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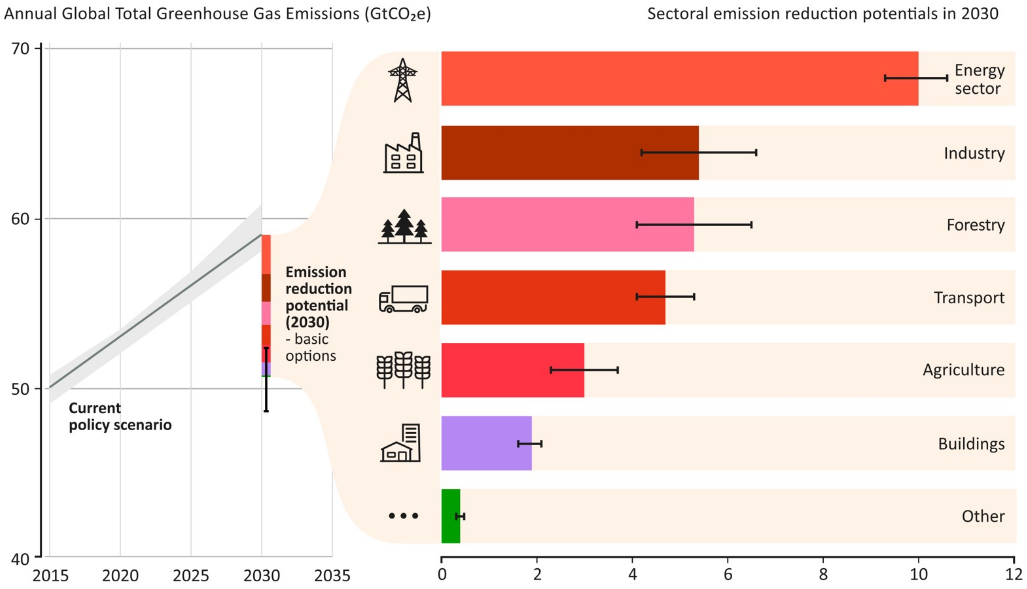
Grid-aware Aggregation and Realtime Disaggregation of Distributed Energy Resources in Radial Networks

Panel Session: Optimization for distribution grid operations

Nawaf Nazir (Pacific Northwest National Lab)
Mads Almassalkhi (University of Vermont/Pacific Northwest National Lab)
October 26, 2021
11:00 AM - 12:30 PM

Beneficial electrification and flexible demand

Electrifying energy, transportation, and building sectors are key to GHG reductions



Combine renewables and efficiency with **electrification of end use**. [1]

Flexible demand enables significantly more renewable generation and reduces duck-curve ramping effects [2]

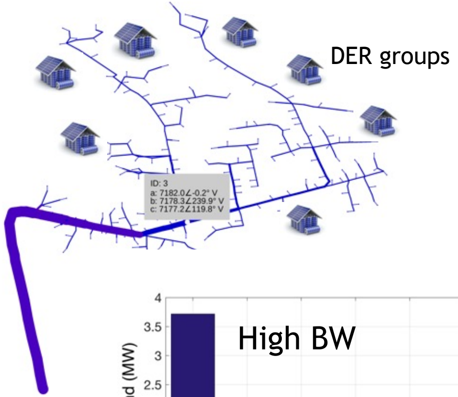
59GW of DR today will become **200GW of flexible demand by 2030** [3]

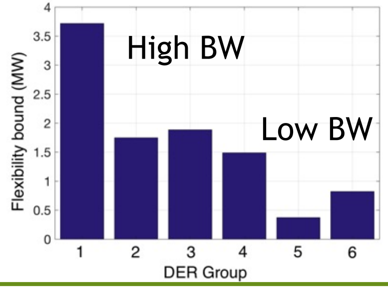
Need to manage millions of behind-the-meter loads

[1] UN Environmental Program, Emission Gap Report 2019 (source for figure, too)
[2] Goldenberg, et al, "Demand Flexibility: The Key To Enabling A Low-cost, Low-carbon Grid," Tech. Rep., Rocky Mountain Institute, 2018.
[3] Hledik et al, "The National Potential for Load Flexibility: Value And Market Potential Through 2030," *Tech. Rep*., The Brattle Group, 2019.

What is the role of the distribution grid/network?

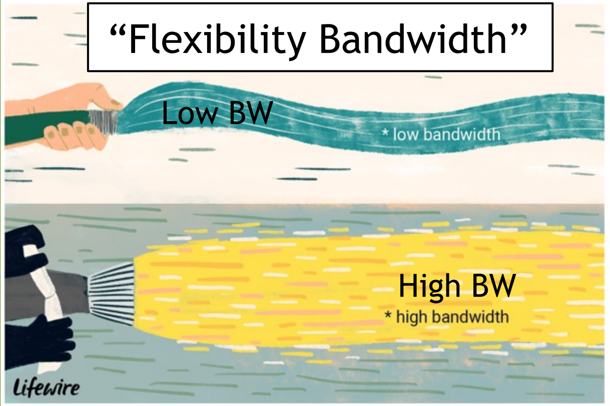
Utility (grid information/data)
- Needs to ensure grid reliability
- Wants to protect grid data
- Lack direct access to devices
- Knows grid availability



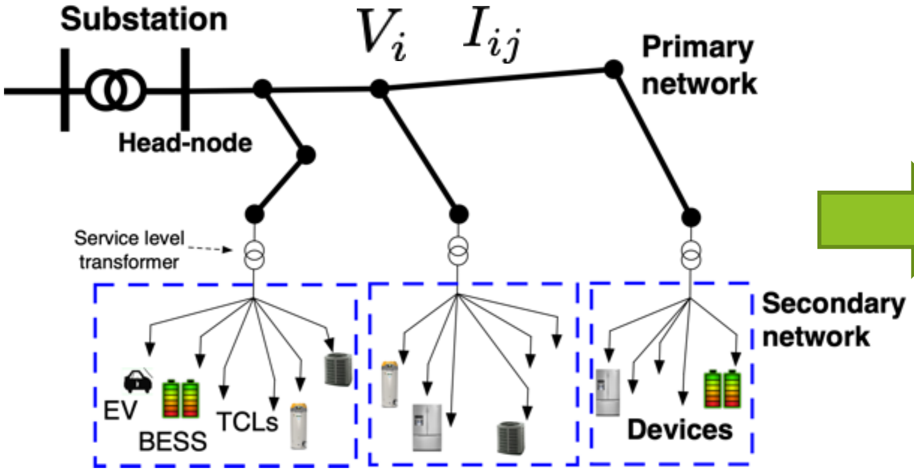


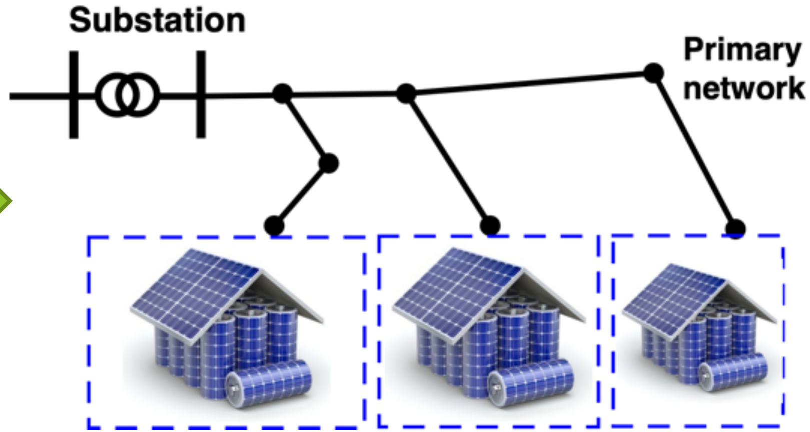
Fundamental *asymmetries* in information & control

Aggregators (device control)
- Needs to ensure device QoS
- Wants to provide market services
- Lack direct access to grid data
- Knows device availability



Motivating example: aggregation





$$m_i \leq p_i \leq M_i$$

Feeder

$$\Delta p := \left[\sum_{i=1}^{n} m_i, \sum_{i=1}^{n} M_i\right]$$

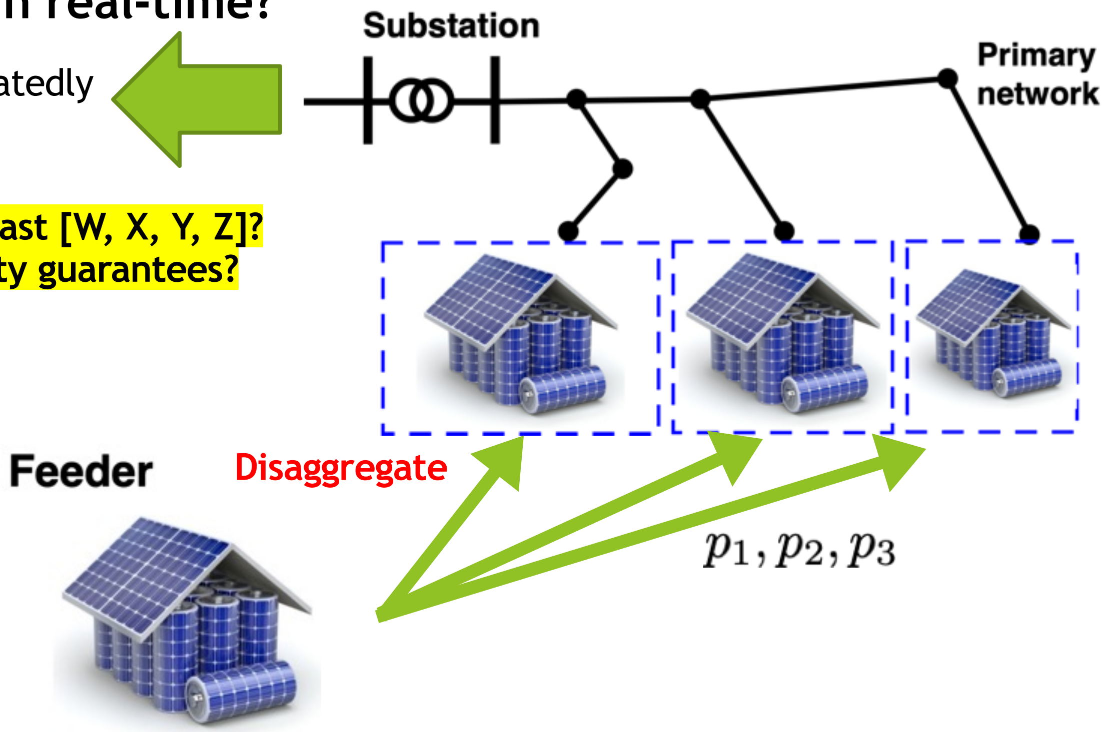
Bid flexibility into whole-sale ISO market (MW)

Motivating example: disaggregation

Can we solve disaggregation in real-time?

- Solve grid optimization problem repeatedly
  - \+ Guarantees grid reliability!
  - \- Can DisAgg problem be solved fast [W, X, Y, Z]?
    - \- Can we provide admissibility guarantees?

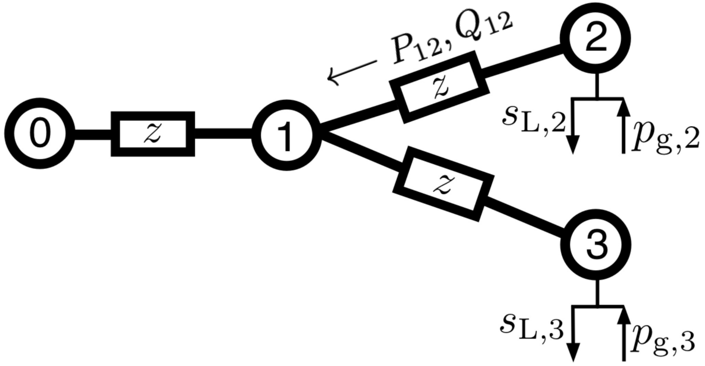
Requested flexibility from ISO (MW)



[W] Almassalkhi, et al, "Hierarchical, Grid-Aware, and Economically Optimal Coordination of Distributed Energy Resources in Realistic Distribution Systems," Energies, 2020.
[X] **Nawaf Nazir**, Pavan Racherla, and Mads Almassalkhi, "Optimal multi-period dispatch of distributed energy resources in unbalanced distribution feeders", IEEE Trans. on Power Systems, 2020
[Y] **Nawaf Nazir** and M. Almassalkhi, "Voltage positioning using co-optimization of controllable grid assets," IEEE Trans. on Power Systems, 2020.
[Z] **S. Brahma, Nawaf Nazir**, et al, "Optimal and resilient coordination of virtual batteries in distribution feeders," IEEE Trans. on Power Systems, 2020

Finding set of admissible (active) injections

Simple 3-node balanced distribution feeder with 2 controllable nodes modeled with *DistFlow:*



$v_i := |V_i|^2$ and $l_{ij} := |I_{ij}|^2$

$$v_j = v_i + 2r_{ij}P_{ij} + 2x_{ij}Q_{ij} - |z_{ij}|^2 l_{ij}$$

$$P_{ij} = p_j + \sum_{h:h\to j} (P_{jh} - r_{jh} l_{jh})$$

$$Q_{ij} = q_j + \sum_{h:h\to j} (Q_{jh} - x_{jh} l_{jh})$$

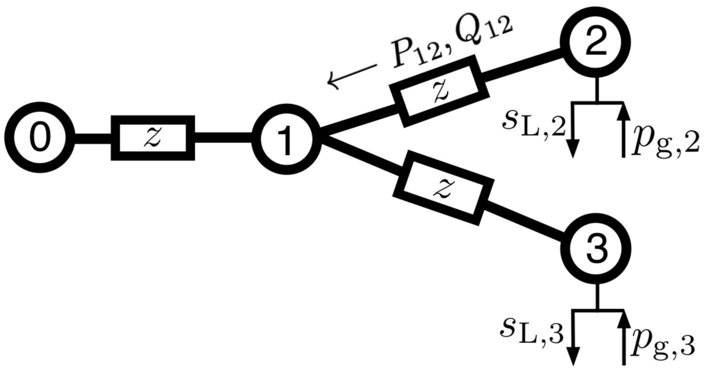
$$l_{ij}(P_{ij}, Q_{ij}, v_j) = \frac{P_{ij}^2 + Q_{ij}^2}{v_j},$$

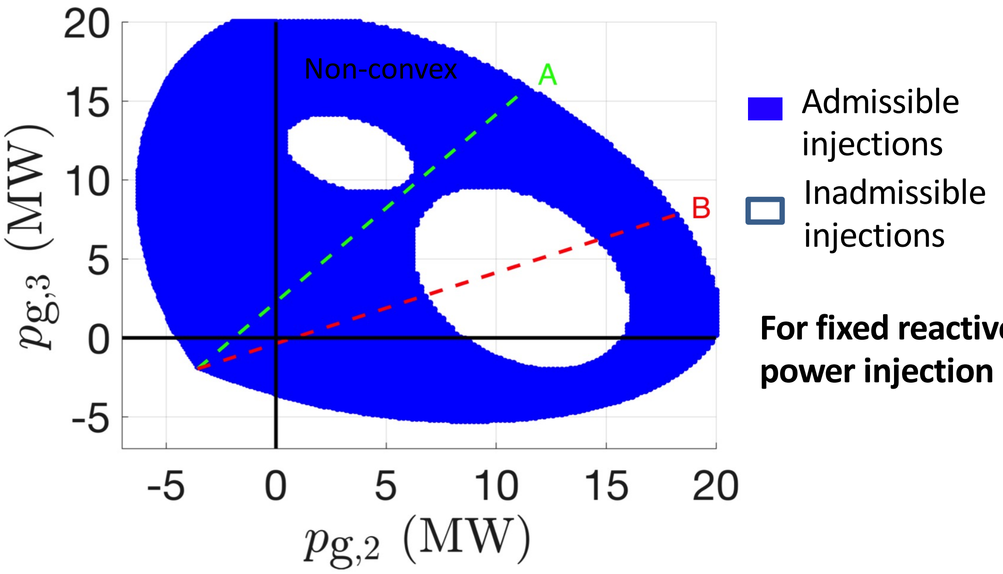
The only nonlinear relation

Network limits: $v_i \in [\underline{v}_i, \bar{v}_i], l_{ij} \in [\underline{l}_{ij}, l_{ij}]$

Finding set of admissible (active) injections

Simple 3-node balanced distribution feeder with 2 controllable nodes



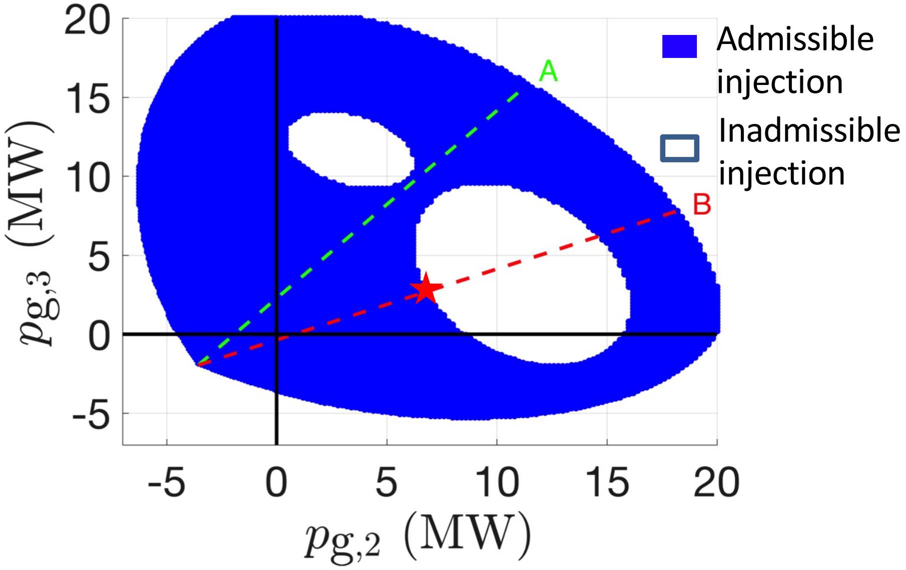


For fixed reactive power injection

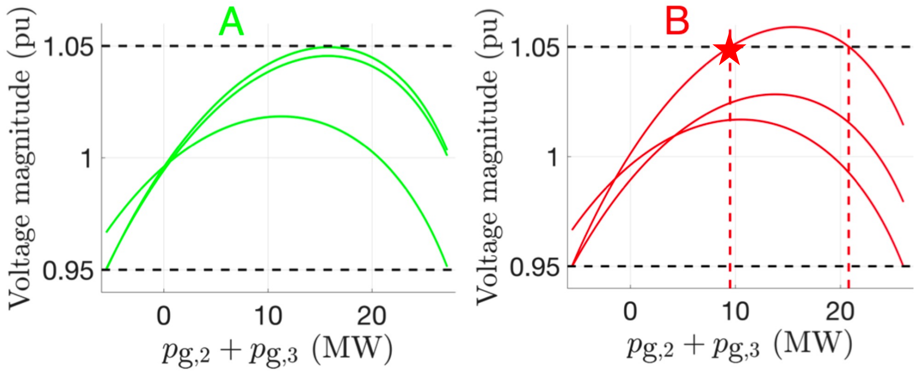
Network limits: $v_i \in [\underline{v}_i, \bar{v}_i], l_{ij} \in [\underline{l}_{ij}, \bar{l}_{ij}]$

Finding set of admissible (active) injections

Simple 3-node balanced distribution feeder example:



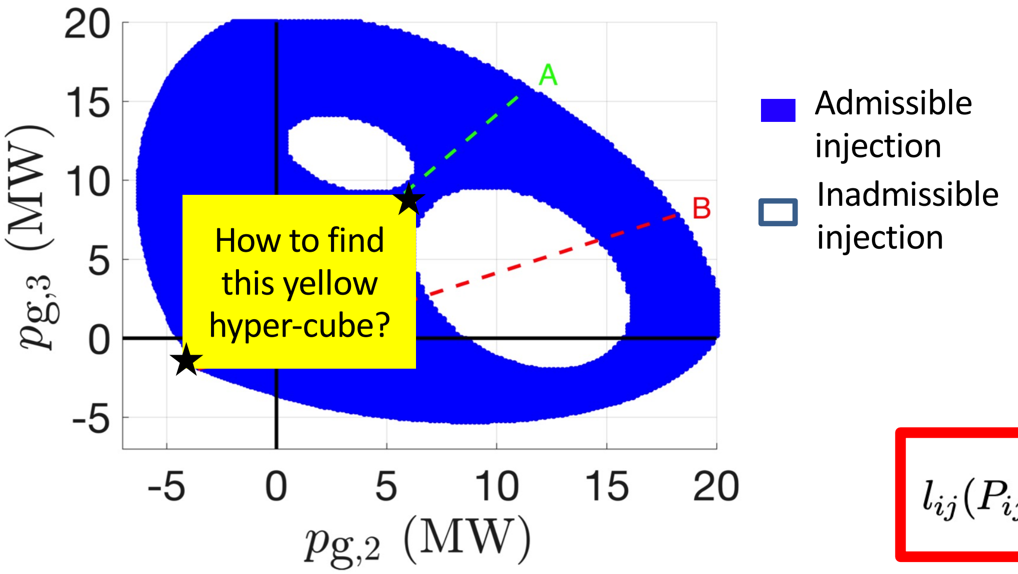
Network limits: $v_i \in [\underline{v}_i, \bar{v}_i], l_{ij} \in [\underline{l}_{ij}, \bar{l}_{ij}]$



The two controllable active power resources are <u>limited in aggregate by the network</u> – i.e., their individual limits are coupled

Finding set of admissible (active) injections

Goal: find largest hyperrectangle to determine p_g limts (decoupled)



$$v_j = v_i + 2r_{ij}P_{ij} + 2x_{ij}Q_{ij} - |z_{ij}|^2 l_{ij}$$

$$P_{ij} = p_j + \sum_{h:h\to j} (P_{jh} - r_{jh}l_{jh})$$

$$Q_{ij} = q_j + \sum_{h:h\to j} (Q_{jh} - x_{jh}l_{jh})$$

$$\boxed{l_{ij}(P_{ij}, Q_{ij}, v_j) = \frac{P_{ij}^2 + Q_{ij}^2}{v_j},}$$

Idea: replace non-convex constraint with a convex inner approximation

Convex inner approximation via proxy variables

If we can find envelope $l_{\text{lb},ij} \leq \boxed{l_{ij}(P_{ij},Q_{ij},v_j)=\frac{P_{ij}^2+Q_{ij}^2}{v_j},} \leq l_{\text{ub},ij}$

Then, we can create proxy variables that upper (+) and lower (-) bound the actual (P, Q, V)

$$\left.\begin{aligned}
P^+ &:= Cp - D_{\text{R}} l_{\text{lb}} \\
P^- &:= Cp - D_{\text{R}} l_{\text{ub}} \\
Q^+ &:= Cq - D_{\text{X}_+} l_{\text{lb}} - D_{\text{X}_} l_{\text{ub}} \\
Q^- &:= Cq - D_{\text{X}_+} l_{\text{ub}} - D_{\text{X}_} l_{\text{lb}} \\
V^+ &:= v_0 \mathbf{1}_n + M_{\text{p}} p + M_{\text{q}} q - H_+ l_{\text{lb}} - H_- l_{\text{ub}} \\
V^- &:= v_0 \mathbf{1}_n + M_{\text{p}} p + M_{\text{q}} q - H_+ l_{\text{ub}} - H_- l_{\text{lb}}
\end{aligned}\right\}$$

Given a nominal operating point, $x_{ij}^0 := (P_{ij}^0, Q_{ij}^0, v_j^0)$

$$\boxed{l_{ij} \approx l_{ij}^0 + \mathbf{J}_{ij}^\top \delta_{ij} + \frac{1}{2}\delta_{ij}^\top \mathbf{H}_{\text{e},ij}\delta_{ij}}$$

$$\delta_{ij} := \begin{bmatrix} P_{ij} - P_{ij}^0 \\ Q_{ij} - Q_{ij}^0 \\ v_j - v_j^0 \end{bmatrix}, \quad \mathbf{J}_{ij} := \begin{bmatrix} \frac{\partial l_{ij}}{\partial P_{ij}} \\ \frac{\partial l_{ij}}{\partial Q_{ij}} \\ \frac{\partial l_{ij}}{\partial v_j} \end{bmatrix}\Bigg|_{x_{ij}^0} = \begin{bmatrix} \frac{2P_{ij}^0}{v_j^0} \\ \frac{2Q_{ij}^0}{v_j^0} \\ -\frac{(P_{ij}^0)^2+(Q_{ij}^0)^2}{(v_j^0)^2} \end{bmatrix}$$

$$\mathbf{H}_{\text{e},ij} := \begin{bmatrix} \frac{2}{v_j^0} & 0 & \frac{-2P_{ij}^0}{(v_j^0)^2} \\ 0 & \frac{2}{v_j^0} & \frac{-2Q_{ij}^0}{(v_j^0)^2} \\ \frac{-2P_{ij}^0}{(v_j^0)^2} & \frac{-2Q_{ij}^0}{(v_j^0)^2} & 2\frac{(P_{ij}^0)^2+(Q_{ij}^0)^2}{(v_j^0)^3} \end{bmatrix} \succeq 0^*$$

and from this model, we can explicitly define upper and lower bounds on l_{ij} that yield a convex inner approximation.

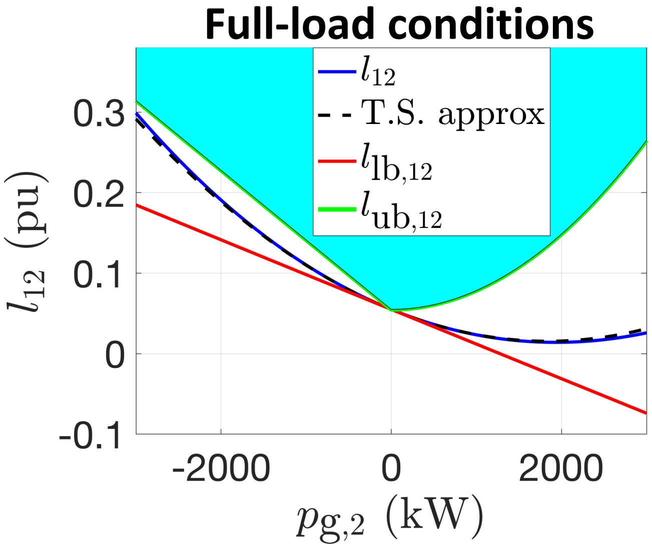
*N. Nazir and M. Almassalkhi, "Voltage Positioning Using Co-Optimization of Controllable Grid Assets in Radial Networks," in *IEEE Transactions on Power Systems*, vol. 36, no. 4, pp. 2761-2770, July 2021, doi: 10.1109/TPWRS.2020.3044206.

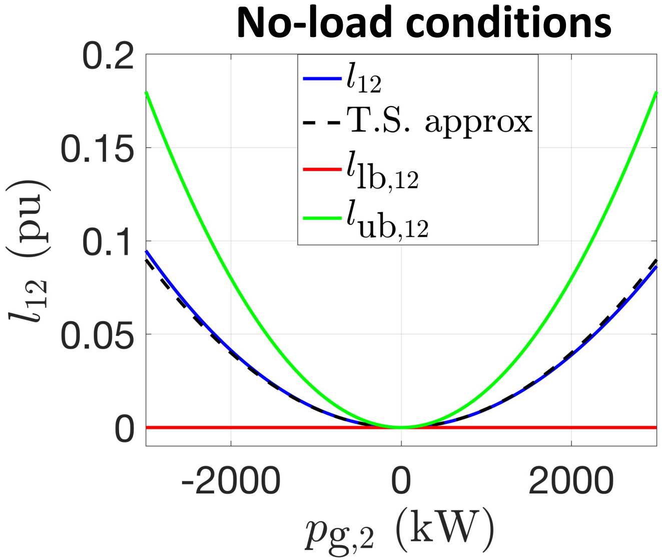
Convex inner approximation via proxy variables

$$\underbrace{l_{\mathrm{lb},ij} := f_{\mathrm{lb},ij}(P_{ij}^-, Q_{ij}^-, v_j^-, P_{ij}^+, Q_{ij}^+, v_j^+, x_{ij}^0)}_{\text{Has been shown to be affine}} \le l_{ij} \le \underbrace{f_{\mathrm{ub},ij}(P_{ij}^-, Q_{ij}^-, v_j^-, P_{ij}^+, Q_{ij}^+, v_j^+, x_{ij}^0) \le l_{\mathrm{ub},ij}}_{\text{Has been shown to be convex (SOC)}}$$

Has been shown to be **affine**

Has been shown to be **convex** (SOC)





For mathematical details, please see:

Nawaf Nazir and Mads Almassalkhi. "*Grid-aware aggregation and realtime disaggregation of distributed energy resources in radial networks.*" (Rev02)

Convex inner approximation via proxy variables

$$
\left.\begin{aligned}
&P^{+} := Cp - D_{\mathrm{R}} l_{\mathrm{lb}} \\
&P^{-} := Cp - D_{\mathrm{R}} l_{\mathrm{ub}} \\
&Q^{+} := Cq - D_{\mathrm{X}_{+}} l_{\mathrm{lb}} - D_{\mathrm{X}_{-}} l_{\mathrm{ub}} \\
&Q^{-} := Cq - D_{\mathrm{X}_{+}} l_{\mathrm{ub}} - D_{\mathrm{X}_{-}} l_{\mathrm{lb}} \\
&V^{+} := v_0 \mathbf{1}_n + M_{\mathrm{p}} p + M_{\mathrm{q}} q - H_{+} l_{\mathrm{lb}} - H_{-} l_{\mathrm{ub}} \\
&V^{-} := v_0 \mathbf{1}_n + M_{\mathrm{p}} p + M_{\mathrm{q}} q - H_{+} l_{\mathrm{ub}} - H_{-} l_{\mathrm{lb}} \\
&0 \le l_{\mathrm{lb},ij} := f_{\mathrm{lb},ij}(P_{ij}^{-}, Q_{ij}^{-}, v_j^{-}, P_{ij}^{+}, Q_{ij}^{+}, v_j^{+}, x_{ij}^{0}) \\
\text{Current limits} \quad &f_{\mathrm{ub},ij}(P_{ij}^{-}, Q_{ij}^{-}, v_j^{-}, P_{ij}^{+}, Q_{ij}^{+}, v_j^{+}, x_{ij}^{0}) \le l_{\mathrm{ub},ij} \le \bar{l}_{ij} \\
\text{Voltage limits} \quad &\underline{V} \le V^{-}, \quad V^{+} \le \bar{V} \\
\text{Active power limits} \quad &\underline{p}_i \le p_i \le \bar{p}_i
\end{aligned}\right\} \mathcal{X}(x^0)
$$

Feasible set represents a <u>convex</u> inner approximation

informs

Determining active injection limits (corners)

p_i^+ **maximum** active power injection at *each* node:

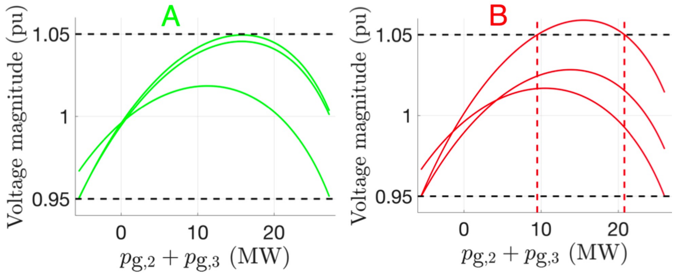
$$p^+(x^0) = \arg\max_p \sum_{i=1}^{N} f_i(p_i)$$
$$\text{s.t. } p \in \mathcal{X}(x^0)$$

p_i^- **minimum** active power injection at *each* node:

$$p^-(x^0) = \arg\min_p \sum_{i=1}^{N} f_i(p_i)$$
$$\text{s.t. } p \in \mathcal{X}(x^0)$$

Theorem: If $p_i \in [p_i^-, p_i^+]\ \forall i \Rightarrow \underline{V} \leq V^-(p) \leq V(p) \leq V^+(p) \leq \overline{V}$

Proof is conditioned upon: *dV^+/dp, $dV^-/dp \geq 0$*



Monotonicity conditions:

More load → higher voltage

Less load → lower voltage

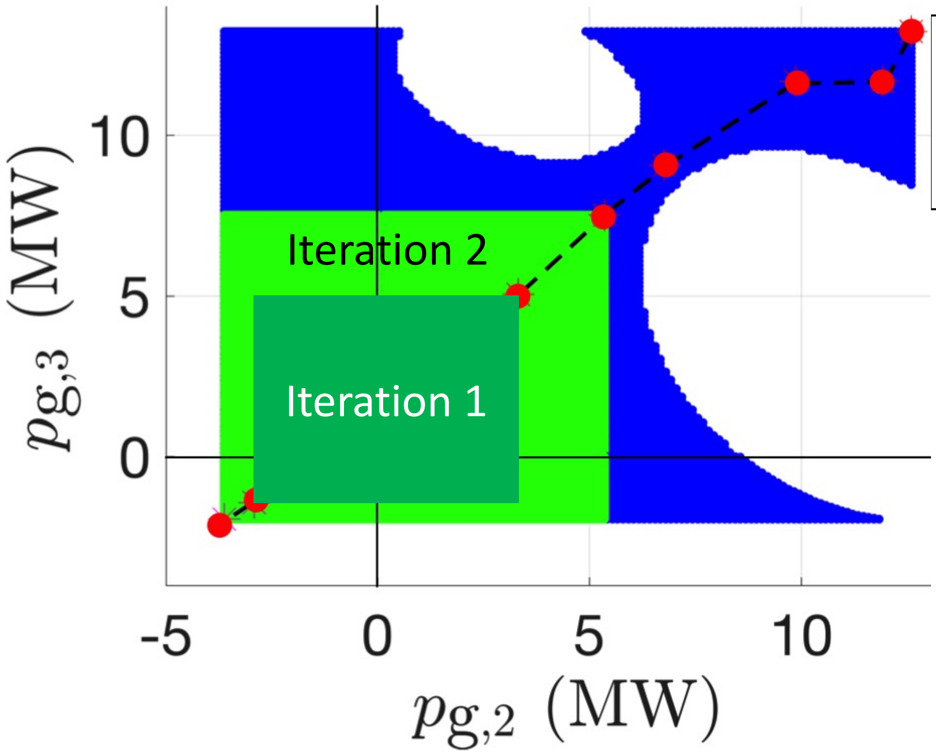
Bonus: *objective is feeder's hosting capacity!*

For mathematical proofs, please see:

Nawaf Nazir and Mads Almassalkhi. "*Grid-aware aggregation and realtime disaggregation of distributed energy resources in radial networks*." (Rev02)

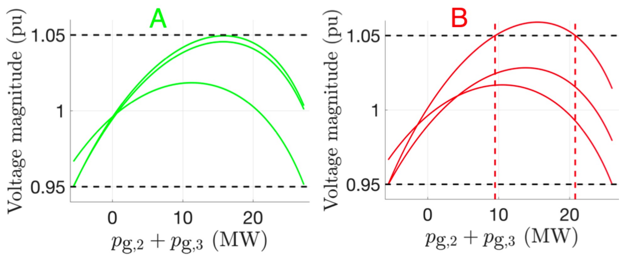
Algorithm for growing region

Requires coordination



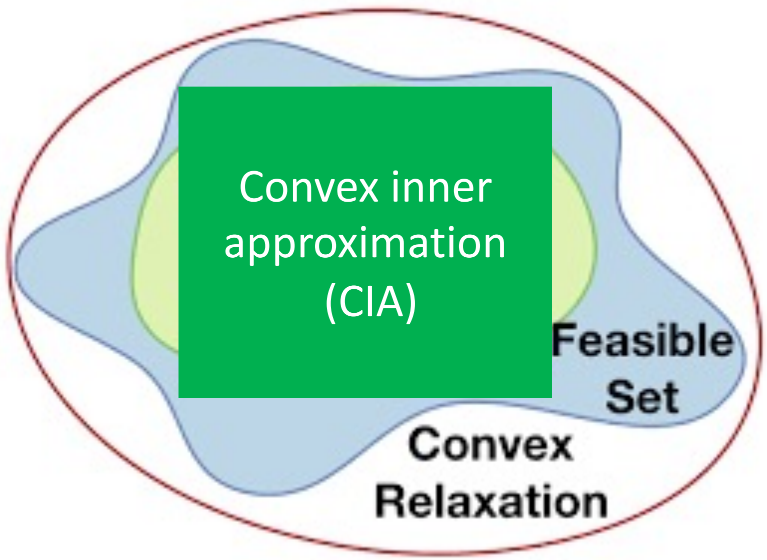
Blue injection pairs are admissible
White violates voltage constraints
Green satisfies monotonicity conditions
Red dots are feasible iterates

Example: after 2nd iteration, monotonicity conditions fail to hold and CIA is found.



Note: for iterations ≥ 3, coordination is required (along piecewise affine path)

What about conservativeness?



Original Image source: D. Lee, H. D. Nguyen, K. Dvijotham and K. Turitsyn, "Convex Restriction of Power Flow Feasibility Sets," in *IEEE Transactions on Control of Network Systems*, vol. 6, no. 3, pp. 1235-1245, Sept. 2019.

Comparing hosting capacity results*

System	CIA (MW)	NLP (MW)	CR (MW)
13-node	[-1.5, 9.1]	[-1.5, 9.7]	[-1.5, 12]
37-node	[-2.7, 5.3]	[-2.7, 5.3]	[-2.7, 16]
123-node	[-4.5, 13.9]	[-4.5, 14]	[-4.5, 24]

Convex relaxation (CR) over-estimates maximum reactive power capability

Nonlinear (NLP) has no optimality guarantees AND does not guarantee that entire range is admissible (i.e., no holes)

Proposed (CIA) method is **<u>not overly conservative</u>** and entire range is admissible

*Nawaf Nazir and Mads Almassalkhi. "*Grid-aware aggregation and realtime disaggregation of distributed energy resources in radial networks*." (Rev02)

What about existence of solution?

Leverage sufficient conditions from [*] in two ways:

- At each iteration, verify existence of (new) operating point *x_0* with explicit test condition
- Augment CIA formulation with *N* linear inequalities and *N* SOC constraints (still convex)

$$\boxed{\begin{aligned} &\sum_{j=1}^{N} t_{ij} < \chi \quad \forall i = 1,\dots,N \\ &\left\| \begin{bmatrix} a_{ij}^{\mathrm{w}} & b_{ij}^{\mathrm{w}} \\ b_{ij}^{\mathrm{w}} & -a_{ij}^{\mathrm{w}} \end{bmatrix} \begin{bmatrix} p_{\mathrm{g},j} \\ q_{\mathrm{g},j} \end{bmatrix} \right\|_2 \leq t_{ij} \quad \forall j = 1,\dots,N. \end{aligned} \qquad \text{(C3)}}$$

Added conservativeness from existence guarantees: *small impact*

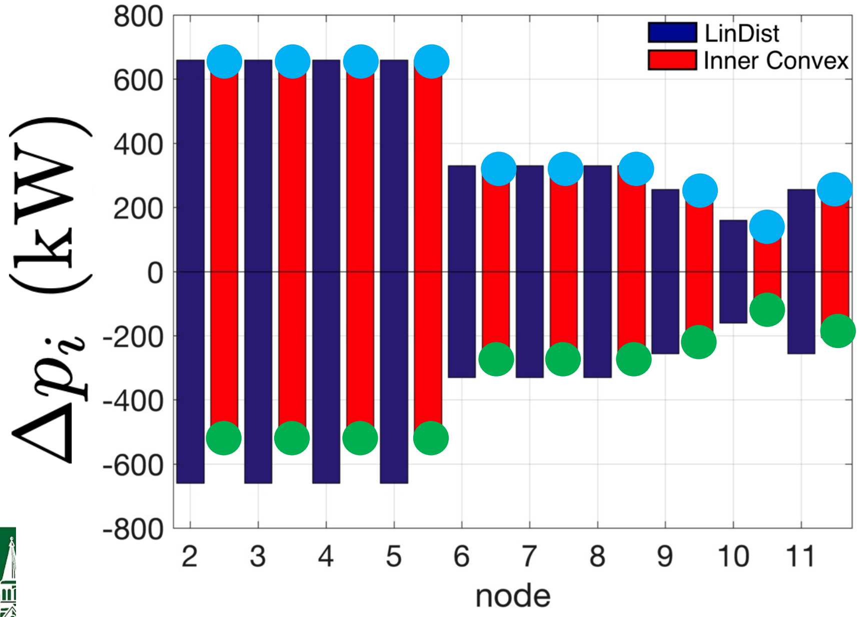
Type	13-node	37-node	123-node
Without C3 (MW)	[-1.5, 9.1]	[-2.7, 5.3]	[-4.5, 13.9]
With C3 (MW)	[-1.5, 8.8]	[-2.7, 5.3]	[-4.5, 13.8]

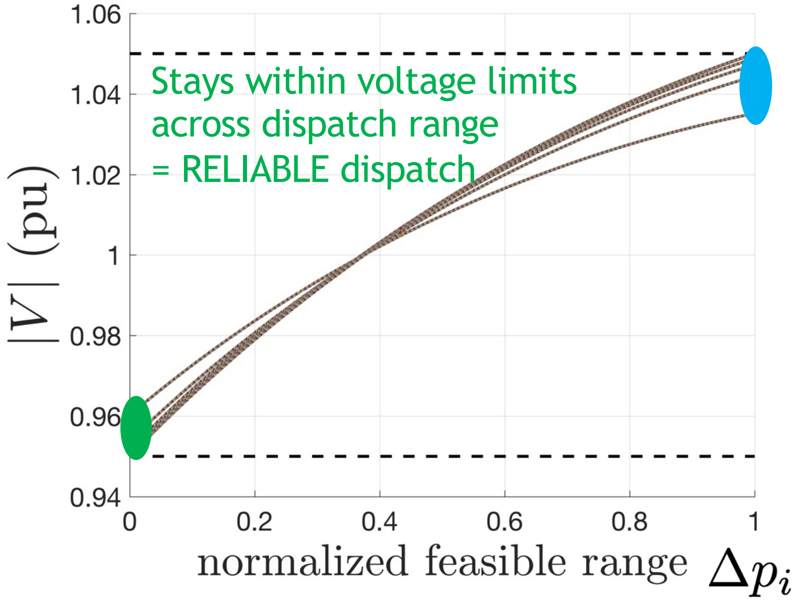
[*] C.Wang, A.Bernstein, J.LeBoudec, and M.Paolone,"*Explicit conditions on existence and uniqueness of load-flow solutions in distribution networks,*" *IEEE Transactions on Smart Grid*, vol. 9, no. 2, pp. 953–962, 2018.

When found, inner approximations offer guarantees

- Consider flexible resources on 10 nodes in a small network: a *10-dimensional hypercube*

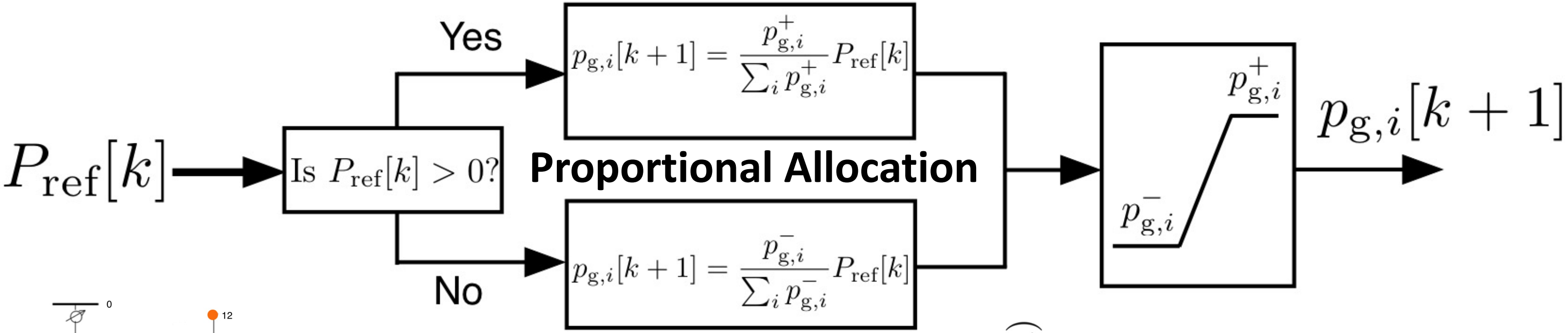
$$\Delta p_i := [p_i^-, p_i^+]$$

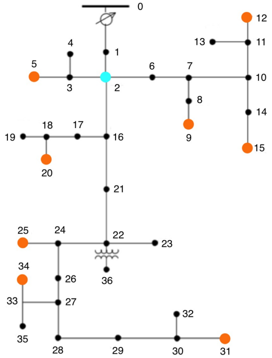




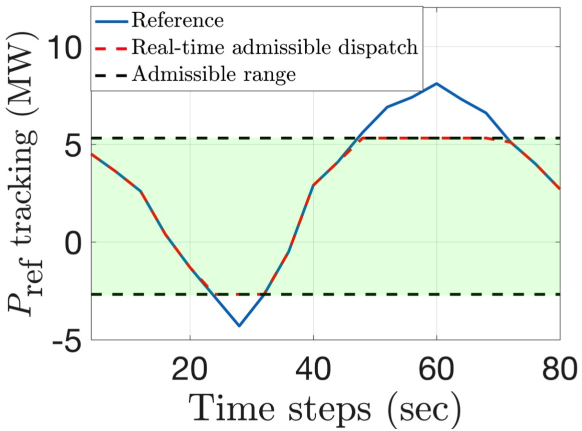
Can now do disaggregation in realtime

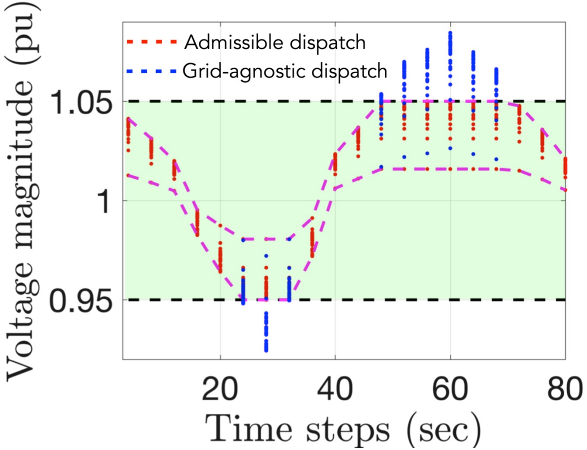
Nodal hosting capacities $[p_i^-, p_i^+]$ enable an open-loop, distributed, and **grid-aware DER control policy**





IEEE 37-node network
(from Baker/Dall'Anese)

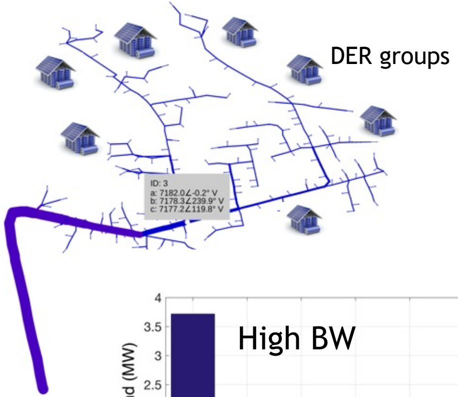


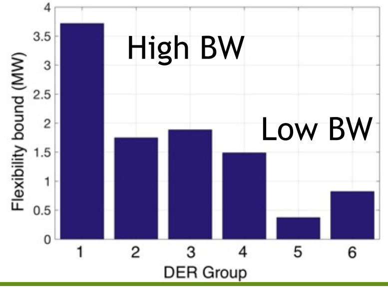


For details and other case studies, please see:
N. Nazir and M. Almassalkhi, "*Convex inner approximation of the feeder hosting capacity limits on dispatchable demand,*" IEEE Conference on Decision and Control (CDC), 2019.
-, "*Grid-aware aggregation and realtime disaggregation of distributed energy resources in radial networks*", under review in IEEE Transactions on Power Systems (Rev02), 2021

Putting it all together

Utility (grid information/data)
- Needs to ensure grid reliability
- Wants to protect grid data
- Lack direct access to devices
- Knows grid availability





Fundamental *asymmetries* in information & control

Aggregators (device control)
- Needs to ensure device QoS
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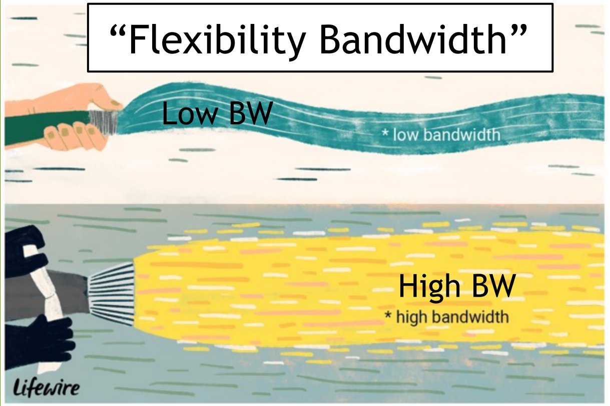

Future direction

- Consider wind farm collector networks and reactive power capability of network
- Extend to market context with multiple aggregators within DSO network
- Study extension to unbalanced and meshed networks
- Consider role of feedback and available measurements/data for aggregators

Thank you! Questions/comments?

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