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RC+EI for Electricity CPS:

Pooling markets, Demand management, Security analysis

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Main questions

* How to incentivize residential consumers to partly shift/reduce demand? [*Schwartz, Amin*]
* How to improve market outcomes for electricity pooling markers in the presence of strategic producers with private information? [*Teneketzis, Rasouli*]
* What are the incentives for theft? How to improve security investments in a regulated environment? [*Amin, Schwartz*]
* How to assess vulnerability of smart distribution networks and design defender (control) strategies in the face of attacks? [*Amin, Shelar*]

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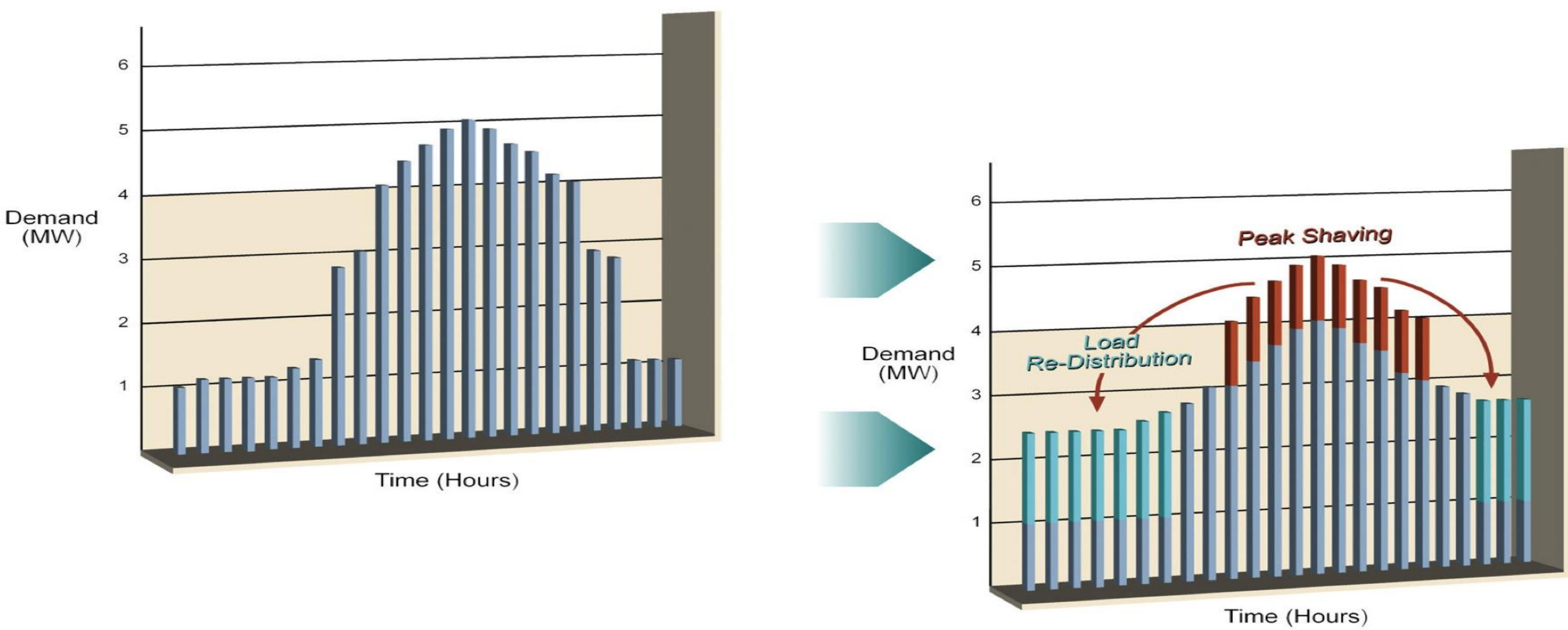
Project 1: Demand management

* Reward-based demand response for electricity distribution
  * Question: How to incentivize consumers to partly shift/reduce demand?
  * Researchers: G. Schwartz (Berkeley), S. Amin (MIT), H. Tembine (Supélec), S. Sastry (Berkeley)



Contribution: Reward-based demand response mechanism

* Ideas from economics of public good provisioning
* Incentive mechanism: Randomized reward (lottery):
  * user participation is voluntary
  * expected reward of a participating user is proportional to his contribution to the total public good (total shifted demand)
  * users and utility share risks of demand variability (in contrast to real time pricing where risk of demand fluctuations is shifted to users)
  * each user bears risk when it is the cheapest for him
  * both consumers and distribution utility are strictly better off using / employing the incentive mechanism

Project 2: Security against theft

* Theft and security in electricity distribution
  * Question: What are the incentives for electricity theft / insecurities under regulatory constraints?
  * Researchers: S. Amin, G. Schwartz, A. Cardenas (UT Dallas)

A man stands on a stepladder to fix tangled overhead electric power cables at a residential area in Noida, India, June 1, 2011 (Parivartan Sharma/Courtesy Reuters).

Contribution: Motoring and enforcement policies for theft management

- Ideas from detection theory and incentive regulation
- Persistent electricity theft in some jurisdictions, but not others. This is the first game theoretic analysis so far!
- Findings:
  - For certain regulatory regimes, electricity distributors make sub-optimal investment in monitoring
  - User steals less when (i) fines are higher (ii) detection probability is higher
  - Distributor invests more in monitoring when (i) costs of monitoring lower (ii) user stealing higher

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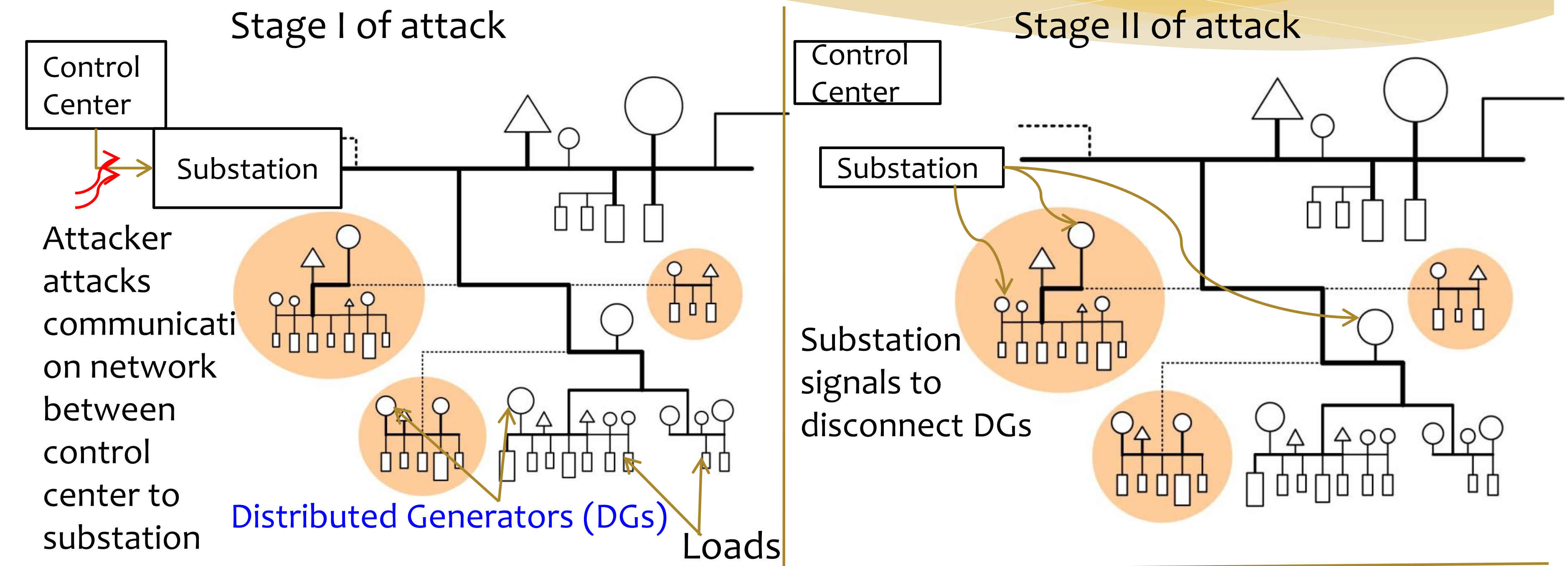
Project 3: Vulnerability analysis



Researchers: D. Shelar and S. Amin (joint with EPRI researchers)

Approach:

i) Model attacker's objectives of load-shedding, equipment damage.

ii) Compute worst-case attack plans and determine optimal response.

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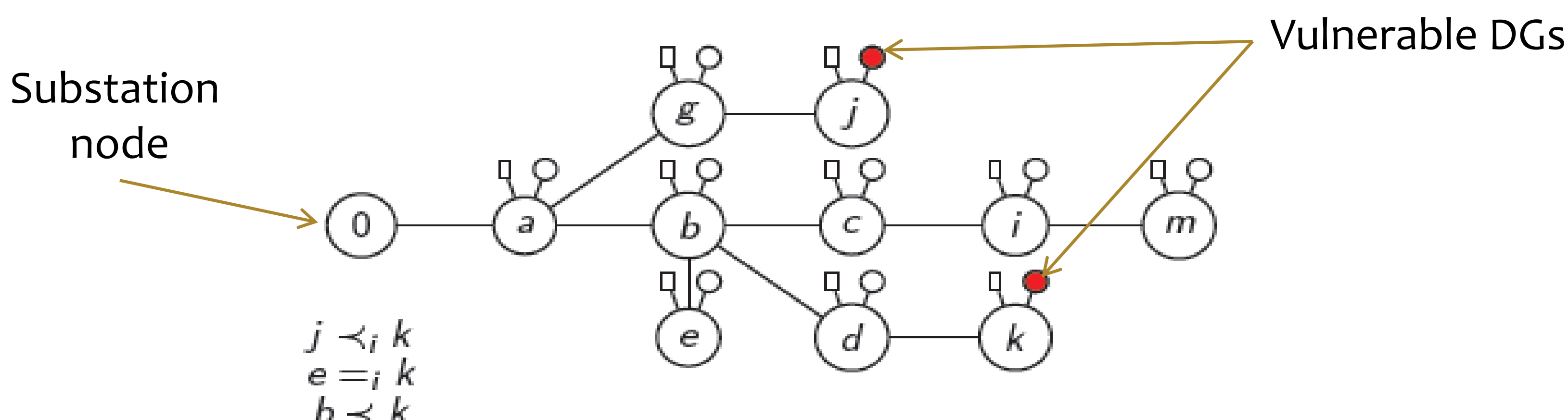
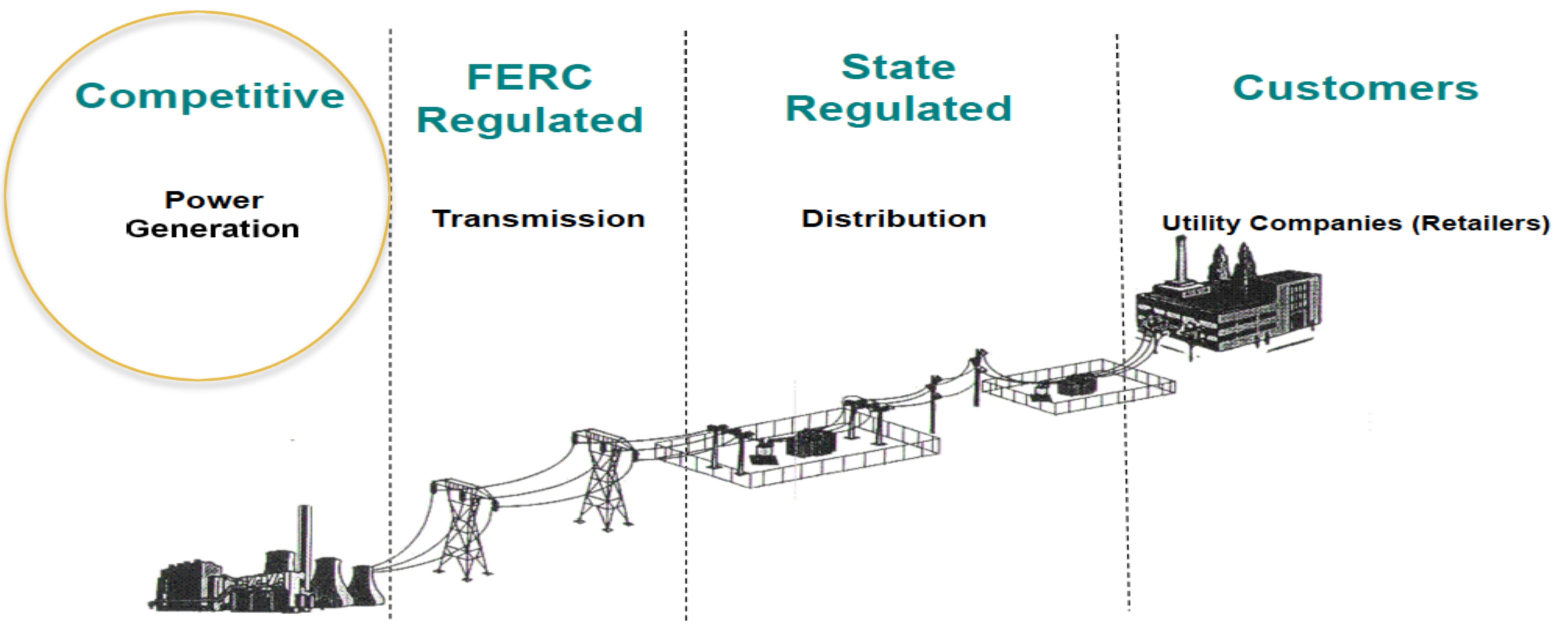
Contribution: Optimal Interdiction plans

- Optimal interdiction plans under power control and, if needed, partial load/demand shedding strategies of defender depend on relative locations of DGs on the network
- For a tree network with const. loads & homogenous DGs, attacker will prefer to disrupt *downstream DGs over upstream.*
- Extension to dynamic loads and nonhomogeneous DGs
- Example: DG disruption at node *k* will have larger effect on voltage at node *i* (in comparison to disruption at node *j*).



Project 4: Electricity pooling markets

* Market mechanism for electricity pooling markets
* With strategic producers possessing asymmetric information
* Researchers: M. Rasouli and D. Teneketzis (U of Michigan)



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Main features

* Technical features
  * Largely non-storable commodity
  * Interconnected flows
  * Physical line limits
* Market features
  * Demand with low price elasticity
  * Supply limited by generators' capacity
* Pooling market: Independent System Operator (ISO), a non-profit entity, running the market

Current market: Supply function model

* Producers bid price-production curves to the ISO
* ISO runs uniform /discriminatory price auction; clears the market
  * Example: California ISO, MISO, PJM, British Markets
* Challenges: Producers may manipulate the market because of
  1. their strategic behavior
  2. private information: production cost function
  3. => markets power due to oligopolistic nature of industry and technical/market features mentioned before
  * Example: 2000 California electricity crisis

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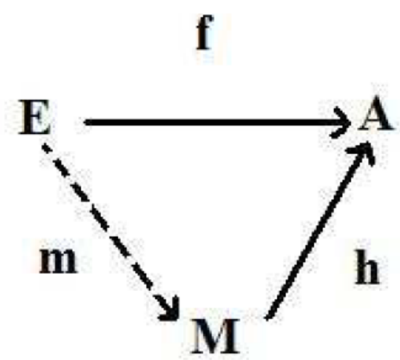
Contribution: Novel market mechanism

* Mechanism for electricity pooling market that implements the optimal social welfare correspondence in Nash equilibrium.



* The mechanism is
  * price efficient (price at equilibrium is marginal cost of production),
  * individually rational,
  * budget balanced.
* Every producer reports one price and one production value.

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Producer's model

* Strategic and self-profit maximizers
* Fixed generation capacity $x_i > 0$, $i = 1,2,\ldots N$ [common knowledge]
* Private production cost function $C_i(e_i)$, $i = 1,2,\ldots N$, where $C_i(0)=0$, $C'_i(e_i)>0$, $C''_i(e_i)>0$.
* Producer i's utility function:

$$u_i(e_i,t_i) = -Ci(e_i) + t_i$$

for e_i the energy produced by i and t_i the amount of money producer i receives for the energy he produces

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Demand model

* Elastic [inelastic demand presented by M. Rasouli in Young Researcher Talk]
* Aggregate demand with utility $u_d\ (D)$, the benefit of the consumers' society from
* consuming energy *D*, as common knowledge, $u_d(0)=0,\ u'_d(D)>0,\ u''_d\ (D)<0$
* The consumers' total utility:

$$u_d\ (D)-\Sigma\ t_i$$

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Centralized problem

- Centralized problem for elastic demand

$$\max_{e_i, i \in I} \quad u_D\left(\sum_{i \in I} e_i\right) - \sum_{i \in I} C_i(e_i)$$
$$s.t. \quad 0 \le e_i \le x_i$$

  - Convex problem with unique solution
  - Corner solution, $e_i^*=0$ for all i is possible (e.g., expensive production)

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Mechanism for elastic demand

- Message space

$$\mathcal{M}_i := [0, x_i] \times \mathcal{R}_+, m_i = (\hat{e}_i, p_i)$$

- Allocation Space

$$\mathcal{A}_i := [0, x_i] \times \mathcal{R}, a_i = (e_i, t_i)$$

- Outcome function $h : \mathcal{M} \to \mathcal{A}$

$$h(m) = (\mathbf{e}, \mathbf{t}) = (e_1, \ldots, e_N, t_1, \ldots, t_N)$$

$$t_i = t_{i,1} + t_{i,2} + t_{i,3}.$$

paid by the demand to producer *i*

collected by ISO from producers to align individual incentives with social welfare

distributed among producers by ISO to achieve budget balance among producers

Our mechanism vs supply function market

* In proposed mechanism, producers send only one point of their supply function ($\hat{e}_i$, p_i)

* At equilibrium, the proposed price will be the same across producers, *p* and is truthfully reported, i.e.,

$$p^* = C'_i(\hat{e}^*_i) \quad \text{if} \quad 0 \le \hat{e}^*_i \le x_i$$

* Proposed mechanism induces the optimal social welfare in NE, while the SFM does not necessarily.

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At equilibrium

* EXISTENCE OF NE - The game induced by the mechanism has at least one and at most two NE.
* TRIVIAL NE - There is always a Nash equilibrium with $m^*_i = (0, 0)$, for all *i*, that is, no production and no payment.
* NE IMPLEMENTATION - The second NE exists *iff* the centralized problem has interior solution; for this NE, the dispatch of electricity will correspond to the centralized solution.
* PARETO DOMINANCE - In case of two NE, the non-trivial NE Pareto dominates the trivial NE.

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Properties of mechanism

- The game induced by the mechanism is
  - individually rational
  - budget balance
  - implements socially optimal outcome in NE
  - price efficient

$$
\begin{aligned}
p_i^* = p_{i+1}^* &= p^* \\
p^* &= u'\Big(\sum_{i \in I} e_i^*\Big) \\
t_i^* &= p^* e_i^* \\
\frac{\partial t_i}{\partial e_i}\Big|_{\mathbf{m}^*} &= p^* .
\end{aligned}
$$

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Concluding remarks on Project 4

- Mechanism overview
  - Pooling market with N strategic producers and 1 non-strategic demand.
  - Producers are strategic with private information and exercise market power
  - We designed a mechanism that implements optimal social welfare under Nash equilibrium concept.
  - The mechanism is individually rational, price efficient and budget balance.
  - Every producer report's one price and one production value.
  - Price at equilibrium is marginal cost of production.
- Implementation of the mechanism
  - Implementation of the mechanism requires iterative exchange of messages
  - We have adopted mass-action interpretation of NE, for which the tâtonnement process, m, of message exchange to converge to equilibrium is unknown.

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