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CHARACTERIZING THE REACTIVE POWER CAPABILITY OF WIND FARM COLLECTOR NETWORKS

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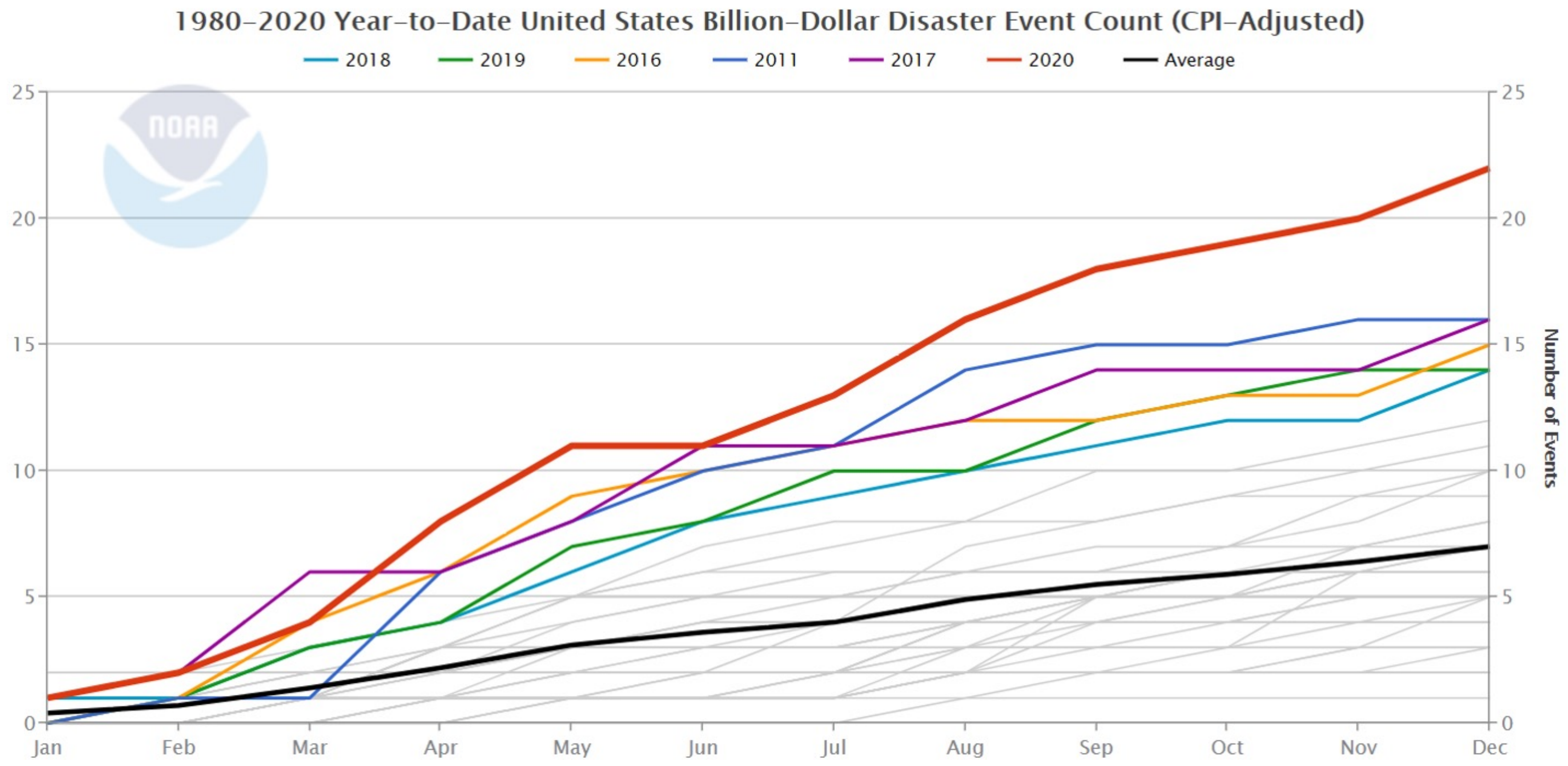
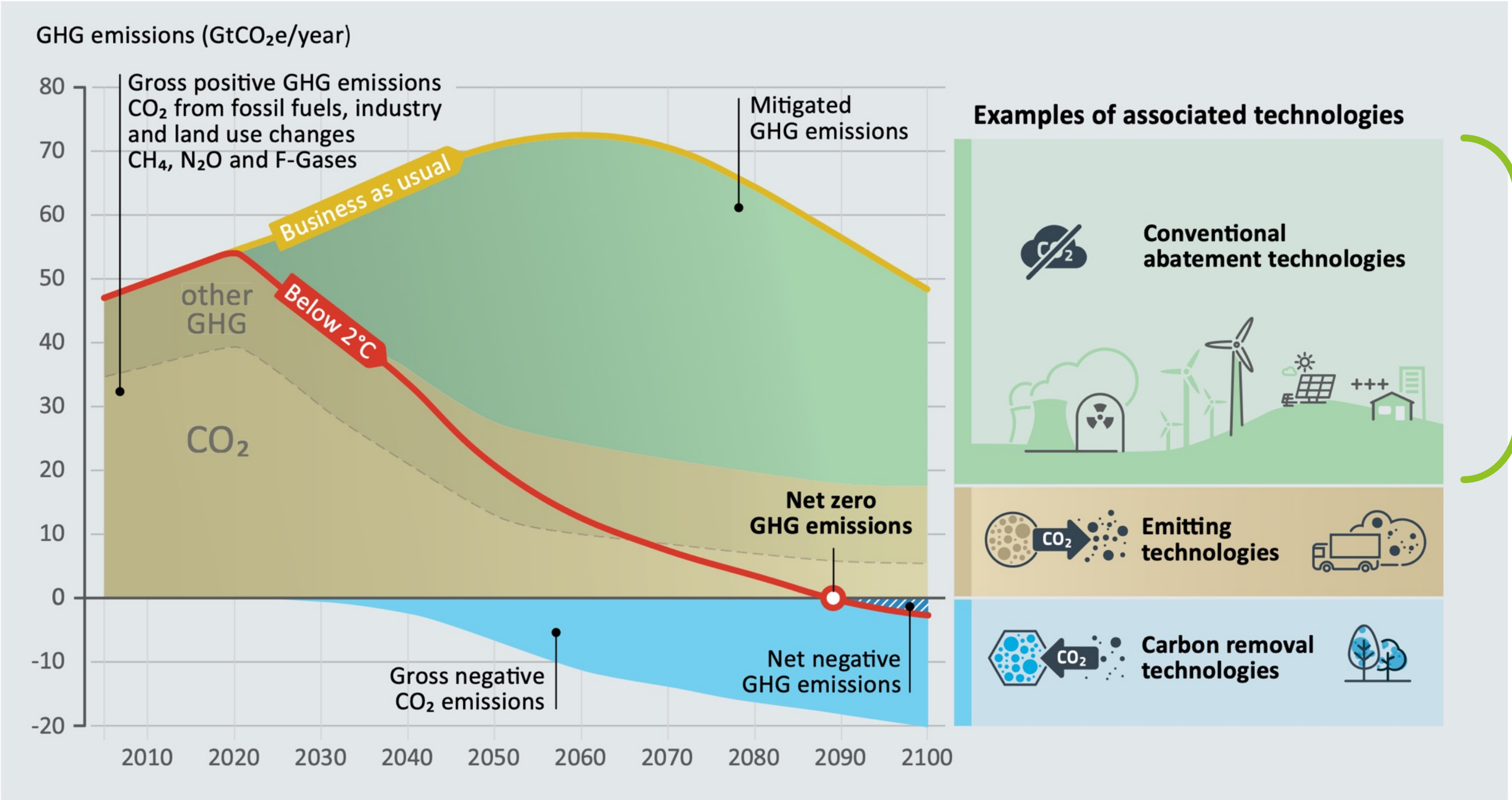
Climate challenges are real



NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2020)

Solutions? If they work, they will matter!



Requires massive TW-scale renewable integration

A massive power systems problem!

UN Environmental Program, Emission Gap Report 2017 (Chapter 7)

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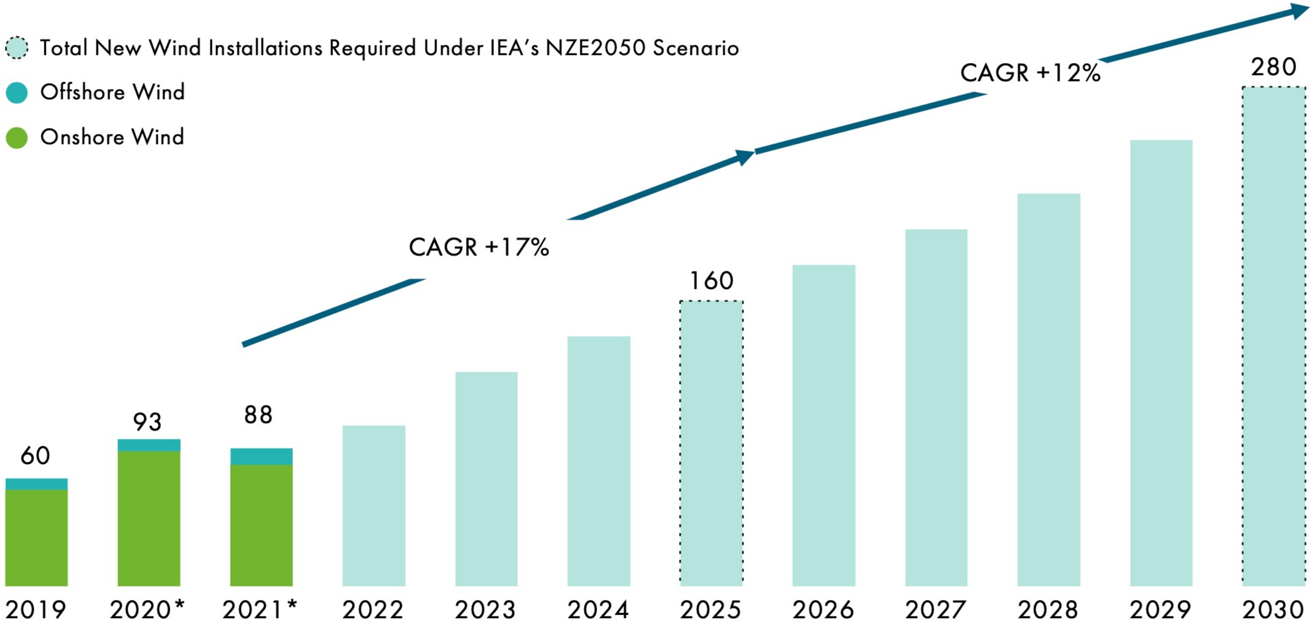
The answer is blowing in the wind…

Source: wikipedia

Annual wind installations must increase dramatically to reach net zero by 2050

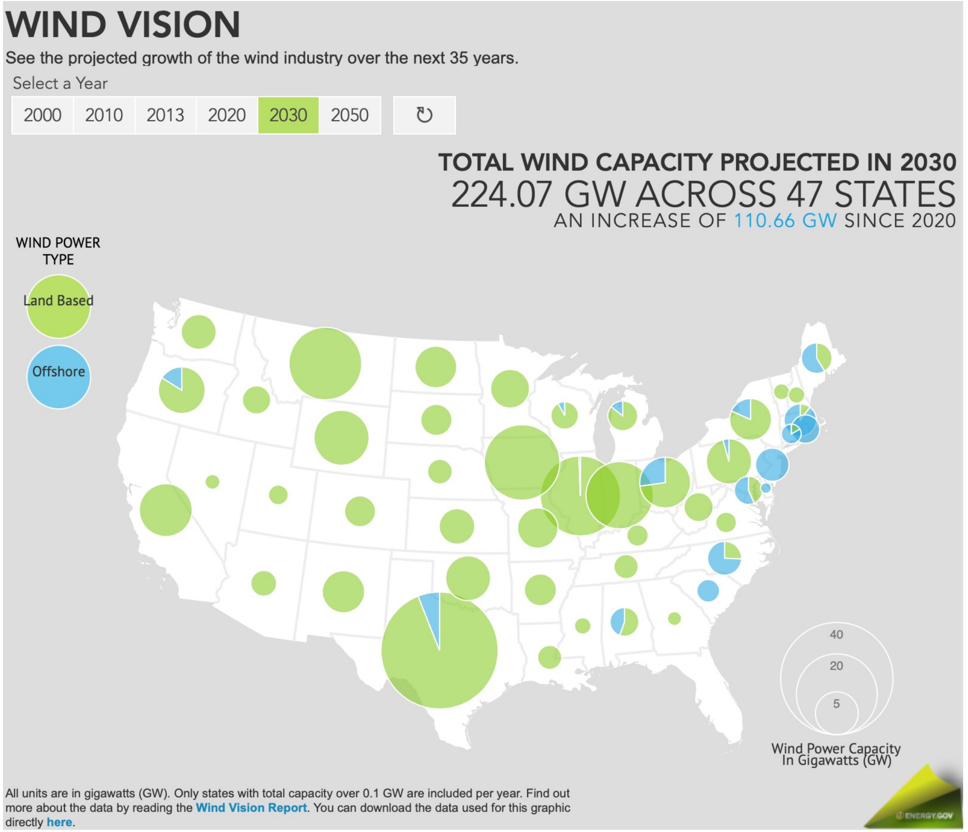
New global wind installations (GW)



Source: GWEC Market Intelligence; IEA World Energy Outlook (2020), volume in 2022-2024 and 2026-2029 are estimates

The answer is blowing in the wind…

Source: wikipedia



Source: https://www.energy.gov/eere/wind/wind-vision

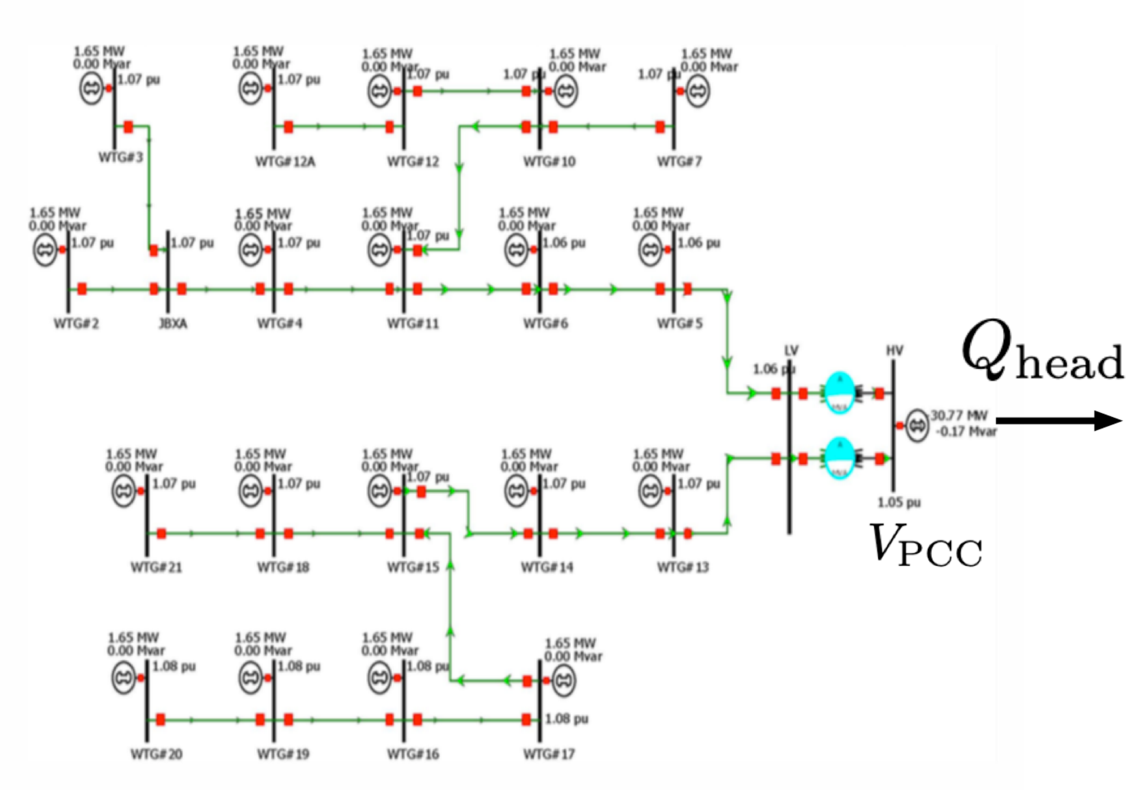
US will double its wind capacity between 2020 and 2030

More wind generation, more reliability issues

- Wind farms must take an active role in regulate voltage at interconnection points with transmission systems

- Reactive power support from wind farm networks is important for reliability.

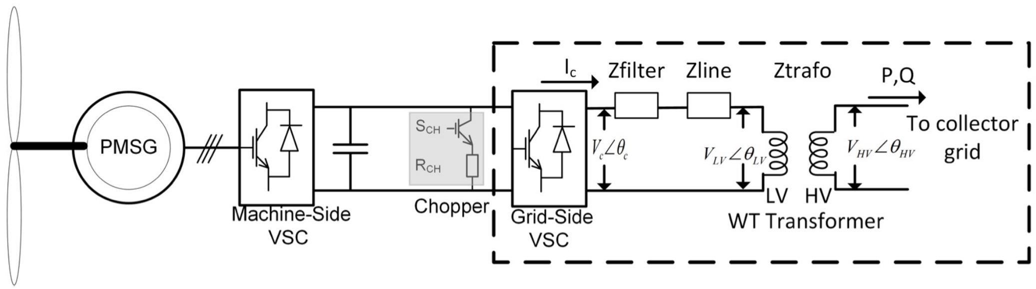
- **Question:** How much reactive power support can a wind farm offer?

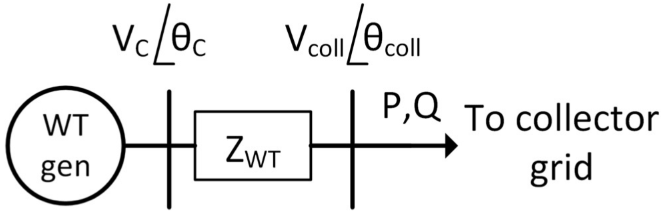


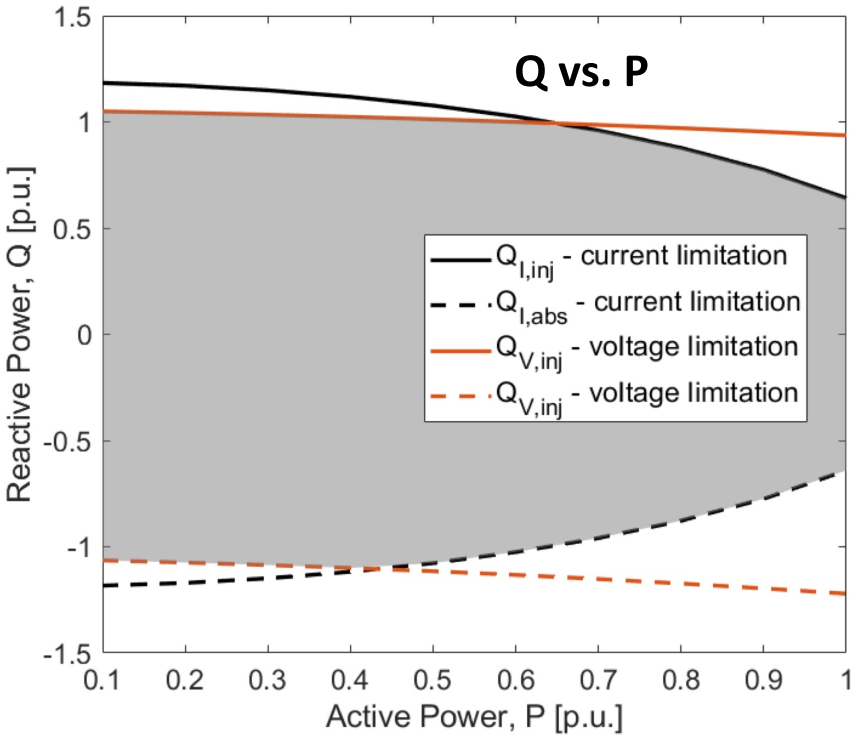
Reactive power capability of a single WT

- We understand reactive power support from a single WT well

Type 4 WT with its single-line diagram & reactive power capability:







Source of images: Sarkar, M., Altin, M., Sørensen, P. E., & Hansen, A. D. (2019). Reactive Power Capability Model of Wind Power Plant Using Aggregated Wind Power Collection System. *Energies*, *12*(9), [en12091607]. https://doi.org/10.3390/en12091607

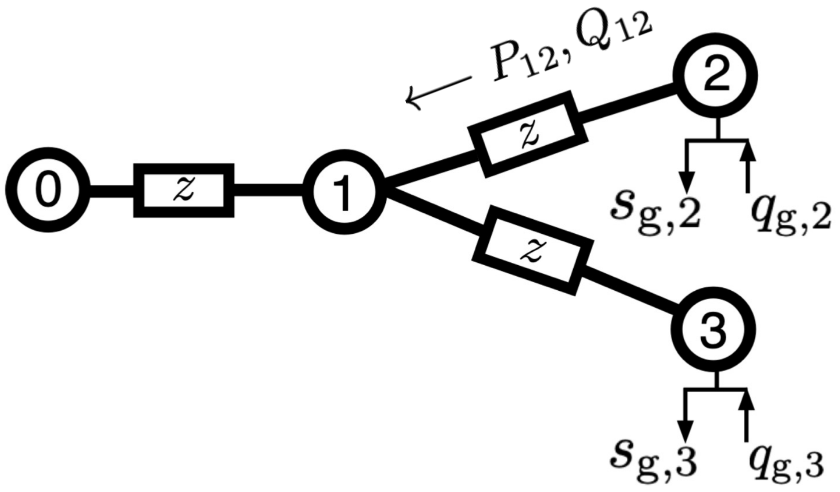
Reactive power capability of a wind farm

- Simple idea: just aggregate reactive power capability curves from *N* WTs
  – Overestimates reactive power support from wind farm due to network constraints
    - Protection systems will automatically limit reactive power when network limits are reached

- A better idea
  – Explicitly consider the wind farm collector network and AC physics and find *maximum reactive power injection limits* for given active power generation
    - **Technical challenge**: this is a nonconvex optimization problem (NP-hard)

Reactive power capability of a wind farm

- Simple 3-node, 2-WT collector network represented by *DistFlow* model:



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

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

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

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

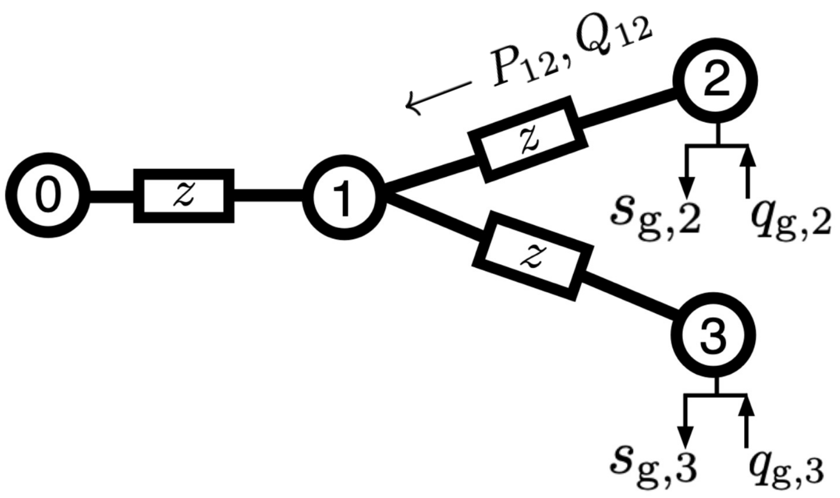
$$l_{ij}(P_{ij}, Q_{ij}, v_j) = \frac{P_{ij}^2 + Q_{ij}^2}{v_j},$$

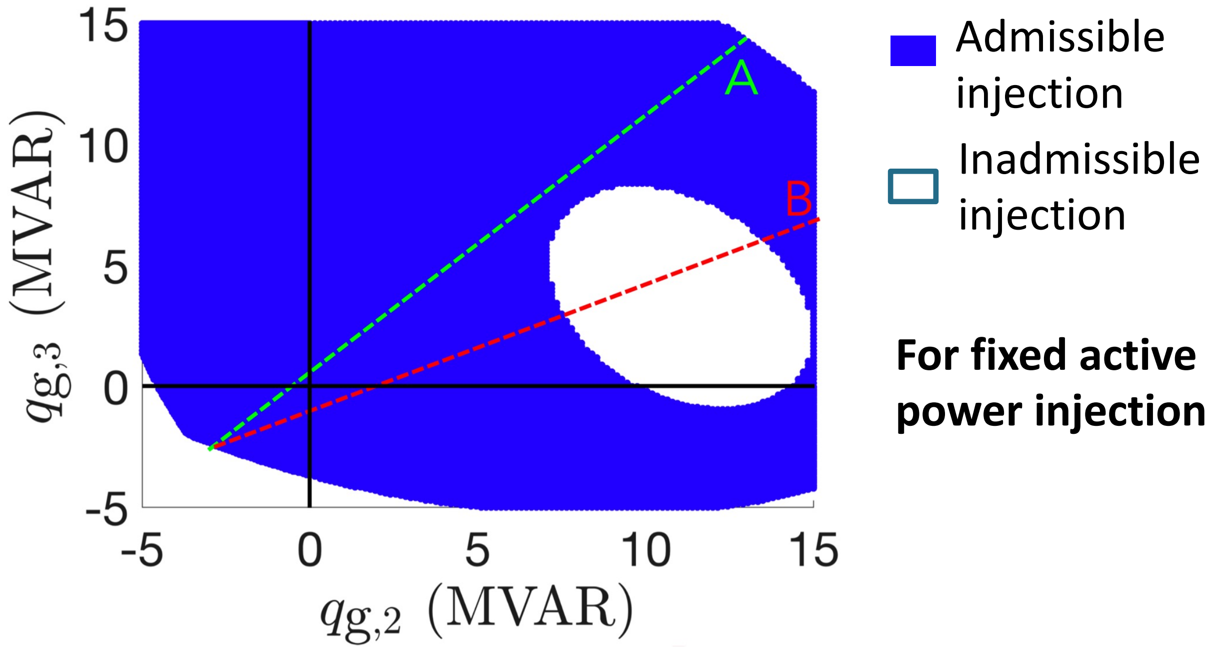
The only non-convex constraint

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

Reactive power capability of a wind farm

- Simple 3-node, 2-WT collector network represented by *DistFlow* model:





For fixed active power injection

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

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Reactive power capability of a wind farm

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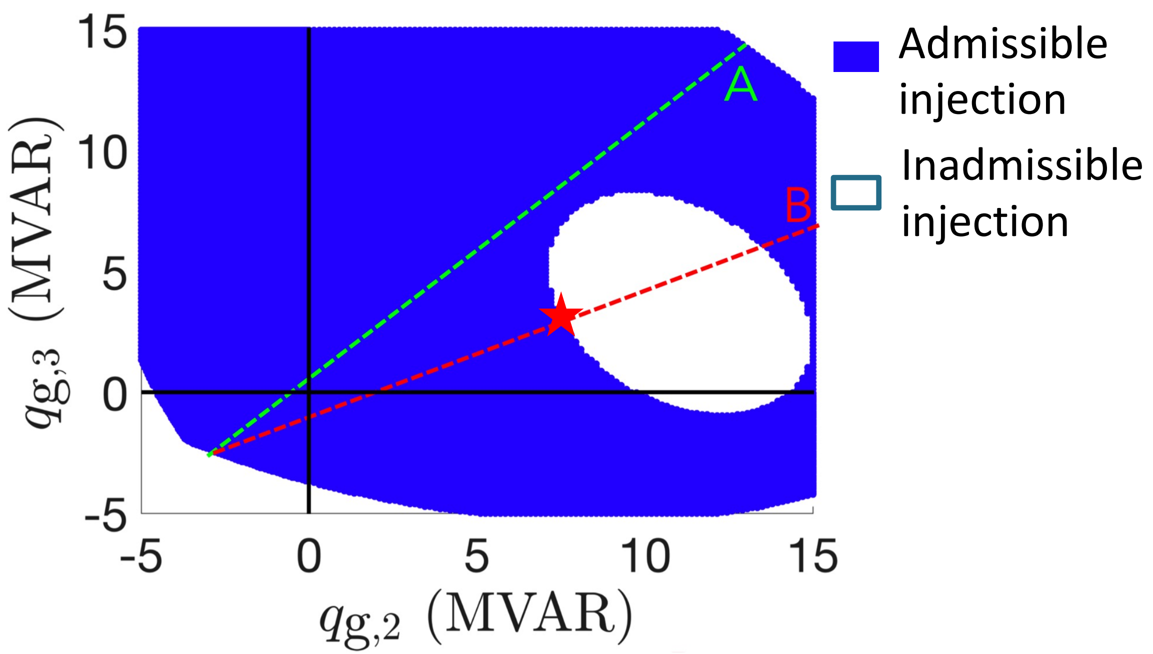

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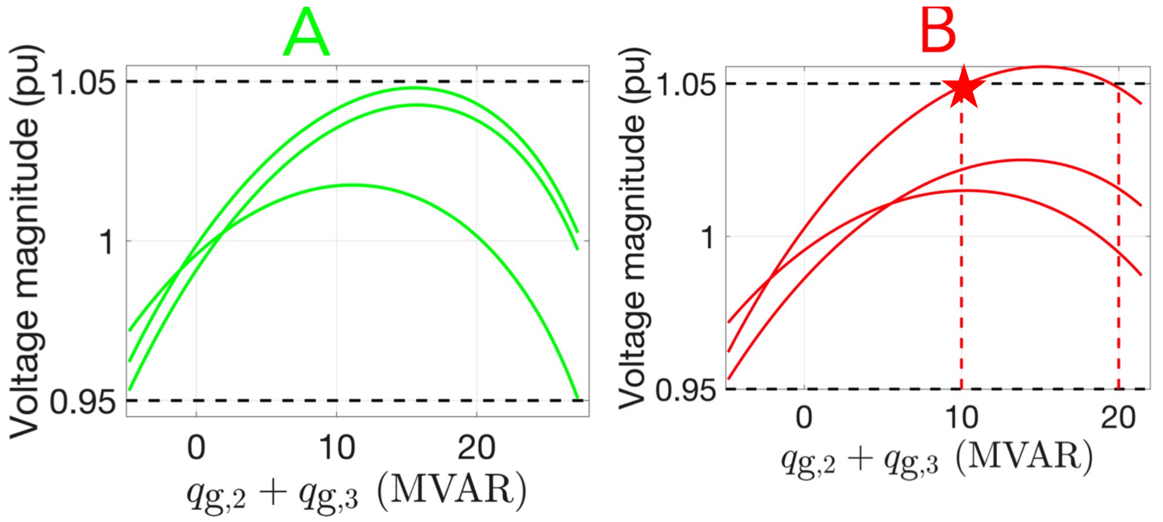
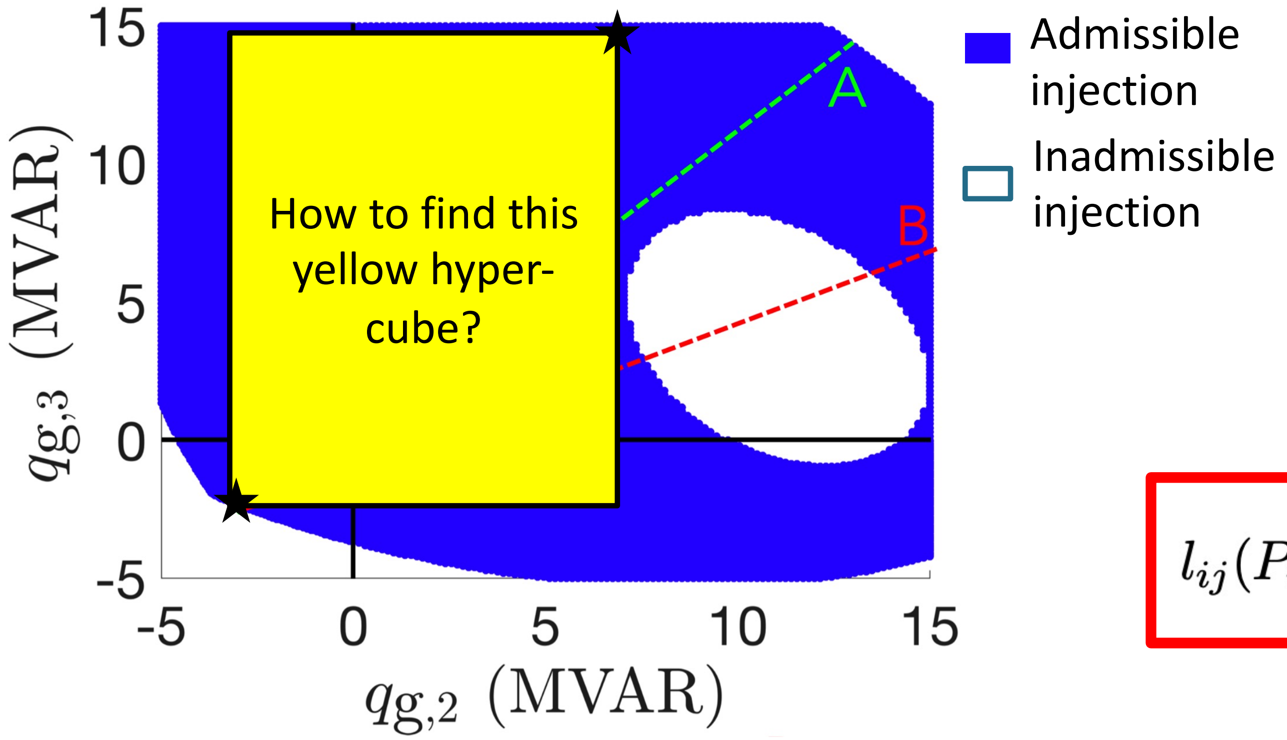


The two WTs reactive power outputs are limited in aggregate by the network – i.e., their individual limits are coupled

Reactive power capability of a wind farm

- **Goal**: find largest rectangle to get Q-limits for each WT (decouple)



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

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

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

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

Idea: replace non-convex constraint with a convex envelope

Convex inner approximation via proxy variables

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

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

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

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

we can construct a 2nd order Taylor-series expansion:

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

and from this model, we can use proxy vars to **explicitly** define upper and lower bounds

Convex inner approximation via proxy variables

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

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

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

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*." (Under review, IEEE Transactions, Rev 02).

Convex inner approximation via proxy variables

$$P^+ := Cp - D_\mathrm{R} l_\mathrm{lb}$$
$$P^- := Cp - D_\mathrm{R} l_\mathrm{ub}$$
$$Q^+ := Cq - D_{\mathrm{X}_+} l_\mathrm{lb} - D_{\mathrm{X}_-} l_\mathrm{ub}$$
$$Q^- := Cq - D_{\mathrm{X}_+} l_\mathrm{ub} - D_{\mathrm{X}_-} l_\mathrm{lb}$$
$$V^+ := v_0 \mathbf{1}_n + M_\mathrm{p} p + M_\mathrm{q} q - H_+ l_\mathrm{lb} - H_- l_\mathrm{ub}$$
$$V^- := v_0 \mathbf{1}_n + M_\mathrm{p} p + M_\mathrm{q} q - H_+ l_\mathrm{ub} - H_- l_\mathrm{lb}$$
$$0 \leq l_{\mathrm{lb},ij} := f_{\mathrm{lb},ij}(P_{ij}^-, Q_{ij}^-, v_j^-, P_{ij}^+, Q_{ij}^+, v_j^+, x_{ij}^0)$$

Current limits $$f_{\mathrm{ub},ij}(P_{ij}^-, Q_{ij}^-, v_j^-, P_{ij}^+, Q_{ij}^+, v_j^+, x_{ij}^0) \leq l_{\mathrm{ub},ij} \leq \bar{l}_{ij}$$

Voltage limits $$\underline{V} \leq V^-, \quad V^+ \leq \bar{V}$$

WT reactive power limits $$\underline{q}_i \leq q_i \leq \bar{q}_i$$

Feasible set of convex inner approximation $\mathcal{X}(x^0)$ **is convex**

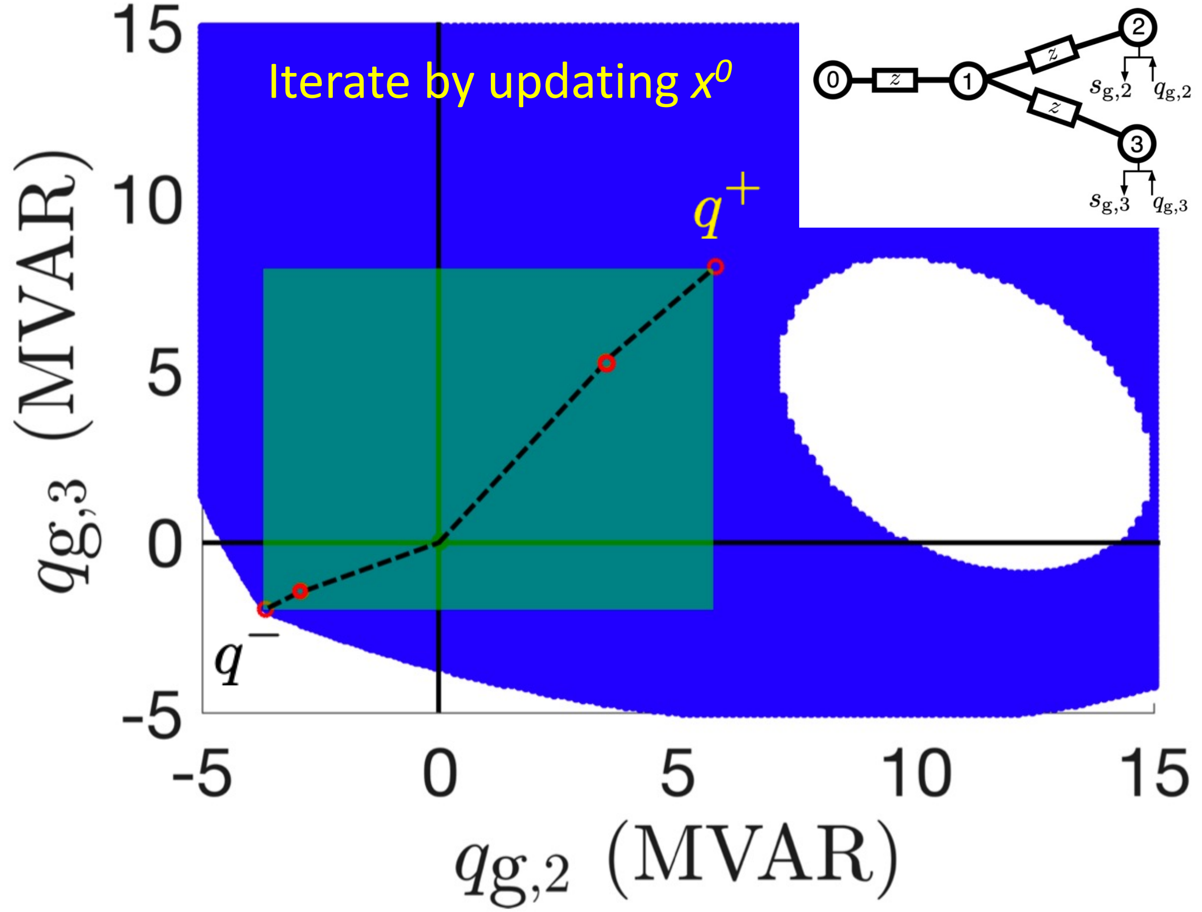
Find network's reactive power capability

q_i^+ **maximum** reactive power limits at *each* WT, where

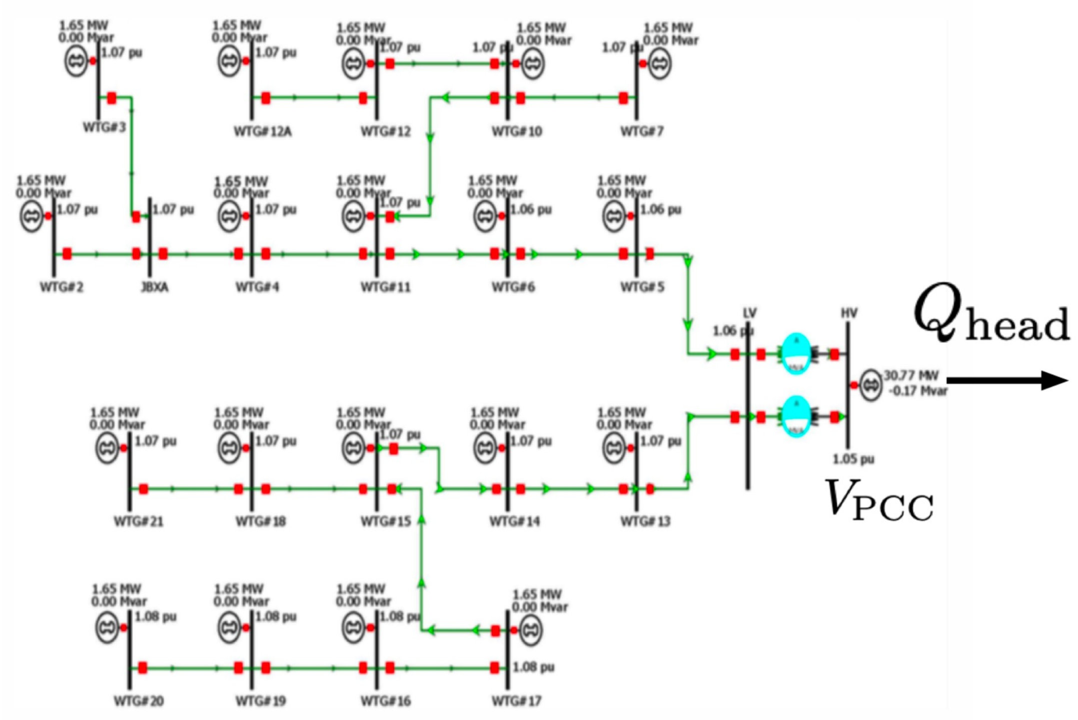
$$q^+(x^0) = \arg\max_q \; Q_{10}^- \quad \text{s.t. } q \in \mathcal{X}(x^0)$$

q_i^- **minimum** reactive power limit at *each* WT, where

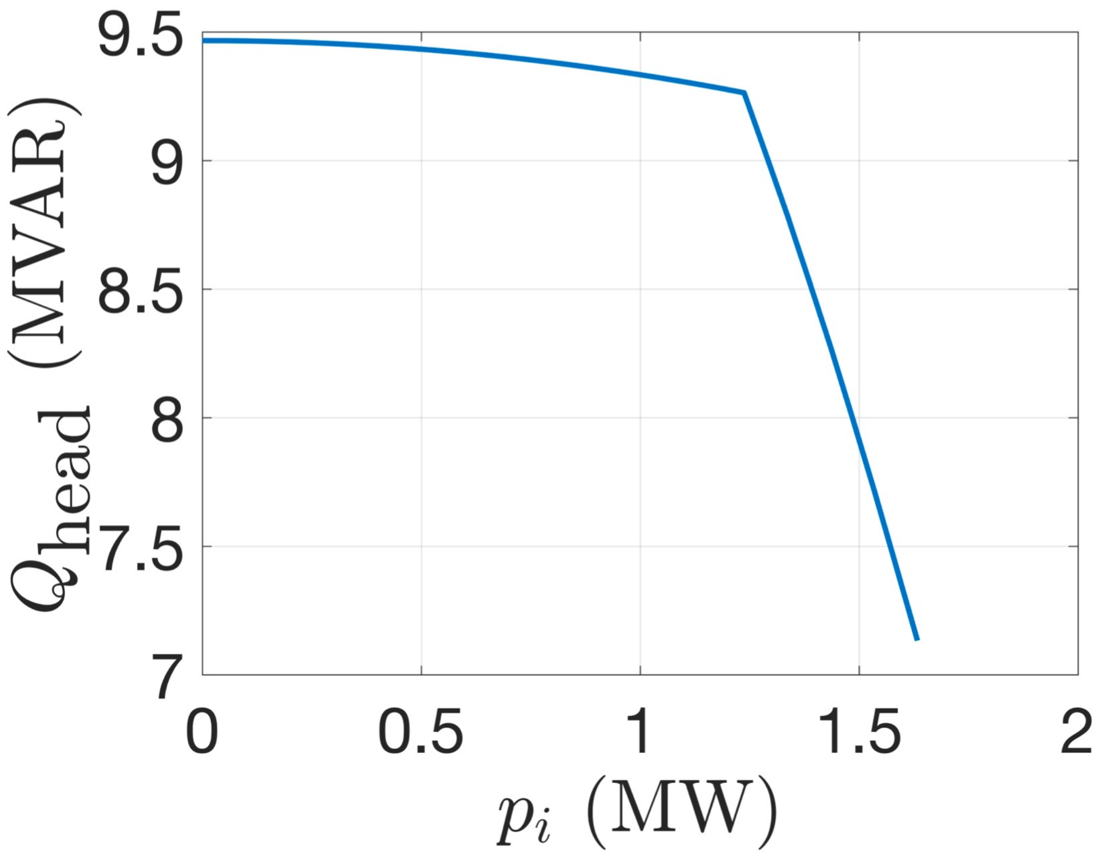
$$q^-(x^0) = \arg\min_q \; Q_{10}^+ \quad \text{s.t. } q \in \mathcal{X}(x^0)$$



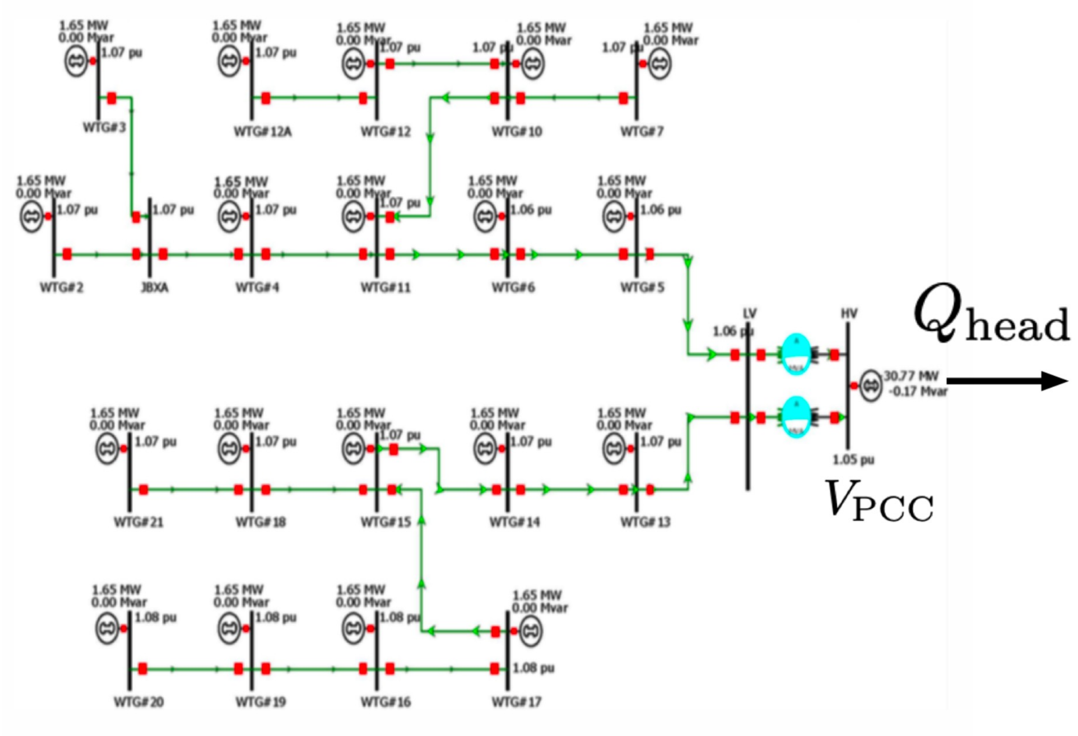
Finding network's reactive power capability



Farm has 19 WTs. Each turbine is rated at 1.65MW, [-0.5, 0.5] MVAr

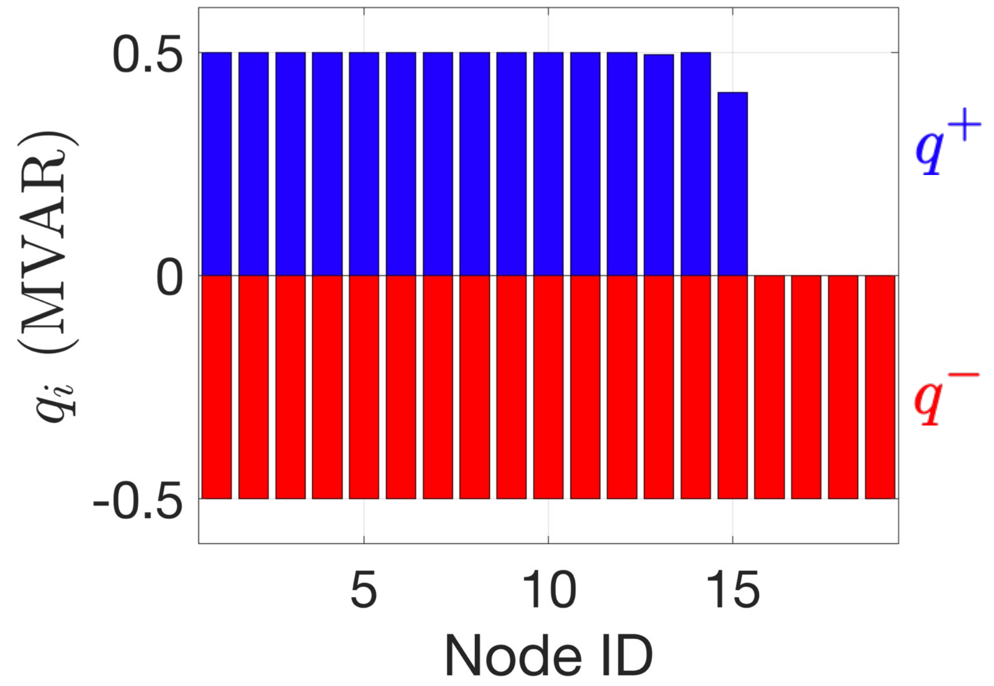


Finding network's reactive power capability

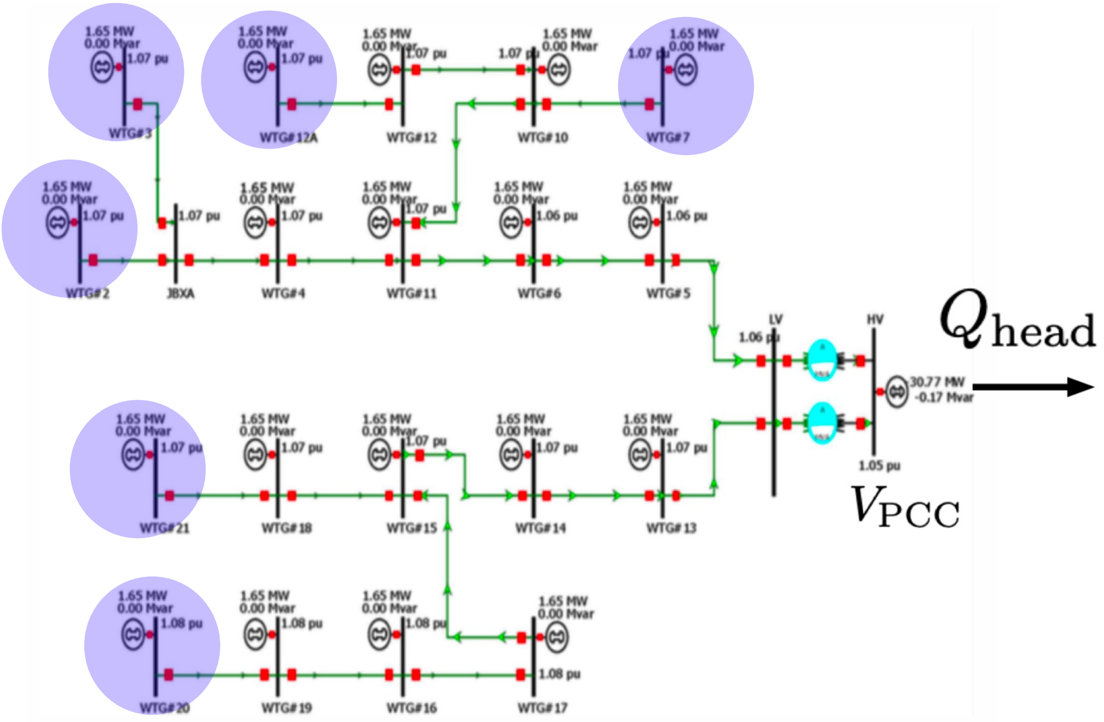


Farm has 19 WTs. Each turbine is rated at 1.65MW, [-0.5, 0.5] MVAr

Scenario 1: all WTs at rated active power

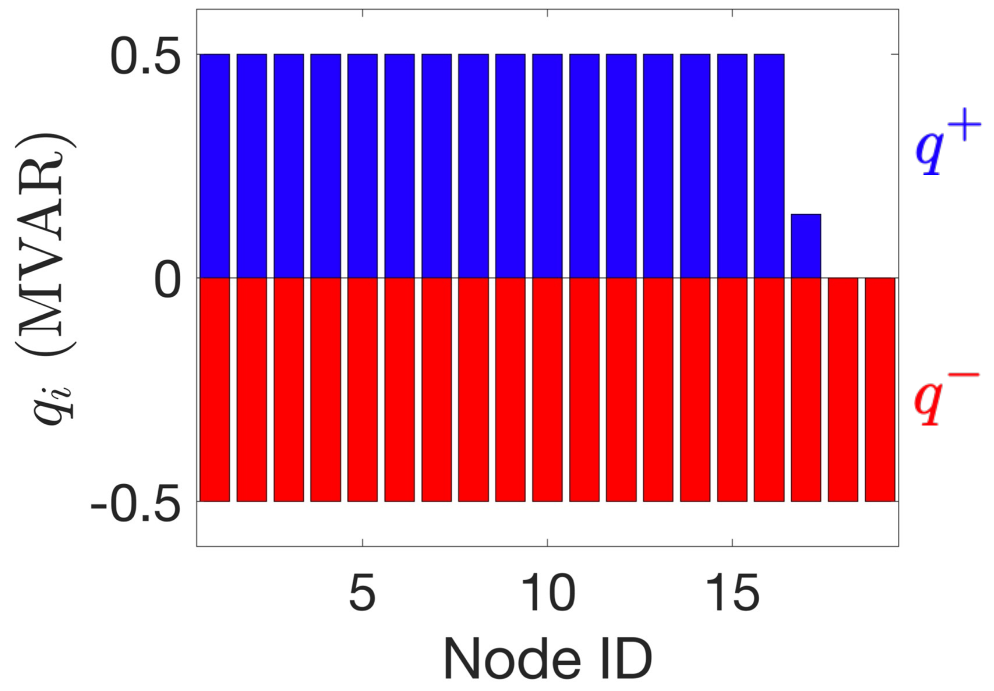


Finding network's reactive power capability

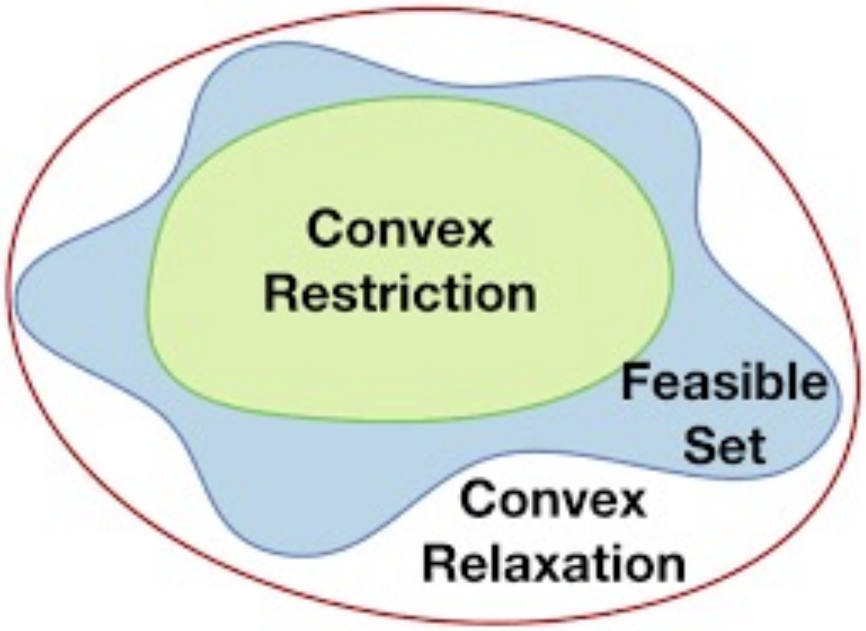


Farm has 19 WTs. Each turbine is rated at 1.65MW, [-0.5, 0.5] MVAr

Scenario 2: some WTs at rated power; rest 0



Is convex restriction overly conservative?



Scheme	Scenario 1	Scenario 2
CIA-based	[-9.9,7.0]	[-9.8,7.9]
Nonlinear	[-9.9,7.0]	[-9.8,7.9]
Relaxation	[-9.9,9.1]	[-9.8,9.3]

Relaxation over-estimates maximum reactive power capability (not surprising).
Nonlinear has no optimality guarantees AND does not guarantee that entire range is admissible (i.e., no holes)
Proposed CIA-based method is not overly conservative and formulation is convex (so range is admissible)

Next steps

- Design and test real-time network-aware WT controllers
- Study collector network topology vs. reactive power capability
- Compare methods with state-of-the-art
- Consider protection systems and real-world collector networks

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THANK YOU FOR ATTENDING!
QUESTIONS? COMMENTS?

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