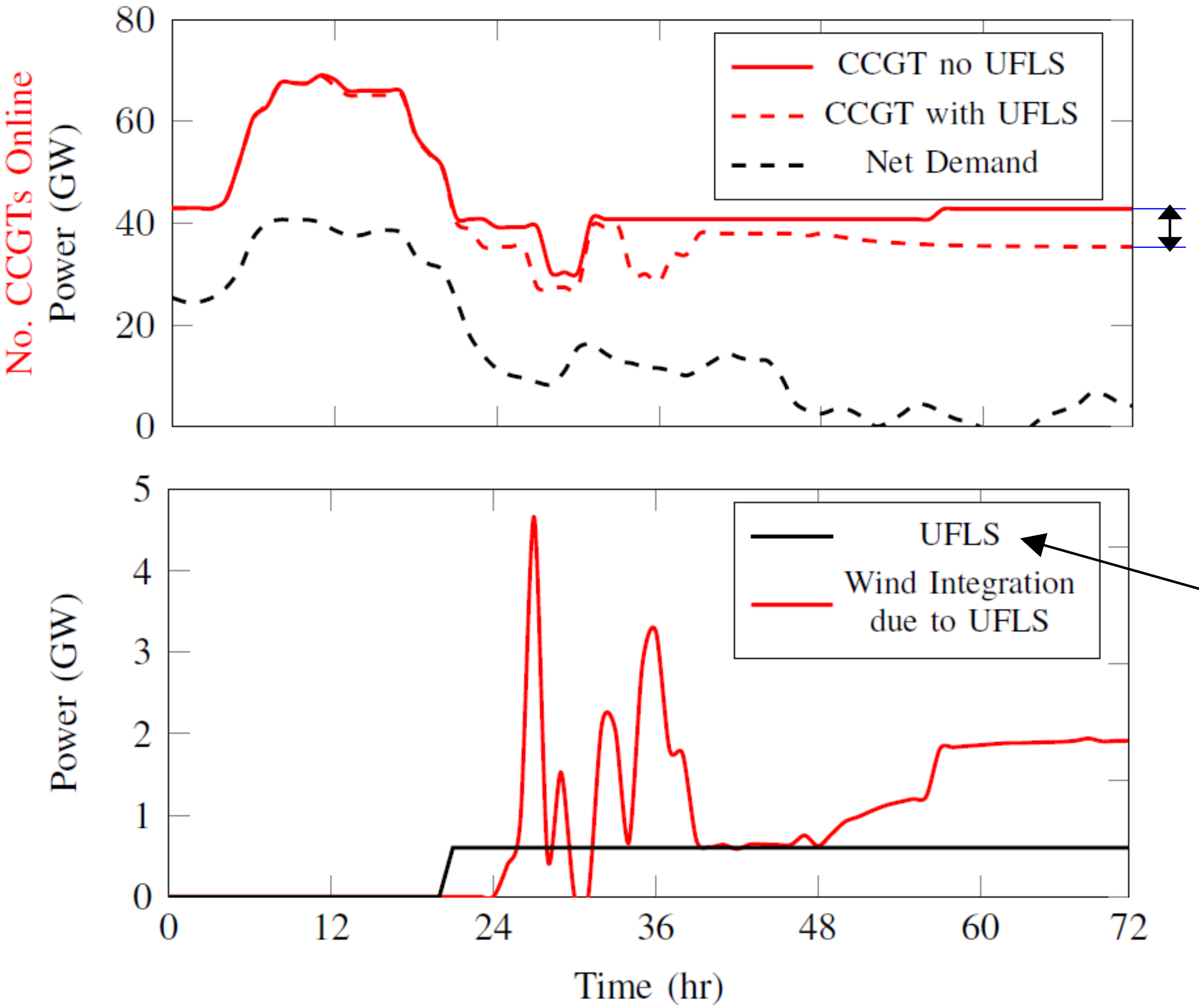
Volume of UFLS needed (decision variable)

Where do these **savings come from?**

→ next slide

Results: value of UFLS for largest loss

Example of 72 hours of operation:



If some **UFLS is considered as a 'service'**, **fewer gas plants are needed** to increase inertia and frequency response (economic and emissions savings)

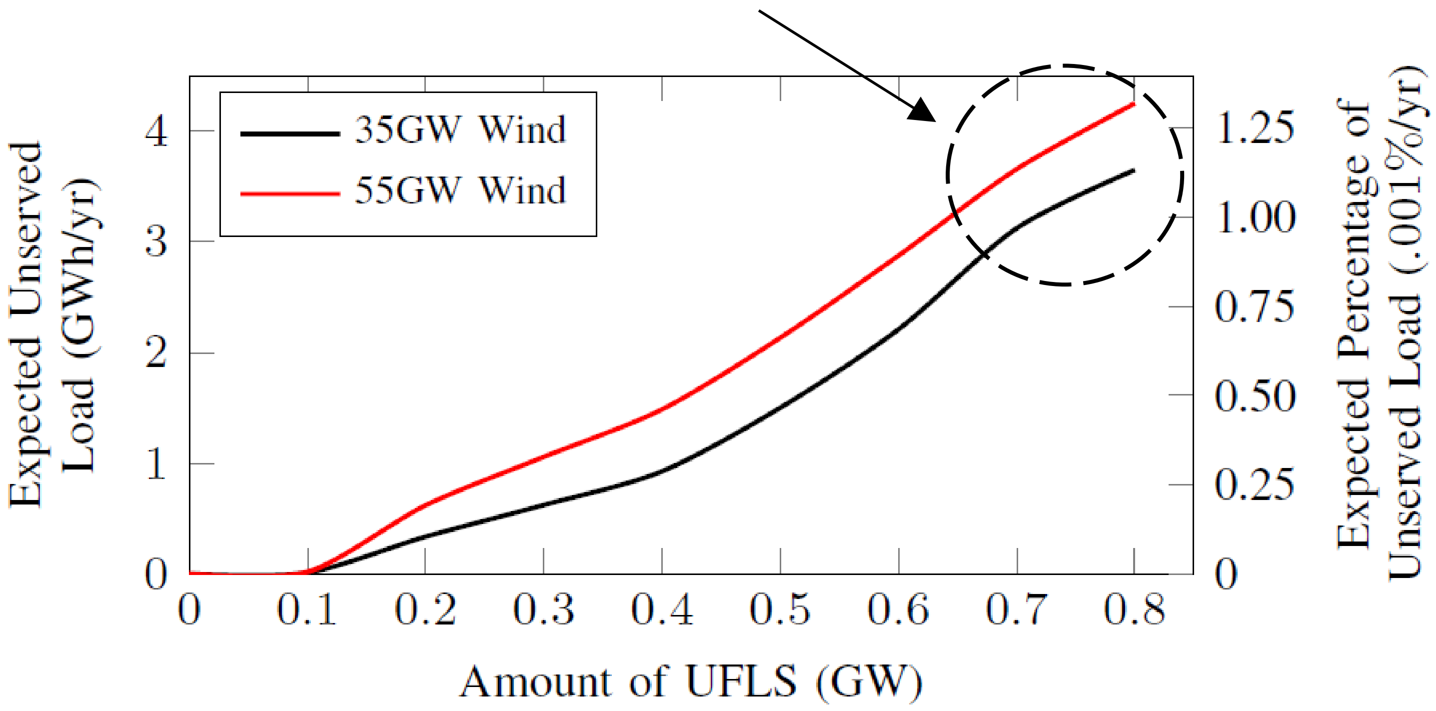
UFLS 'accepted'

(not necessarily activated)

Results: risk of UFLS for largest loss

The previous results come from a **risk neutral optimisation**:
the <u>expected cost is minimised</u>

However, this still **provides high levels of reliability**:
only **0.001% expected unserved energy**



Assumption for **outage rate** of large nuclear:
1.8 occurrences/yr

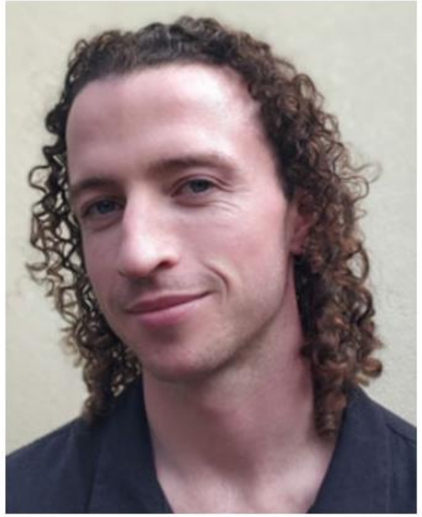
(historical data shows that this assumption is even somewhat conservative)

Communication requirements with UFLS relays

- Previous results assume that **UFLS relay settings can be updated every hour**: a communication network is needed for this

- This framework is **also compatible with traditional UFLS schemes** that have **no communication with relays**
    - In this case, **savings** from the UFLS service **decrease by up to £180m/year** for Great Britain

Thank you for your attention!



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