T&D integration: Unlocking Flexibility of Distributed Energy Resources

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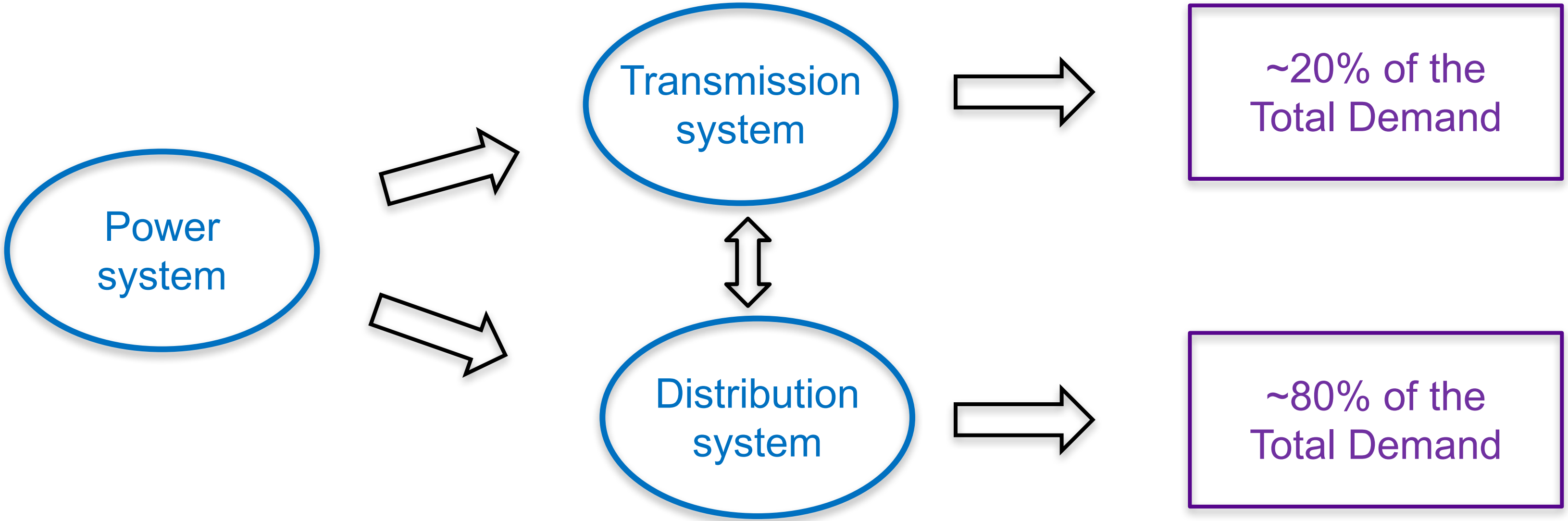
T&D Integration as Part of Urban Grids



Transmission demand

- Bulk, observable, controllable, predictable and schedulable

Distribution demand

- Distributed, unobservable (“behind-the-meter”),
- Limited controllability, predictable and schedulability relative to the transmission demand

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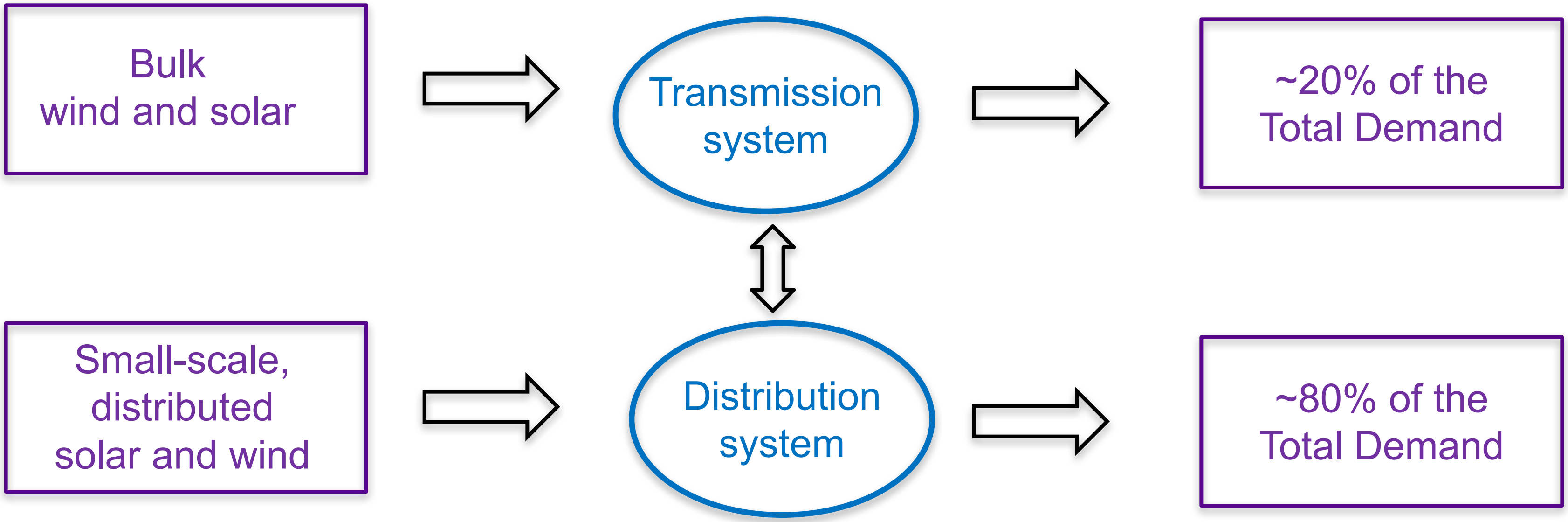
T&D Integration as Part of Urban Grids



Transmission Renewables

- Observable and geographically dispersed → ideal case of the CLT → $$$
- Provide grid support services → self-mitigate integration implications→ $$$

} Benefits saturate quickly

Distribution Renewables

- Located in the same geographical areas
- Locked “behind the meter” → unobservable to the system → no value/remuneration

T&D Integration: A Closer Look at the Distribution System

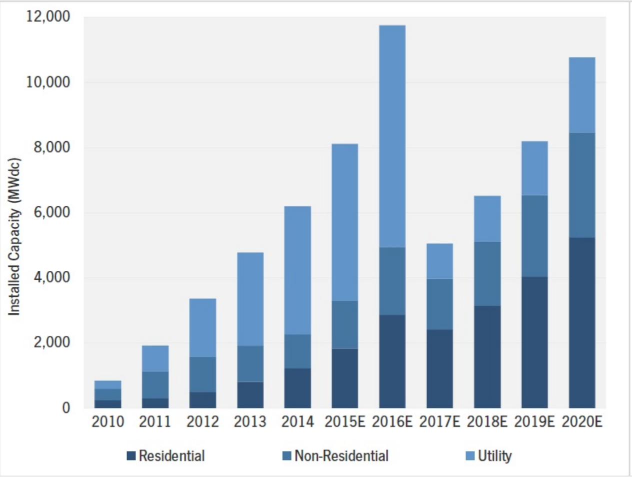
Increasing Uncertainty

Small-scale, distributed solar and wind

Distribution system

Increasing Flexibility (Not harvested yet!)

~80% of the Total Demand

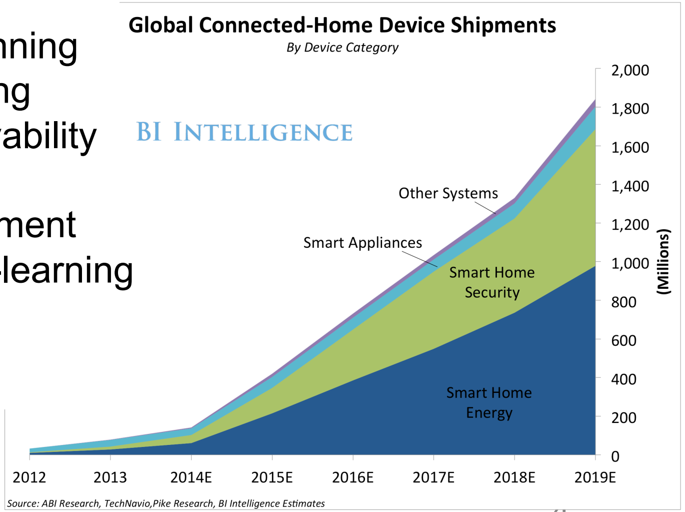


Still

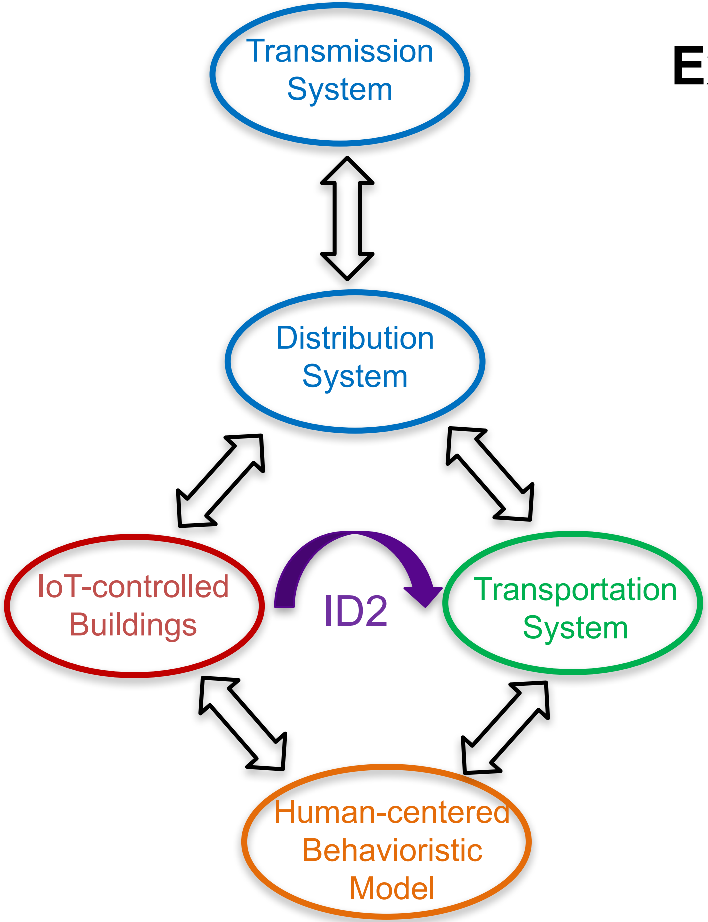
- Centralized operations/planning
- Single-actor decision making
- Sparse “smartness”/observability
- Vague incentives
- Unorganized data management
- Machine learning without r-learning

Emerging Trends

- Cost/benefit analysis
- Ad-hoc, yet very sensible, demonstration studies
- Least-cost resiliency



T&D Integration: Components



Explore Internal Flexibility Sources

- Define a formal model of each CPS system
- Define a formal behavioristic model
- Define interfaces between systems
- Define uncertain parameters
- Value the interfaces

T&D Integration: Distribution System

Distribution System

Generation cost

$$\max_{\mathcal{V}^{\mathrm{D}}} o^{\mathrm{D}} := \left[\sum_{b \in \mathcal{B}^{\mathrm{D}}} L_b^{\mathrm{p}} T - \sum_{i \in \mathcal{I}^{\mathrm{U}}} C_i^{\mathrm{O}} g_i^{\mathrm{p}} + \lambda_{b_0} (p_{b_0}^{\mathrm{O}} - p_{b_0}^{\mathrm{B}}) \right]$$

Tariff Payments

Trading in the whole-sale market

- Fixed tariff – for simplicity of derivations; can and should be time- and location-specific

T&D Integration: Distribution System

Distribution System

$$\max_{\mathcal{V}^{\mathrm{D}}} o^{\mathrm{D}} := \left[\sum_{b \in \mathcal{B}^{\mathrm{D}}} L_b^{\mathrm{p}} T - \sum_{i \in \mathcal{I}^{\mathrm{U}}} C_i^{\mathrm{O}} g_i^{\mathrm{p}} + \lambda_{b_0} (p_{b_0}^{\mathrm{O}} - p_{b_0}^{\mathrm{B}}) \right]$$

$$g_i^{\mathrm{p}} \leq \overline{G}_i^{\mathrm{p}}, \quad \forall i \in \mathcal{I}^{\mathrm{D}} \tag{2}$$

$$g_i^{\mathrm{p}} \geq \underline{G}_i^{\mathrm{p}}, \quad \forall i \in \mathcal{I}^{\mathrm{D}} \tag{3}$$

$$g_i^{\mathrm{q}} \leq \overline{G}_i^{\mathrm{q}}, \quad \forall i \in \mathcal{I}^{\mathrm{D}} \tag{4}$$

$$g_i^{\mathrm{q}} \geq \underline{G}_i^{\mathrm{q}}, \quad \forall i \in \mathcal{I}^{\mathrm{D}} \tag{5}$$

Power limits on generation assets

- This representation can accommodate non-conventional generation resources (e.g. “prosumers”)
- Uncertain availability can be modeled by imposing uncertainty sets on the right hand-side parameters of (2)-(5)

T&D Integration: Distribution System

Distribution System

$$\max_{\mathcal{V}^{\mathrm{D}}} o^{\mathrm{D}} := \Big[\sum_{b \in \mathcal{B}^{\mathrm{D}}} L_b^{\mathrm{p}} T - \sum_{i \in \mathcal{I}^{\mathrm{U}}} C_i^{\mathrm{O}} g_i^{\mathrm{p}} + \lambda_{b_0} (p_{b_0}^{\mathrm{O}} - p_{b_0}^{\mathrm{B}}) \Big]$$

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$$g_i^{\mathrm{q}} \geq \underline{G}_i^{\mathrm{q}}, \quad \forall i \in \mathcal{I}^{\mathrm{D}} \tag{5}$$

Power limits on generation assets

$$(f_l^{\mathrm{p}})^2 + (f_l^{\mathrm{q}})^2 \leq \overline{S}_l^2, \quad \forall l \in \mathcal{L}^{\mathrm{D}} \tag{6}$$

$$(f_l^{\mathrm{p}} - a_l R_l)^2 + (f_l^{\mathrm{q}} - a_l X_l)^2 \leq \overline{S}_l^2, \quad \forall l \in \mathcal{L}^{\mathrm{D}} \tag{7}$$

$$v_{r(l)} - 2(R_l f_l^{\mathrm{p}} + X_l f_l^{\mathrm{q}}) + a_l (R_i^2 + X_l^2) = v_{o(l)}, \quad \forall l \in \mathcal{L}^{\mathrm{D}} \tag{8}$$

$$\big[(f_l^{\mathrm{p}})^2 + (f_l^{\mathrm{q}})^2\big] \frac{1}{a_l} \leq v_{o(l)}, \quad \forall l \in \mathcal{L}^{\mathrm{D}} \tag{9}$$

AC power flow constraints via SOC

T&D Integration: Distribution System

Distribution System

$$\max_{\mathcal{V}^{\mathrm{D}}} o^{\mathrm{D}} := \left[\sum_{b \in \mathcal{B}^{\mathrm{D}}} L_b^{\mathrm{p}} T - \sum_{i \in \mathcal{I}^{\mathrm{U}}} C_i^{\mathrm{O}} g_i^{\mathrm{p}} + \lambda_{b_0} (p_{b_0}^{\mathrm{O}} - p_{b_0}^{\mathrm{B}}) \right]$$

$$f_{l|o(l)=b}^{\mathrm{p}} - \sum_{l|r(l)=b} (f_l^{\mathrm{p}} - a_l R_l) - \sum_{i \in I_b^{\mathrm{U}}} g_i^{\mathrm{p}} + L_b^{\mathrm{p}} + v_b G_{l|o(l)=b} = 0, \quad \forall b \qquad (10)$$

$$f_{l|o(l)=b}^{\mathrm{q}} - \sum_{l|r(l)=b} (f_l^{\mathrm{q}} - a_l X_l) - \sum_{i \in I_b^{\mathrm{U}}} g_i^{\mathrm{p}} + L_b^{\mathrm{p}} - v_b B_{l|o(l)=b} = 0, \quad \forall b \qquad (11)$$

Nodal power balances

$$- \sum_{l|r(l)=b_0} (f_l^{\mathrm{p}} - a_l R_l) - p_{b_0}^{O} + p_{b_0}^{B} + v_{b_0} G_{l|o(l)=b_0} = 0 \qquad (12)$$

“Root” bus balance

Exchange with the transmission system

T&D Integration: Transmission System

Transmission System

Distribution Bids

Distribution Offers

$$\max_{\mathcal{V}^{\mathrm{T}}} o^{\mathrm{T}} := \left[\sum_{b \in \mathcal{B}^{\mathrm{T}}} C_b^{\mathrm{B}} D_b^{\mathrm{p}} + \sum_{b \in \mathcal{B}^{\mathrm{D}}} C_b^{\mathrm{B}} p_b^{\mathrm{B}} - \sum_{i \in \mathcal{I}^{\mathrm{T}}} C_i^{\mathrm{O}} g_i^{\mathrm{p}} - \sum_{i \in \mathcal{I}^{\mathrm{U}}} C_b^{\mathrm{O}} p_b^{\mathrm{O}} \right] \quad (19)$$

Demand Bids

Gen Offers

T&D Integration: Transmission System

Transmission System

$$\max_{\mathcal{V}^{\mathrm{T}}} o^{\mathrm{T}} :=$$

$$\left[\sum_{b \in \mathcal{B}^{\mathrm{T}}} C_b^{\mathrm{B}} D_b^{\mathrm{p}} + \sum_{b \in \mathcal{B}^{\mathrm{D}}} C_b^{\mathrm{B}} p_b^{\mathrm{B}} - \sum_{i \in \mathcal{I}^{\mathrm{T}}} C_i^{\mathrm{O}} g_i^{\mathrm{p}} - \sum_{i \in \mathcal{I}^{\mathrm{U}}} C_b^{\mathrm{O}} p_b^{\mathrm{O}} \right] \quad (19)$$

$$\sum_{i \in \mathcal{I}_b} g_i^{\mathrm{p}} + \sum_{l | r(l) = b} f_l^{\mathrm{p}} - \sum_{l | o(l) = b} f_l^{\mathrm{p}} + p_b^{O} - p_b^{B} = L_b^{\mathrm{p}} : (\lambda_b), \quad \forall b \in \mathcal{B}^{+} \quad (20)$$

$$\sum_{i \in I_b} g_i^{\mathrm{p}} + \sum_{l | r(l) = b} f_l^{\mathrm{p}} - \sum_{l | o(l) = b} f_l^{\mathrm{p}} = L_b^{\mathrm{p}} : (\lambda_b), \quad \forall b \in \mathcal{B}^{\mathrm{T}} \setminus \{\mathcal{B}^{+}\} \quad (21)$$

Nodal power balances

T&D Integration: Transmission System

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Transmission System

$$\max_{\mathcal{V}^{\mathrm{T}}} o^{\mathrm{T}} := \Big[\sum_{b\in\mathcal{B}^{\mathrm{T}}} C_b^{\mathrm{B}} D_b^{\mathrm{p}} + \sum_{b\in\mathcal{B}^{\mathrm{D}}} C_b^{\mathrm{B}} p_b^{\mathrm{B}} - \sum_{i\in\mathcal{I}^{\mathrm{T}}} C_i^{\mathrm{O}} g_i^{\mathrm{p}} - \sum_{i\in\mathcal{I}^{\mathrm{U}}} C_b^{\mathrm{O}} p_b^{\mathrm{O}}\Big] \quad (19)$$

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$$g_i^{\mathrm{p}} \le \overline{G}_i^{\mathrm{p}} : (\overline{\alpha}_i), \quad \forall i \in \mathcal{I}^{\mathrm{T}} \quad (22)$$

$$g_i^{\mathrm{p}} \ge \underline{G}_i^{\mathrm{p}} : (\underline{\alpha}_i), \quad \forall i \in \mathcal{I}^{\mathrm{T}} \quad (23)$$

Nodal power balances (20)–(21)

Gen limits (22)–(23)

T&D Integration: Transmission System

Transmission System

$$\max_{\mathcal{V}^{\mathrm{T}}} o^{\mathrm{T}} :=$$

$$\left[\sum_{b\in\mathcal{B}^{\mathrm{T}}} C_b^{\mathrm{B}} D_b^{\mathrm{p}} + \sum_{b\in\mathcal{B}^{\mathrm{D}}} C_b^{\mathrm{B}} p_b^{\mathrm{B}} - \sum_{i\in\mathcal{I}^{\mathrm{T}}} C_i^{\mathrm{O}} g_i^{\mathrm{p}} - \sum_{i\in\mathcal{I}^{\mathrm{U}}} C_b^{\mathrm{O}} p_b^{\mathrm{O}}\right] \quad (19)$$

$$\sum_{i\in\mathcal{I}_b} g_i^{\mathrm{p}} + \sum_{l|r(l)=b} f_l^{\mathrm{p}} - \sum_{l|o(l)=b} f_l^{\mathrm{p}} + p_b^{O} - p_b^{B} = L_b^{\mathrm{p}} : (\lambda_b), \quad \forall b \in \mathcal{B}^{+} \quad (20)$$

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$$p_b^{O} \leq \overline{P}_b : (\overline{\psi}_b), \quad \forall b \in \mathcal{B}^{+} \quad (24)$$

$$p_b^{B} \leq \overline{P}_b : (\underline{\psi}_b), \quad \forall b \in \mathcal{B}^{+} \quad (25)$$

Nodal power balances (20)–(21)

Gen limits (22)–(23)

Interface limits (24)–(25)

T&D Integration: Transmission System

Transmission System

$$\max_{\mathcal{V}^{\mathrm{T}}} o^{\mathrm{T}} :=$$

$$\Big[\sum_{b\in\mathcal{B}^{\mathrm{T}}} C^{\mathrm{B}}_b D^{\mathrm{p}}_b + \sum_{b\in\mathcal{B}^{\mathrm{D}}} C^{\mathrm{B}}_b p^{\mathrm{B}}_b - \sum_{i\in\mathcal{I}^{\mathrm{T}}} C^{\mathrm{O}}_i g^{\mathrm{p}}_i - \sum_{i\in\mathcal{I}^{\mathrm{U}}} C^{\mathrm{O}}_b p^{\mathrm{O}}_b\Big] \quad (19)$$

Nodal power balances

$$\sum_{i\in\mathcal{I}_b} g^{\mathrm{p}}_i + \sum_{l|r(l)=b} f^{\mathrm{p}}_l - \sum_{l|o(l)=b} f^{\mathrm{p}}_l + p^{O}_b - p^{B}_b = L^{\mathrm{p}}_b : (\lambda_b), \quad \forall b \in \mathcal{B}^{+} \quad (20)$$

$$\sum_{i\in I_b} g^{\mathrm{p}}_i + \sum_{l|r(l)=b} f^{\mathrm{p}}_l - \sum_{l|o(l)=b} f^{\mathrm{p}}_l = L^{\mathrm{p}}_b : (\lambda_b), \quad \forall b \in \mathcal{B}^{\mathrm{T}} \backslash \{\mathcal{B}^{+}\} \quad (21)$$

Gen limits

$$g^{\mathrm{p}}_i \le \overline{G}^{\mathrm{p}}_i : (\overline{\alpha}_i), \quad \forall i \in \mathcal{I}^{\mathrm{T}} \quad (22)$$

$$g^{\mathrm{p}}_i \ge \underline{G}^{\mathrm{p}}_i : (\underline{\alpha}_i), \quad \forall i \in \mathcal{I}^{\mathrm{T}} \quad (23)$$

Interface limits

$$p^{O}_b \le \overline{P}_b : (\overline{\psi}_b), \quad \forall b \in \mathcal{B}^{+} \quad (24)$$

$$p^{B}_b \le \overline{P}_b : (\underline{\psi}_b), \quad \forall b \in \mathcal{B}^{+} \quad (25)$$

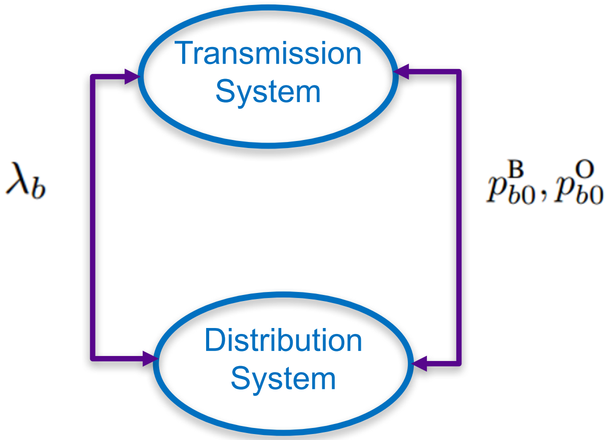
DC power flow constraints

$$f^{\mathrm{p}}_l = \frac{1}{X_l}(\theta_{o(l)} - \theta_{r(l)}) : (\xi_l), \quad \forall l \in \mathcal{L}^{\mathrm{T}} \quad (26)$$

$$f^{\mathrm{p}}_l \le \overline{F}_l : (\overline{\delta}_l), \quad \forall l \in \mathcal{L}^{\mathrm{T}} \quad (27)$$

$$f^{\mathrm{p}}_l \ge -\overline{F}_l : (\underline{\delta}_l), \quad \forall l \in \mathcal{L}^{\mathrm{T}} \quad (28)$$

T&D Integration: Interface



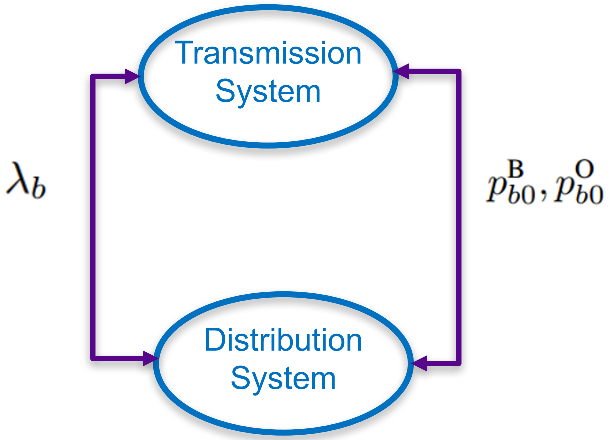
Assumptions on the interface

- One interface per distribution grid
- Active power only
- Reactive power is balanced by each system independently
- Self-reserve (revised later)

Distribution grid objective → $$\max_{\mathcal{V}^{\mathrm{D}}} o^{\mathrm{D}} \quad (30)$$

Distribution grid constraints → $$D(\mathcal{V}^{\mathrm{D}}) \leq 0 \quad (31)$$

T&D Integration: Coordination



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$$\max_{\mathcal{V}^{\mathrm{D}}} o^{\mathrm{D}} \tag{30}$$

$$D(\mathcal{V}^{\mathrm{D}}) \leq 0 \tag{31}$$

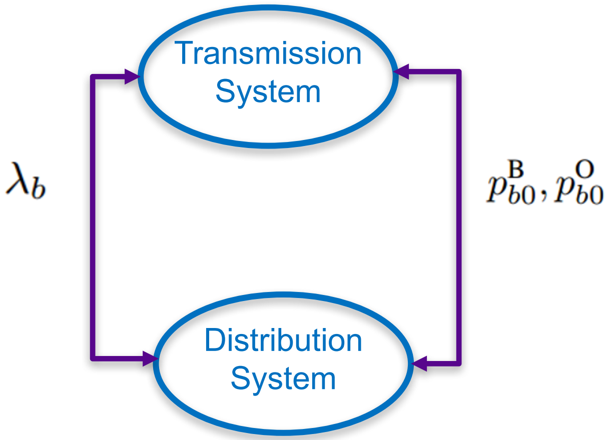
Transmission grid objective →

$$p_{b0}^{\mathrm{B}}, p_{b0}^{\mathrm{O}}, \lambda_b \in \arg \max_{\mathcal{V}^{\mathrm{T}}} o^{\mathrm{T}} \tag{32}$$

Transmission grid constraints →

$$T(\mathcal{V}^{\mathrm{T}}) \leq 0, \tag{33}$$

T&D Integration: Coordination



Assumptions on the interface

- One interface per distribution grid
- Active power only
- Reactive power is balanced by each system independently
- Self-reserve (revised later)

Bi-level problem

$$\max_{\mathcal{V}^{\mathrm{D}}} o^{\mathrm{D}} \tag{30}$$

$$D(\mathcal{V}^{\mathrm{D}}) \leq 0 \tag{31}$$

$$p^{\mathrm{B}}_{b0}, p^{\mathrm{O}}_{b0}, \lambda_b \in \arg \max_{\mathcal{V}^{\mathrm{T}}} o^{\mathrm{T}} \tag{32}$$

$$T(\mathcal{V}^{\mathrm{T}}) \leq 0, \tag{33}$$

T&D Integration: Solution technique

Three-step solution approach*:

- Step 1: Dualize the lower-level (transmission) problem
- Step 2: Invoke the strong duality theorem (SDT) condition
- Step 3: Replace the lower-level problem with its dual problem and SDT condition

$$\max_{\mathcal{V}^{\mathrm{D}} \cup \mathcal{V}^{\mathrm{T}} \cup \mathcal{V}^{\hat{\mathrm{T}}}} \quad o^{\mathrm{D}} \tag{34}$$ ← Bilinear product

$$D(\mathcal{V}^{\mathrm{D}}) \leq 0 \tag{35}$$

Transmission grid constraints → $$T(\mathcal{V}^{\mathrm{T}}) \leq 0 \tag{36}$$

Dual transmission grid const. → $$\hat{T}(\mathcal{V}^{\hat{\mathrm{T}}}) \leq 0 \tag{37}$$

STD condition → $$o^{\mathrm{T}} = o^{\hat{\mathrm{T}}} \tag{38}$$

*In fact, this reformulation can be further strengthened.

T&D Integration: Bilinear product

$$o^{\mathrm{D}} := \Big[\underbrace{\sum_{b \in \mathcal{B}^{\mathrm{D}}} L_b^{\mathrm{p}} T - \sum_{i \in \mathcal{I}^{\mathrm{U}}} C_i^{\mathrm{O}} g_i^{\mathrm{p}} +}_{} \underbrace{\lambda_{b_0} (p_{b_0}^{\mathrm{O}} - p_{b_0}^{\mathrm{B}})}_{\text{Bilinear product}} \Big]$$

Bilinear product

Linearization is straightforward with KKT conditions:

$$p_b^O \leq \overline{P}_b : (\overline{\psi}_b), \quad \forall b \in \mathcal{B}^+$$
$$p_b^B \leq \overline{P}_b : (\underline{\psi}_b), \quad \forall b \in \mathcal{B}^+$$

Bilinear product leads to:

$$\lambda_{b_0} (p_{b_0}^{\mathrm{O}} - p_{b_0}^{\mathrm{B}}) = C_b^{\mathrm{O}} p_b^{\mathrm{O}} \underbrace{- \overline{\psi}_b \overline{P}_b^{\mathrm{O}} + \underline{\psi}_b \underline{P}_b^{\mathrm{B}}}_{\text{Linear}} - C_b^{\mathrm{B}} p_b^{\mathrm{B}}.$$

Linear

T&D Integration: Interpretation

$$\lambda_{b_0}(p_{b_0}^{\mathrm{O}} - p_{b_0}^{\mathrm{B}}) = \underbrace{C_b^{\mathrm{O}} p_b^{\mathrm{O}} - \overline{\psi}_b \overline{P}_b^{\mathrm{O}}}_{\text{O-component}} + \underbrace{\underline{\psi}_b \underline{P}_b^{\mathrm{B}} - C_b^{\mathrm{B}} p_b^{\mathrm{B}}}_{\text{B-component}}.$$

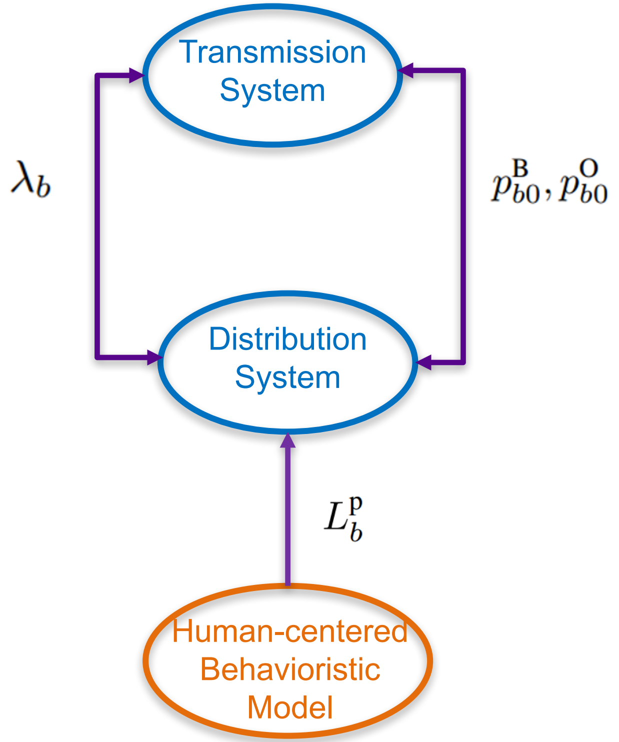
$$p_b^O \le \overline{P}_b : (\overline{\psi}_b), \quad \forall b \in \mathcal{B}^+$$

$$p_b^B \le \overline{P}_b : (\underline{\psi}_b), \quad \forall b \in \mathcal{B}^+$$

Value of the interface:

- Function of the limit
- Function of the transmission's system value of extra resources
- "Greedy" distribution system is penalized

T&D Integration: Demand is Still Exogenous (!)



$$f^{\mathrm{p}}_{l|o(l)=b} - \sum_{l|r(l)=b} (f^{\mathrm{p}}_{l} - a_l R_l) - \sum_{i \in I^{\mathrm{U}}_{b}} g^{\mathrm{p}}_{i} + L^{\mathrm{p}}_{b} + v_b G_{l|o(l)=b} = 0, \quad \forall b \in \mathcal{B}^{\mathrm{D}} \backslash \{b_0\} \quad (10)$$

"Exogenous" demand means

- Humans act rationally
- Limited selectivity
- Homogenous loads

T&D Integration: Games with Subjective Consumers

Prospect Theory

- Developed in 1970-s
- Limited use in real-life applications
- Saad + Poor's groups applied to some smart grid problems

Subjective Utility of Consumers:

$$U_b(\mathbf{L}) = \sum_{\mathbf{k}\in\mathbf{K_b}} \mathbf{l_k} \prod_{\mathbf{i}\setminus\{\mathbf{k}\}} \omega_{\mathbf{i}} \cdot \mathbf{u_k}$$

Weight of each appliance can be obtained via learning

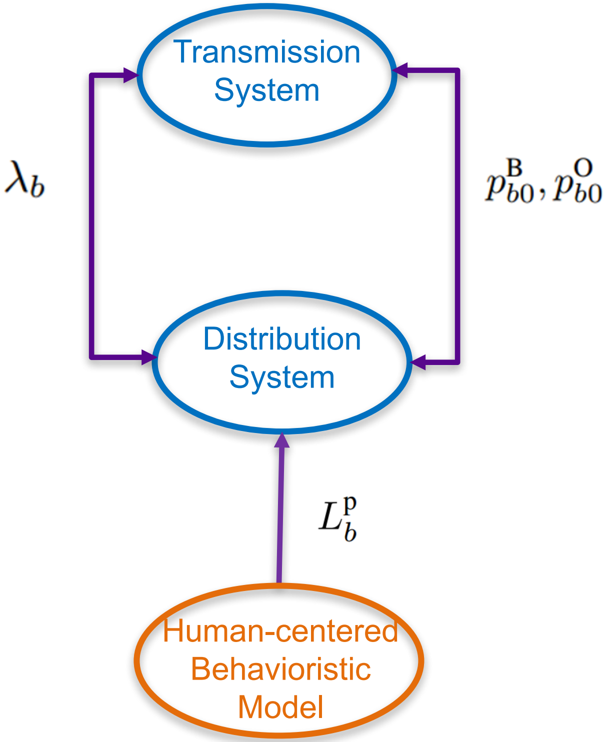
Rank

$$w_i = \sum_{k=1}^{5} \frac{r_k}{5} \frac{d_k^i}{d_{max}}$$

Net consumption

T&D Integration: Games with Subjective Consumers

T&D Integration with Subjective Consumers



$$\max_{\mathcal{V}^{\mathrm{D}} \cup \mathcal{V}^{\mathrm{T}} \cup \mathcal{V}^{\hat{\mathrm{T}}}} \quad o^{\mathrm{D}}$$

$$D(\mathcal{V}^{\mathrm{D}}) \leq 0$$

$$T(\mathcal{V}^{\mathrm{T}}) \leq 0$$

$$\hat{T}(\mathcal{V}^{\hat{\mathrm{T}}}) \leq 0$$

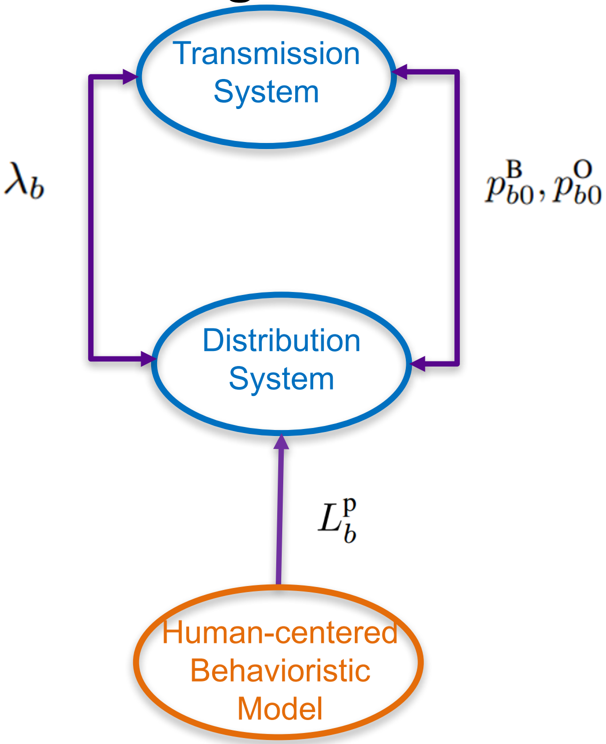
$$o^{\mathrm{T}} = o^{\hat{\mathrm{T}}}$$

$$\Updownarrow$$

$$U_b(\mathbf{L}) = \sum_{\mathbf{k} \in \mathbf{K_b}} \mathbf{l_k} \prod_{\mathbf{i} \backslash \{\mathbf{k}\}} \omega_{\mathbf{i}} \cdot \mathbf{u_k}$$

T&D Integration: Games with Subjective Consumers

T&D Integration with Subjective Consumers



$$\max_{\mathcal{V}^{\mathrm{D}} \cup \mathcal{V}^{\mathrm{T}} \cup \mathcal{V}^{\hat{\mathrm{T}}}} \quad o^{\mathrm{D}}$$

$$D(\mathcal{V}^{\mathrm{D}}) \leq 0$$

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$$o^{\mathrm{T}} = o^{\hat{\mathrm{T}}}$$

$$\Updownarrow$$

$$U_b(\mathbf{L}) = \sum_{\mathbf{k} \in \mathbf{K_b}} \mathbf{l_k} \prod_{\mathbf{i} \setminus \{\mathbf{k}\}} \omega_{\mathbf{i}} \cdot \mathbf{u_k}$$

This game is solved using Progressive Hedging!

Advantages:

- Decomposable
- Scalable

Disadvantages:

- Not selective
- Optimality is questionable

T&D Integration: Uncertain Factors

Transmission System

- Some nodal injections (wind, solar)

Distribution System

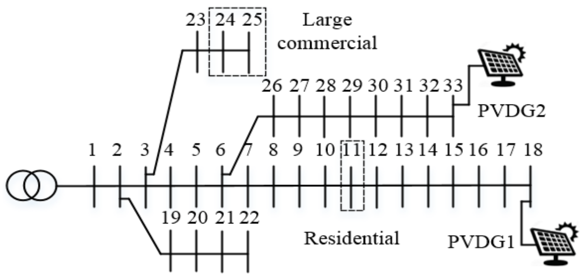
- Some nodal injections (primarily, solar)
- Whole-sale prices
- Availability of DERs
- Work in Progress: Topology uncertainty

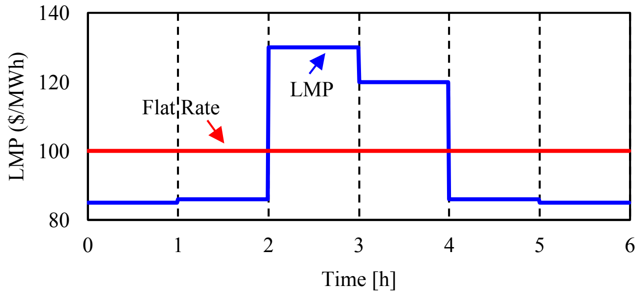
Humans

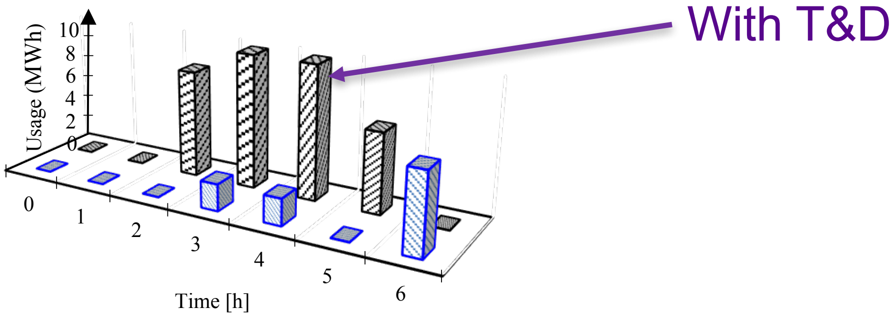
- Consumption preferences (weights)

T&D Integration: Simple Case Study

Impact of the Integration on the Usage of DERs





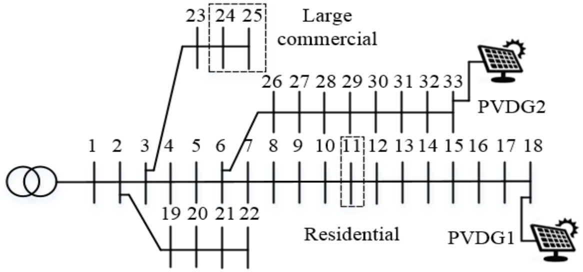


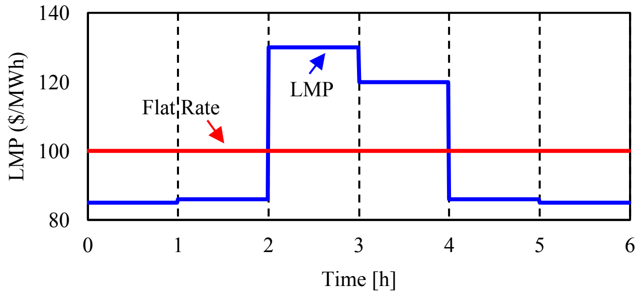
Two-fold impact:

- Higher usage
- Higher frequency

T&D Integration: Simple Case Study

T&D Cost Performance





COST PERFORMANCE

LMP Uncertainty, %	Utility's Whole-sale Revenue ($)	Utility Cost ($)	Consumer Cost ($)
5	81.6	5038.5	7985.7
10	163.2	4956.9	7904.1
15	244.8	4875.3	7822.5
20	326.4	4793.6	7740.9
25	408.0	4712.1	7659.3
30	489.6	4630.5	7577.7

Observation:

- Utility and customers benefits from the whole-sale uncertainty

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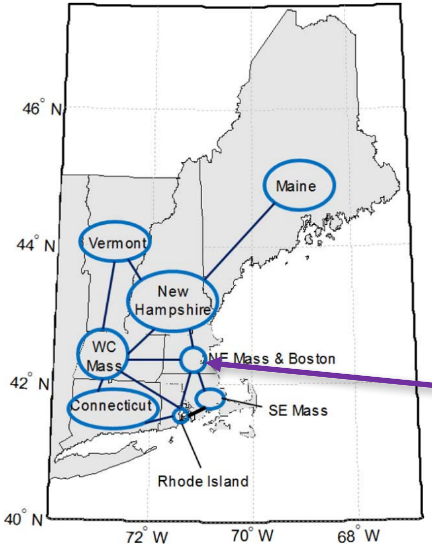
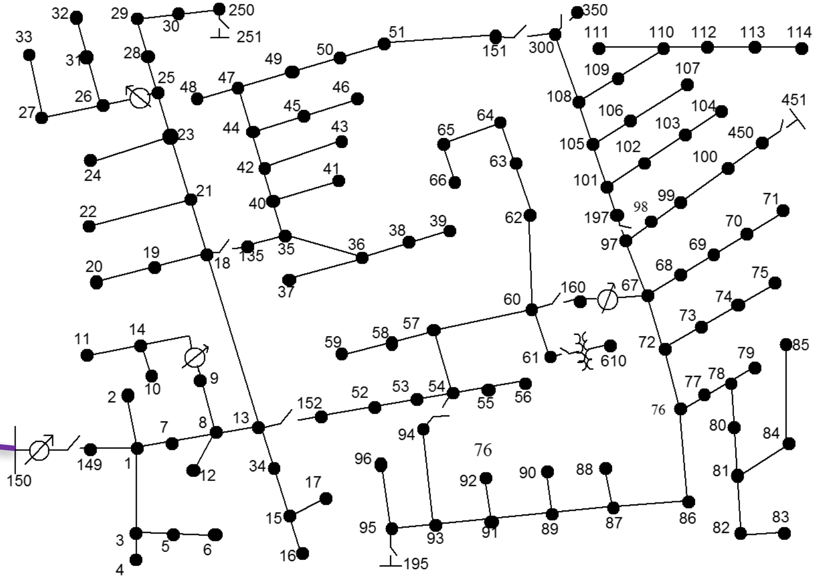
T&D Integration: Case Study

8-zone ISO NE testbed



123-bus IEEE Test Feeder



- Prospective RES and DER portfolios
- Reserve included
- Multi-period case/30 DA samples

T&D Integration: Case Study

Impact of Uncertainty

Cost Metric w/out TD

$$V^{\mathrm{TD}} = C^{\mathrm{W/out\ TD}} - C^{\mathrm{TD}}$$

Value

Cost Metric with TD

Transmission System

- Some nodal injections (wind, solar)

Distribution System

- Some nodal injections (primarily, solar)
- Whole-sale prices
- Availability of DERs

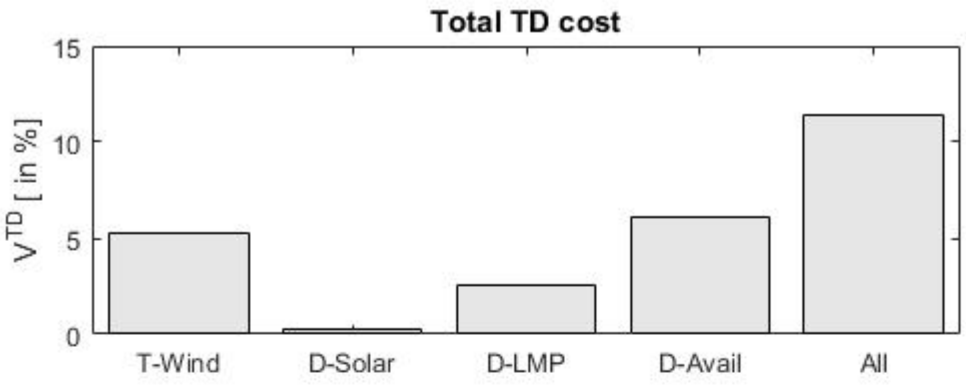
Humans

- Consumption preferences (weights)

T&D Integration: Case Study

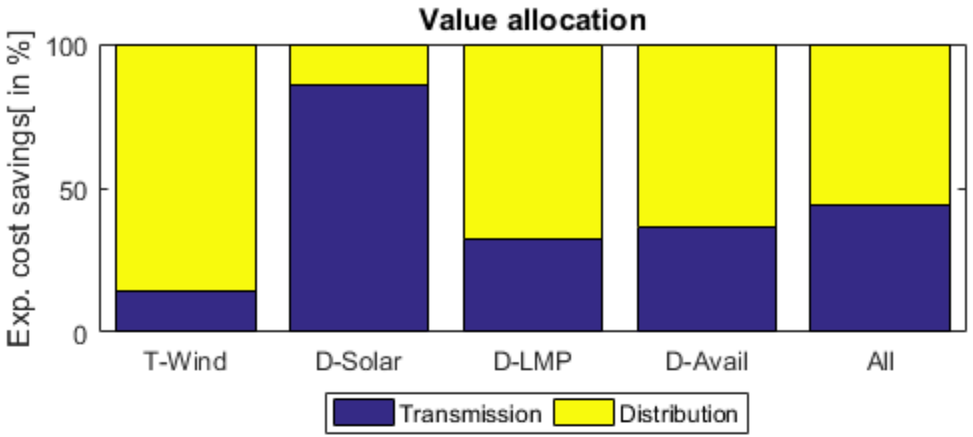
Impact of Uncertainty

$$V^{\mathrm{TD}} = C^{\mathrm{W/out\ TD}} - C^{\mathrm{TD}}$$



- Both systems benefit from the TD integration in presence of uncertainty
- Uncertainty affects the value selectively

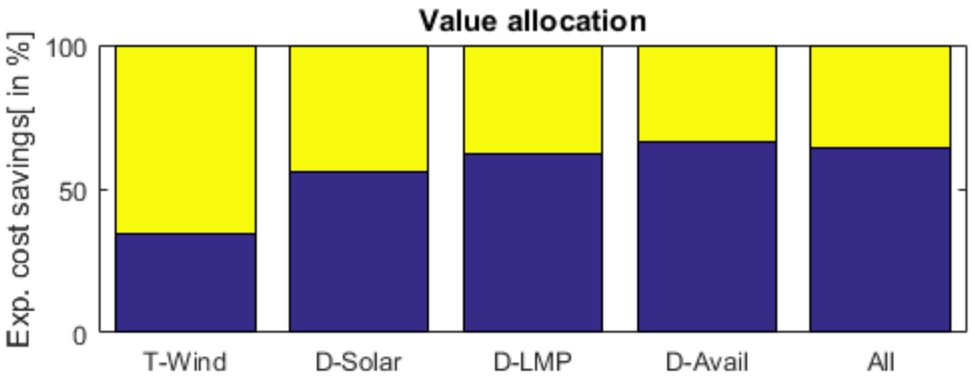
Impact of Uncertainty



- Distribution system gains most of cost savings
- It empirically motivates to pursue consumer-payment-minimization welfare functions (see Lu; Arroyo; etc)

T&D Integration: Case Study

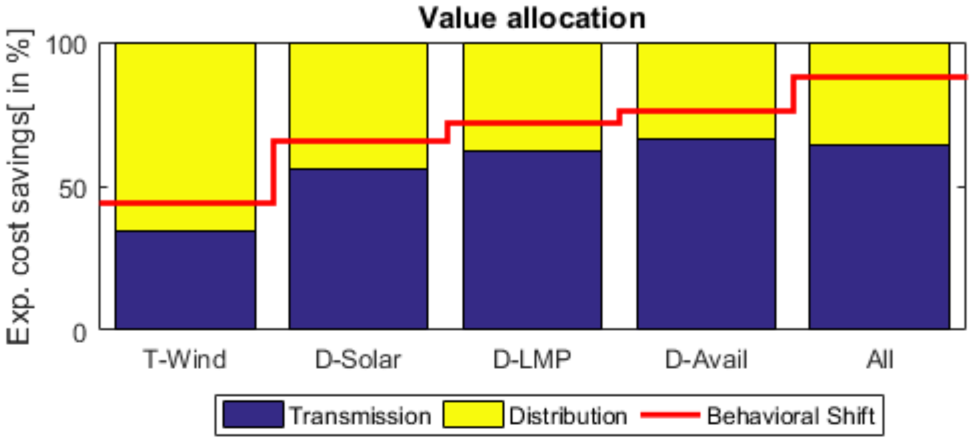
Impact of Uncertainty (with joint TD reserve)



- The total value increases by 12.1%
- Transmission system is more suitable for providing reserve services
- Reserve-wise distribution system is less flexible

T&D Integration: Case Study

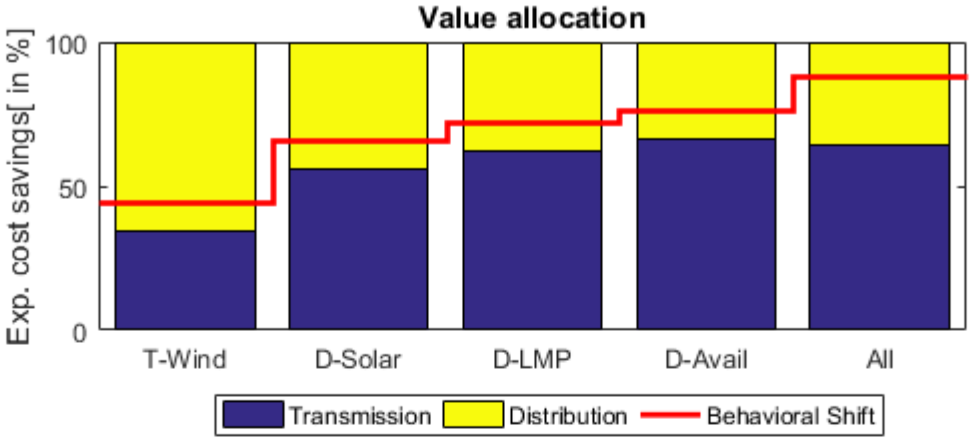
Impact of Human Behavior (with joint TD reserve)



- The total value reduces by 9.8%
- Human behavior tilts the allocation of the cost savings
- It may hamper distribution system’s cost savings quite significantly

T&D Integration: Case Study

Impact of Human Behavior (with joint TD reserve)



- The total value reduces by 9.8%
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Conclusion

"All models are wrong, but some are useful"

- Distribution grid benefits from whole-sale (transmission) uncertainty
- Superposition of benefits is a complex function of uncertainty
- Joint TD reserve hinders some benefits of the interface
- T&D integration is of greater value for dealing with T rather than D uncertainty (also, related to wind-load and solar-load correlations)
- Ignoring behavioristic aspects leads to overestimating T&D benefits, primarily to the distribution grid

Q&A

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