HARVARD
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Electricity Market for Distribution Networks

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Oct. 17th, 2016

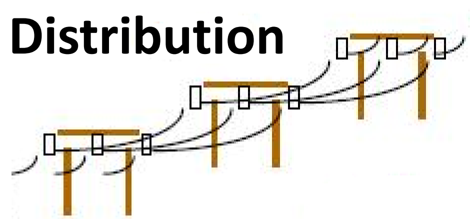
Electricity Grid 1.0

Power plant

Transmission

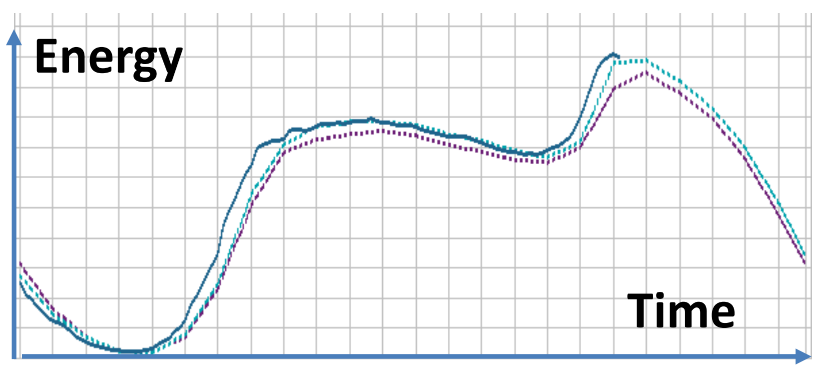
Users

Distribution



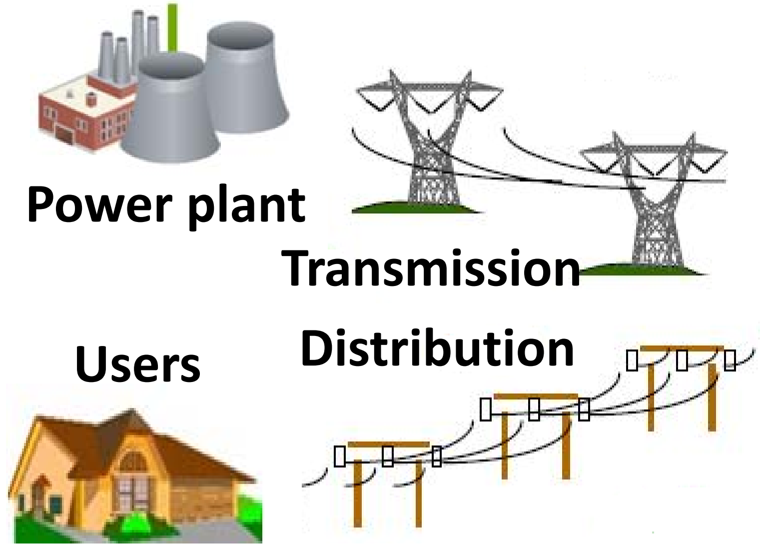
Supply = Demand

Unresponsive
Predictable



12 AM **12 AM**

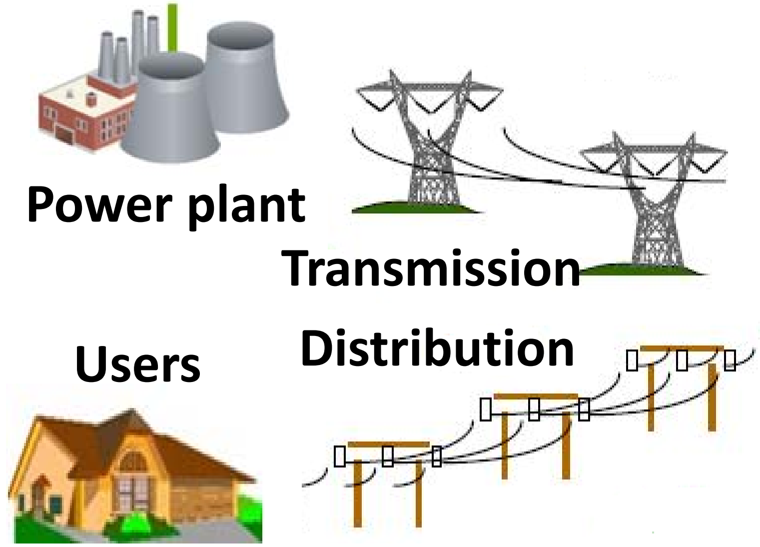
Electricity Grid 1.0



Supply = Demand

Controllable | **Unresponsive**
Predictable

Transmission market



Supply = Demand

Trans. Market

Controllable

Unresponsive

Predictable

A Monthly Bill

Forward Energy Market

e.g., Day-ahead market (one day forward);

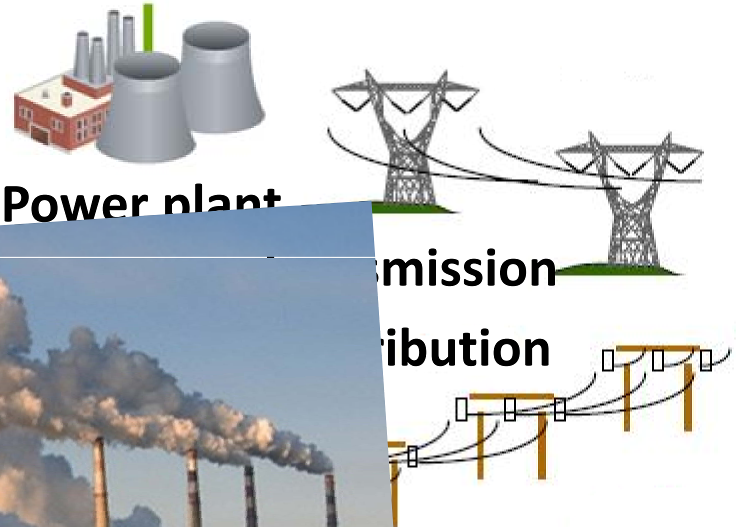
Real-time Energy Market

e.g., Every five minutes in PJM;

Ancillary service market

e.g., Spinning reserve market; (short-term, unexpected changes)

Transmission market



Demand

Unresponsive

Predictable

market (one day forward);

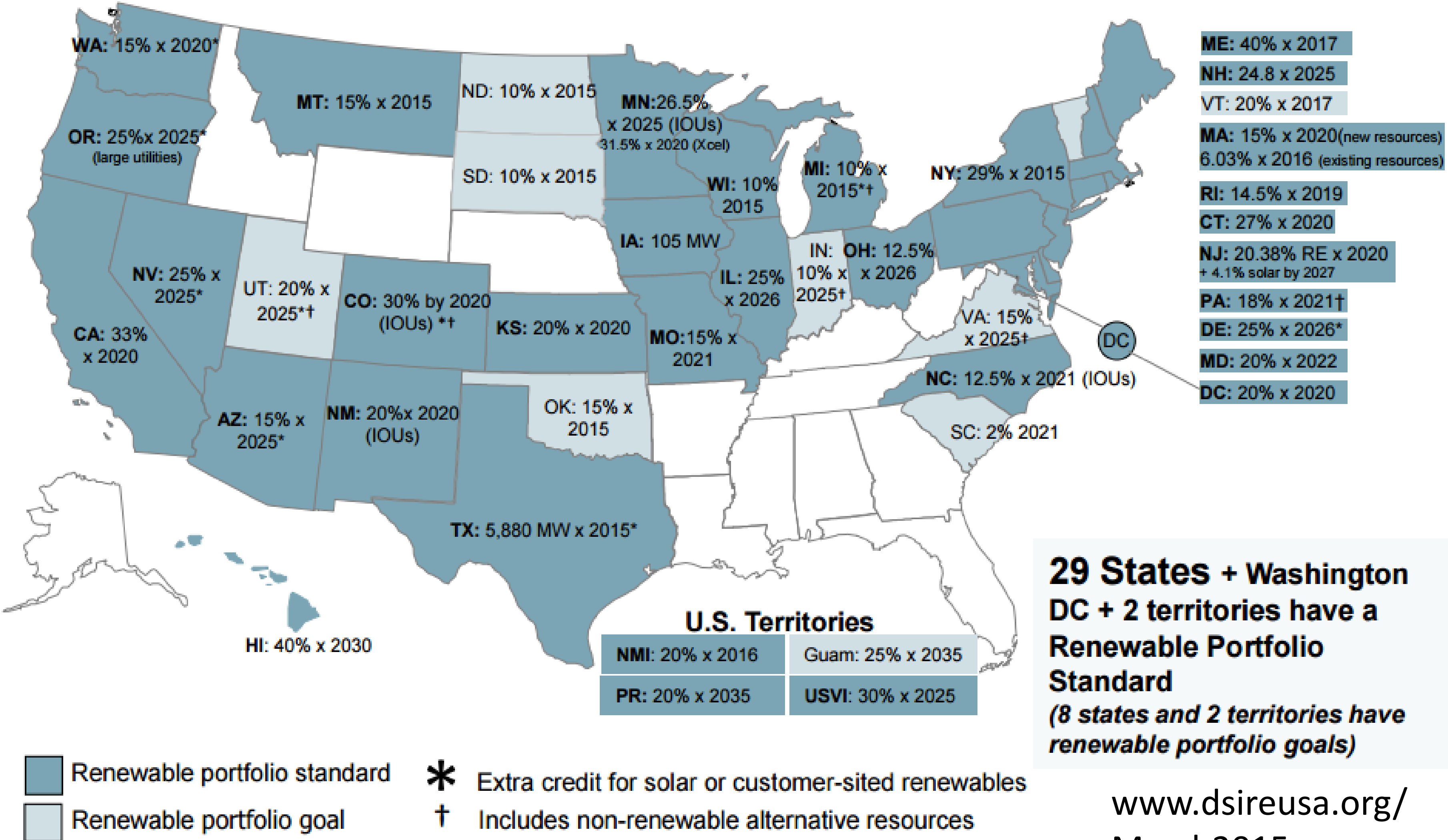
Real-time Energy Market

e.g., Every five minutes in PJM;

Ancillary service market

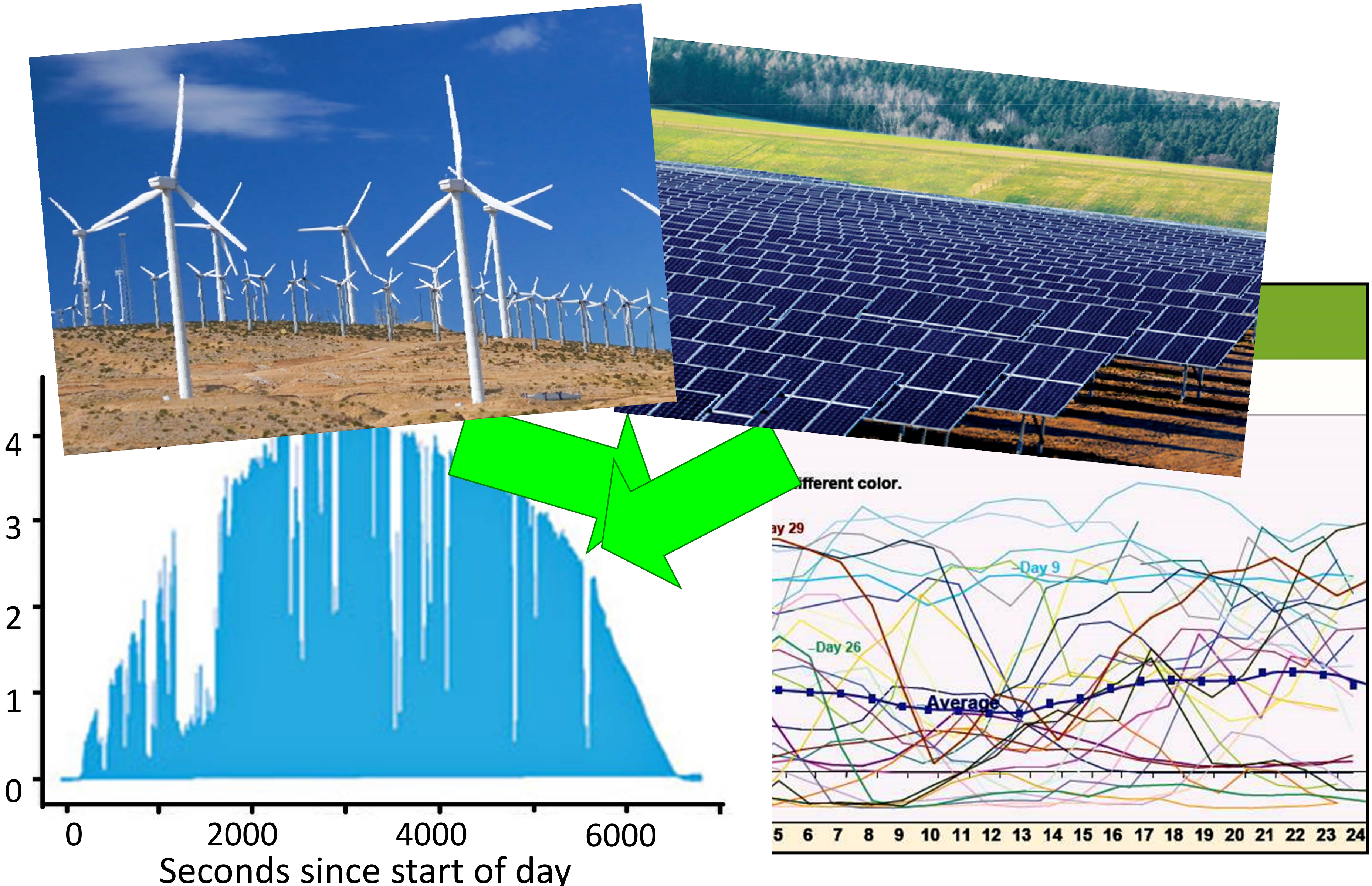
e.g., Spinning reserve market; (short-term, unexpected changes)

Renewable energy



www.dsireusa.org/
March2015

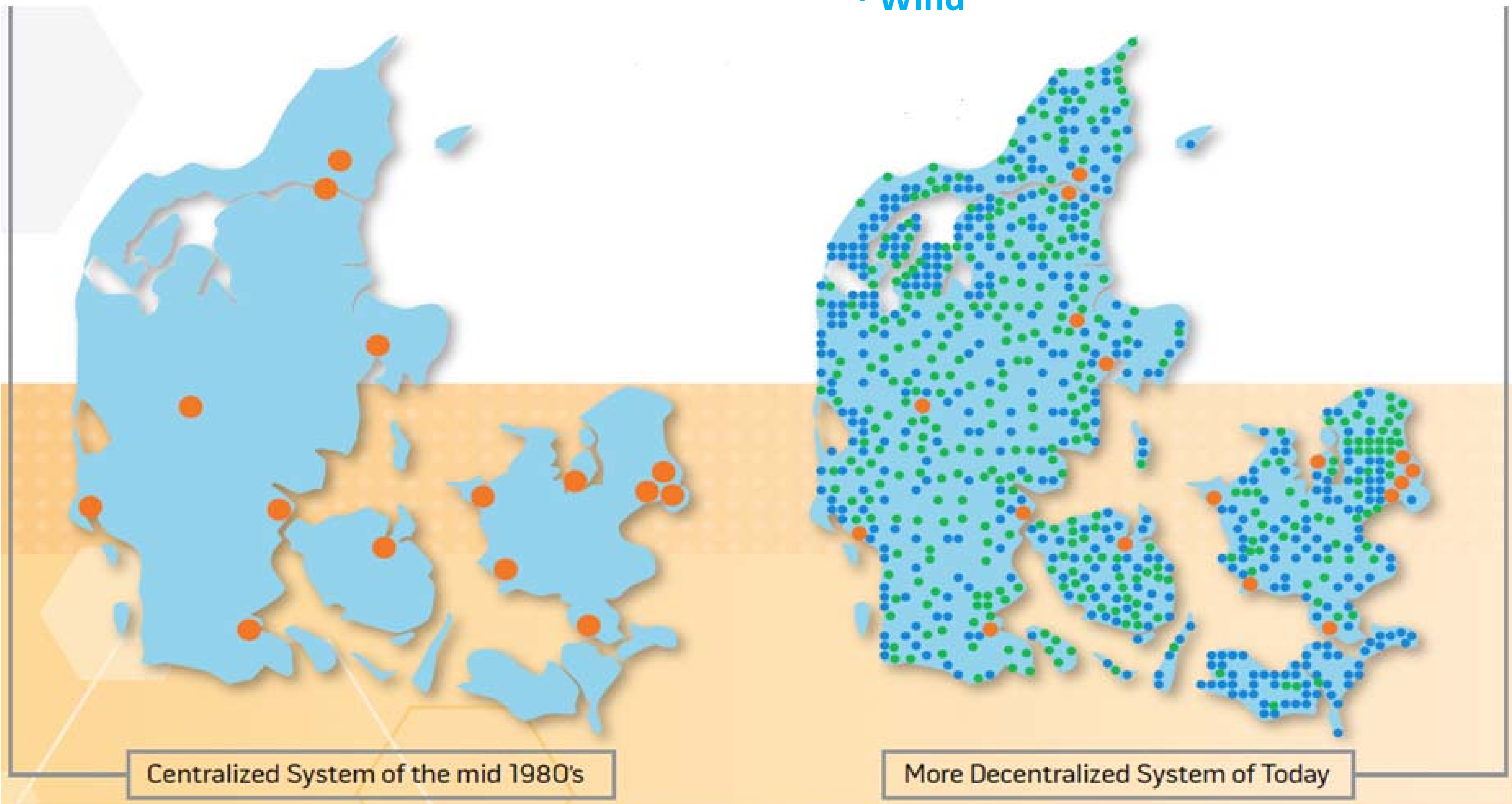
Random and intermittent



Source: Rosa Yang, EPRI

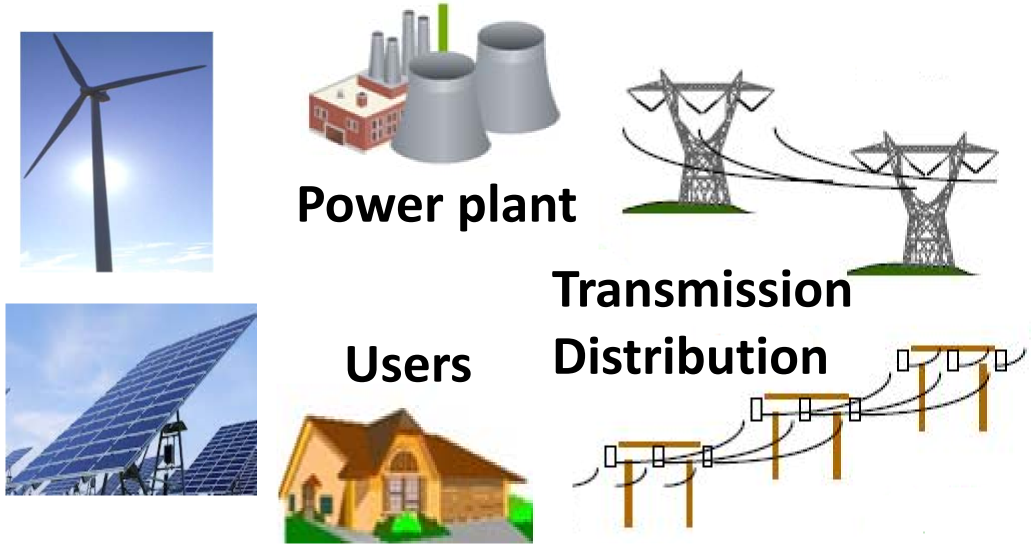
More distributed

- Small CHP (Combined Heat & Power)
- Large CHP (Combined Heat & Power)
- Wind



Denmark's progress over the past decades

Tomorrow's Grid 2.0



Supply = Demand

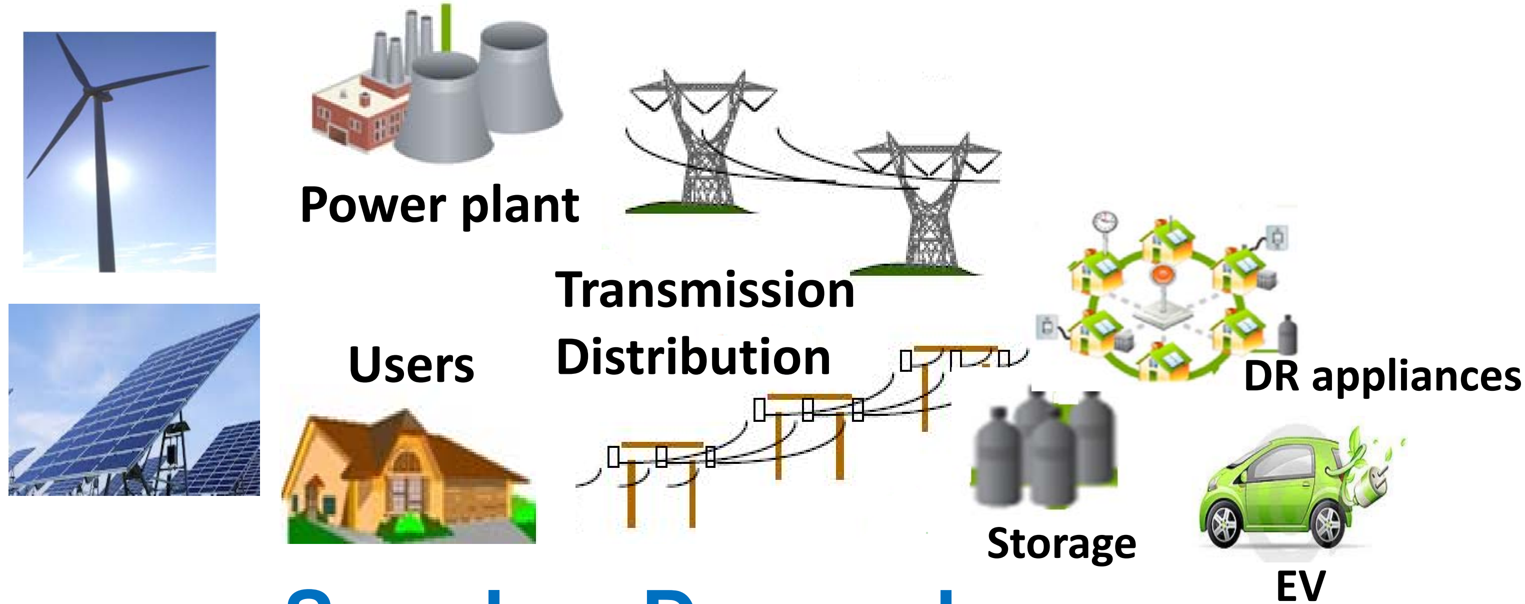
Less controllable   **Responsive ← Unresponsive**

Highly uncertain

Distributed

Large scale

Tomorrow's Grid 2.0



Supply = Demand

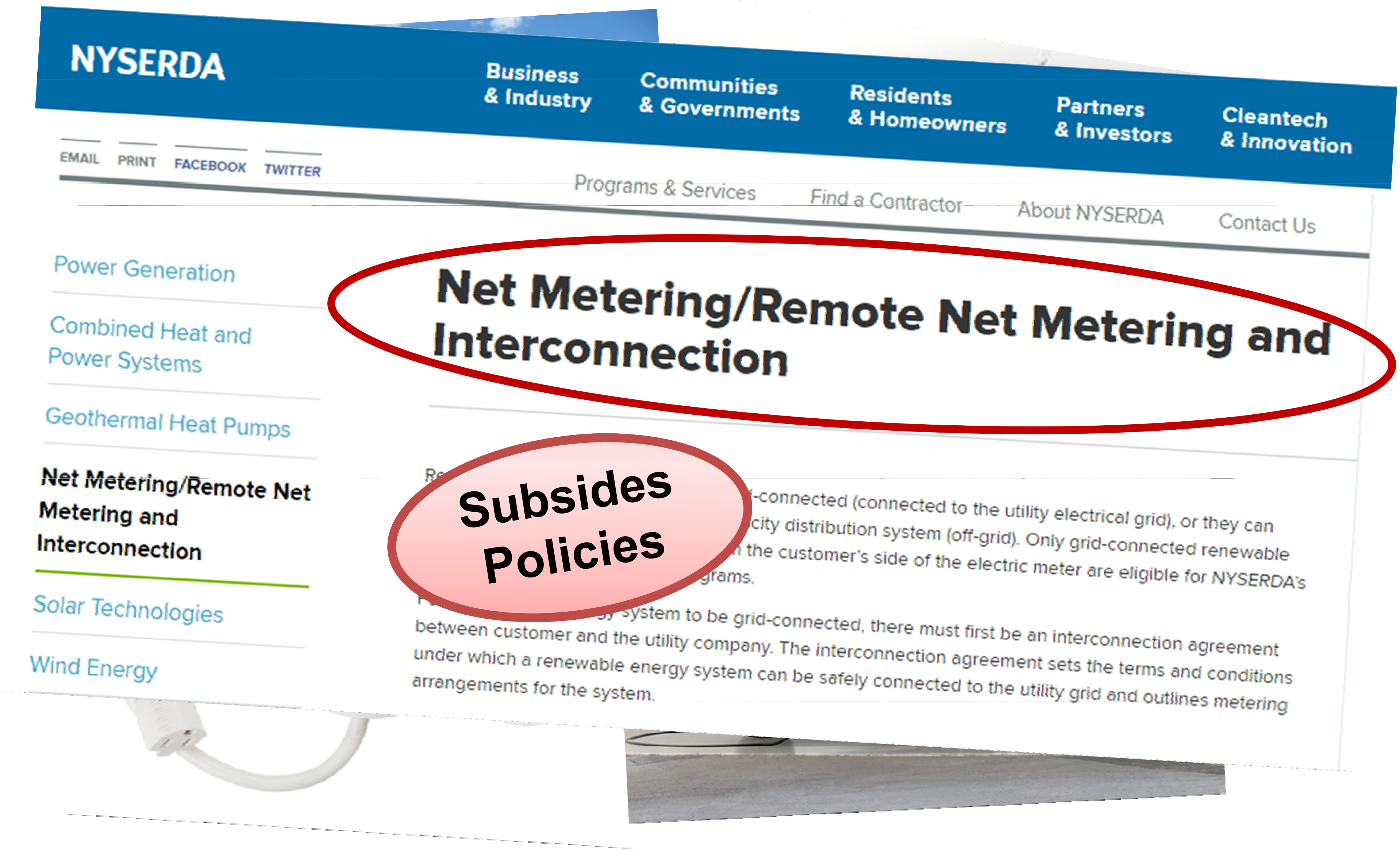
Less controllable **Responsive**
Highly uncertain
Distributed
Large scale

Solar PVs
Wind turbines

Distributed Energy Resources

Smart appliances
Storage
Electric vehicles

Transforming Electricity Grid: DER



Debate over solar rates simmers in the Nevada desert

February 27, 2016

The future of home-based solar power is on the line in Nevada, as solar advocates and utility companies debate how to **regulate so-called 'net energy metering' rates** for customers using solar panels **connected to the grid.**

Sources: PBS

Electricity Market for Distribution Networks: Challenges

Power Engineering:
Power flow, system dynamics, operation constraints

Human Incentive:
Strategic behavior, self-interested, market power

Uncertainties:
Renewable energy, user’s behavior, emergency

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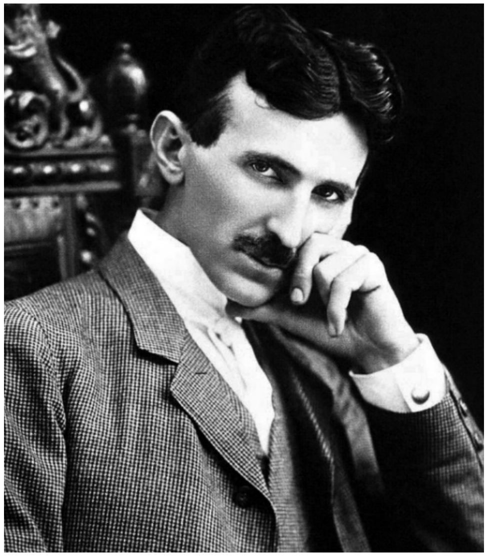
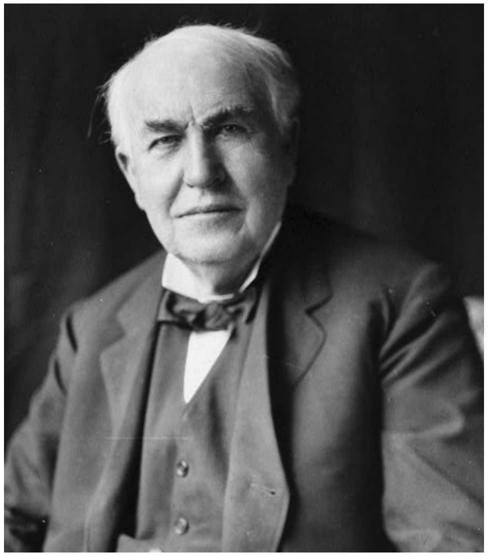
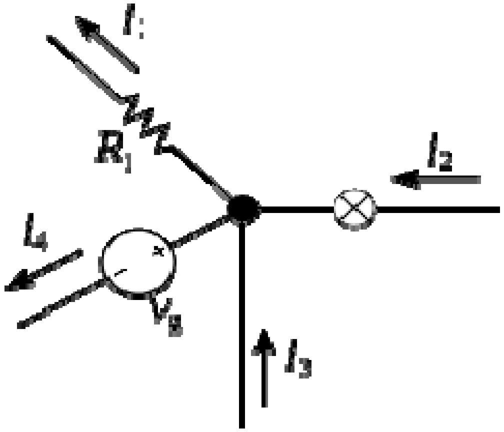
Transmit and Distribute Power

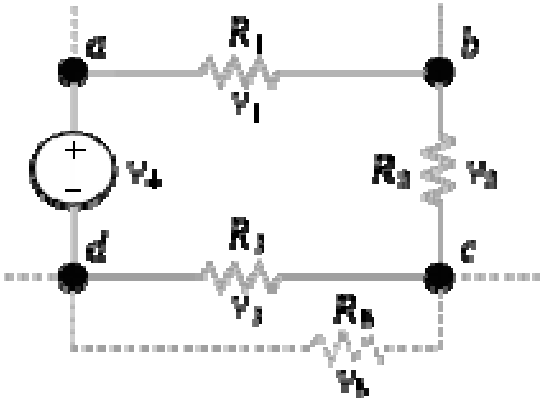




Kirchhoff's law

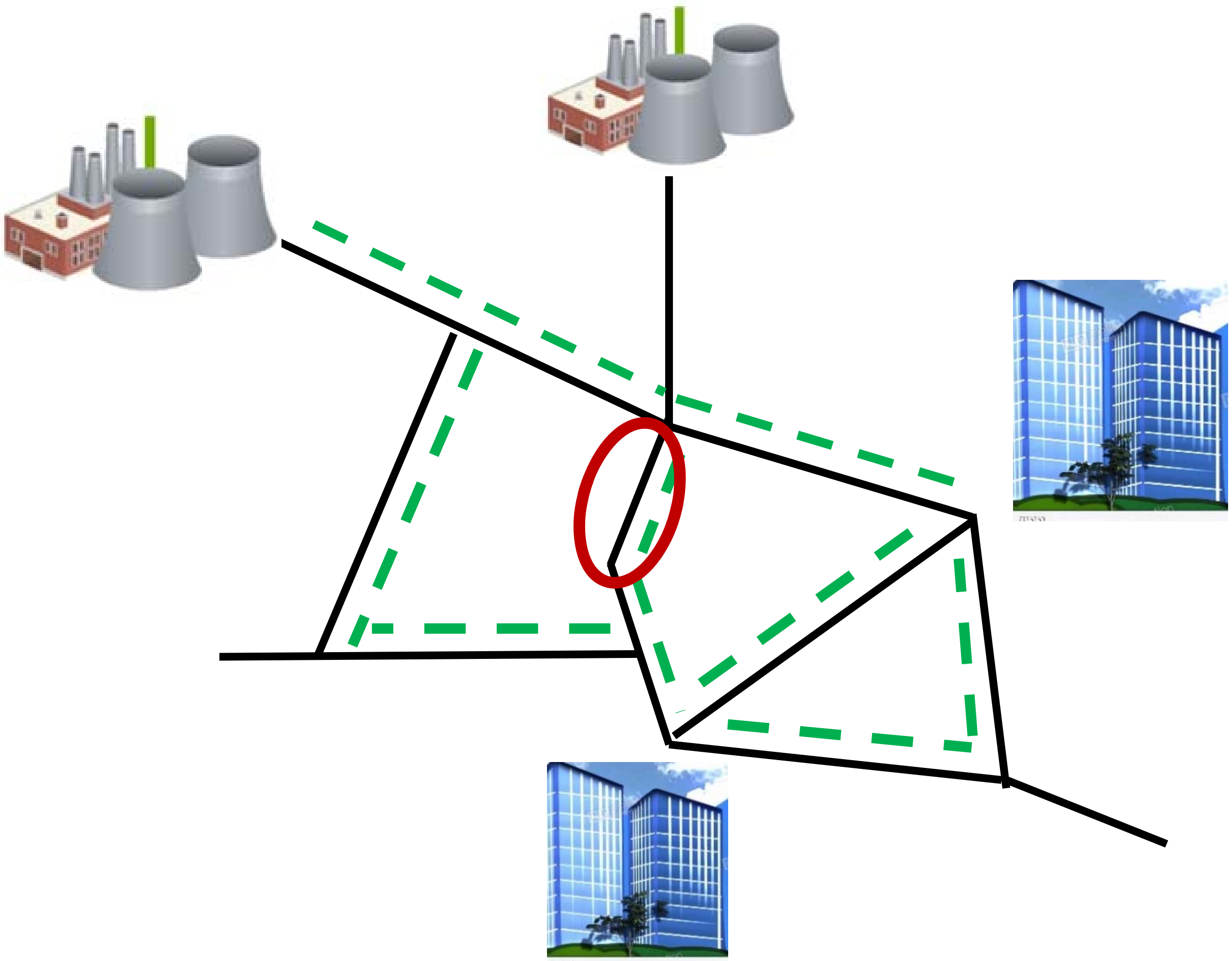


$$i_1 - i_2 - i_3 + i_4 = 0$$



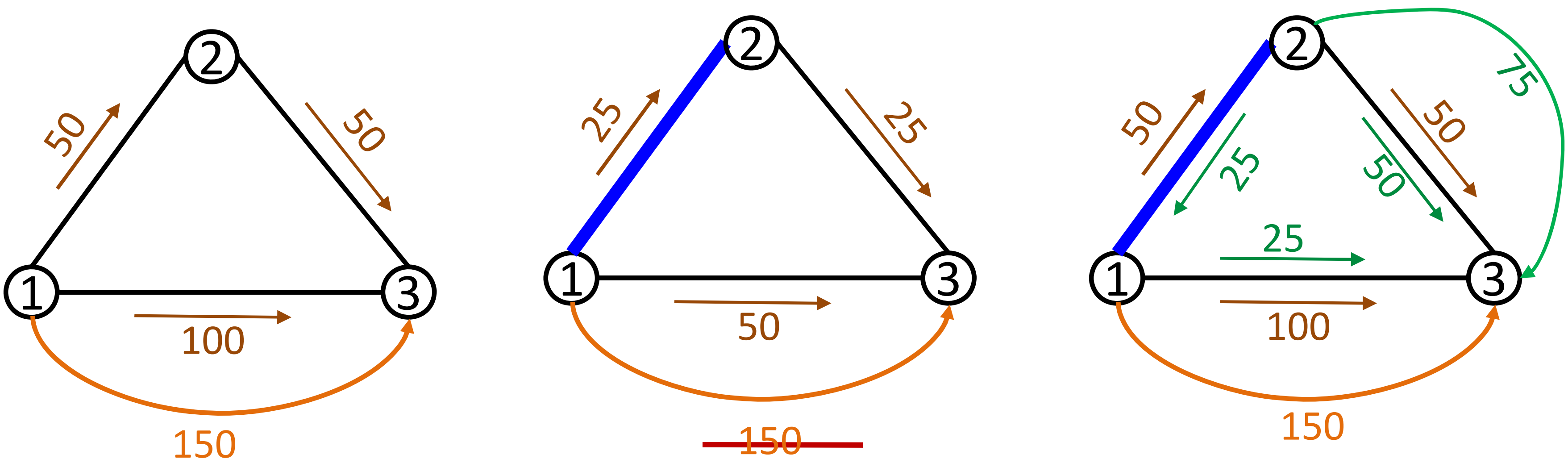
$$v_1 + v_2 + v_3 - v_4 = 0$$

Transmit and Distribute Power: Kirchhoff's Law



Capacity constraint on any line or node limit the entire flow

Challenges: An Example

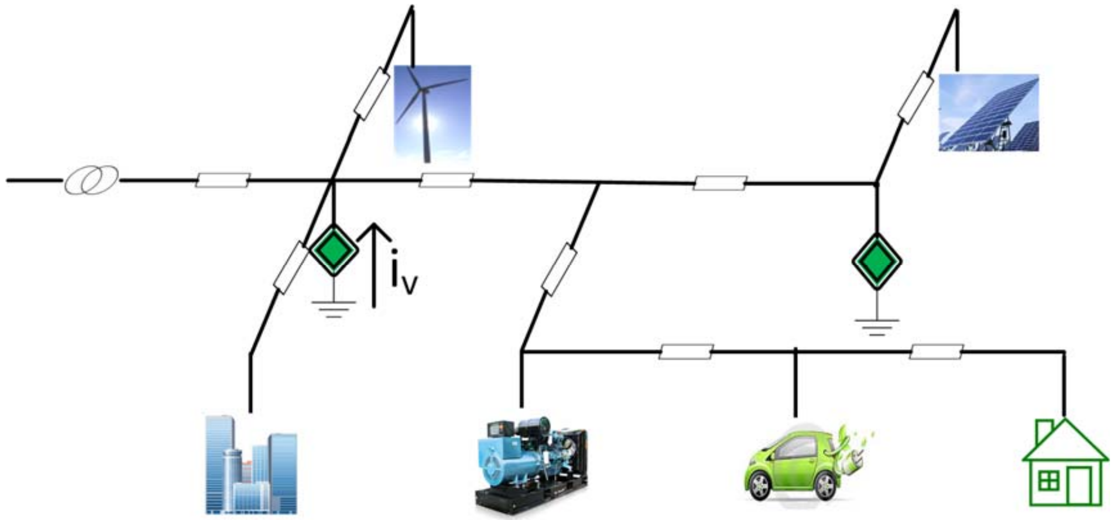


Line 1-2 capacity: 25

Transaction 2→3 alleviates congestions on line 1-2

1, 2: generation nodes/buses; 3: load bus (two users)

How much to pay for public distribution service?



Social Welfare

$$\max_{d,g,y,u,l} \quad B(d) - C(g)$$

Benefit Cost

$$\text{s.t.} \quad d - g = y$$

$$L(y,u) = l$$

$$f(y,u) \le 0$$

Physical Constraints

d: demand;

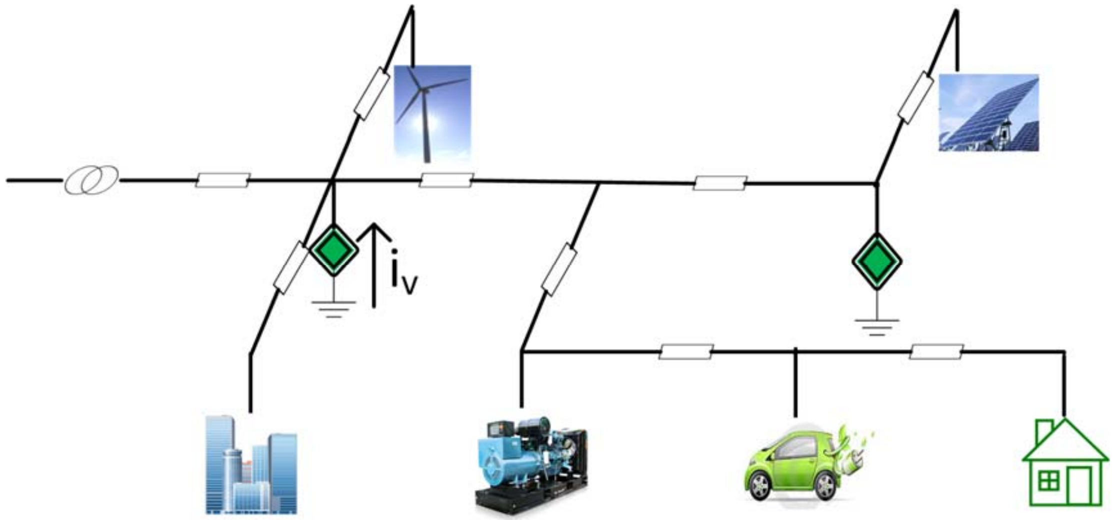
g: generation;

y: net power injection

u: other physical variables

l: power losses;

How much to pay for public distribution service?



Social Welfare

$$\max_{d,g,y,u,l} \quad B(d) - C(g)$$

$$\text{s.t.} \quad d - g = y$$

$$L(y,u) = l$$

$$f(y,u) \le 0$$

(d, g) ←

Individual

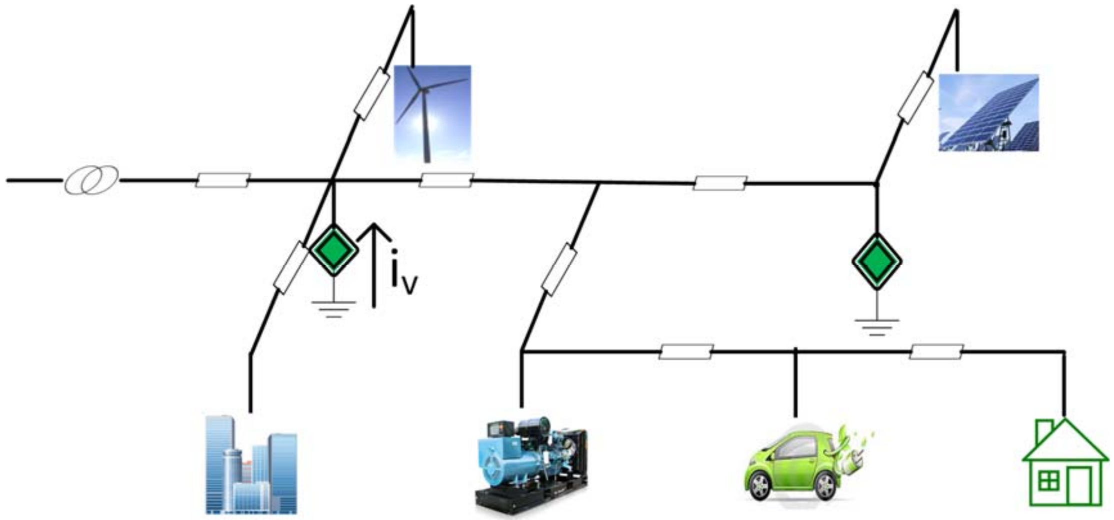
$$\max_{d} \; B(d) - p \cdot d$$

price

$$\max_{g} \; p \cdot g - C(g)$$

How to set the price?

How to choose the prices?



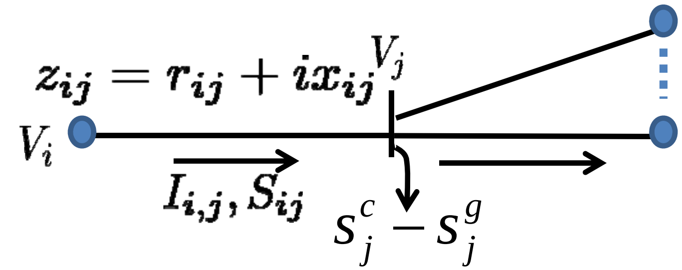
Social Welfare

$$\max_{d,g,y,u,l} \quad B(d) - C(g)$$
$$\text{s.t.} \quad d - g = y$$
$$L(y,u) = l$$
$$f(y,u) \le 0$$

Given an convex problem, duality of the optimization provide efficient prices, p^*

Challenges: Nonconvexity

Nonconvex Optimal Power Flow



$$\min \quad C\left(\sum_{(0,j)} P_{0j}\right) - \sum_i U_i(p_i) + \sum_{i,j} r_{i,j} \, |I_{i,j}|^2$$

$$\text{over} \quad x := (S, \ell, v, p, q)$$

$s_j := p_j + iq_j \quad S_j := P_j + iQ_j$

$\ell_{ij} := |I_{i,j}|^2 \qquad v_i := |V_i|^2$

$$\text{s. t.} \quad \boxed{\ell_{ij} = |S_{ij}|^2 / v_i \,,}$$

Nonconvex

$$v_j = v_i + 2\,\mathrm{Re}\left(z_{ij}^* S_{ij}\right) - |z_{ij}|^2 \ell_{ij} \,,$$

$$\sum_{i \to j} \left(S_{ij} - z_{ij}\ell_{ij}\right) - \sum_{j \to k} S_{jk} = s_j \,,$$

Branch flow model

$$\underline{v}_i \le v_i \le \overline{v}_i \,,$$

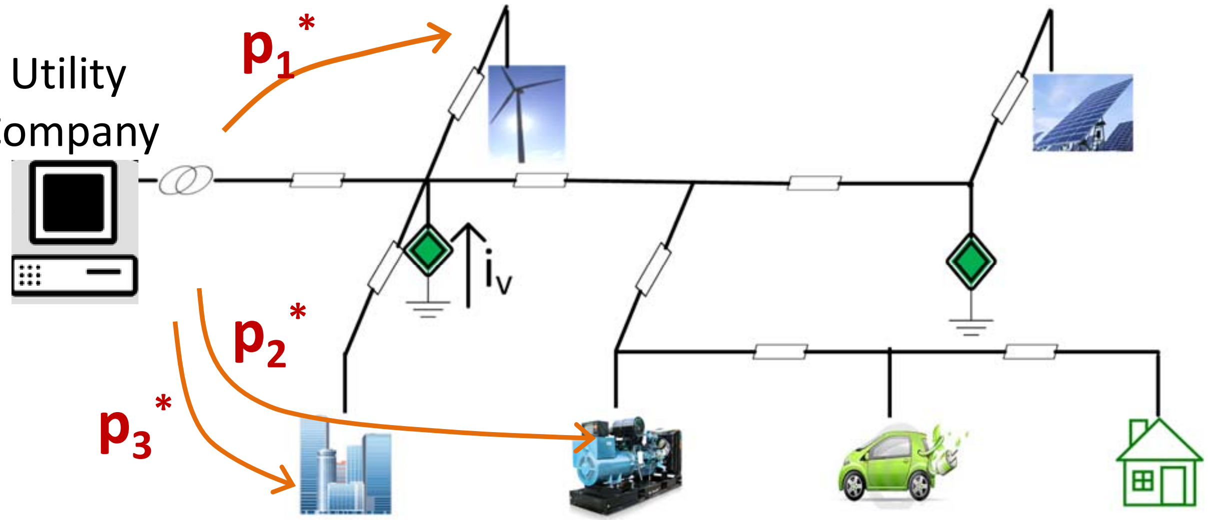
$$\underline{q}_i \le q_i \le \overline{q}_i \,,$$

$$\underline{p}_i \le p_i \le \overline{p}_i \,,$$

Convexification gives exact solutions
[Lavaei 2011, Li 2012, Gan 2012, 2013]

Baran & Wu 1989, Chiang & Baran 1990

Efficient Prices: Market Equilibrium (d^*, g^*, p^*)



Social Welfare

$$\max_{d,g,y,u,l} \quad B(d) - C(g)$$

$$\text{s.t.} \quad d - g = y$$

$$L(y,u) = l$$

$$f(y,u) \le 0$$

(d^*, g^*) ←

Individual

$$\max_{d} \; B(d) - p^* \cdot d$$

$$\max_{g} \; p^* \cdot g - C(g)$$

A Distributed Algorithm to Reach the Equilibrium

Utility company gathers requests

↓

Utility company updates price

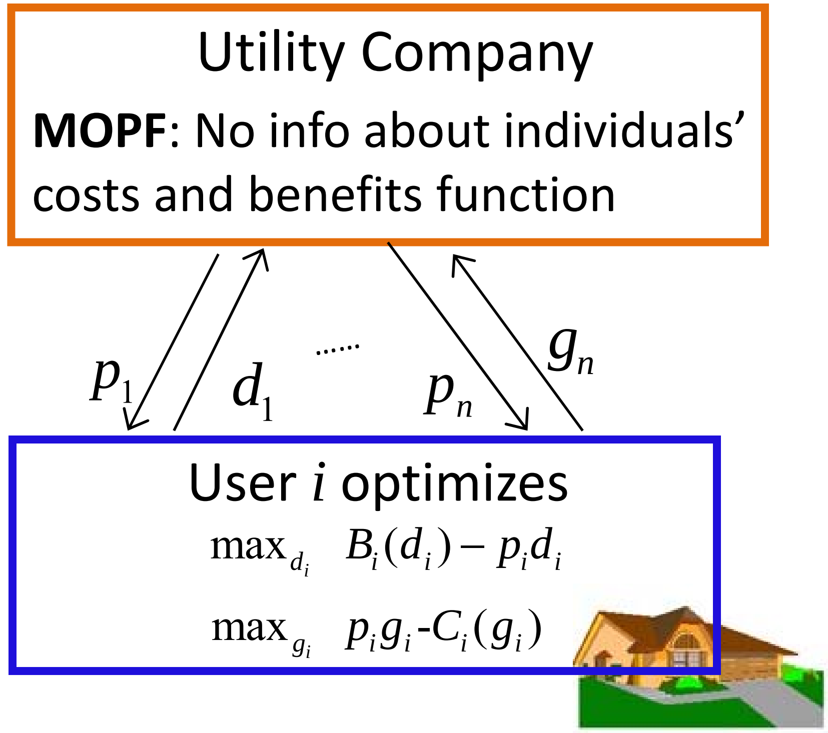
↓

Individual *i* receives the price

↓

Individual *i* updates its request

Privacy for individuals

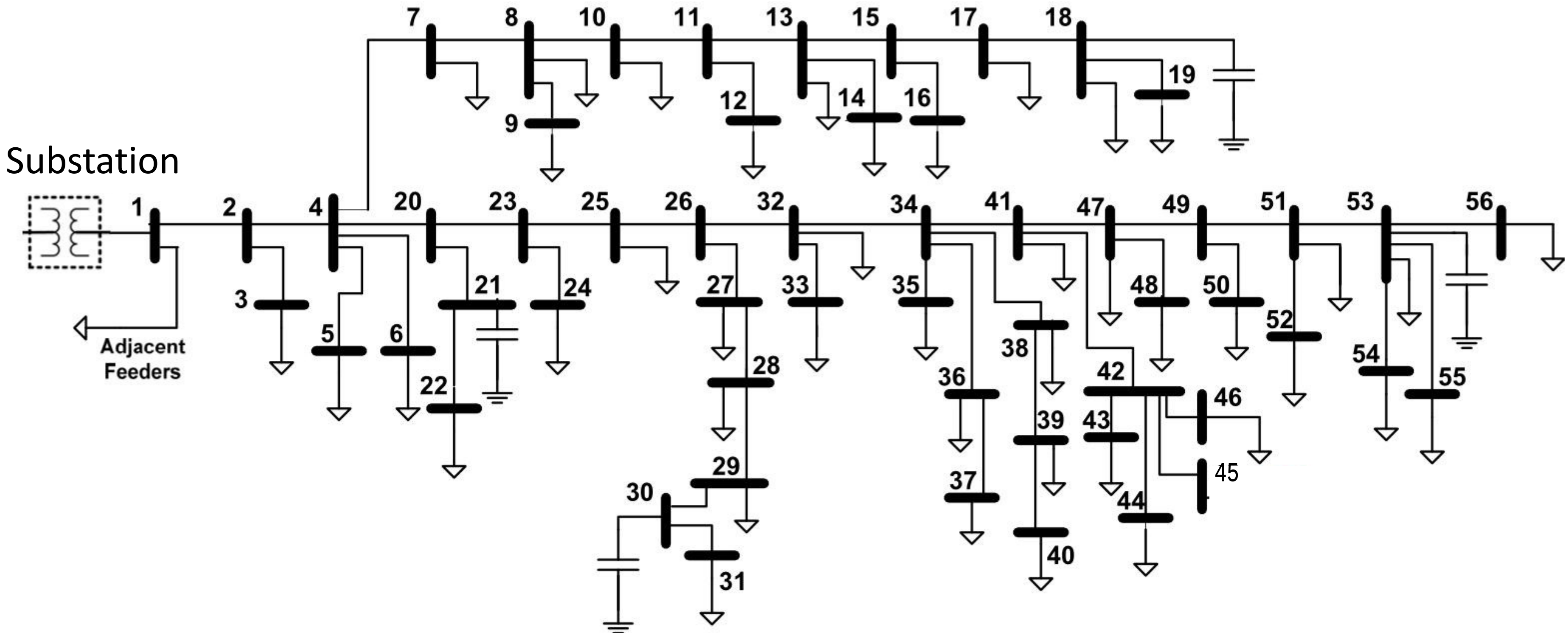


***Theorem** [Li et al. 2012, 2014]:* The distributed algorithm converges to market equilibrium over a radial distribution network.

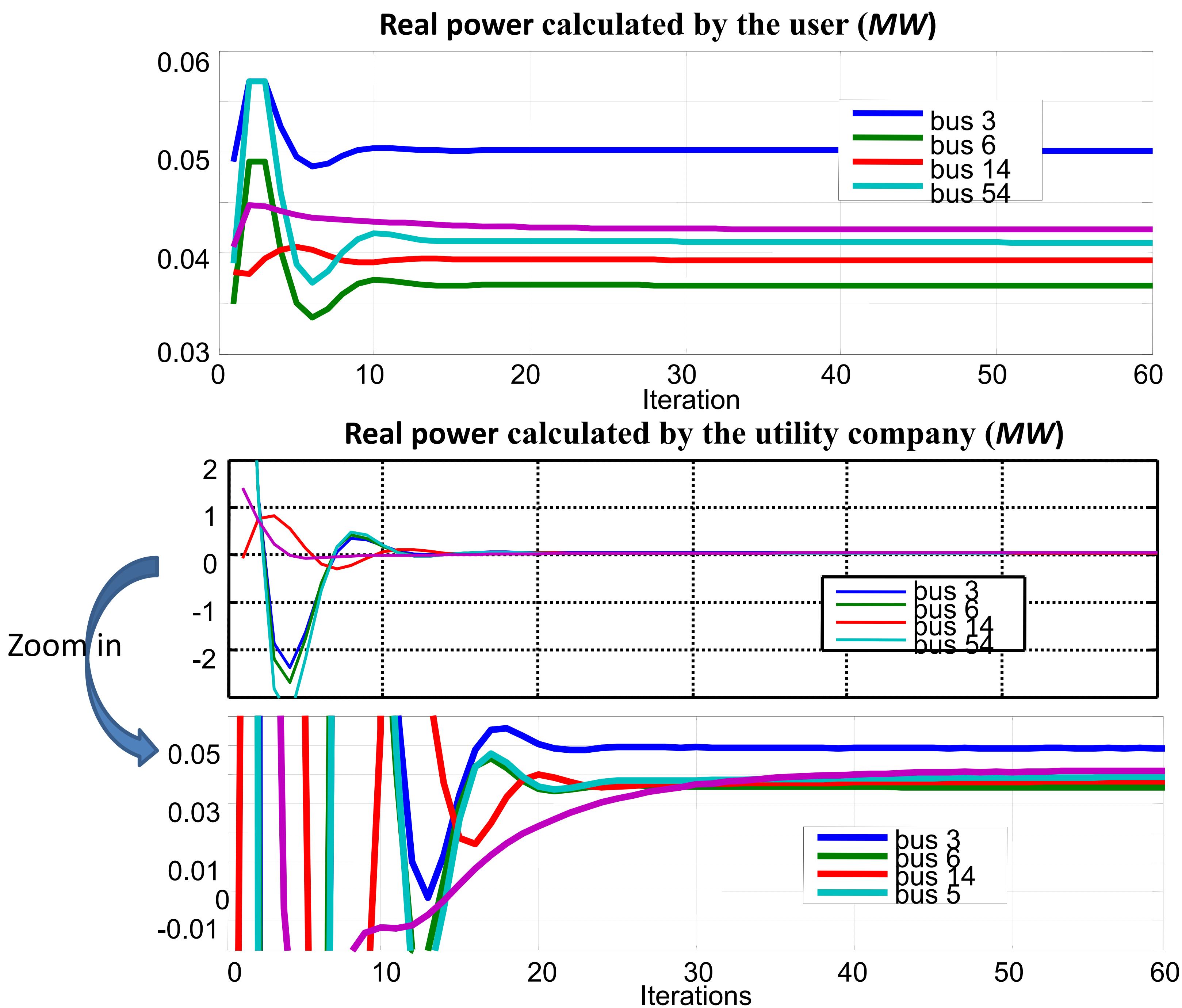
***Recent work**:* Distributed algorithms with **limited communication**.

[2015, 2016]

Case studies

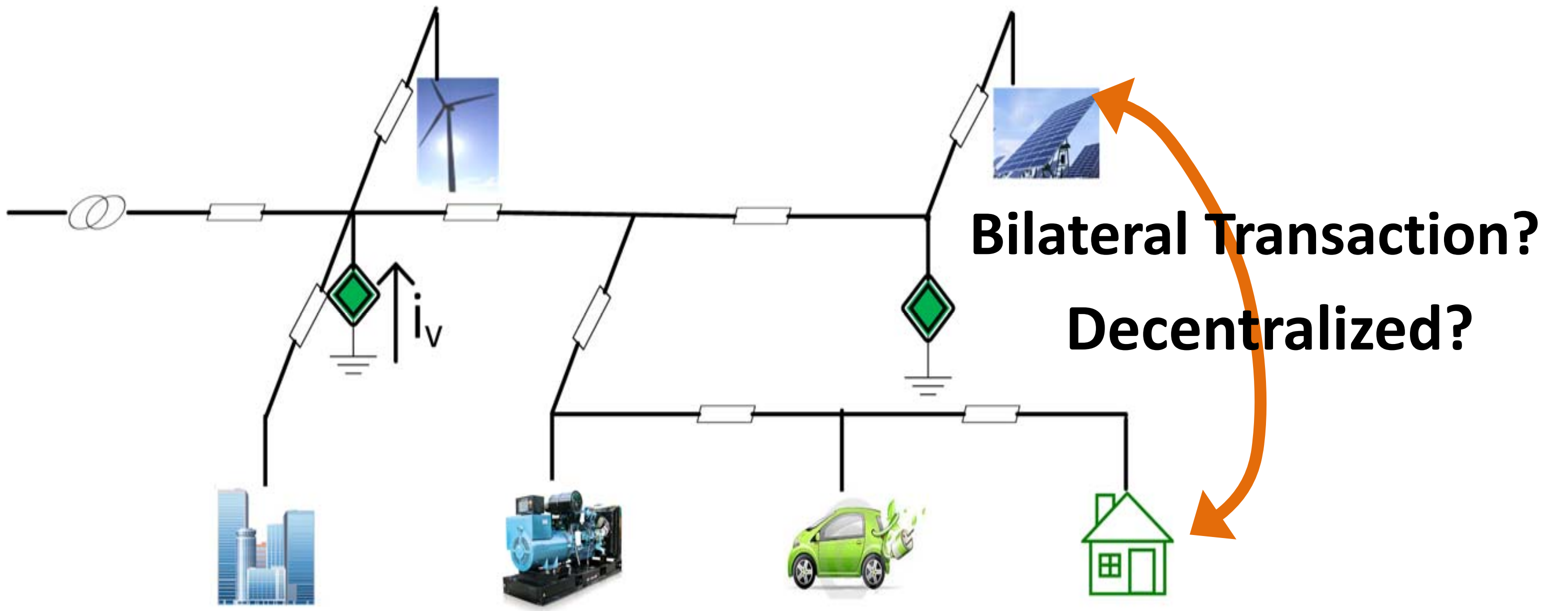


Schematic Diagram of a South California Edison distribution System



Real power calculated by the user (MW)
0.06
0.05
0.04
0.03
0
10
20
30
40
50
60
Iteration
bus 3
bus 6
bus 14
bus 54
Real power calculated by the utility company (MW)
2
1
0
-1
-2
bus 3
bus 6
bus 14
bus 54
Zoom in
0.05
0.03
0.01
0
-0.01
bus 3
bus 6
bus 14
bus 5
0
10
20
30
40
50
60
Iterations

How about decentralized market?



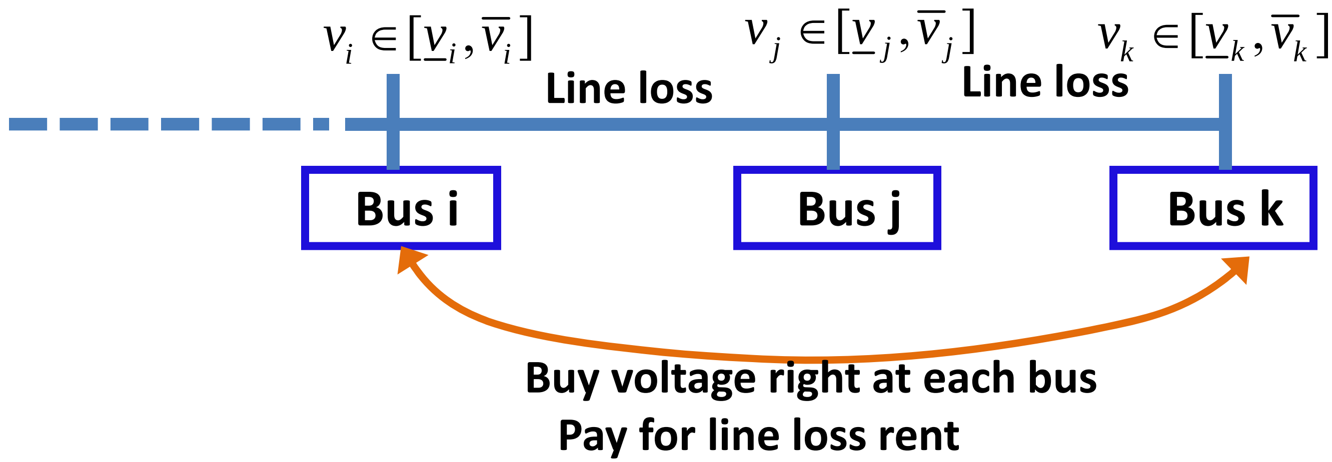
Challenge: Externality:

Any local change induces a (complicated) global change!

Delivery Service (in distribution networks)

- Voltage support (constraint): $\underline{v}_i \le v_i \le \overline{v}_i$
- Power loss

Market rule



Each Bilateral Transaction

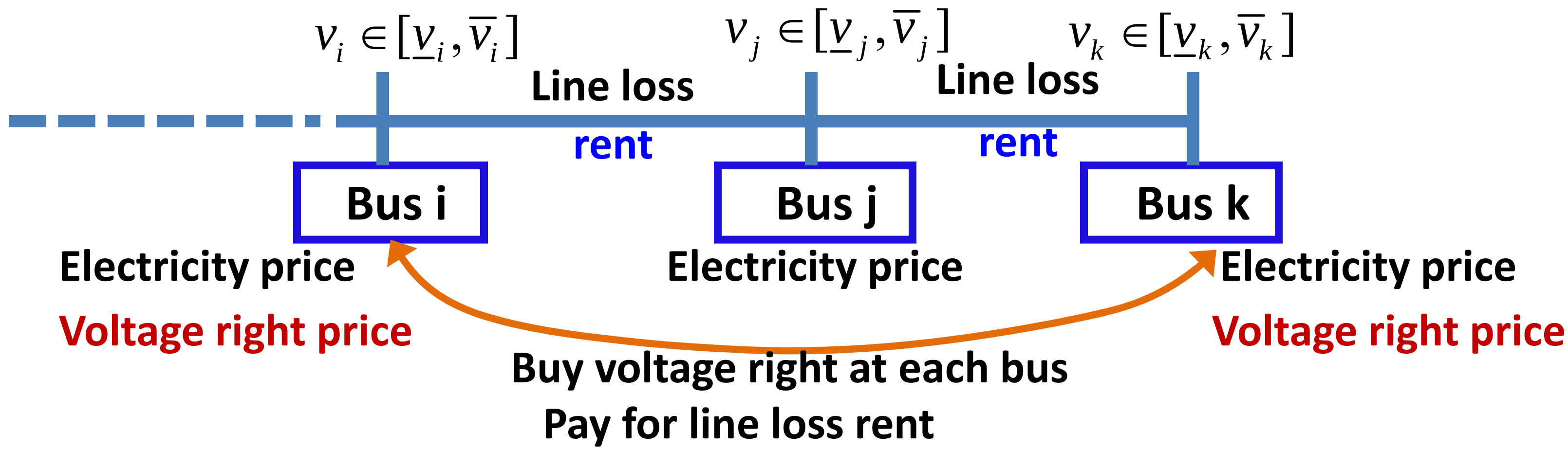
- Buy voltage right (constraint) at each bus
- Pays for line loss rent of each line

Q: **Budget balance** on the voltage right and also the power loss?

Voltage right at each bus = Σ_i voltage right bought by transaction i

Power losses at each line = Σ_i Losses paid by transaction i

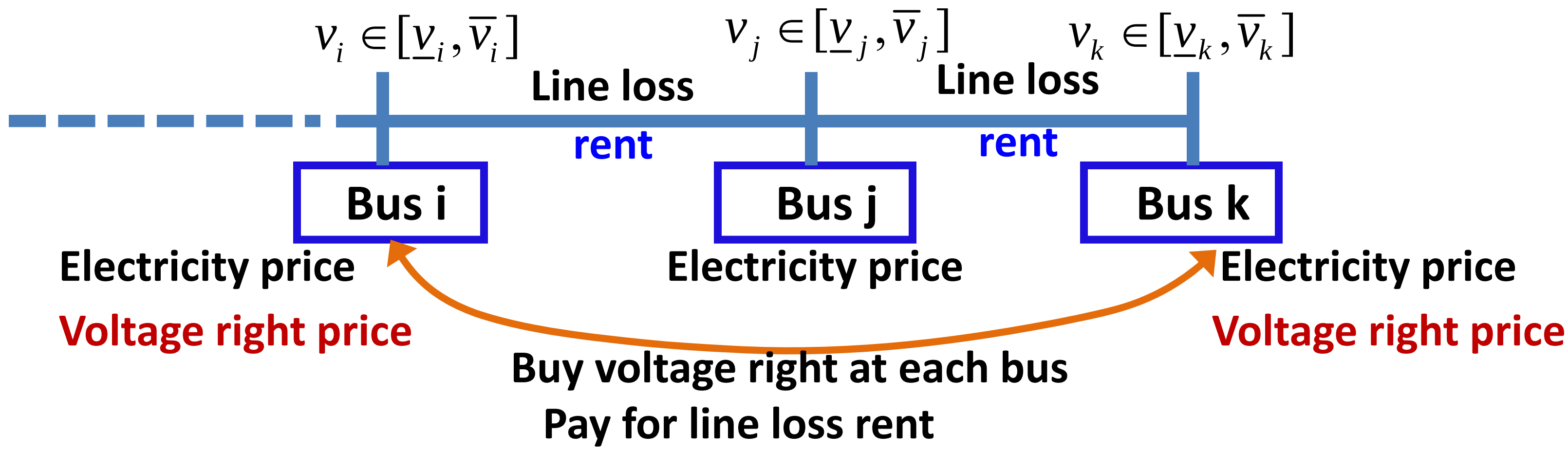
Market Prices and Equilibrium



- Each user/generator maximizes net benefit/profit given elec. prices

$$\max_{d} \; B(d) - p \cdot d \qquad\qquad \max_{g} \; p \cdot g - C(g)$$

Market Prices and Equilibrium



- Each user/generator maximizes net benefit/profit given elec. price
- For each unit transaction between any two node i and k

Elec. Price i = Elec Price j + Sum(Voltage right price*Quantity$_1$) + Sum (Line loss rent * Quantity$_2$)

- Voltage right price is 0 if there is excess voltage capacity supply

Question: How to determine Quantity$_1$,Quantity$_2$?

How to determine the quantities?

Duality of the Social Welfare Maximization

$$\begin{aligned} \max_{d,g,y,u,l} \quad & B(d) - C(g) \\ \text{s.t.} \quad & d - g = y \\ & L(y,u) = l \\ & f(y,u) \leq 0 \end{aligned}$$

+

Budget Balance Constraints on Voltage Right and Line Losses

→

Quantity$_1$
Quantity$_2$
Prices

For each unit transaction between any two node i and k

Price i = Price j + Sum(Voltage right price*Quantity$_1$)
+ Sum (Line loss rent * Quantity$_2$)

How to determine the quantities?

One Allocation Rule for Voltage Right and Line Losses

Quantity$_1$: $\bar{\beta}_i^k = \frac{(v_k - v_k^{nom}) R_{ki}}{\sum_{j=1}^n R_{kj} p_j}; \quad \underline{\beta}_i^k = -\frac{(v_k - v_k^{nom}) R_{ki}}{\sum_{j=1}^n R_{kj} p_j}.$

Quantity$_2$: $\phi_i^k = \frac{L_k L_{k,i}}{\sum_{j=1}^n L_{k,j} p_j}$

R: resistance
V: voltage
p: power injection
P,Q: real/reactive power flow
L: line losses

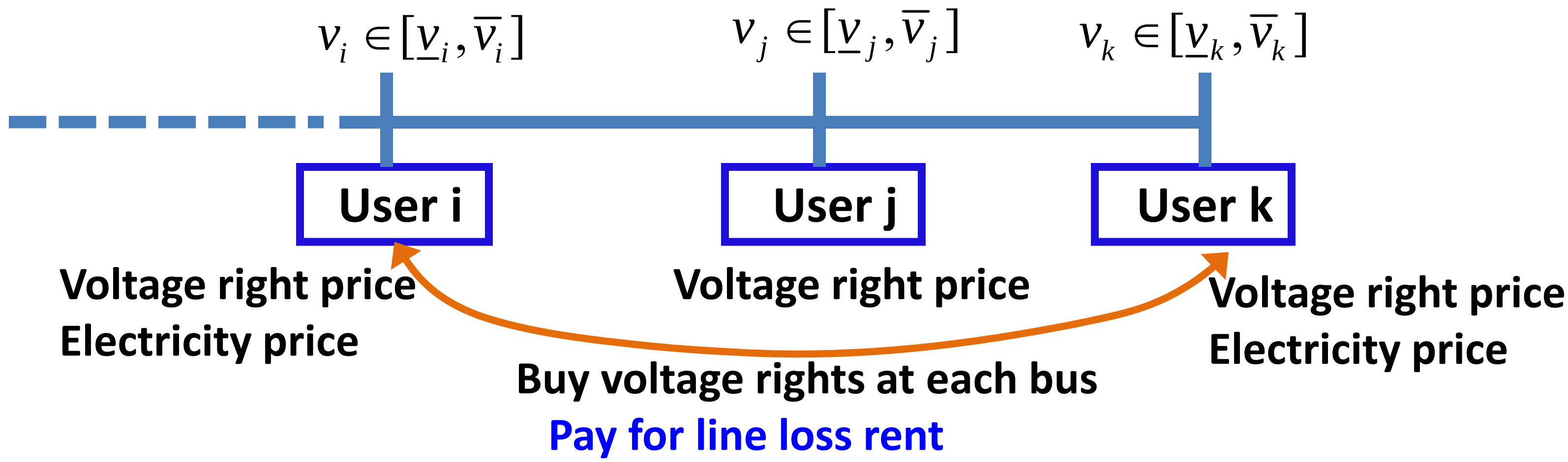
L_k denote the line losses on $(k, \pi(k))$

$$L_{k,i} = r_k \begin{cases} \frac{2P_k}{v_k} - \frac{P_k^2+Q_k^2}{v_k^2} R_{ki}, & \text{if } k \in \mathcal{P}_i, \\ -\frac{P_k^2+Q_k^2}{v_k^2} R_{ki}, & \text{otherwise.} \end{cases}$$

For each unit transaction between any two node i and k

Price i = Price j + Sum(Voltage right price*Quantity$_1$)
+ Sum (Line loss rent * Quantity$_2$)

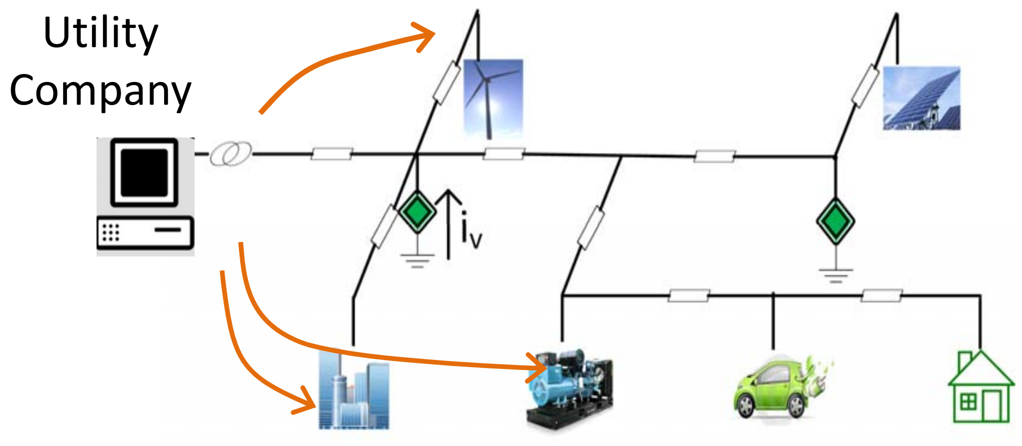
Competitive Market Equilibrium



Theorem (Li 2015):
Under the designed market rule, there exists a competitive market equilibrium that is socially optimal.

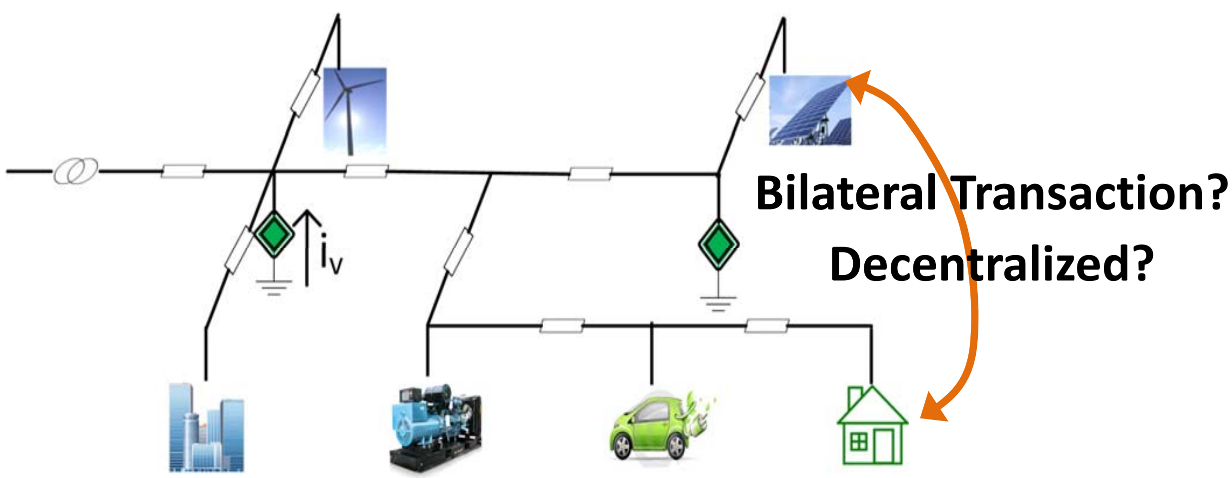
So far…

Scheme 1:



Markets are efficient

Scheme 2:



Electricity Market for Distribution Networks:

Power Engineering:

Power flow, system dynamics, operation constraints

Markets efficiently allocate delivery costs to individuals (transactions)

Human Incentive:

Strategic behavior, self-interested, market power

Uncertainties:

Renewable energy, user's behavior, emergency

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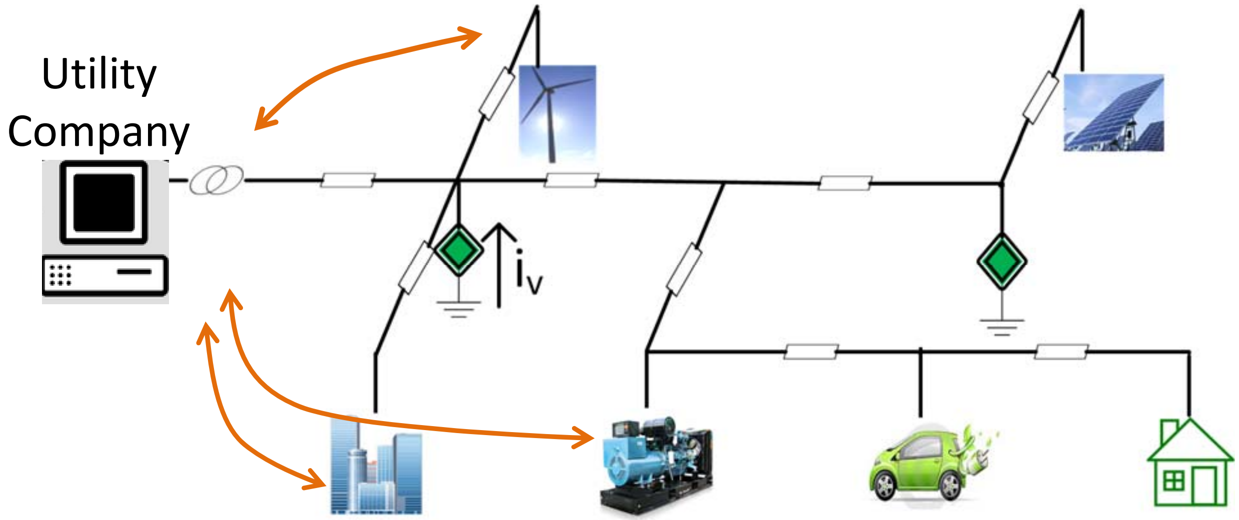
Recall...



Social Welfare

$$\max_{d,g,y,u,l} \quad B(d) - C(g)$$

$$\text{s.t.} \quad d - g = y$$

$$L(y, u) = l$$

$$f(y, u) \leq 0$$

Individuals need to report info.

*What if they **DON'T** report **true** info.?*

Supply Function Bidding for Demand Response

- Supply deficit (or surplus) on electricity: d

  weather change, unexpected events, …
- Supply is inelastic

Problem: How to allocate the deficit among customers?

load (demand) as a resource to allocate

Supply function bidding

- Customer i load to shed: q_i
- Customer i reports a supply function (SF):

$$q_i(b_i, p) = b_i p$$

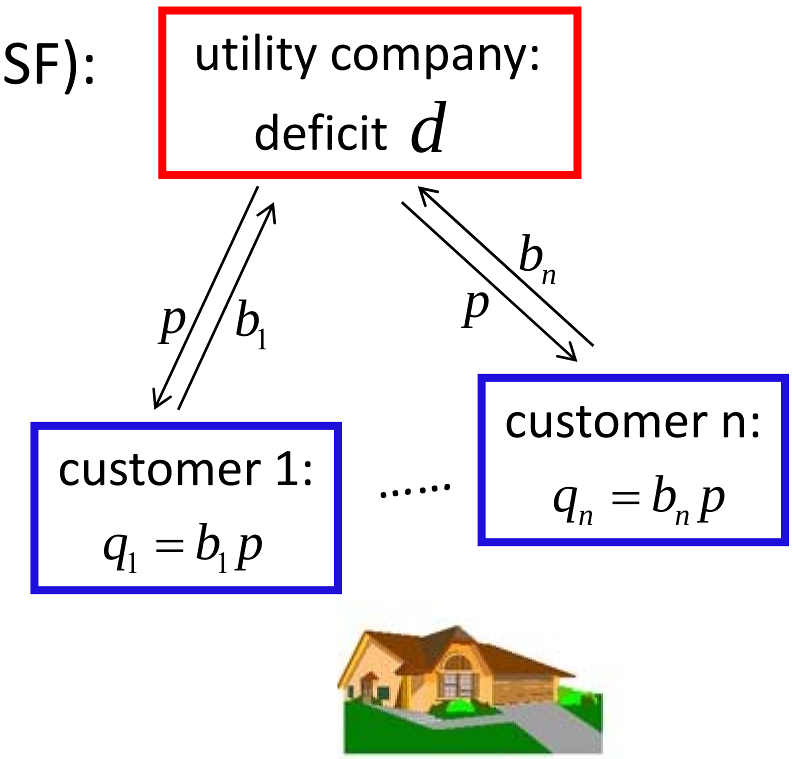
  - p : price for load shedding
  - b_i: price sensitivity

- Market-clearing pricing p:

$$\sum_i q_i(b_i, p) = d$$

$$\Downarrow$$

$$p = p(b) \triangleq d \,/ \sum_i b_i$$



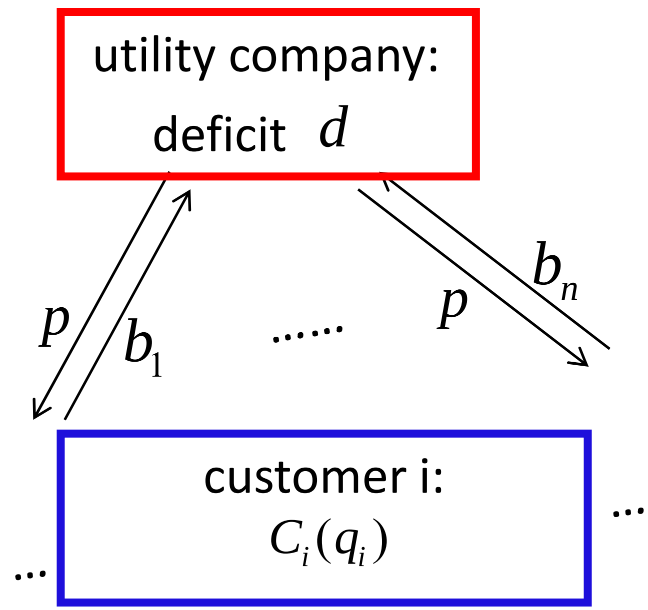
Load Shedding Cost

- Customer i cost (or disutility) function:

$$C_i(q_i)$$

- **Social welfare: Optimal Global Cost**

$$\min_{q_i} \quad \sum_i C_i(q_i)$$
$$s.t. \quad \sum_i q_i = d$$



Question:

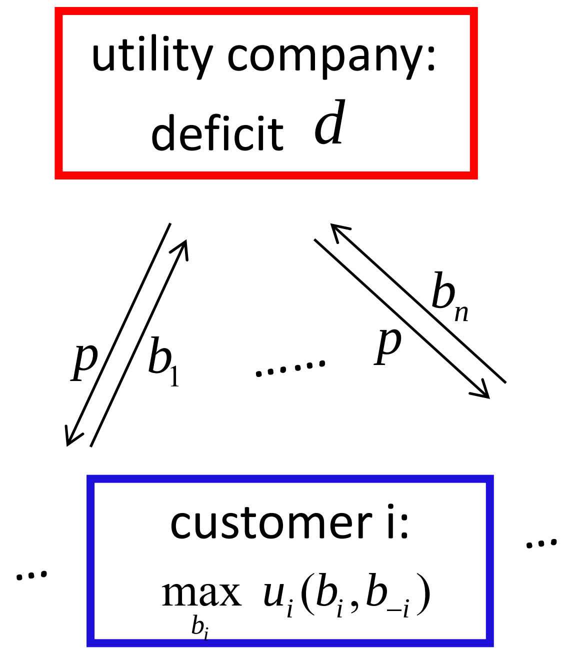
Can the supply function bidding achieves the optimal global cost?

Strategic demand response

- Customer i's net revenue: $u_i = p\, q_i - C_i(q_i)$
- Note: Price p is a function of bidding b
- Price-anticipating, strategic customer

with $\max_{b_i} \; u_i(b_i, b_{-i})$

$$u_i(b_i, b_{-i}) = p(b) q_i(b_i, p(b)) - C_i(q_i(b_i, p(b)))$$



- **Definition**: A supply function profile b^* is a **Nash equilibrium** if, for all customers i,

$$u_i(b_i^*, b_{-i}^*) \geq u_i(b_i, b_{-i}^*), \;\; \forall b_i \geq 0$$

Nash equilibrium

Theorem (Li, Chen, Dahleh, 2015)

Assume $|N| \geq 3$. The demand response game has a unique Nash equilibrium. Moreover, the equilibrium solves the following convex optimization problem:

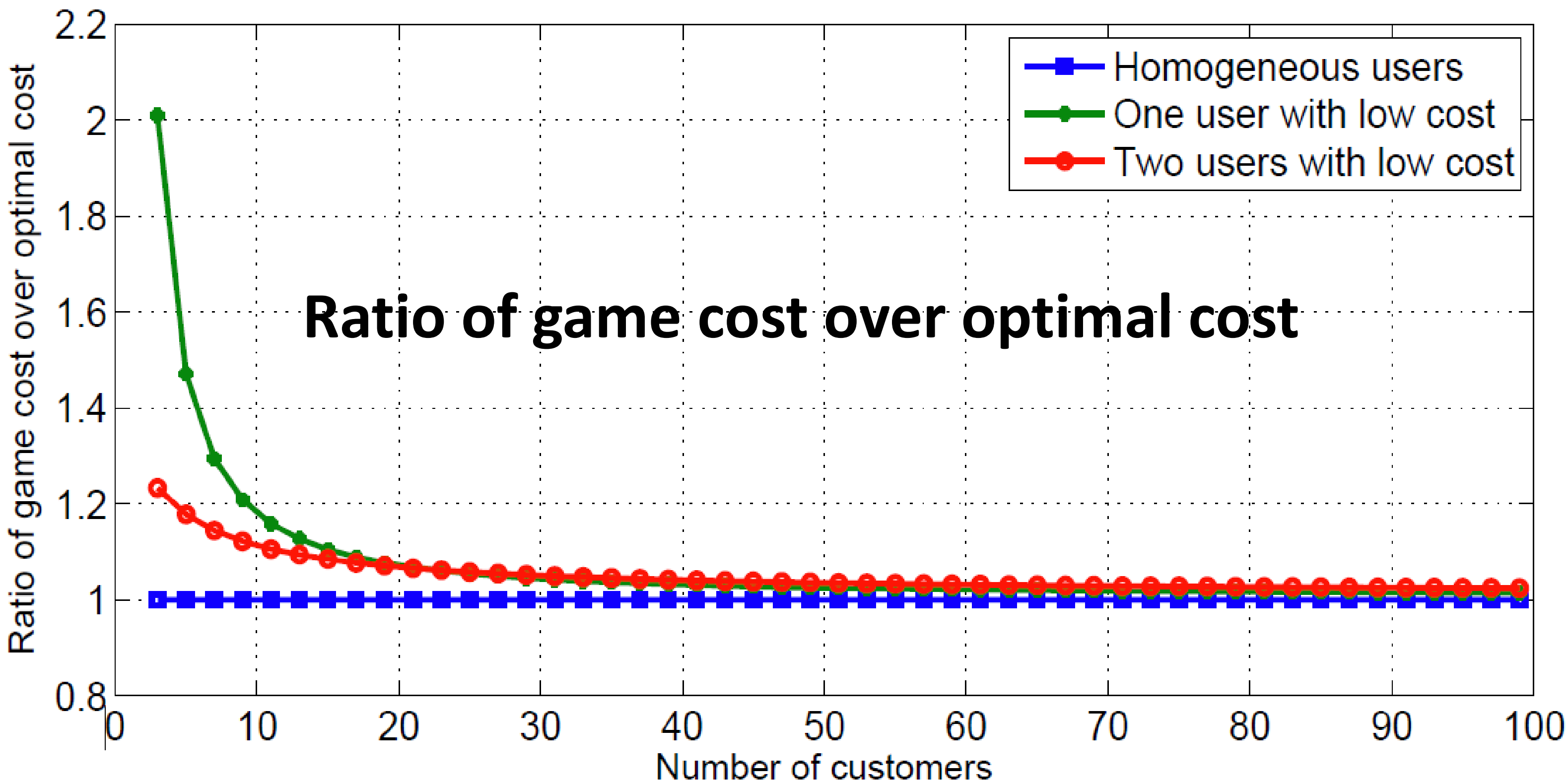
$$\min_{0 \leq q_i < d/2} \quad \sum_i D_i(q_i)$$
$$s.t. \quad \sum_i q_i = d,$$

with

$$D_i(q_i) = C_i(q_i) + \Delta C_i(q_i) \longleftarrow \text{False cost}$$

$$\Delta C_i(q_i) := \frac{q_i}{d-2q_i} C_i(q_i) - \int_0^{q_i} \frac{d}{(d-2x_i)^2} C_i(x_i) dx_i > 0$$

Efficiency Loss



Question:

Is there a way to make individuals report truthful information?

This Talk: Electricity Market in Distribution Networks

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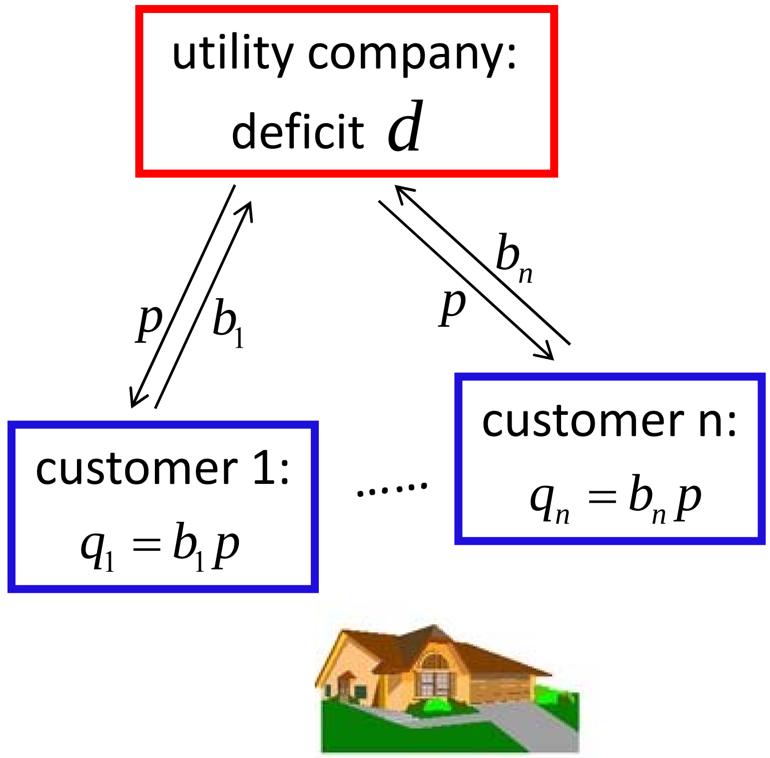
Recall: Supply Function Bidding

- A supply deficit d
- Customer i reduced load: q_i
- Customer i reports a supply function (SF)
- Cost function of load shedding

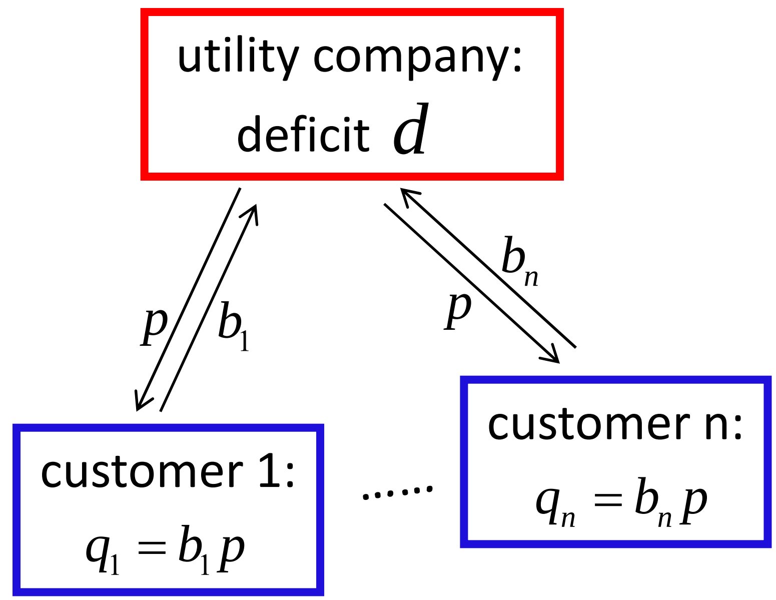
$$C_i(q_i)$$



Recall: Supply Function Bidding

- A **forecasted** supply deficit d **in the future**
- Customer i reduced load: q_i
- Customer i reports a supply function (SF)
- Cost function of load shedding **in the future**

$$C_i(q_i)$$



Caution: The information is uncertain!

Challenge: How to guarantee reliability?


EMPIRE
BAKERY EQUIPMENT


EMPIRE
BAKERY EQUIPMENT

Incentivizing Reliability in Demand Response

A group of customers:

- are able to reduce loads, e.g., 2-4pm in the next day

A reliability target:

- e.g. 1000 kW can be reduced with probability 99%

Challenges:

- Costly to reduce loads
- Uncertainty in the cost and ability to respond

Current practice (e.g., PJM, Con Edison, SCE, etc):

- Enlisting large number of consumers,
- Offering rewards in an order based on experience
- Unguaranteed reliability as customers opt out in the process

Two Period Mechanism

Time 0

Agents report with knowledge of type (C_i)

Uncertain, Random Cost

Mechanism selects agents to prepare for reducing loads and determines **rewards R_i**, **penalty Q_i**

Time 1

Agents resolve uncertainty in ability to respond

Agents decide on responses, if possible

Mechanism pays rewards and collects penalties

Fixed Reward R Mechanism

Direct Mechanism

- Mechanism computes agent maximum acceptable penalty M_i
- Select customers in decreasing order of M_i until reliability target is met
- Calculate critical payment Q_i as penalty for non-response

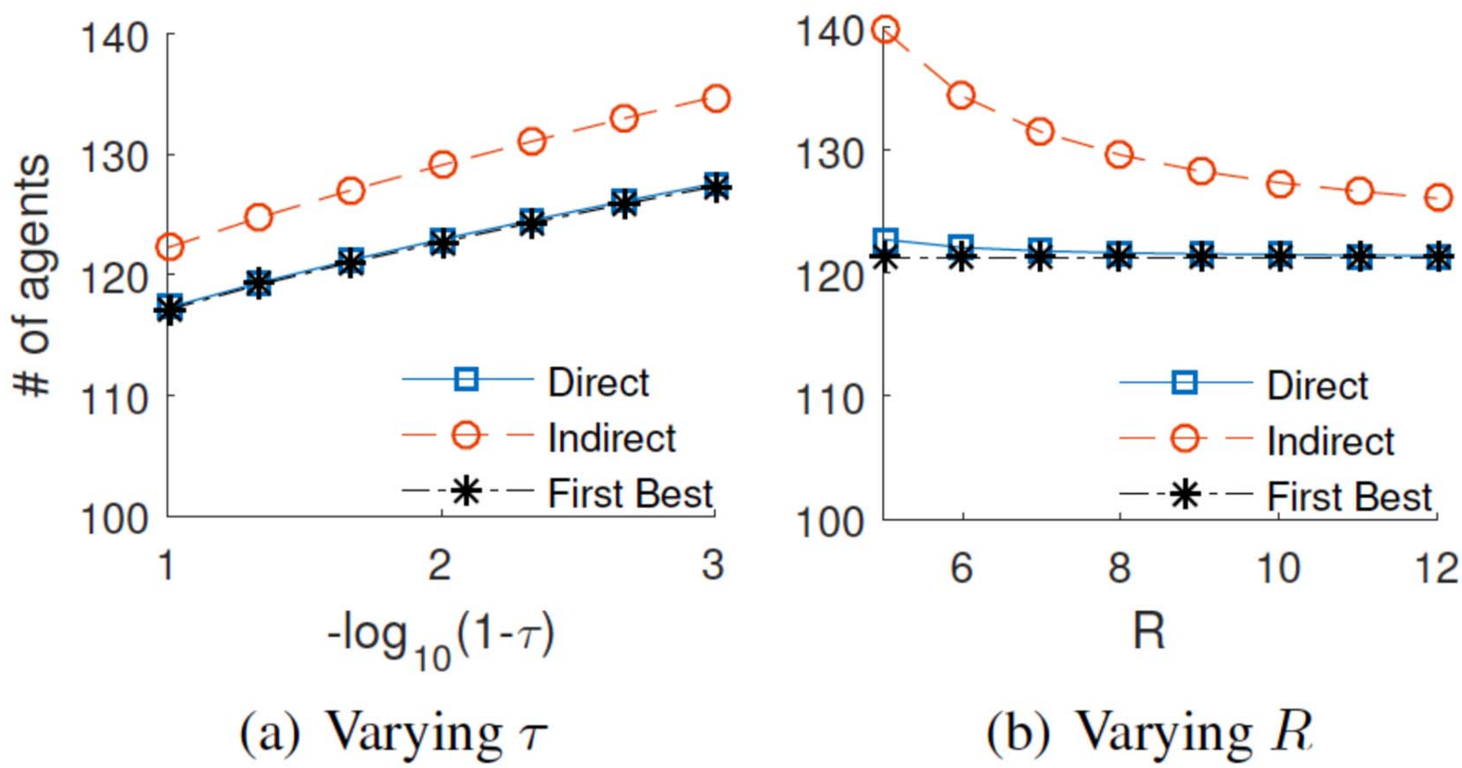
Indirect Mechanism

- Agents reports their maximum acceptable penalty M_i

Theorem [Ma, Robu, Li, Parkes, 2016]:
If the reward R is large enough, both direct and indirect mechanism guarantee truthful telling, individual rationality, and the reliability target.

Direct, Indirect Vs. First Best

- **First Best**: suppose individual uncertainty is available; select to optimize the reliability
- n = 500, M = 100, fix R = 10 or reliability τ = 98%



Conclusion and Discussion

Power Engineering:

Power flow, System dynamics, operation constraints

Markets efficiently allocate delivery costs to individuals (transactions)

Human Incentive:

Strategic behavior, self-interested, market power

Supply function bidding: Efficiency loss from strategic behavior

Uncertainties:

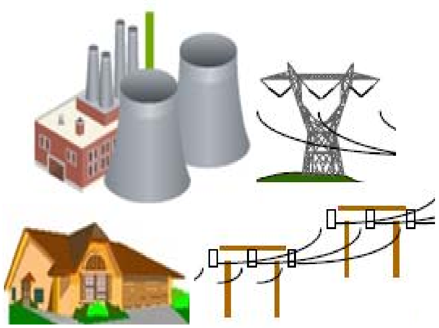
Renewable energy, user's behavior, emergency

Mechanism design to ensure reliability

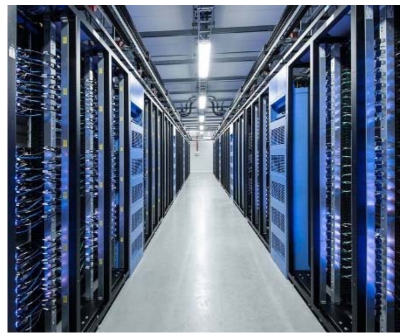
Challenge and future work:

A market: takes account of engineering and human factors, achieves (sub)-optimal efficiency, and ensures reliability

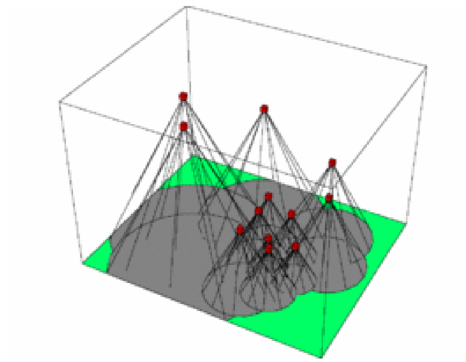
Research Interest
Network Optimization, Control, Economics



Power Systems



Data Center



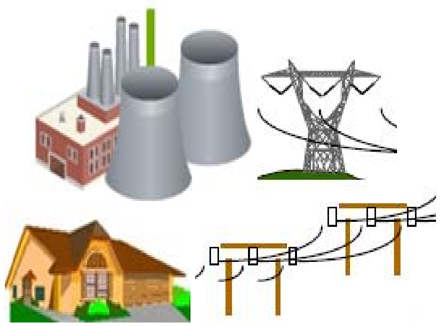
Sensor Network

Transportation
Internet network
Parallel computing
Social network
Etc…

Design general theories and tools for:

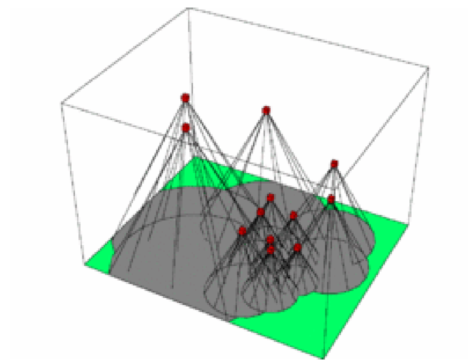
*Distributed/**Local** Control Laws* → *Desired **Global** System Behavior*

Research Interest
Network Optimization, Control, Economics



Power Systems

Data Center



Sensor Network

Transportation
Internet network
Parallel computing
Social network
Etc…

Foundational Theories ⇔ **Practical Algorithms** ⇔ **Real Implementation**

Foundational Theories

- Comm./Comp. complexity
- Tradeoff between efficiency, robustness, computation, and communication

Practical Algorithms

- Optimal first-order distributed methods
- Regularized methods
- Physical measurement-aid algorithms

Real Implementation

- Distributed power capping in data center
- Microgrid energy management

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