# Distribution Network Security with Distributed Energy Resource Aggregators

**Subhonmesh Bose**

Department of Electrical and Computer Engineering

Coordinated Science Laboratory

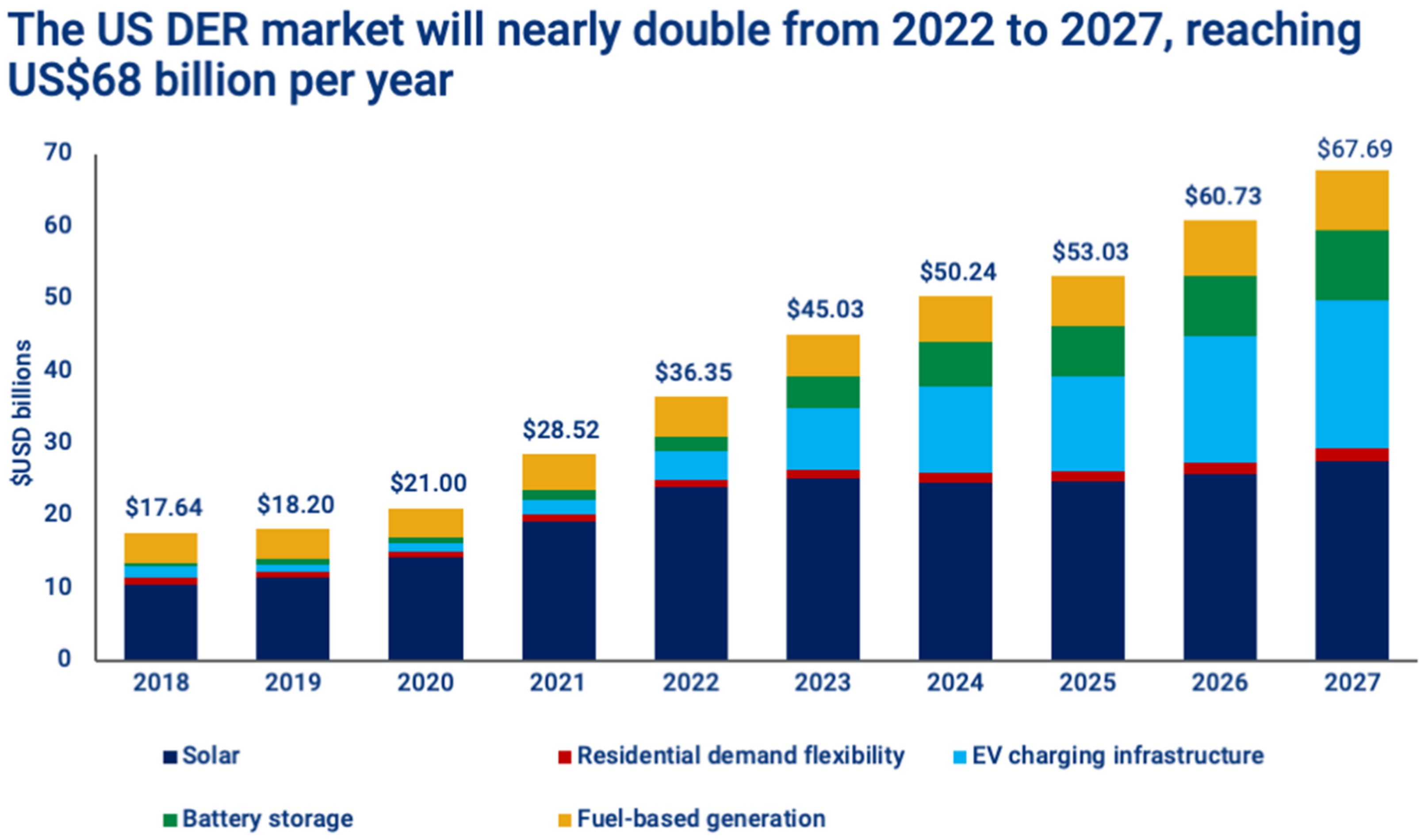
University of Illinois Urbana-Champaign

Joint work with C. Chen (Cornell), A. N. Madavan (UIUC),
N. Dahlin (U. Albany), L. Tong (Cornell)

# The Emerging Landscape of Distributed Energy Resources (DERs)

Distributed solar, storage, EV infrastructure, demand management, etc.

Driving forces: FERC Orders 745, 841, 841-A, culminating in FERC Order 2222 in 2020.




Source: Wood Mackenzie Grid Edge, US Distributed Solar and Energy Storage Service

A complex marketplace with DER owner-operators, DER aggregators (DERAs), distribution utility, possibly a distribution system operator (DSO) and the transmission system operator (TSO).

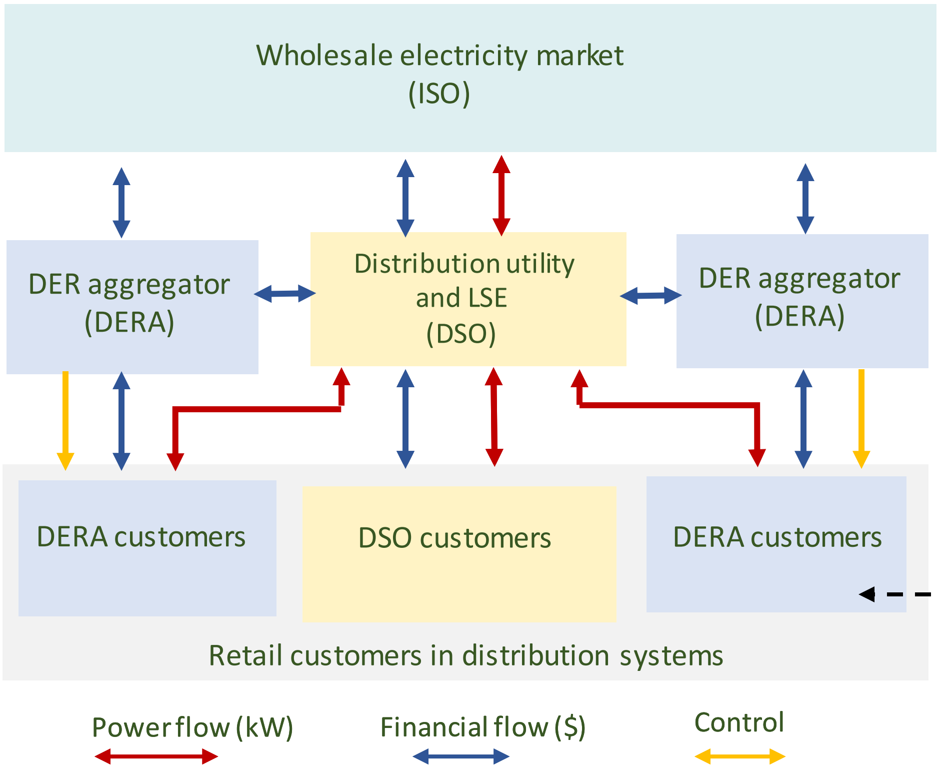
# Ensuring Distribution Network Security

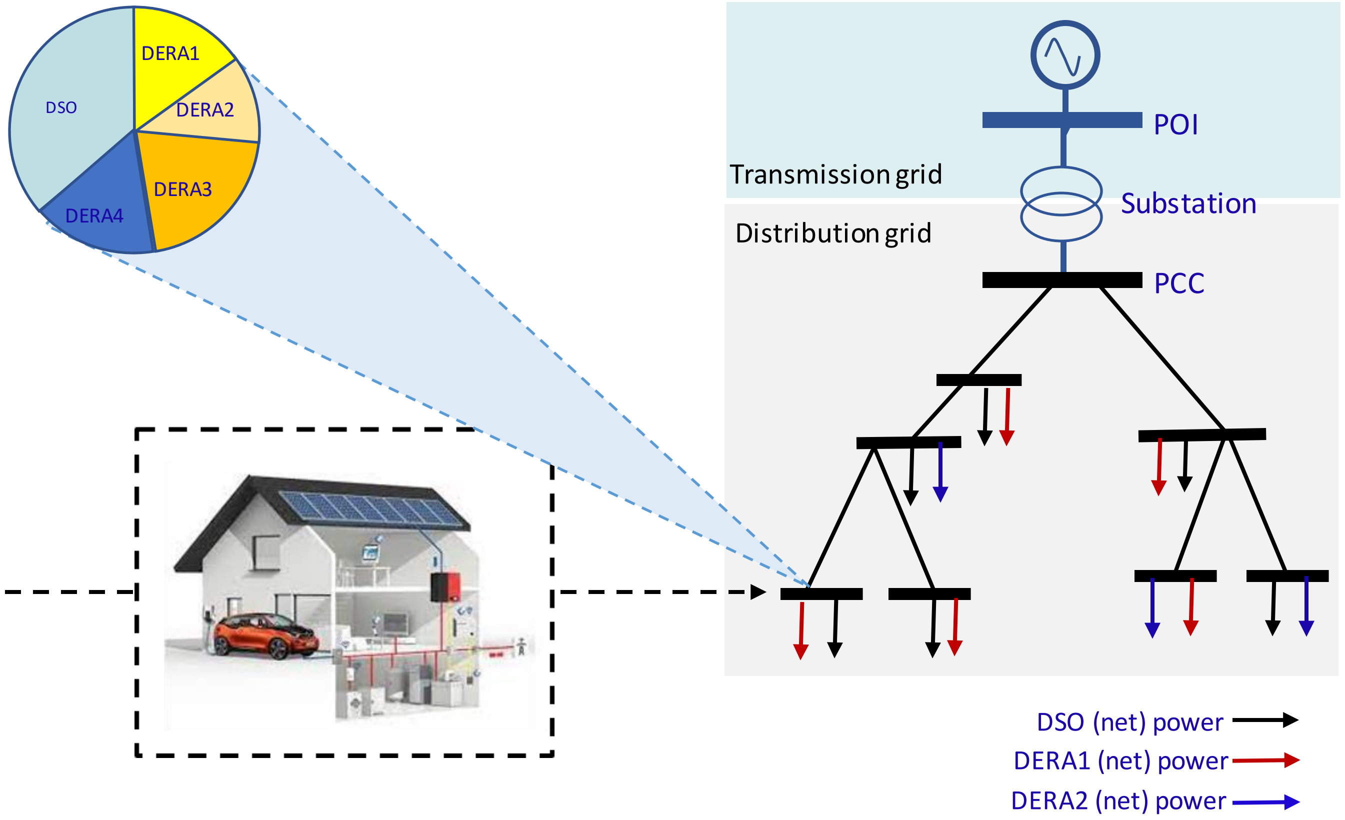
Voltage limits
Power flow limits

| Type I | Type II | Type III | Type IV |
|---|---|---|---|
| Limit Hosting Capacity | Limit Network Access | Local Energy Market | Command and Control |

*…this talk*

Increasing levels of DSO's control



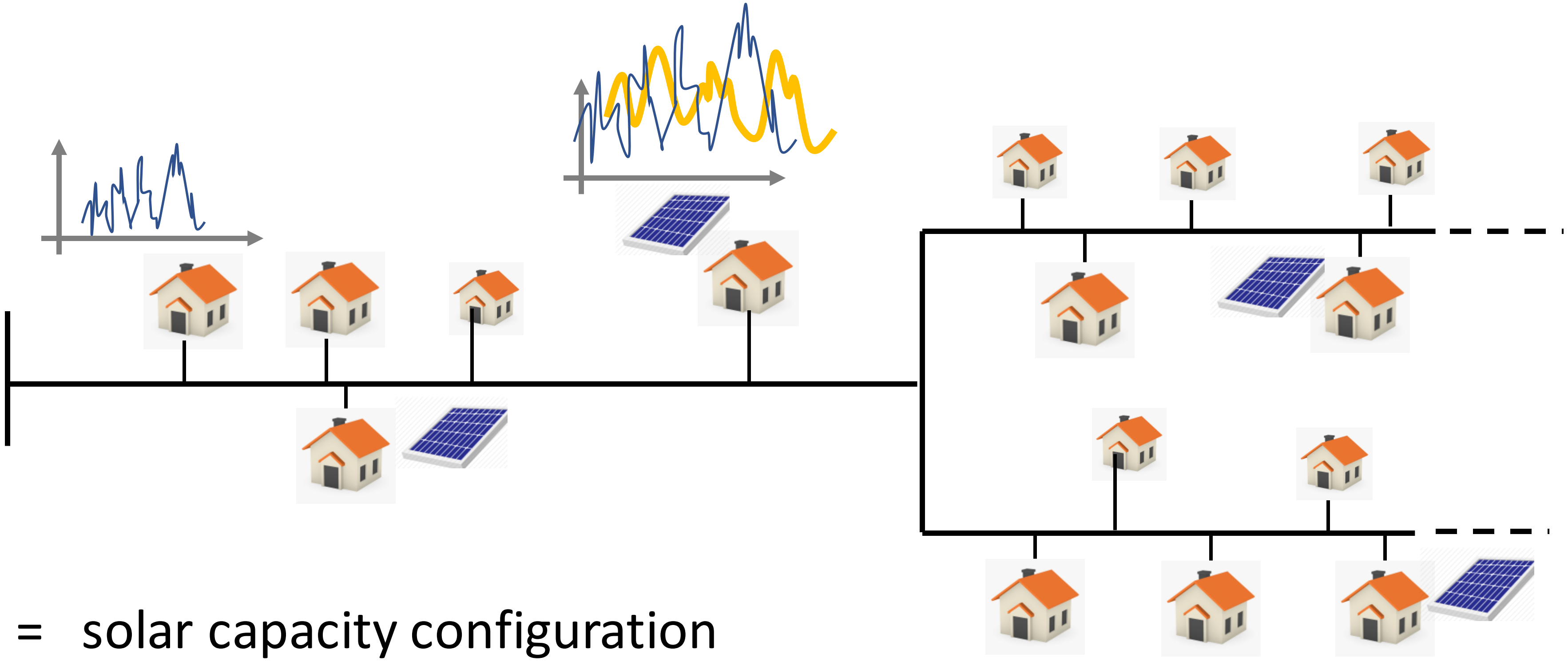
| Type I | Type II | Type III | Type IV |
|---|---|---|---|
| Limit Hosting Capacity | Limit Network Access | Local Energy Market | Command and Control |

# The Hosting Capacity Problem

Risk-Based Hosting Capacity Analysis in Distribution Systems
A. N. Madavan, N. Dahlin, S. Bose, and L. Tong
IEEE Transactions on Power Systems, 39.1, 355-36 (2024)

# The Hosting Capacity Problem

$\Omega$ = scenarios of solar irradiance and loads



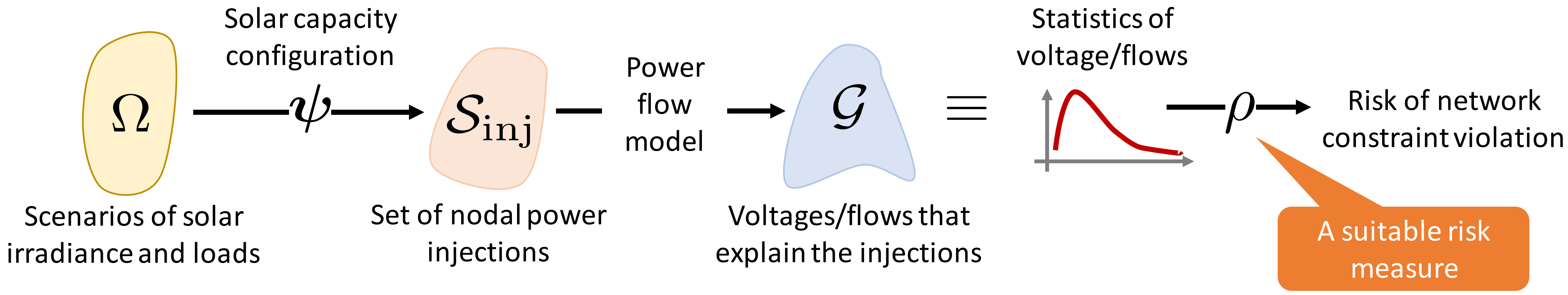
$\psi$ = solar capacity configuration

$\Omega$ = scenarios of solar irradiance and loads

$\psi$ = solar capacity configuration

# The Hosting Capacity Problem

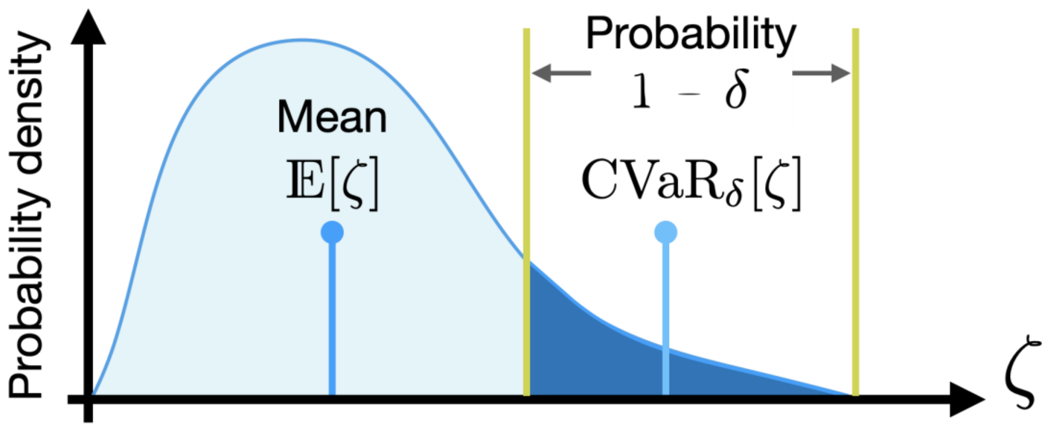
Can the distribution network host a solar capacity configuration, given the scenarios of solar irradiance and loads? Are the risks of constraint violation acceptable?




Q1. Does a capacity configuration have acceptable risks of constraint violation?

Q2. Maximize total installed capacity among acceptable configurations.

# $\rho$ … the risk measure: Conditional Value at Risk (CVaR)




For losses with continuous distributions, conditional value at risk with parameter $\delta$ measures the expected tail loss in the worst $1-\delta$ fraction of the outcomes.

$$\text{CVaR}_\delta(\zeta) := \min_z \left\{ z + \frac{1}{1-\delta}\mathbb{E}[\zeta - z]^+ \right\}.$$

Rockafellar and Uryasev 2000, 2002

*…retains convexity of an underlying deterministic optimization problem*

*…allows the use of off-the-shelf solvers with convergence guarantees*

# The Questions

$\Omega$ = scenarios of solar irradiance and loads

$\psi$ = solar capacity configuration

Bus voltage magnitudes
Power flows over lines

Encode a constraint for a *particular* scenario $\omega \in \Omega$ in inequality constraints

$$g_i(\psi; \omega) \leq 0$$

Encode a constraint *across* scenarios in $\Omega$ via a risk-sensitive inequality constraint

$$\text{CVaR}_{\delta_i} \left[ g_i(\psi; \Omega) \right] \leq 0$$

Q1. Does a capacity configuration have acceptable risks of constraint violation?
Q2. Maximize total installed capacity among acceptable configurations.

# The Feasibility and the Optimization Problems

$$\boldsymbol{\alpha}(\omega) \odot \boldsymbol{\psi} - \boldsymbol{p}_D(\omega) = \overline{\boldsymbol{B}}^\top \boldsymbol{P}(\omega) + \boldsymbol{R} \odot \boldsymbol{L}(\omega) \quad \text{a.s.},$$
$$\boldsymbol{\eta}_G \odot \boldsymbol{\alpha}(\omega) \odot \boldsymbol{\psi} - \boldsymbol{q}_D(\omega) = \overline{\boldsymbol{B}}^\top \boldsymbol{Q}(\omega) + \boldsymbol{X} \odot \boldsymbol{L}(\omega) \quad \text{a.s.},$$
$$\boldsymbol{B}\boldsymbol{W}(\omega) = 2\left[\boldsymbol{R} \odot \boldsymbol{P}(\omega) + \boldsymbol{X} \odot \boldsymbol{Q}(\omega)\right] - \left(\boldsymbol{R}^2 + \boldsymbol{X}^2\right) \odot \boldsymbol{L}(\omega) \quad \text{a.s.},$$
$$[\boldsymbol{B}_+ \boldsymbol{W}(\omega)] \odot \boldsymbol{L}(\omega) \geq [\boldsymbol{P}(\omega)]^2 + [\boldsymbol{Q}(\omega)]^2 \quad \text{a.s.},$$

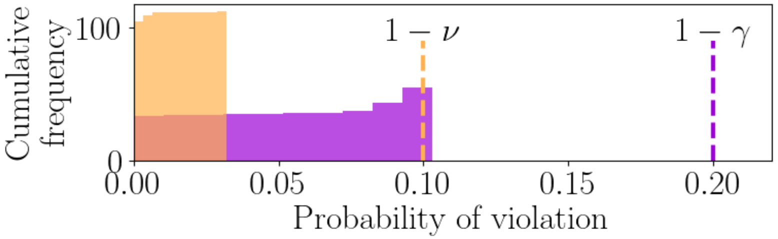
*An SOCP relaxation*

$$\mathrm{CVaR}_\nu\left[\boldsymbol{W}(\omega)\right] \leq \overline{\boldsymbol{W}},$$
$$\mathrm{CVaR}_\nu\left[-\boldsymbol{W}(\omega)\right] \leq -\underline{\boldsymbol{W}},$$
$$\mathrm{CVaR}_\gamma\left[[\boldsymbol{P}(\omega)]^2 + [\boldsymbol{Q}(\omega)]^2\right] \leq \overline{\boldsymbol{S}}^2.$$

*CVaR-based risk assessment*

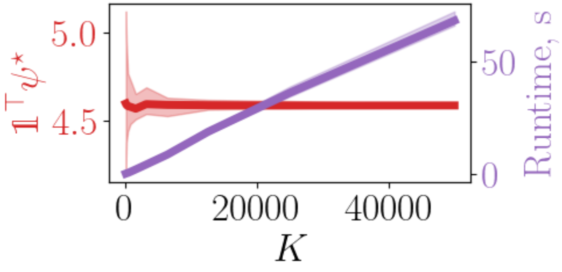
- CVaR-based formulation retains convexity
- Scenario approximations can be cast as a second-order cone program

*CVaR-based constraint enforcement ensures probabilistic guarantees...*

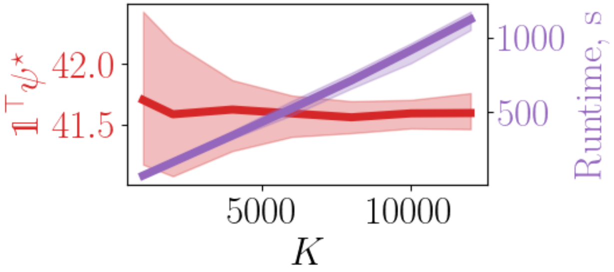



*Increasing number of scenarios reduces variability...*

Illustrative 3-bus Example

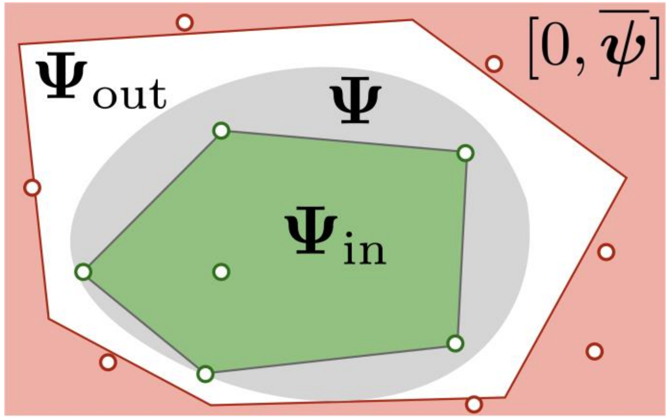



SCE 56-bus Example




*...but increases problem dimension and runtime.*

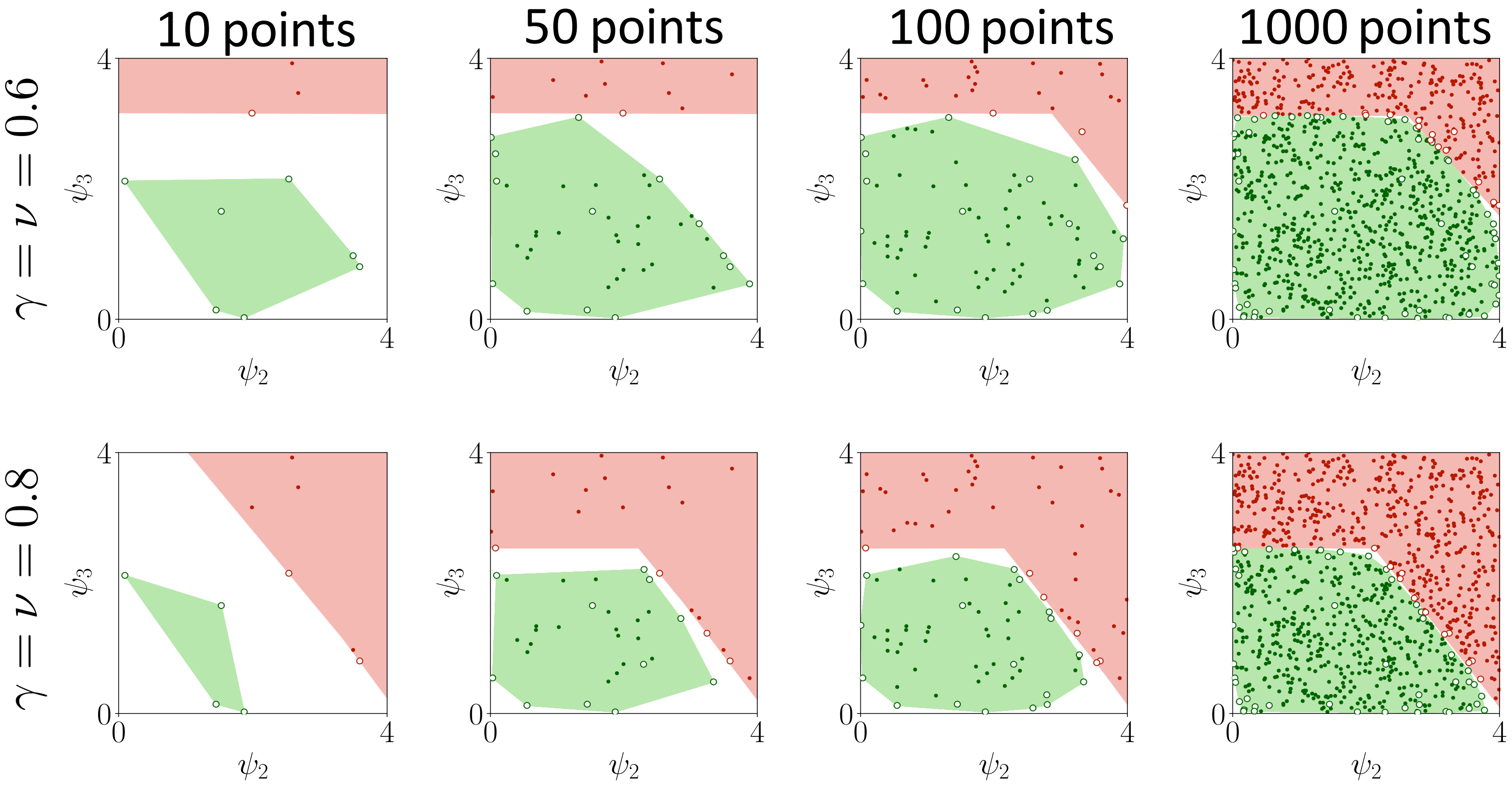
# Build on Past Knowledge in the Feasibility Problem




*…convexity of the set allows sequential inner and outer approximations*

| Test | Mean Runtime (s) | Frequency |
|---|---|---|
| $\psi \in \Psi_{\text{in}}$ test | $9.678 \times 10^{-4}$ | 451 |
| $\psi \notin \Psi_{\text{out}}$ test | $1.195 \times 10^{-6}$ | 489 |
| Solving opt when $\psi \in \Psi_{\text{in}}$ | 46.288 | 47 |
| Solving opt when $\psi \notin \Psi_{\text{out}}$ | 133.107 | 13 |

As you test more configurations for acceptability, the faster the algorithm becomes in certifying acceptability of new test configurations



| Type I | Type II | Type III | Type IV |
| --- | --- | --- | --- |
| Limit Hosting Capacity | Limit Network Access | Local Energy Market | Command and Control |

# Auctioning Network Access Allocation

Wholesale Market Participation of DERAs: DSO-DERA-ISO Coordination
C. Chen, S. Bose, T. D. Mount, and L. Tong
IEEE Transactions on Power Systems (Accepted, 2024)

# Robust Network Access Allocation

Maximize induced social welfare while allocating access limits subject to network constraints under all DSO and DERA net-injections

$$\underset{\underline{C},\overline{C},\overline{P},\underline{P}}{\text{maximize}} \quad \sum_{k=1}^{K} \varphi_k(\underline{C}_k, \overline{C}_k) - J(\overline{P}, \underline{P}),$$

Benefit of DERA    Cost of DSO

subject to

....

$$\overline{P} = \sum_{k=1}^{K} \overline{C}_k + \overline{p}_0,$$ Clearing injection access

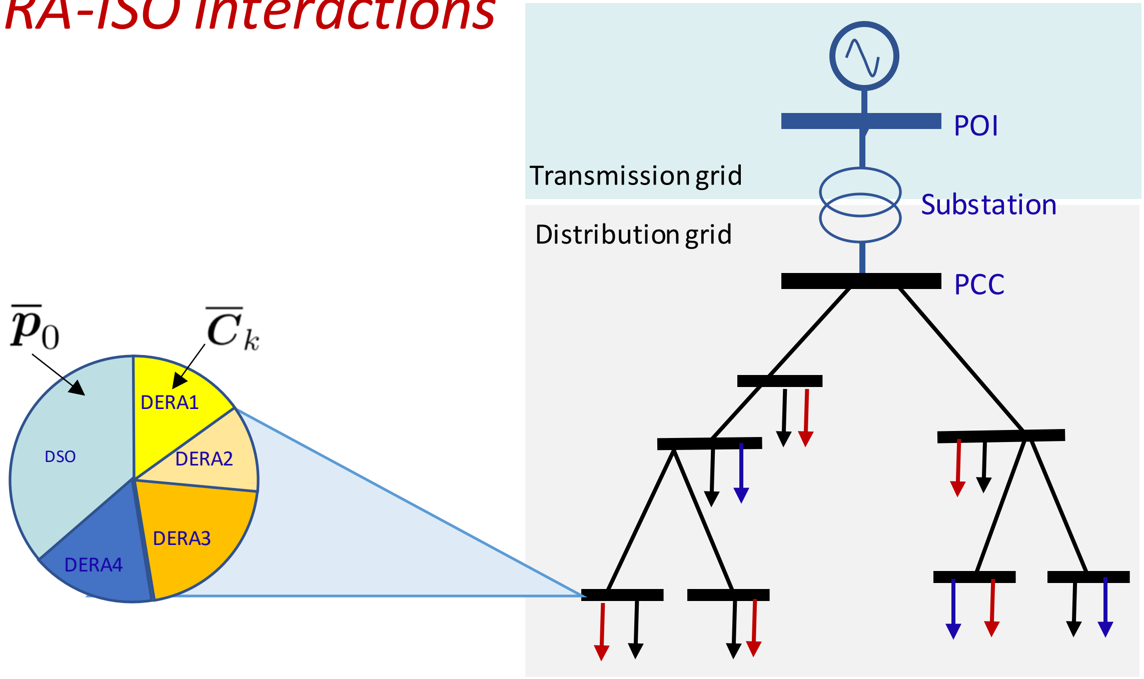
$$\underline{P} = \sum_{k=1}^{K} \underline{C}_k + \underline{p}_0,$$ Clearing withdrawal access

$$\underline{b} \leq A\left(\sum_{k=1}^{K} p_k + p_0\right) \leq \overline{b},$$

for all $p_k \in [-\underline{C}_k, \overline{C}_k], p_0 \in [-\underline{p}_0, \overline{p}_0]$,

for $k = 1, \ldots, K$.

*...does not require the DSO to intervene in real-time DERA-ISO interactions*



# Reformulate Robust Constraints

Payment by DERA *k* : $\mathcal{P}_k(\underline{\boldsymbol{C}}_k^\star, \overline{\boldsymbol{C}}_k^\star) := \overline{\boldsymbol{\lambda}}^{\star,\top} \overline{\boldsymbol{C}}_k^\star + \underline{\boldsymbol{\lambda}}^{\star,\top} \underline{\boldsymbol{C}}_k^\star$

Surplus of DERA *k* : $\Pi_k^{\text{DERA}} := \varphi_k(\underline{\boldsymbol{C}}_k^\star, \overline{\boldsymbol{C}}_k^\star) - \mathcal{P}_k(\underline{\boldsymbol{C}}_k^\star, \overline{\boldsymbol{C}}_k^\star)$

Surplus of DSO: $\Pi^{\text{DSO}} := \sum_{k=1}^{K} \mathcal{P}_k(\underline{\boldsymbol{C}}_k^\star, \overline{\boldsymbol{C}}_k^\star) - \left(J(\overline{\boldsymbol{P}}^\star, \underline{\boldsymbol{P}}^\star) - J(\overline{\boldsymbol{p}}_0, \underline{\boldsymbol{p}}_0)\right)$

$$\underset{\underline{\boldsymbol{C}}, \overline{\boldsymbol{C}}, \overline{\boldsymbol{P}}, \underline{\boldsymbol{P}}}{\text{maximize}} \quad \sum_{k=1}^{K} \varphi_k(\underline{\boldsymbol{C}}_k, \overline{\boldsymbol{C}}_k) - J(\overline{\boldsymbol{P}}, \underline{\boldsymbol{P}}),$$

subject to

Benefit of DERA

Cost of DSO

....

$$\overline{\boldsymbol{P}} = \sum_{k=1}^{K} \overline{\boldsymbol{C}}_k + \overline{\boldsymbol{p}}_0,$$

Clearing injection access

$$\underline{\boldsymbol{P}} = \sum_{k=1}^{K} \underline{\boldsymbol{C}}_k + \underline{\boldsymbol{p}}_0,$$

Clearing withdrawal access

$$\underline{\boldsymbol{b}} \le \boldsymbol{A}\left(\sum_{k=1}^{K} \boldsymbol{p}_k + \boldsymbol{p}_0\right) \le \overline{\boldsymbol{b}},$$

for all $\boldsymbol{p}_k \in [-\underline{\boldsymbol{C}}_k, \overline{\boldsymbol{C}}_k], \boldsymbol{p}_0 \in [-\underline{\boldsymbol{p}}_0, \overline{\boldsymbol{p}}_0]$,

for $k = 1, \ldots, K$.

Locational Marginal Access Price (LMAP)

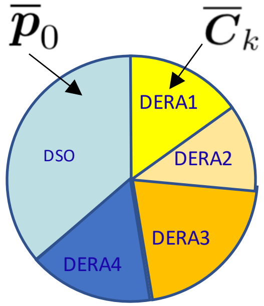
Maximize ...

$$\overline{\boldsymbol{\lambda}}: \quad \overline{\boldsymbol{P}} = \sum_{k=1}^{K} \overline{\boldsymbol{C}}_k + \overline{\boldsymbol{p}}_0,$$

$$\underline{\boldsymbol{\lambda}}: \quad \underline{\boldsymbol{P}} = \sum_{k=1}^{K} \underline{\boldsymbol{C}}_k + \underline{\boldsymbol{p}}_0,$$

$$\overline{\boldsymbol{\mu}}: \quad \boldsymbol{A}_+ \overline{\boldsymbol{P}} + \boldsymbol{A}_- \underline{\boldsymbol{P}} \le \overline{\boldsymbol{b}},$$

$$\underline{\boldsymbol{\mu}}: \quad \underline{\boldsymbol{b}} \le -\boldsymbol{A}_+ \underline{\boldsymbol{P}} - \boldsymbol{A}_- \overline{\boldsymbol{P}}.$$



# Properties of the Auction Outcome

Payment by DERA $k$ : $\mathcal{P}_k(\underline{\boldsymbol{C}}_k^\star, \overline{\boldsymbol{C}}_k^\star) := \overline{\boldsymbol{\lambda}}^{\star,\top} \overline{\boldsymbol{C}}_k^\star + \underline{\boldsymbol{\lambda}}^{\star,\top} \underline{\boldsymbol{C}}_k^\star$

Surplus of DERA $k$ : $\Pi_k^{\text{DERA}} := \varphi_k(\underline{\boldsymbol{C}}_k^\star, \overline{\boldsymbol{C}}_k^\star) - \mathcal{P}_k(\underline{\boldsymbol{C}}_k^\star, \overline{\boldsymbol{C}}_k^\star)$

Surplus of DSO: $\Pi^{\text{DSO}} := \sum_{k=1}^{K} \mathcal{P}_k(\underline{\boldsymbol{C}}_k^\star, \overline{\boldsymbol{C}}_k^\star) - \left(J(\overline{\boldsymbol{P}}^\star, \underline{\boldsymbol{P}}^\star) - J(\overline{\boldsymbol{p}}_0, \underline{\boldsymbol{p}}_0)\right)$

$$\underset{\underline{\boldsymbol{C}},\overline{\boldsymbol{C}},\overline{\boldsymbol{P}},\underline{\boldsymbol{P}}}{\text{maximize}} \quad \sum_{k=1}^{K} \varphi_k(\underline{\boldsymbol{C}}_k, \overline{\boldsymbol{C}}_k) - J(\overline{\boldsymbol{P}}, \underline{\boldsymbol{P}}),$$

Benefit of DERA

Cost of DSO

subject to

....

$$\overline{\boldsymbol{P}} = \sum_{k=1}^{K} \overline{\boldsymbol{C}}_k + \overline{\boldsymbol{p}}_0,$$ Clearing injection access

$$\underline{\boldsymbol{P}} = \sum_{k=1}^{K} \underline{\boldsymbol{C}}_k + \underline{\boldsymbol{p}}_0,$$ Clearing withdrawal access

$$\underline{\boldsymbol{b}} \le \boldsymbol{A}\left(\sum_{k=1}^{K} \boldsymbol{p}_k + \boldsymbol{p}_0\right) \le \overline{\boldsymbol{b}},$$

for all $\boldsymbol{p}_k \in [-\underline{\boldsymbol{C}}_k, \overline{\boldsymbol{C}}_k], \boldsymbol{p}_0 \in [-\underline{\boldsymbol{p}}_0, \overline{\boldsymbol{p}}_0]$,

for $k = 1, \ldots, K$.

*LMAPs are nodally uniform and reflect the DSO's marginal costs, network congestion, and pre-defined access limits.*

*Under reasonable assumptions, DERAs and the DSO have non-negative surpluses.*

*Under reasonable assumptions, LMAPs increase along the distribution feeder.*

# Robust Access Allocation

$$\underset{\underline{C},\overline{C},\overline{P},\underline{P}}{\text{maximize}} \quad \sum_{k=1}^{K} \varphi_k(\underline{C}_k, \overline{C}_k) - J(\overline{P}, \underline{P}),$$

subject to

Benefit of DERA

Cost of DSO

....

$$\overline{P} = \sum_{k=1}^{K} \overline{C}_k + \overline{p}_0,$$ Clearing injection access

$$\underline{P} = \sum_{k=1}^{K} \underline{C}_k + \underline{p}_0,$$ Clearing withdrawal access

$$\underline{b} \leq A\left(\sum_{k=1}^{K} p_k + p_0\right) \leq \overline{b},$$

for all $p_k \in [-\underline{C}_k, \overline{C}_k], p_0 \in [-\underline{p}_0, \overline{p}_0]$,

for $k = 1, \ldots, K$.

# Stochastic Access Allocation

Locational Marginal Access Price (LMAP)

$$\overline{\Lambda} : \quad \overline{P} = \sum_{k=1}^{K} \overline{C}_k + p_0,$$

$$\underline{\Lambda} : \quad \underline{P} = \sum_{k=1}^{K} \underline{C}_k - p_0,$$

$$\text{CVaR}_\delta[A(\sum_{k=1}^{K} p_k + p_0)] \leq \overline{b},$$

$$\text{CVaR}_\delta[-A(\sum_{k=1}^{K} p_k + p_0)] \leq -\underline{b},$$

for all $p_k \in [-\underline{C}_k, \overline{C}_k]$,

for $k = 1, \ldots, K$.

*...robust CVaR Constraints*

# The Data-Driven Counterpart

...with $S$ scenarios of DSO customers' demands

$$\underset{\overline{C},\underline{C},\overline{P}[s],\underline{P}[s],\atop \overline{t},\underline{t},\gamma[s],\overline{\gamma}[s]}{\text{maximize}} \quad \sum_{k=1}^{K} \varphi_k(\underline{C}_k, \overline{C}_k) - \frac{1}{S}\sum_{s=1}^{S} J(\overline{P}[s], \underline{P}[s]),$$

....

in scenario $s$

$$\overline{\lambda}[s]: \quad \overline{P}[s] = \sum_{k=1}^{K} \overline{C}_k + p_0[s],$$

$$\underline{\lambda}[s]: \quad \underline{P}[s] = \sum_{k=1}^{K} \underline{C}_k - p_0[s],$$

$$\overline{\beta}[s]: \quad A_+\overline{P}[s] + A_-\underline{P}[s] - \overline{b} - \overline{t} \leq \overline{\gamma}[s],$$

$$\underline{\beta}[s]: \quad A_-\overline{P}[s] + A_+\underline{P}[s] + \underline{b} - \underline{t} \leq \underline{\gamma}[s],$$

$$\overline{\alpha}[s]: \quad 0 \leq \overline{\gamma}[s],$$

$$\overline{\mu}: \quad \overline{t} + \frac{1}{1-\delta}\frac{1}{S}\sum_{s=1}^{S}\overline{\gamma}[s] \leq 0,$$

$$\underline{\alpha}[s]: \quad 0 \leq \underline{\gamma}[s],$$

$$\underline{\mu}: \quad \underline{t} + \frac{1}{1-\delta}\frac{1}{S}\sum_{s=1}^{S}\underline{\gamma}[s] \leq 0.$$

$$\overline{\Lambda}^\star = \sum_{s=1}^{S} \overline{\lambda}^\star[s],$$

$$\underline{\Lambda}^\star = \sum_{s=1}^{S} \underline{\lambda}^\star[s]$$

# Stochastic Access Allocation

Locational Marginal Access Price (LMAP)

$$\overline{\Lambda}: \quad \overline{P} = \sum_{k=1}^{K} \overline{C}_k + p_0,$$

$$\underline{\Lambda}: \quad \underline{P} = \sum_{k=1}^{K} \underline{C}_k - p_0,$$

$$\mathrm{CVaR}_\delta[A(\sum_{k=1}^{K} p_k + p_0)] \leq \overline{b},$$

$$\mathrm{CVaR}_\delta[-A(\sum_{k=1}^{K} p_k + p_0)] \leq -\underline{b},$$

for all $p_k \in [-\underline{C}_k, \overline{C}_k]$,

for $k = 1, \ldots, K$.

*...robust CVaR Constraints*

# The Data-Driven Counterpart

...with *S* scenarios of DSO customers' demands

$$\underset{\substack{\overline{C},\underline{C},\overline{P}[s],\underline{P}[s],\\ \overline{t},\underline{t},\underline{\gamma}[s],\overline{\gamma}[s]}}{\text{maximize}} \quad \sum_{k=1}^{K} \varphi_k(\underline{C}_k,\overline{C}_k) - \frac{1}{S}\sum_{s=1}^{S} J(\overline{P}[s],\underline{P}[s]),$$

....

in scenario *s*

$$\overline{\lambda}[s]: \quad \overline{P}[s] = \sum_{k=1}^{K} \overline{C}_k + p_0[s],$$

$$\underline{\lambda}[s]: \quad \underline{P}[s] = \sum_{k=1}^{K} \underline{C}_k - p_0[s],$$

$$\overline{\beta}[s]: \quad A_+\overline{P}[s] + A_-\underline{P}[s] - \overline{b} - \overline{t} \leq \overline{\gamma}[s],$$

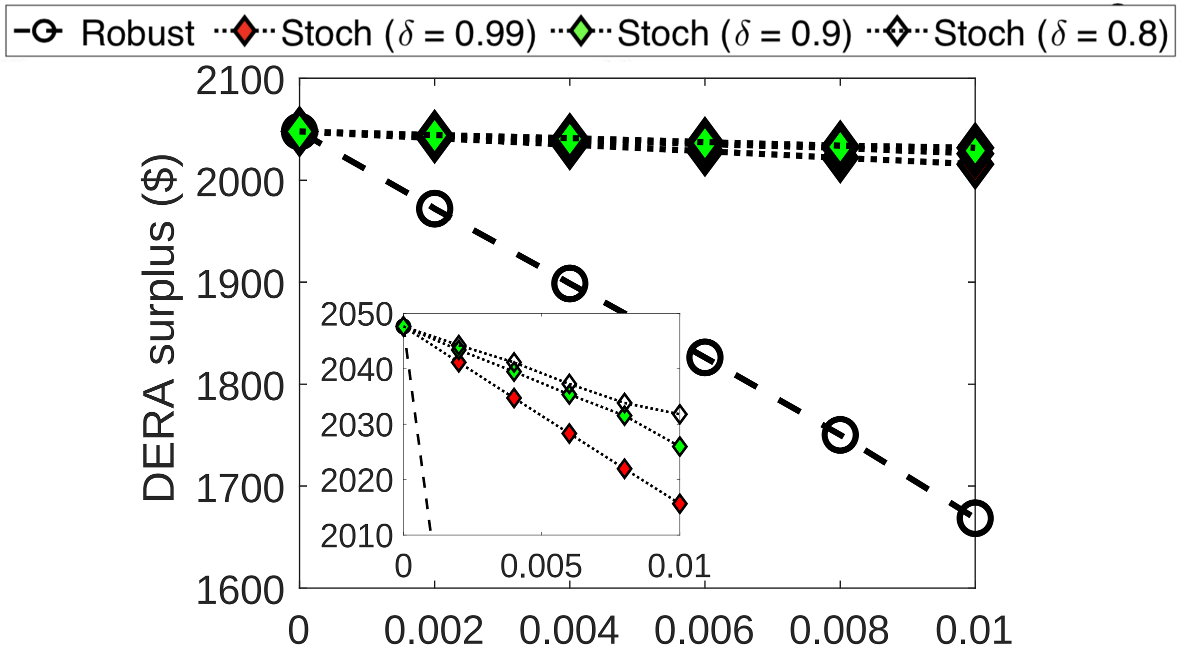
$$\underline{\beta}[s]: \quad A_-\overline{P}[s] + A_+\underline{P}[s] + \underline{b} - \underline{t} \leq \underline{\gamma}[s],$$

$$\overline{\alpha}[s]: \quad 0 \leq \overline{\gamma}[s],$$

$$\overline{\mu}: \quad \overline{t} + \frac{1}{1-\delta}\frac{1}{S}\sum_{s=1}^{S}\overline{\gamma}[s] \leq 0,$$

$$\underline{\alpha}[s]: \quad 0 \leq \underline{\gamma}[s],$$

$$\underline{\mu}: \quad \underline{t} + \frac{1}{1-\delta}\frac{1}{S}\sum_{s=1}^{S}\underline{\gamma}[s] \leq 0.$$




Variance in the injection of DSO's customers

20% gain in surplus by tolerating less than 1% constraint violation risk

| Type I | Type II | Type III | Type IV |
|---|---|---|---|
| Limit Hosting Capacity | Limit Network Access | Local Energy Market | Command and Control |

# Retail Market Design

**Design supply offers/demand bids**

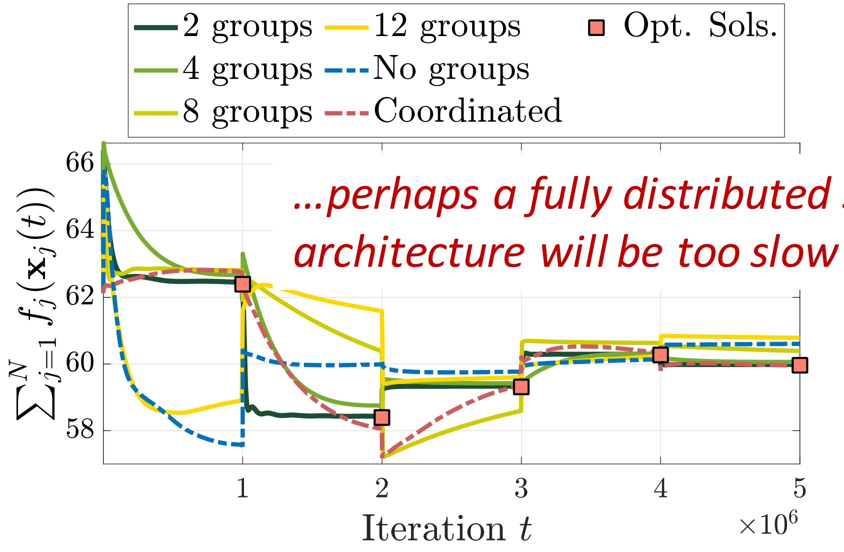
A Scalar-Parameterized Mechanism For Two-Sided Markets
M. Ndrio, K. Alshehri, and S. Bose, IFAC-PapersOnLine 53.2 (2020): 16952-16957.

**Design and analyze price formation**

Pricing Economic Dispatch with AC Power Flow via Local Multipliers and Conic Relaxation
M. Ndrio, A. Winnicki, and S.Bose, IEEE Transactions on Control of Network Systems (Accepted, 2022)

| Type I | Type II | Type III | Type IV |
|---|---|---|---|
| Limit Hosting Capacity | Limit Network Access | Local Energy Market | Command and Control |

# Optimal "Dispatch" of DERs




*...perhaps a fully distributed solution architecture will be too slow*

Distributed Dual Subgradient Methods with Averaging and Applications to Grid Optimization
H. Liu, S. Bose, H. D. Nguyen, Y. Guo, T. T. Doan, and C. L. Beck
Journal of Optimization Theory and Applications
(Accepted, 2024)

| Type I | Type II | Type III | Type IV |
| --- | --- | --- | --- |
| Limit Hosting Capacity | Limit Network Access | Local Energy Market | Command and Control |

# Distribution Network Security with Distributed Energy Resource Aggregators

**Thank you!**


**Subhonmesh Bose**

Department of Electrical and Computer Engineering

Coordinated Science Laboratory

University of Illinois Urbana-Champaign

http://boses.ece.Illinois.edu


*The Hosting Capacity Problem*

*Auctioning Network Access Allocation*

*Retail Market Design*

*Optimal "Dispatch" of DERs*