Dynamic Pricing for Distribution-Grid Congestion Management

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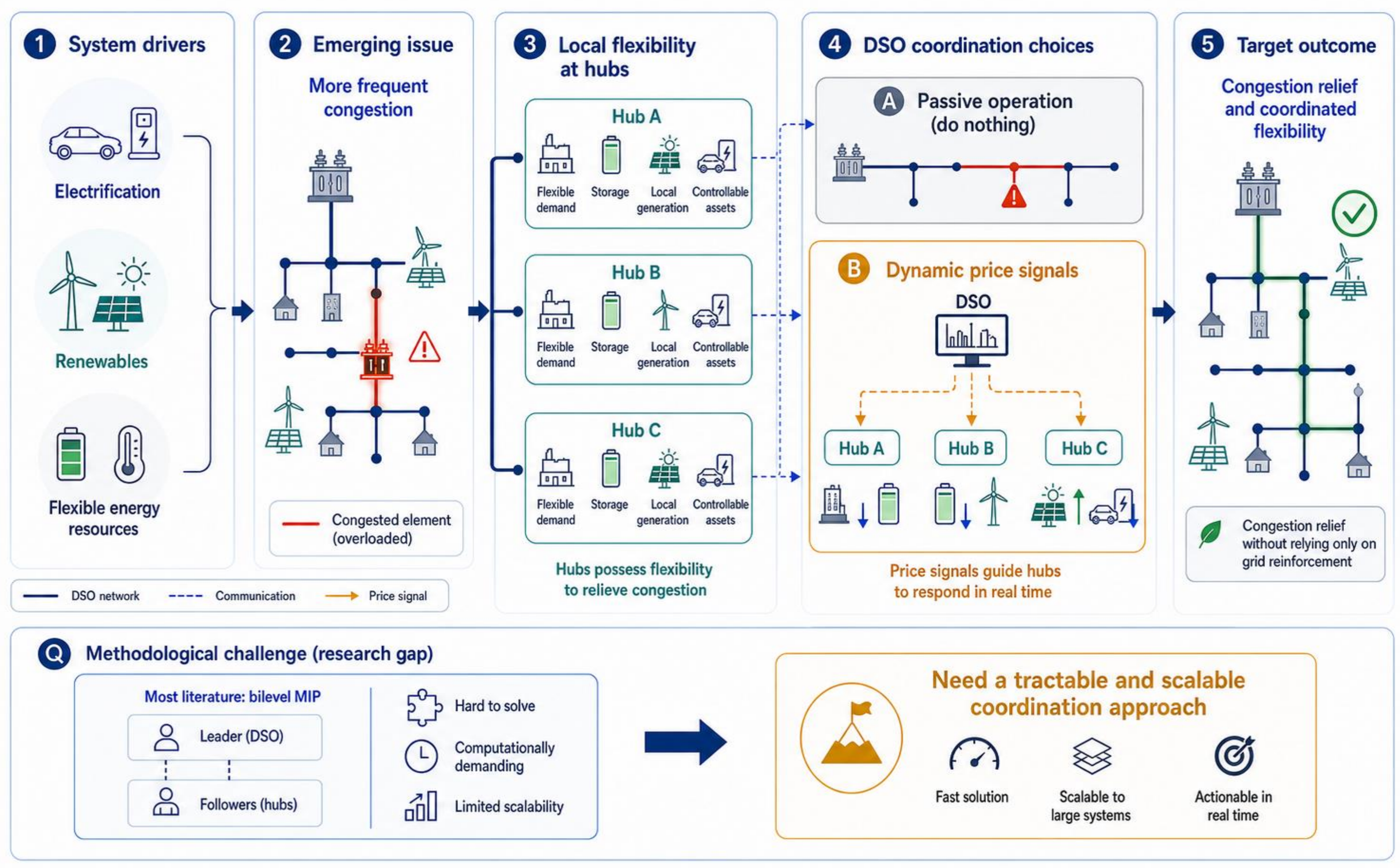
Motivation and Research Questions

I. Can dynamic pricing (via DSO) effectively reduce distribution-grid congestion through local flexibility coordination?

II. Can this problem be modeled and solved using an approach that is more tractable and scalable than standard bilevel MIP methods?



Methodology

A Baseline (No Pricing)

Independent hub operation; DSO only evaluates network consequences.

B Centralized Linear Benchmark (Utopia)

First-best coordinated benchmark; not a market claim.

C Exact Linear Bilevel (MILP)

Leader prices + LP followers; KKT/MILP benchmark.

D Quadratic Follower

The proposed approach.

Math Behind the Methods

B

Universal objects.

- Hubs $i \in \mathcal{H} = \{1, 2, 3\}$, periods $t \in \mathcal{T} = \{0, \ldots, T-1\}$, lines $\ell \in \mathcal{L}$.
- Hub vector $x_{it} = (m^{in}, m^{out}, u, p^{ch}, p^{dis}, e, a, c^{pv}, g, p^{el}, h^{fc}, h)_{it}$.
- Net grid withdrawal: $w_{it} = m^{in}_{it} - m^{out}_{it}$; positive means import, negative means export.
- Effective buy/sell prices: $\pi^{buy}_{it} = \lambda^{buy}_t + \tau^{base}_i + \delta_{it}$, $\pi^{sell}_{it} = \lambda^{sell}_t$.

Common physical balance.

$$m^{in}_{it} - m^{out}_{it} + p^{dis}_{it} - p^{ch}_{it} + g_{it} + \eta^{fc}_i h^{fc}_{it} - p^{el}_{it} - u_{it} - c^{pv}_{it} = D^{fix}_{it} - PV^{avail}_{it}.$$

For the controllable hub withdrawals $w_t = (w_{1t}, w_{2t}, w_{3t})$, line flows are evaluated as

$$f_{\ell t} = f^{bg}_{\ell t} - \sum_{i \in \mathcal{H}} H_{\ell i} w_{it}.$$

Line overload is

$$o^{line}_{\ell t} = \left[|f_{\ell t}| - \bar{f}_\ell\right]_+.$$

Substation import and substation overload are

$$S_t = \sum_{i \in \mathcal{H}} w_{it}, \qquad o^{sub,+}_t = \left[S_t - \bar{S}^+\right]_+, \qquad o^{sub,-}_t = \left[-S_t - \bar{S}^-\right]_+$$

$$f_{\ell t} - \bar{f}_\ell \le z^+_{\ell t}, \quad -f_{\ell t} - \bar{f}_\ell \le z^-_{\ell t}, \quad z^+_{\ell t}, z^-_{\ell t} \ge 0,$$

$$S_t - \bar{S} \le y_t, \quad S_t = \sum_i w_{it}, \quad y_t \ge 0.$$

Stage 1: total congestion.

$$\min \sum_{\ell, t} (z^+_{\ell t} + z^-_{\ell t}) + \sum_t y_t.$$

C

Upper-level price design.

$$\min_{\delta, x, o} \ \alpha_{line} \sum_{\ell, t} o^{line}_{\ell t} + \alpha_{sub} \sum_t o^{sub}_t + \alpha_{level} \|\delta\|_1 + \alpha_{smooth} \|D_t \delta\|_1 + \alpha_{fair} \|D_i \delta\|_1$$

subject to $\delta \in \mathcal{D}$, common network equations, overload epigraphs, and for each hub:

$$x_i \in \arg \min_{x_i \in \mathcal{X}_i} c_i(\delta_i)^\top x_i.$$

Follower LP canonical form.

$$\min c_i(\delta_i)^\top x_i \quad \text{s.t.} \quad A_i x_i = b_i, \quad G_i x_i \le h_i, \quad \ell_i \le x_i \le u_i.$$

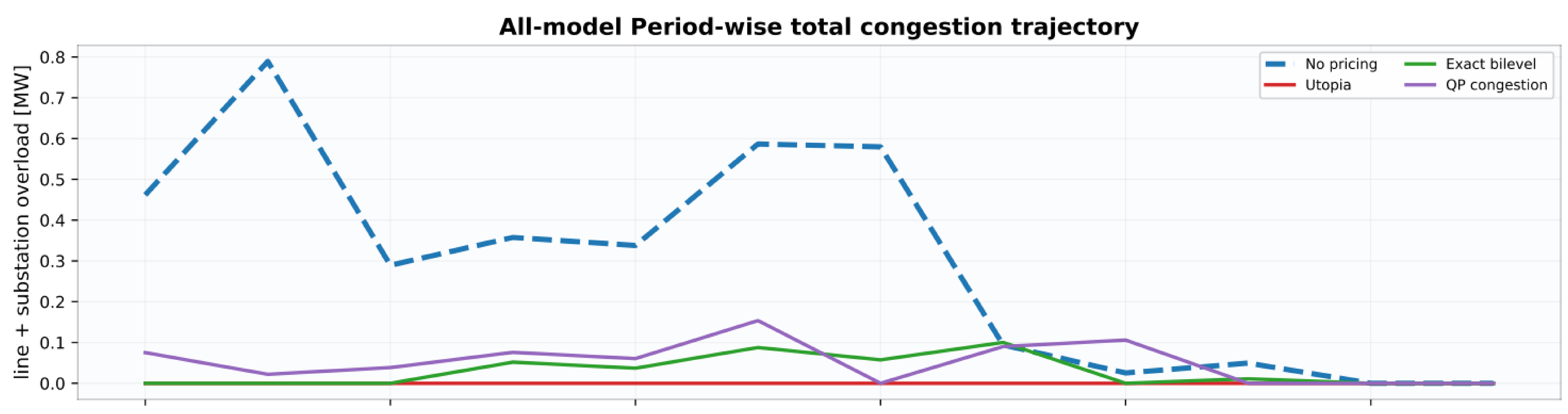
D

$$g(x, \delta) = \frac{1}{2} x^\top Q x + q^\top x + \delta^\top x.$$

An Example

Some Insights

1. From passive network operation to active coordination.
2. Congestion relief depends on timing, not only capacity.
3. Dynamic pricing links economics and physics.
4. Scalable coordination is the key bottleneck.



Ongoing Work and Perspective

- Theoretical Guarantees
- Accuracy Improvement
- Scalability

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