Electric vehicles bidding in Nordic flexibility markets: A distributionally robust chance-constrained program

Jalal Kazempour (DTU)

VAME 2024
May 14, 2024

All credits go to:

Peter Gade
(Industrial PhD student
with IBM and DTU)

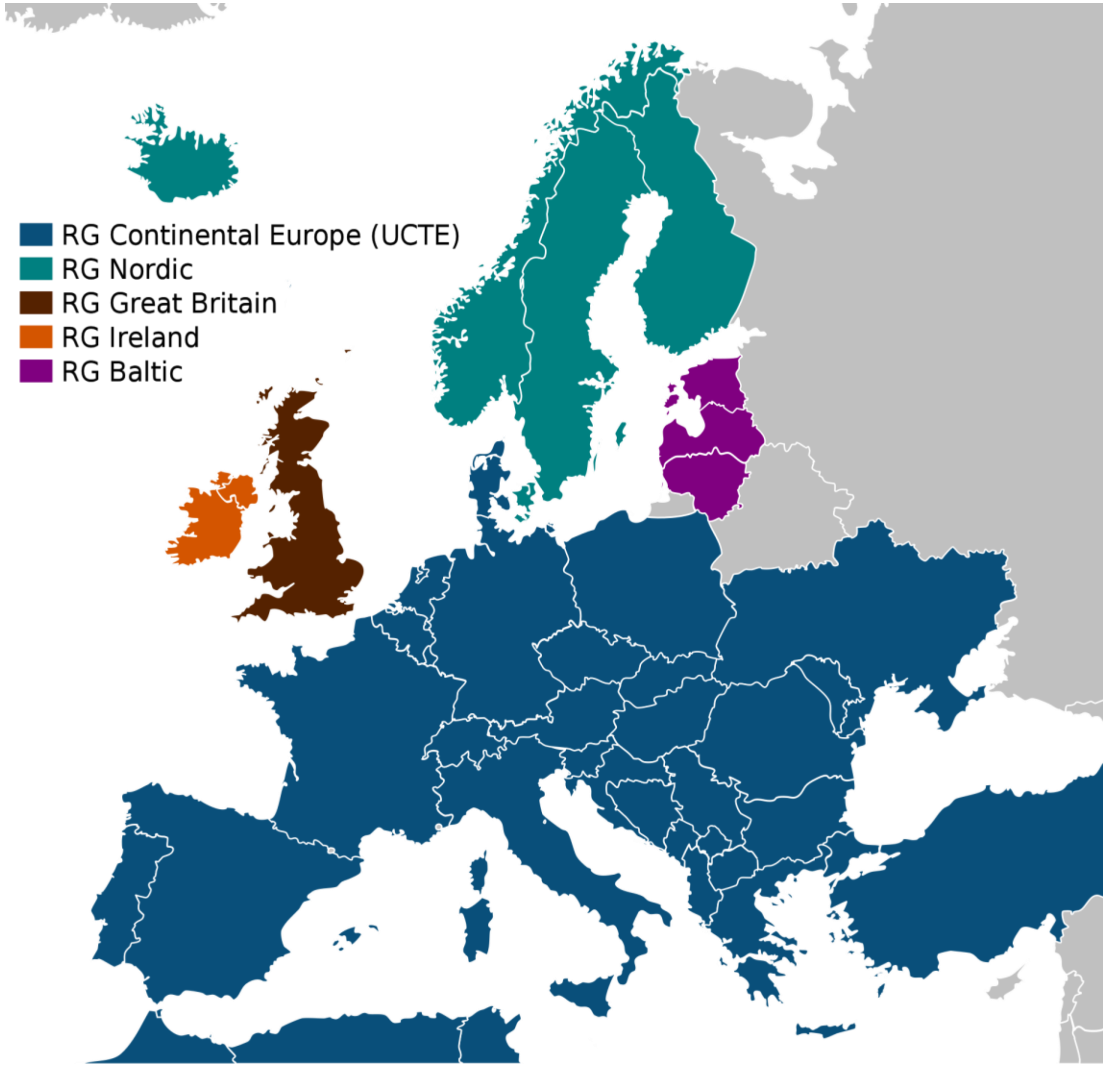
Gustav Lunde
(former MSc student)

Emil Damm
(former MSc student)

And thanks to industrial collaborators:

A background

Synchronous grid areas and corresponding ancillary services



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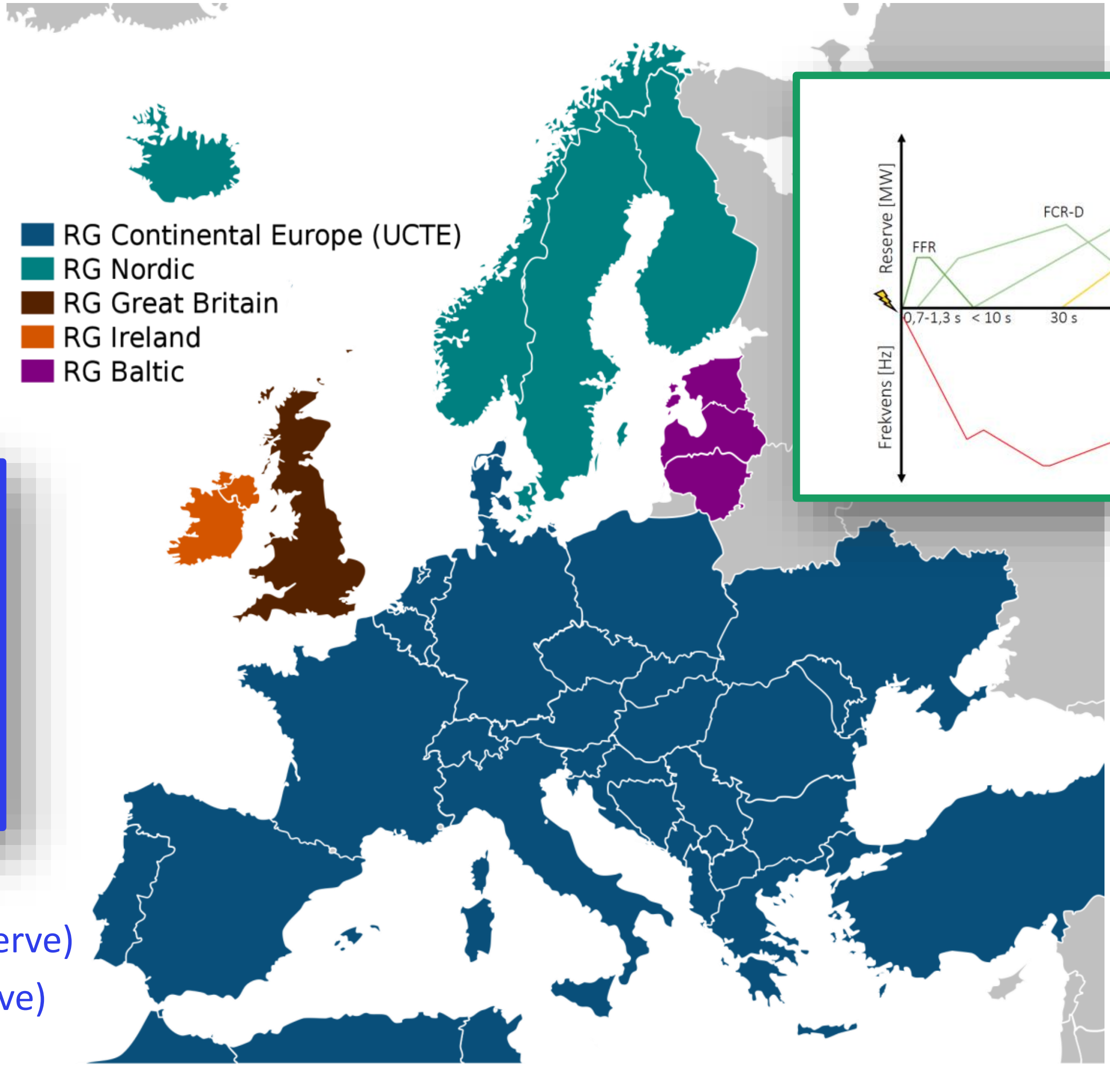
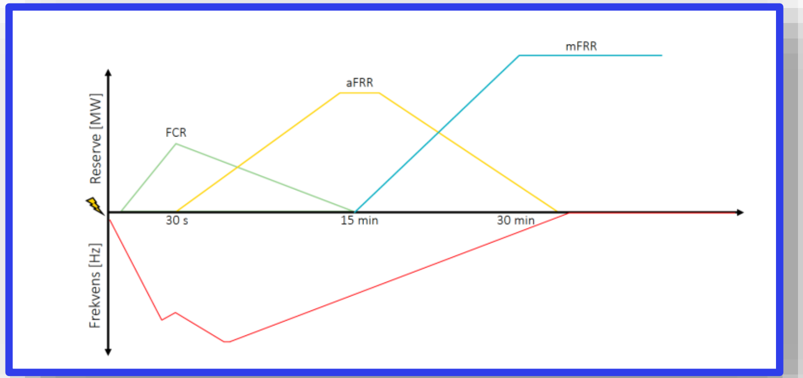
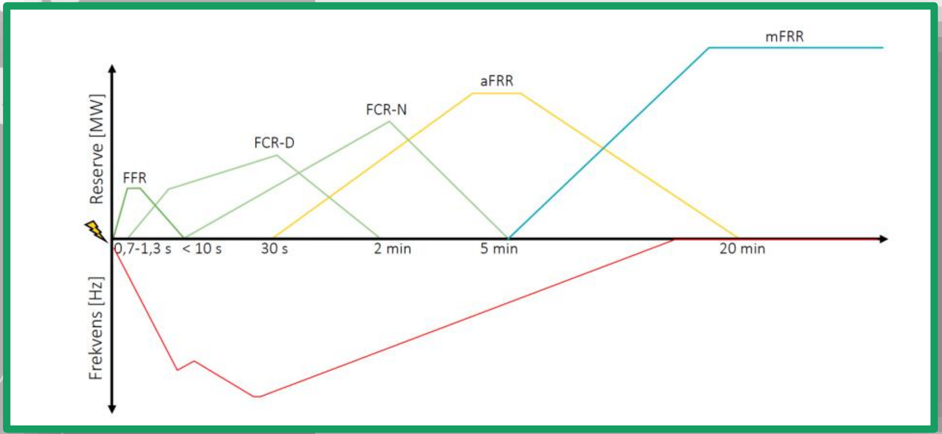


Services in Continental Europe (e.g., DK1)



- **FCR** (frequency containment reserve)
- **aFRR** (automatic frequency restoration reserve)
- **mFRR** (manual frequency restoration reserve)

Services in Nordic (e.g., DK2)



- **FFR** (fast frequency reserve)
- **FCR-D** (D = disturbance)
- **FCR-N** (N =normal)
- **aFRR**
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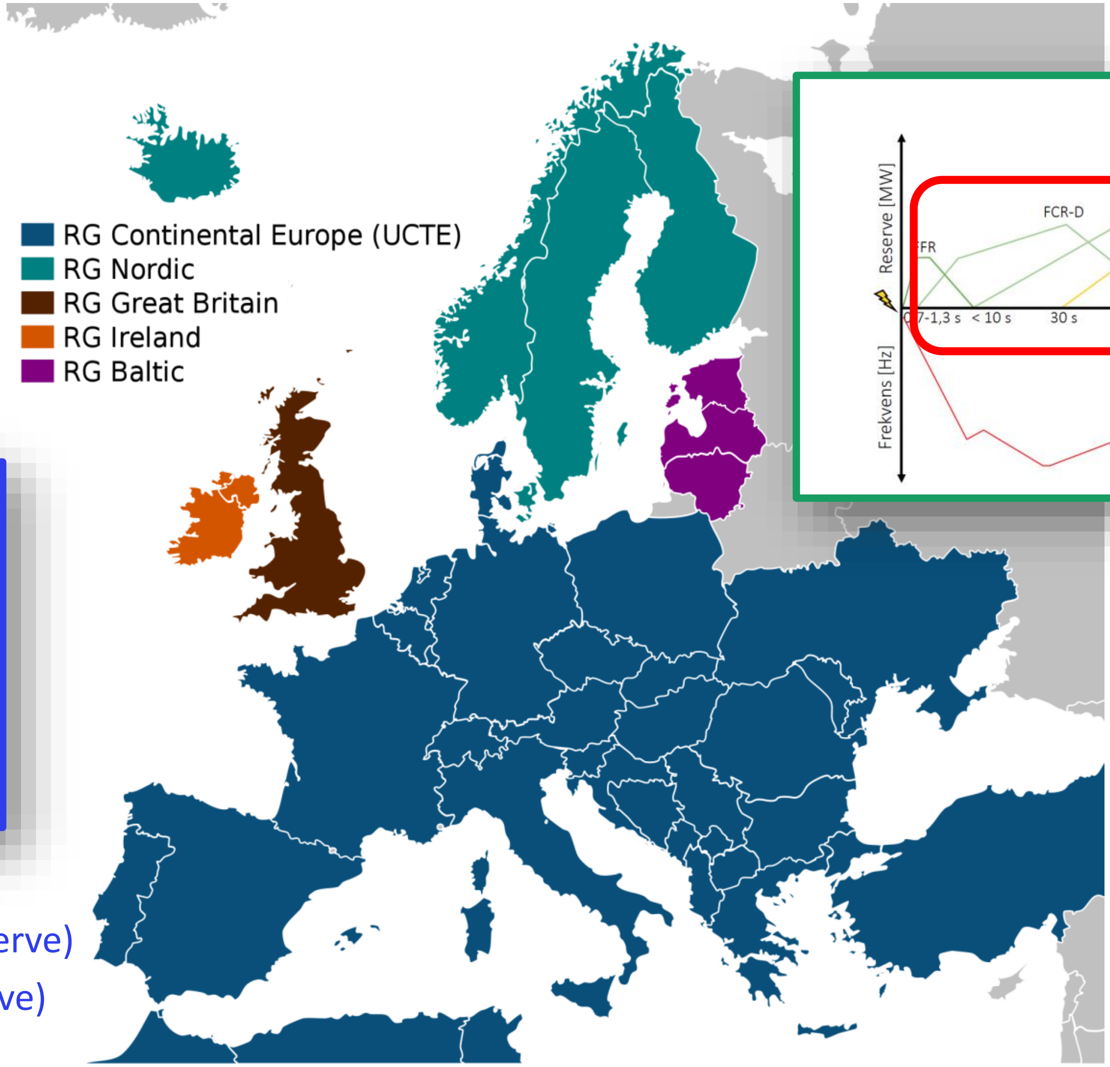

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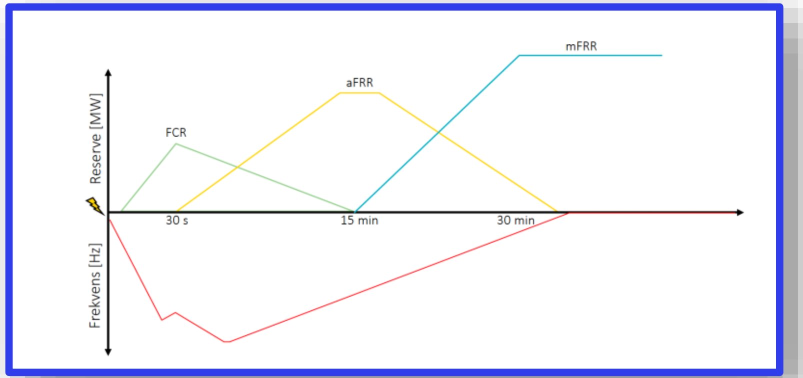

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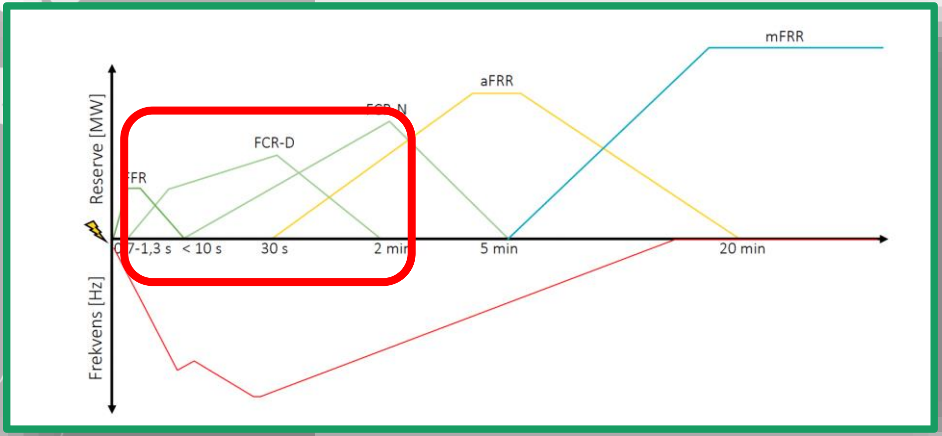

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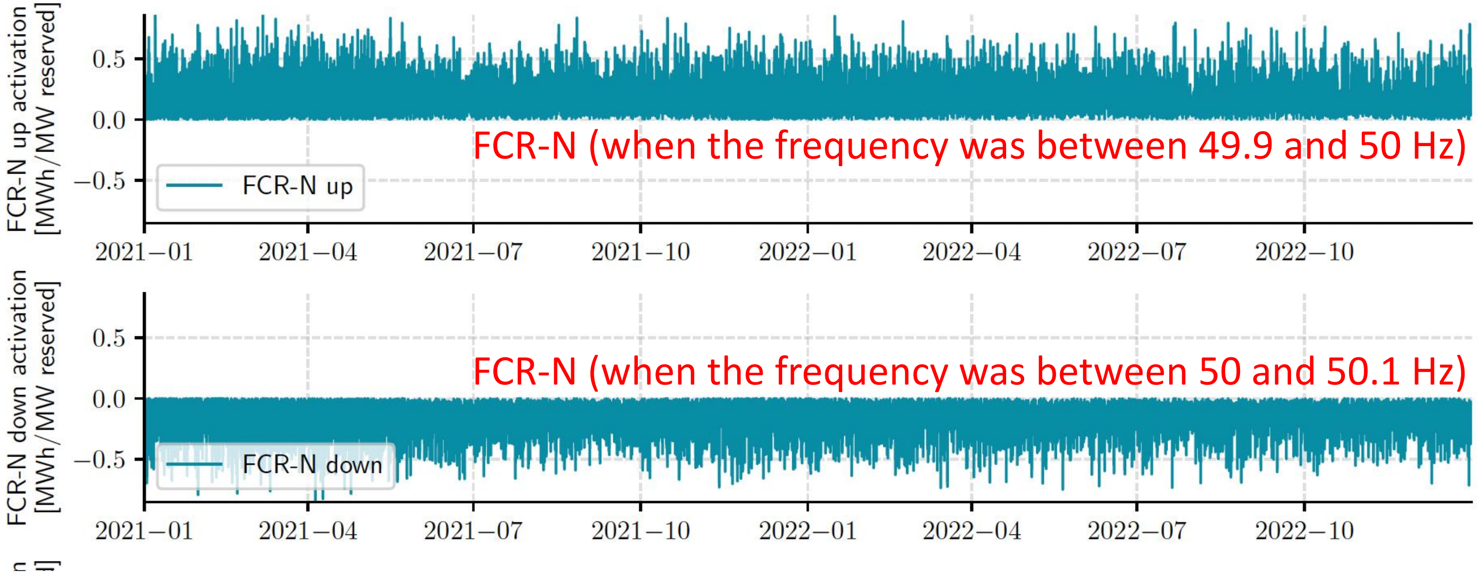
Focus of this talk:
FCR-D services in the Nordic area

Historical data: Activated FCR-D and FCR-N in DK2 (2021-2022)



Normal operation (49.9 < f < 50.1):
FCR-N was activated all the time

Credit: Marco Saretta

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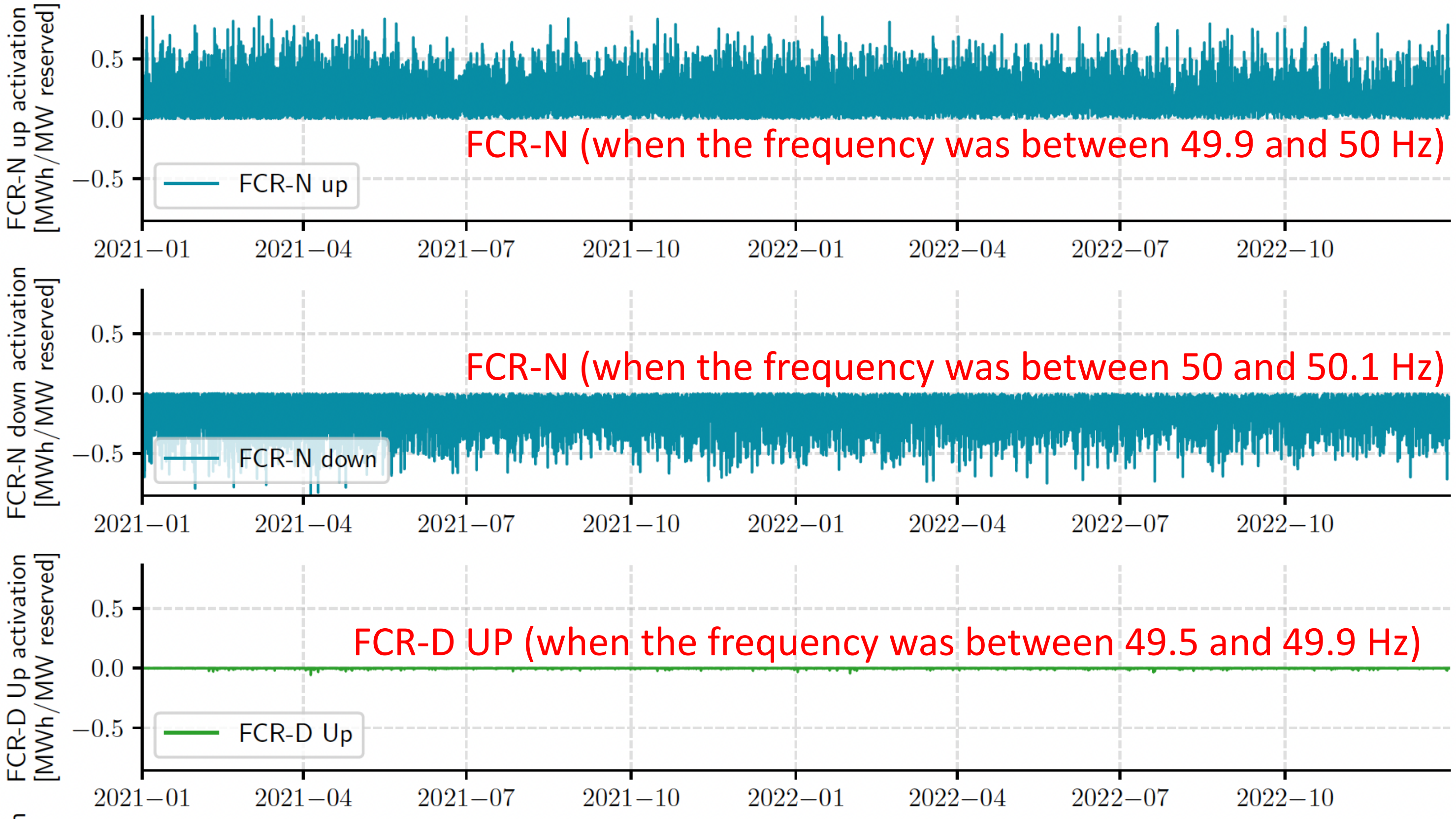

Normal operation (49.9 < f < 50.1):
FCR-N was activated all the time

Operation under disturbance (49.5 < f < 49.9):
The activation for FCR-D UP was very rare

Credit: Marco Saretta

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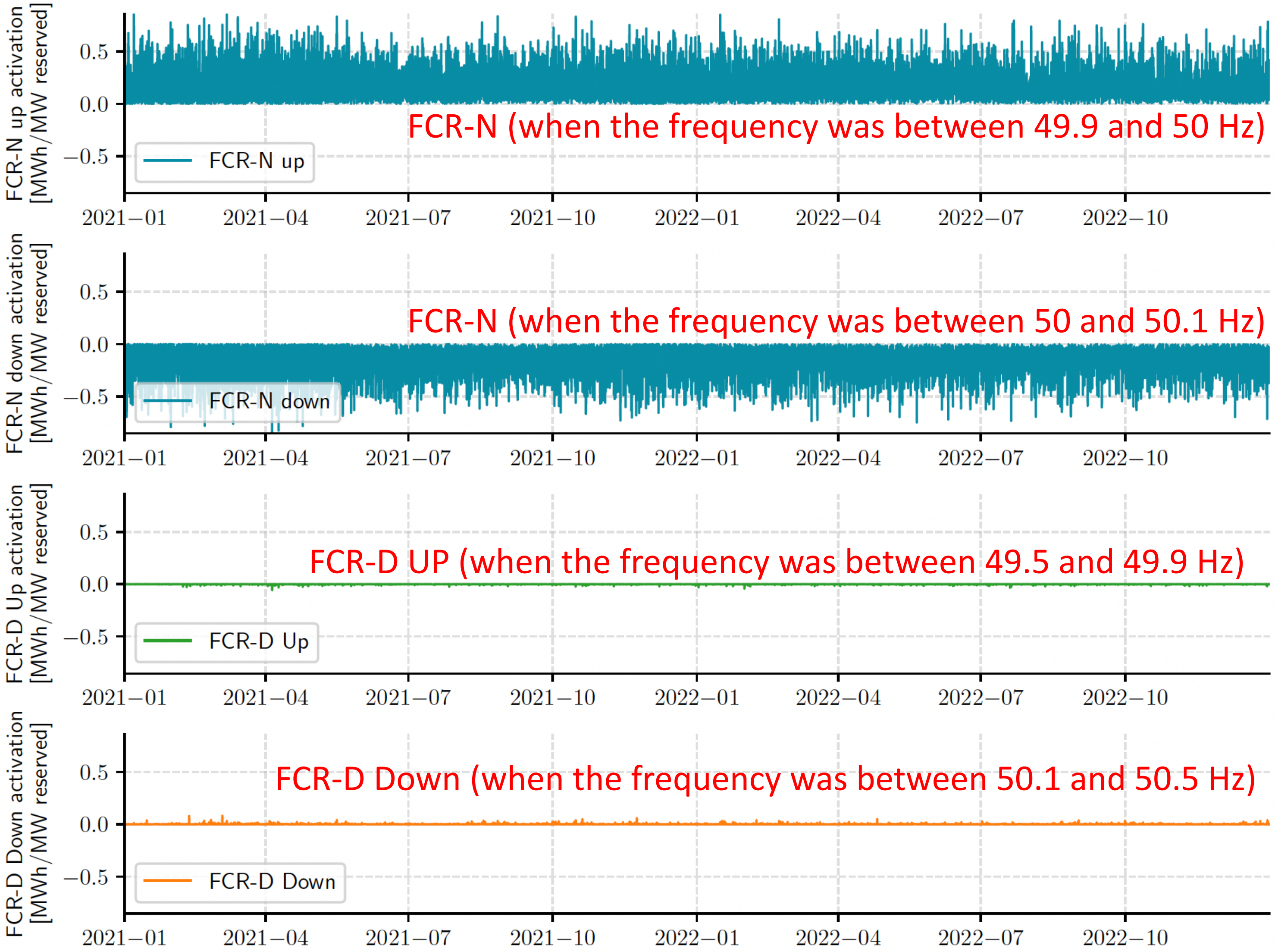

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(49.9 < f < 50.1):
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Operation under disturbance
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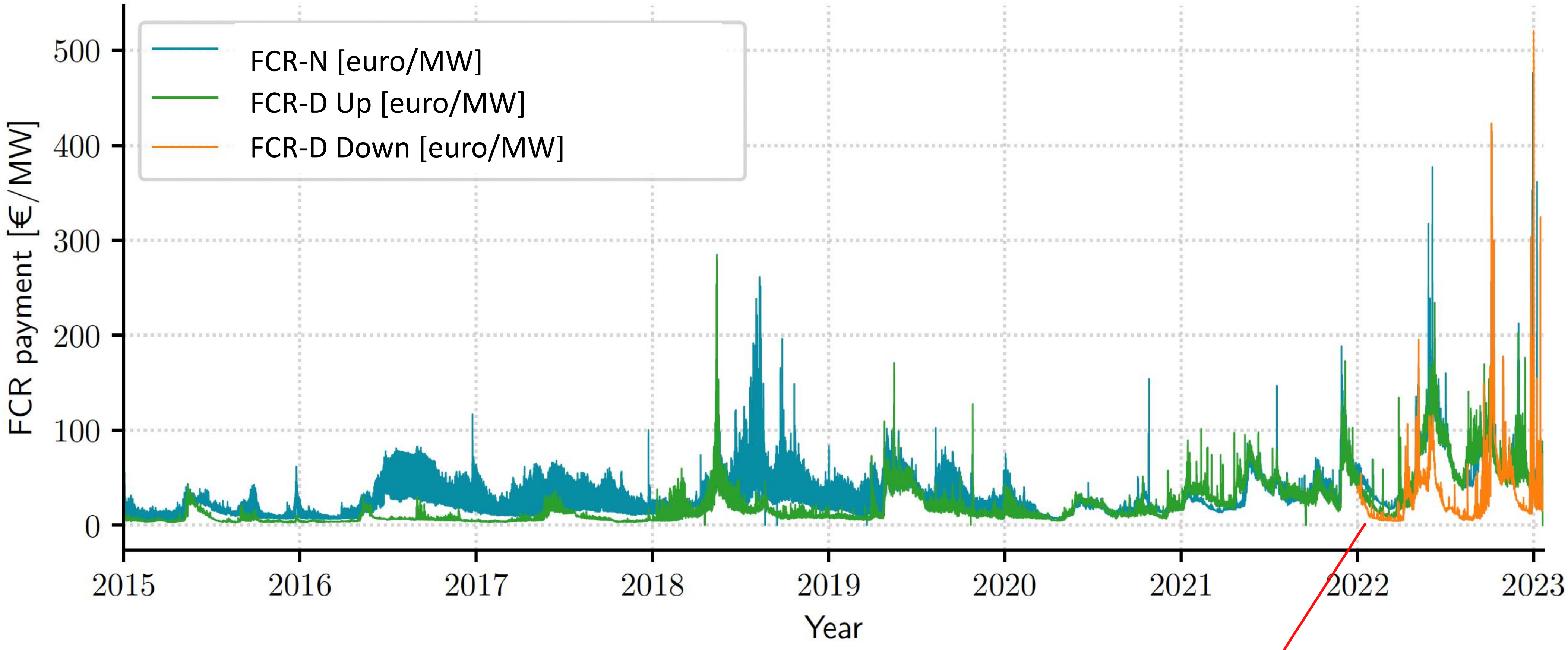
The activation for FCR-D UP was very rare

Operation under disturbance
(50.1 < f < 50.5):
The activation for FCR-D Down was very rare

Credit: Marco Saretta

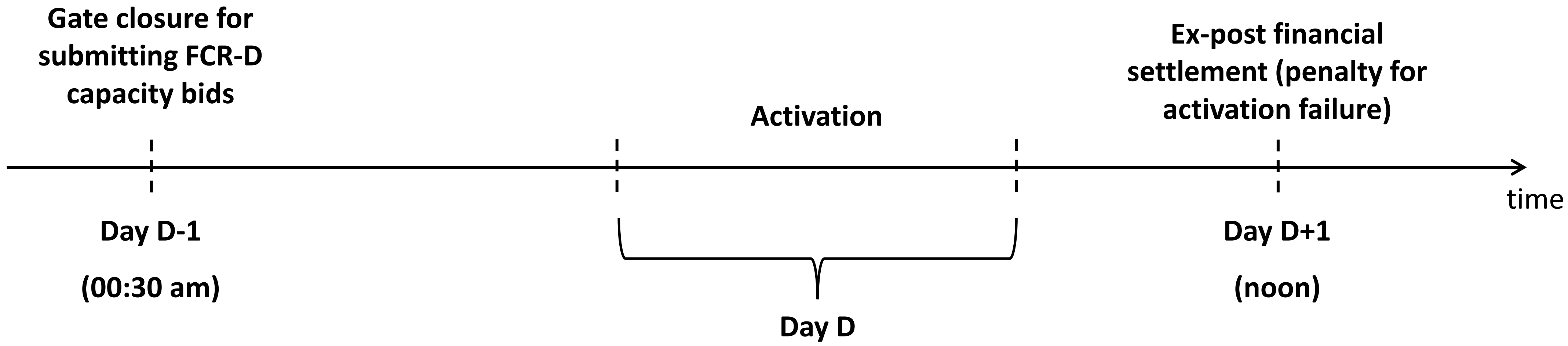
Historical data: FCR-D and FCR-N prices in DK2 (2015-2022)



FCR-D Down (a service when frequency is between 50.1 and 50.5 Hz) started in January 2022

Credit: Marco Saretta

Current market for FCR-D Up/Down in Denmark (DK2) and Sweden (SE1-SE4)



- The FCR-D services are used to be bought in D-2 (until very recently). Now it is in D-1.
- There is a second (optional) market for FCR-D in D-1 in case TSOs realize more FCR-D services should be bought.
- Payment for capacity only (activation is not “energy-intensive”)
- Penalty for activation failure = the cost of alternative source

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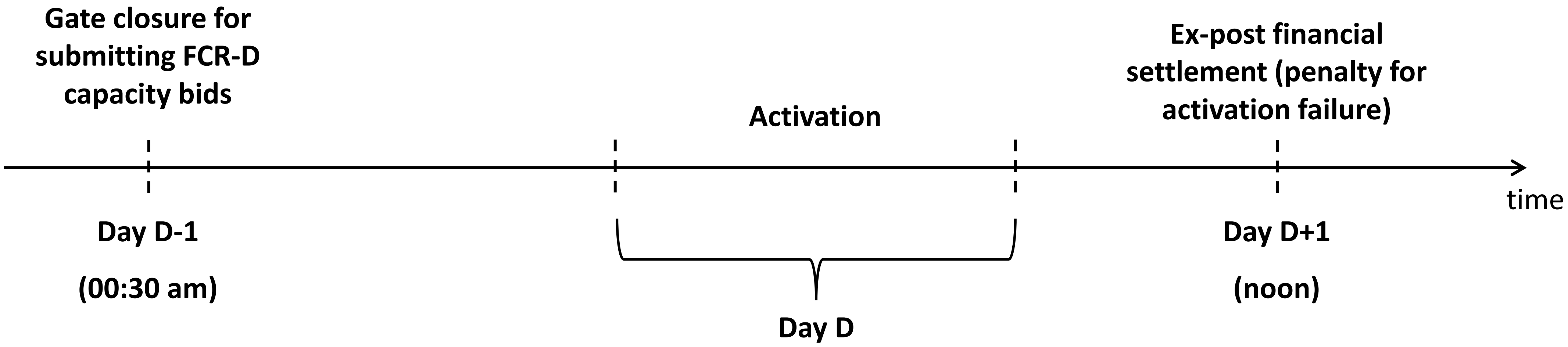

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Nordic TSO obligations to procure FCR services in 2023

	Share [%]	FCR-N [MW]	FCR-D Up [MW]	FCR-D Down [MW]
StatNett	39	234	564	546
FinGrid	20	120	290	280
Svenska Kraftnat	38.3	230	555	536
Energinet	2.7	17	41	38
Nordic obligations	100	600	1450	1400

Source: Energinet report [link]
Outlook for the need in 2030-2040: Energinet report [link]

EV aggregators as FCR-D service providers

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Source: Energinet [link]

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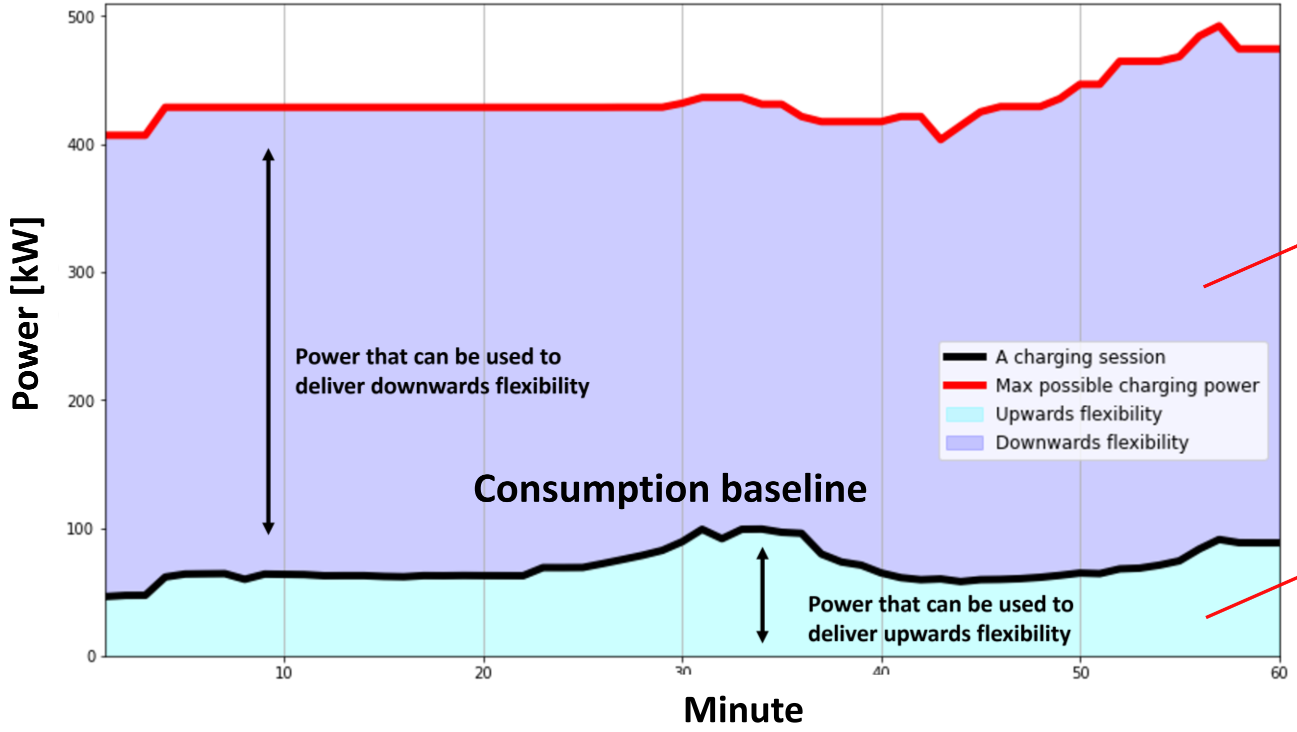
Data for 1400 (residential) charging boxes in Copenhagen

- Provided by Spirii (https://spirii.com/en)
- Time period of March 24, 2022 to March 21, 2023
- Minute-level resolution (the ideal is to have a higher-resolution dataset)

A random historical hour (500 boxes)

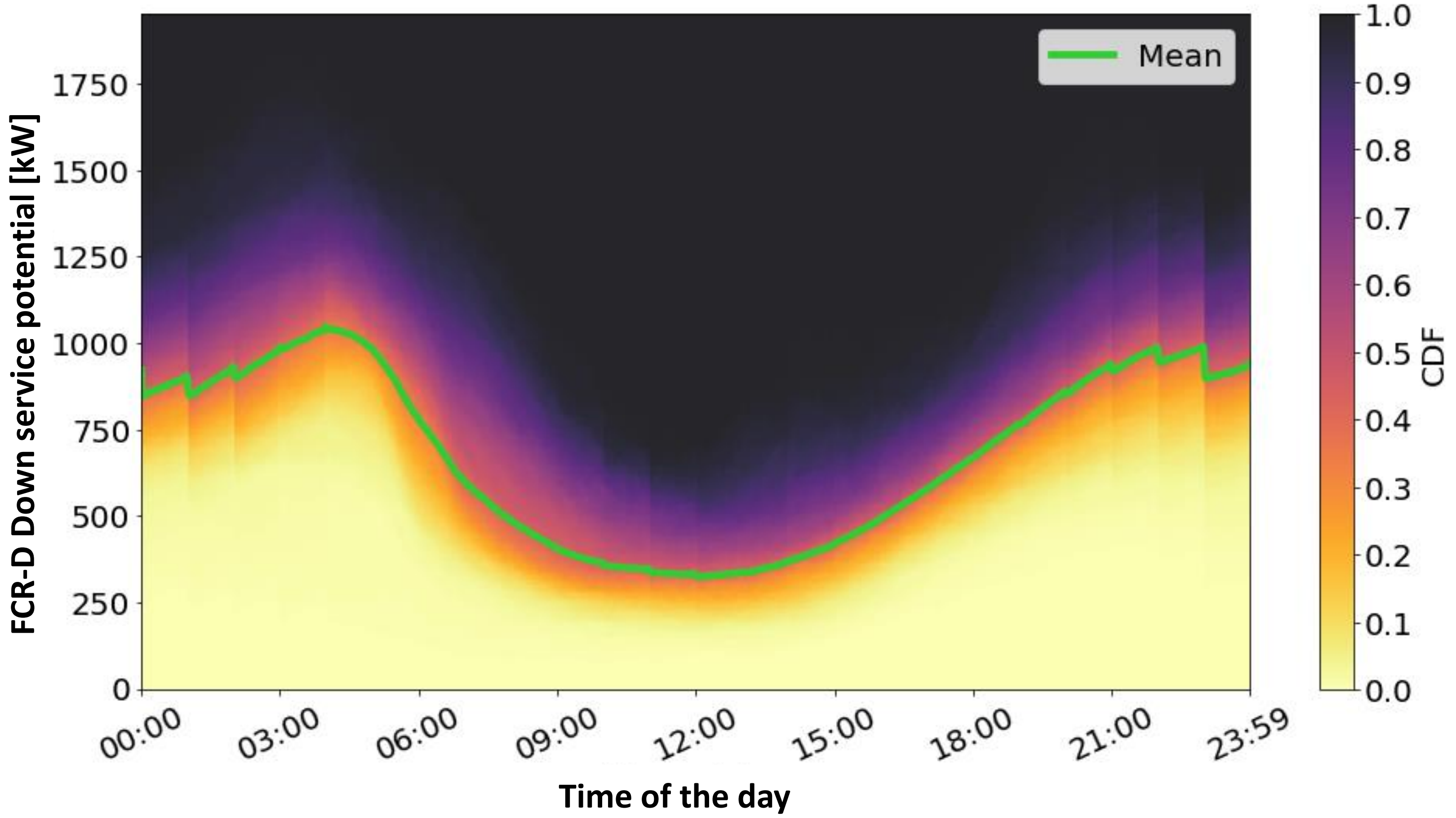


Potential for down-regulation (FCR-D Down)

Potential for up-regulation (FCR-D UP) – no V2G

Data for 1400 (residential) charging boxes in Copenhagen

Probability distribution of potential for FCR-D Down services throughout the day (based on historical data)



Energinet requirements (grid codes) – Part 1/2

The so-called "P-10 rule":

> *"Energinet requires that there must at maximum be bid in capacity corresponding to the 10% percentile with delivery of capacity reserves from fluctuating renewables and flexible consumption. This means, that the participant's prognosis, which must be approved by Energinet, evaluates that the probability is 10% that the sold capacity is not available. This entails that there is a 90% chance that the sold capacity or more is available. This is when the prognosis is assumed to be correct."*

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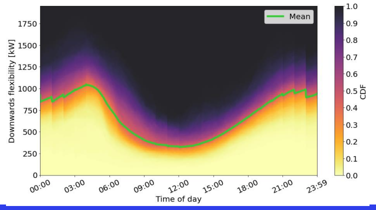
Joint chance constraint:

$$\mathbb{P}\left(c_h^{\downarrow} \leq F_{m,h}^{\downarrow}(\zeta) \quad \forall m \right) \geq 1 - \epsilon \qquad \forall h$$

FCR-D Down bid in hour h [kW]

Probability distribution of the FCR-D Down service availability per minute m

ϵ → 0.9



Energinet requirements (grid codes) – Part 2/2

LER requirement:

“There are additional requirements for units and portfolios with limited energy reservoir (LER) units, such as batteries.”

“If you wish to prequalify 1 MW of FCR from a LER unit, you must reserve 0.25 MW in both directions, which require at least a 1.25 MW LER unit. You must also reserve 24 minutes of energy in both directions, which requires at least 0.4 MWh capacity charged, as well as room to charge the LER unit 0.4 MWh more.”

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Extended joint chance constraint:

$$\mathbb{P}\begin{pmatrix} \frac{1}{4}c_h^{\downarrow} + c_h^{\uparrow} \leq F_{m,h}^{\uparrow}(\zeta) & \forall m \\ c_h^{\downarrow} \leq F_{m,h}^{\downarrow}(\zeta) & \forall m \\ c_h^{\downarrow} \leq F_{m,h}^{\mathrm{E}}(\zeta) & \forall m \end{pmatrix} \geq 1-\epsilon \quad \forall h$$

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FCR-D Up bid in hour *h* [kW]

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DTU

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Extended joint chance constraint:

Probability distribution of the FCR-D Up service availability per minute *m*

$$\mathbb{P}\begin{pmatrix} \frac{1}{4}c_h^{\downarrow} + c_h^{\uparrow} \leq F_{m,h}^{\uparrow}(\zeta) & \forall m \\ c_h^{\downarrow} \leq F_{m,h}^{\downarrow}(\zeta) & \forall m \\ c_h^{\downarrow} \leq F_{m,h}^{\mathrm{E}}(\zeta) & \forall m \end{pmatrix} \geq 1 - \epsilon \quad \forall h$$

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Probability distribution of FCR-D Down availability for the next 24 minutes per minute *m*

FCR-D Up/Down bidding optimization problem for hour *h*

$$\underset{c_h^{\downarrow}\geq 0,\ c_h^{\uparrow}\geq 0}{\text{Maximize}} \quad c_h^{\downarrow} + c_h^{\uparrow}$$

s.t.

$$\mathbb{P}\begin{pmatrix} \frac{1}{4}c_h^{\downarrow} + c_h^{\uparrow} \leq F_{m,h}^{\uparrow}(\zeta) & \forall m \\ c_h^{\downarrow} \leq F_{m,h}^{\downarrow}(\zeta) & \forall m \\ c_h^{\downarrow} \leq F_{m,h}^{\mathrm{E}}(\zeta) & \forall m \end{pmatrix} \geq 1-\epsilon$$

- Sample average approximation approach
- Minimum number of samples based on [1]

[1] J. Luedtke and S. Ahmed, “A sample approximation approach for optimization with probabilistic constraints,” *SIAM Journal of Optimization*, vol. 19, no. 2, pp. 674-699, 2008.

Two solution techniques

First technique: ALSO-X [2]-[3]

Develop an MILP as:

$$\underset{c^{\downarrow}\geq 0,\ c^{\uparrow}\geq 0,\ y_{m,\omega}\in\{0,1\}}{\text{Maximize}} \quad c^{\downarrow}+c^{\uparrow}$$

$$\frac{1}{4}c^{\downarrow}+c^{\uparrow}-F^{\uparrow}_{m,\omega}\leq y_{m,\omega}M^{\uparrow} \qquad \forall m,\omega$$

$$c^{\downarrow}-F^{\downarrow}_{m,\omega}\leq y_{m,\omega}M^{\downarrow} \qquad \forall m,\omega$$

$$c^{\downarrow}-F^{\mathrm{E}}_{m,\omega}\leq y_{m,\omega}M^{\mathrm{E}} \qquad \forall m,\omega$$

$$\sum_{m}\sum_{\omega} y_{m,\omega}\leq q$$

- Index *h* for hours has been dropped for notational simplicity,
- *w* is the index for samples,
- Big *M*s are sufficiently large positive values,
- *q* is [0.1 * 60 * *N*], where *N* is the number of samples. q counts the number of overbid samples.

[2] S. Ahmed, J. Luedtke, Y. Song, and W. Xie, “Nonanticipative duality, relaxations, and formulations for chance-constrained stochastic programs,” *Mathematical Programming*, vol. 162, no. 1, pp. 51–81, 2017.

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$$\sum_{m}\sum_{\omega} y_{m,\omega}\leq q$$

The following iterative but LP algorithm can be solved alternatively (inner convex approximation):

Algorithm 1: ALSO-X

Input: Stopping tolerance parameter δ

Require: Relax the integrality of y

1: $\underline{q}\leftarrow 0, \quad \bar{q}\leftarrow\lfloor 0.1\times 60\times N\rfloor$

2: **while** $\bar{q}-\underline{q}\geq\delta$ **do**

3: Set $q=\dfrac{(\underline{q}+\bar{q})}{2}$,

4: retrieve the optimal solution for LP.

5: Set $\underline{q}=q$ if $\mathbb{P}(y_{m,\omega}*=0)\geq 1-\epsilon$; otherwise, $\bar{q}=q$

6: **end while**

Output: A solution to MILP model.

[2] S. Ahmed, J. Luedtke, Y. Song, and W. Xie, “Nonanticipative duality, relaxations, and formulations for chance-constrained stochastic programs,” *Mathematical Programming*, vol. 162, no. 1, pp. 51–81, 2017.

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Two solution techniques

Second technique: CVaR

Develop an LP as (conservative approach):

$$\underset{c^{\downarrow}\geq 0,\ c^{\uparrow}\geq 0,\ \beta\leq 0,\ \zeta_{m,\omega}}{\text{Maximize}} \quad c^{\downarrow}+c^{\uparrow}$$

$$\frac{1}{4}c^{\downarrow}+c^{\uparrow}-F^{\uparrow}_{m,\omega}\leq \zeta_{m,\omega} \qquad \forall m,\omega$$

$$c^{\downarrow}-F^{\downarrow}_{m,\omega}\leq \zeta_{m,\omega} \qquad \forall m,\omega$$

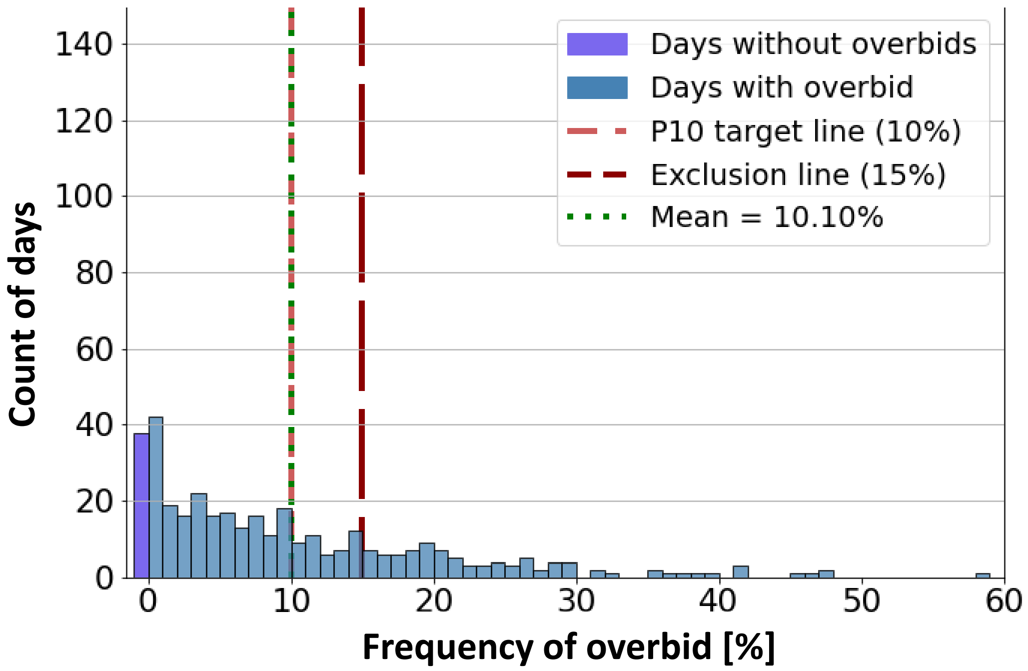
$$c^{\downarrow}-F^{E}_{m,\omega}\leq \zeta_{m,\omega} \qquad \forall m,\omega$$

$$\frac{1}{60N}\sum_{m}\sum_{\omega}\zeta_{m,\omega}-(1-\epsilon)\beta\leq 0$$

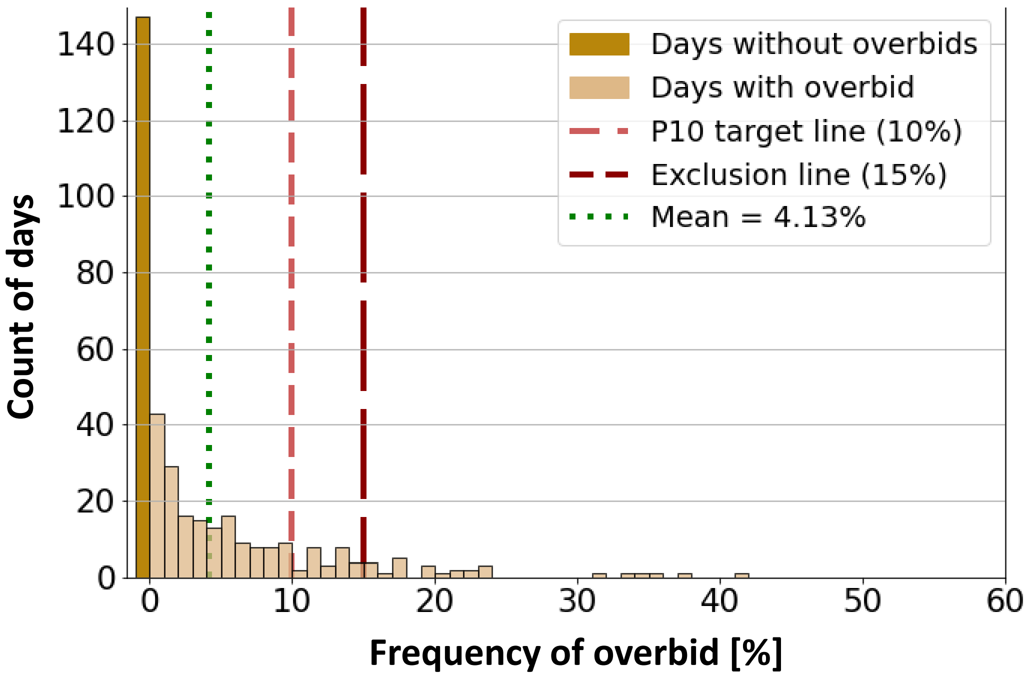
$$\beta\leq \zeta_{m,\omega} \qquad \forall m,\omega$$

Out-of-sample results over a year

ALSO-X

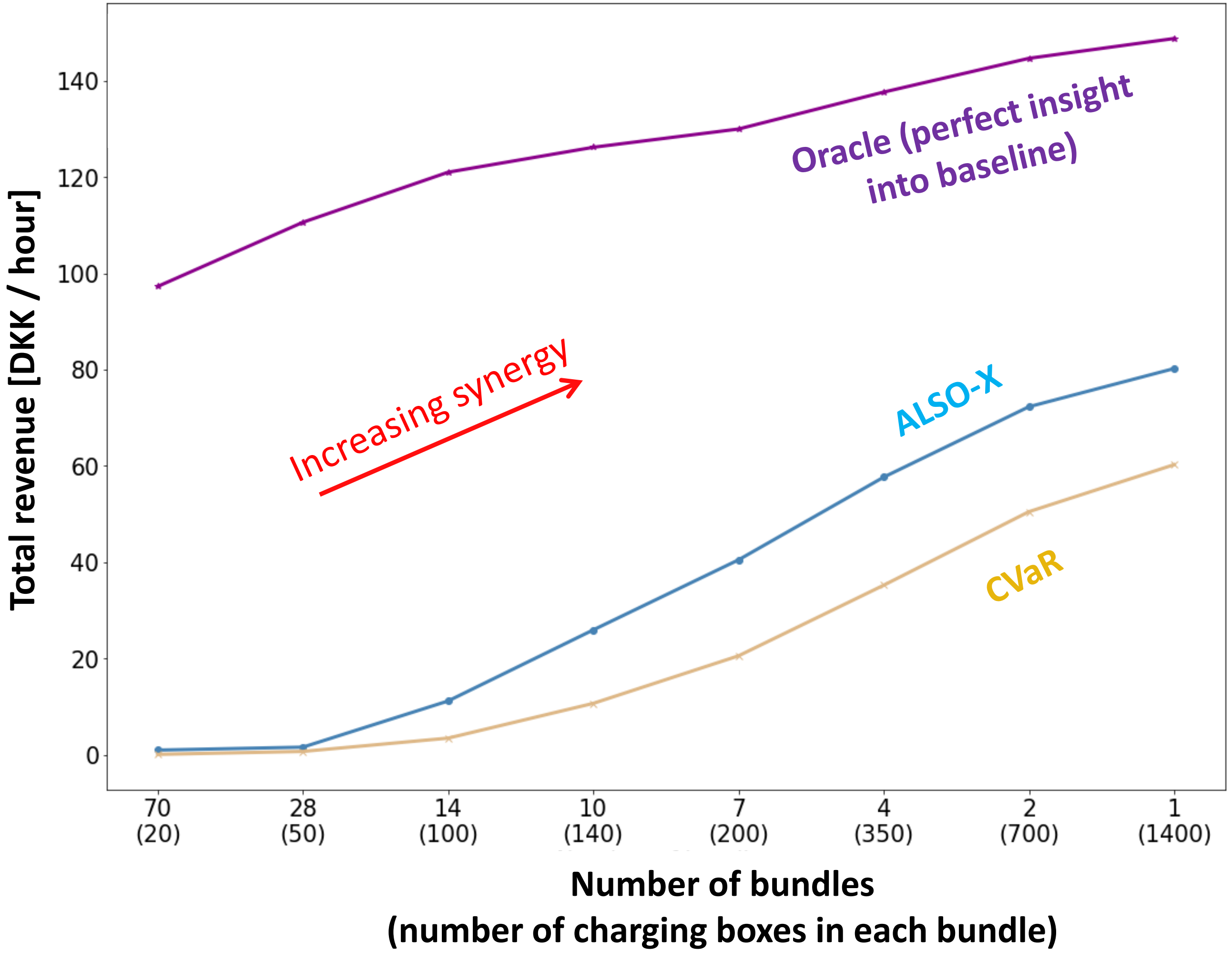


CVaR



Out-of-sample results over a year

Total profit (median) of 1400 charging boxes per hour:



Towards distributional robustness

Wasserstein distributionally robust joint chance-constrained optimization (uncertainty in the right-hand side):

$$\underset{c_h^{\downarrow}\geq 0,\ c_h^{\uparrow}\geq 0}{\text{Maximize}} \quad c_h^{\downarrow} + c_h^{\uparrow}$$

s.t.

$$\min_{\mathbb{P}\in\mathcal{P}} \mathbb{P}\begin{pmatrix} \frac{1}{4}c_h^{\downarrow} + c_h^{\uparrow} \leq F_{m,h}^{\uparrow}(\zeta) & \forall m \\ c_h^{\downarrow} \leq F_{m,h}^{\downarrow}(\zeta) & \forall m \\ c_h^{\downarrow} \leq F_{m,h}^{\mathrm{E}}(\zeta) & \forall m \end{pmatrix} \geq 1-\epsilon \quad \forall h$$

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where

$$\mathcal{P} = \left\{\mathbb{P} : d_W(\mathbb{P}, \hat{\mathbb{P}}_N) \leq \theta\right\}.$$

Radius (given) — θ

Wasserstein distance — d_W

Empirical distribution — $\hat{\mathbb{P}}_N$

Towards distributional robustness

We adopt Proposition 2 of [4] for the exact reformulation of the joint chance constraint:

PROPOSITION 2. *For the safety set* $\mathcal{S}(\boldsymbol{x}) = \{\boldsymbol{\xi} \in \mathbb{R}^K \mid \boldsymbol{a}_m^\top \boldsymbol{x} < \boldsymbol{b}_m^\top \boldsymbol{\xi} + b_m \; \forall m \in [M]\}$, *where* $\boldsymbol{b}_m \neq \mathbf{0}$ *for all* $m \in [M]$, *the chance constrained program* (2) *is equivalent to the mixed integer conic program*

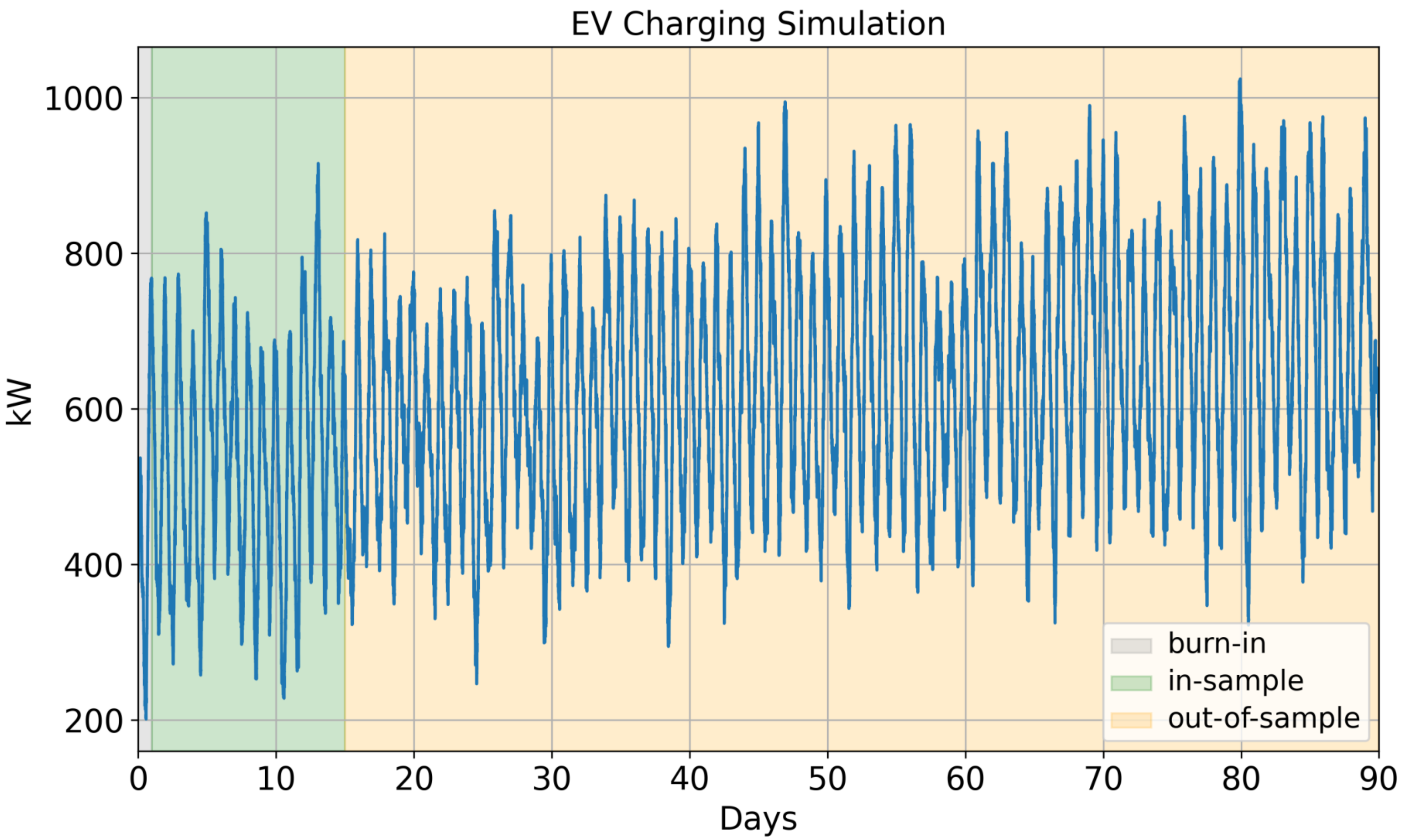
$$
\begin{aligned}
Z^\star_{\text{JCC}} = \min_{\boldsymbol{q},\boldsymbol{s},t,\boldsymbol{x}} \;& \boldsymbol{c}^\top \boldsymbol{x} \\
\text{s.t.} \;& \varepsilon N t - \boldsymbol{e}^\top \boldsymbol{s} \geq \theta N \\
& \frac{\boldsymbol{b}_m^\top \hat{\boldsymbol{\xi}}_i + b_m - \boldsymbol{a}_m^\top \boldsymbol{x}}{\|\boldsymbol{b}_m\|_*} + \mathrm{M} q_i \geq t - s_i \quad \forall m \in [M],\; i \in [N] \\
& \mathrm{M}(1 - q_i) \geq t - s_i \quad \forall i \in [N] \\
& \boldsymbol{q} \in \{0,1\}^N,\; \boldsymbol{s} \geq \mathbf{0},\; \boldsymbol{x} \in \mathcal{X},
\end{aligned}
$$

where M *is a suitably large (but finite) positive constant.*

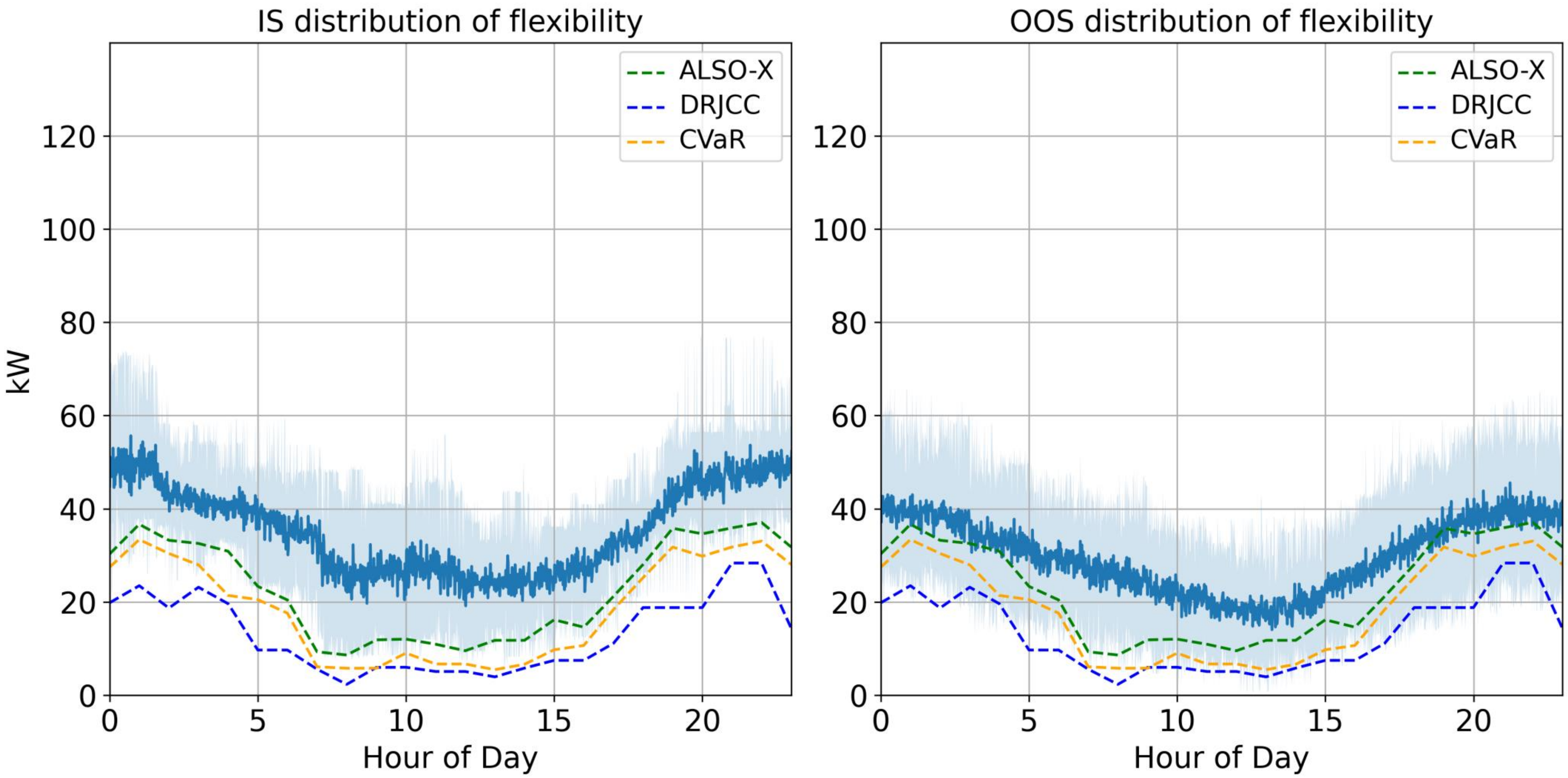
This results in a mixed-integer conic (or linear, depending on the norm) program.

[4] Z. Chen, D. Kuhn, and W. Wiesemann, "Data-driven chance constrained programs over Wasserstein balls," *Operations Research*, accepted in 2022, forthcoming (https://doi.org/10.1287/opre.2022.2330).

Input data: In-sample (IS) vs out-of-sample (OOS)



Results



IS: in-sample
OOS: out-of-sample

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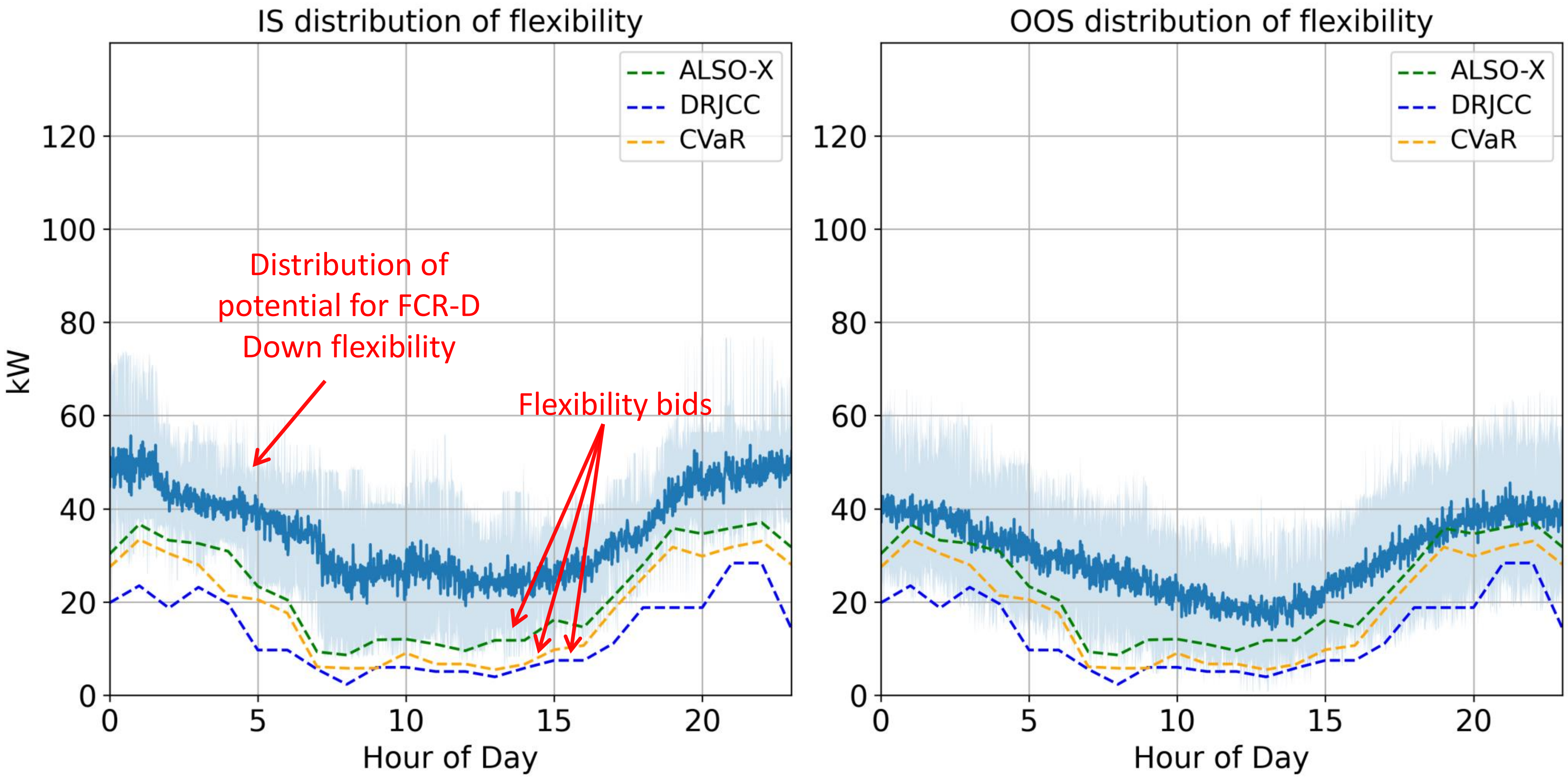

IS: in-sample
OOS: out-of-sample

Takeaways and future directions

- TSO grid codes to be modeled as a joint chance-constrained program
- ALSO-X provides a good approximation
- CVaR, as expected, is conservative
- Distributional robustness can be straightforwardly implemented
- Increasing synergy with more charging boxes in a bundle

Potential future directions

- ❑ Forecasting the baseline instead of using historical data for sampling (will it be useful?)
- ❑ Higher resolution data (enforcing constraints, e.g., per second, instead of minutes)
- ❑ Multi-market bidding (FCR-D, FCR-N, aFRR, etc)
- ❑ Does location matter?
- ❑ More heterogenous aggregation of assets

Thank you!

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