Mechanism Design for Incentive Regulation

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FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

Outline

1. Smart grid challenges

2. Incentive problems in mechanism design

3. Ongoing efforts and results
   - Generation capacity expansion
   - Renewable energy integration
   - Dynamic Price Competition between PEV Charging Stations
   - Transmission Constrained Economic Dispatch: A Public Goods Approach
   - Electricity Pooling Markets

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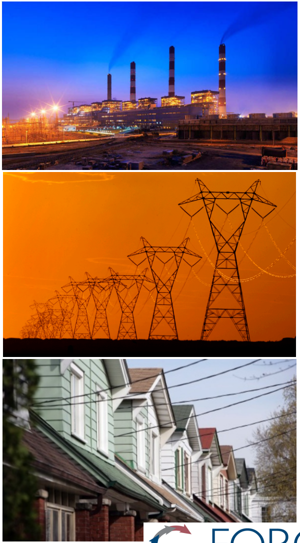
Existing tools

- Control
    - Automatic generation control (AGC)
    - Volt/VAR
- Optimization
    - Economic dispatch
    - Unit commitment
- Markets
    - Wholesale electricity market structure
    - Transmission cost pricing



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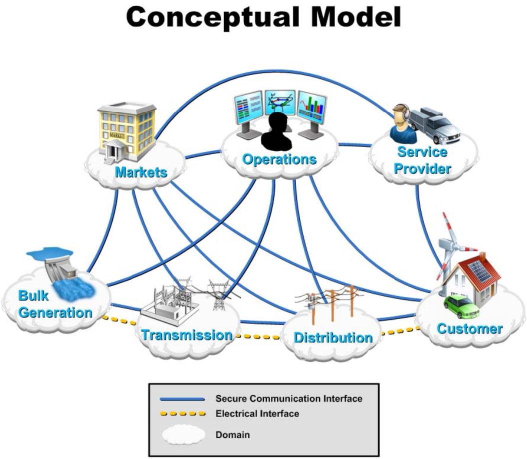
Smart Grid



- Existing tools are not sufficient to address problems arising from market restructuring and smart grid.

New Challenges

- Market restructuring and smart grid introduce new challenges due to
    - asymmetric information
    - strategic behavior
- Our focus: address these challenges within the context of
    - Generation expansion planning
    - Renewable energy integration
- Asymmetric information and strategic behavior are key features of cyber-physical systems (CPS)

Key Features of CPS

- Multi-agent/controller systems
- Agents have different information about CPS
- Agents are strategic and have different objectives
- Need to coordinate/influence the agents' strategies so as to maximize the CPS' utility to its users

Theory of incentives/mechanism design provides methods to achieve coordination

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Incentives/Mechanism Design

- Deals with multi-agent decision-making problems where information is asymmetric and agents are strategic.

Answers the fundamental question:

When can efficient coordination among strategic agents be achieved?

  - When the answer is yes it provides methodologies to achieve coordination
  - When the answer is no it provides guidelines for achieving satisfactory solutions

Incentives/Mechanism Design

- Examples from energy systems illustrating
    - Methodology to achieve efficient coordination when answer is yes
    - Methodology to achieve satisfactory coordination when answer is no

Mechanism Design - Implementation Theory

$$\begin{tikzcd}
\mathscr{E} \arrow[rr, "\gamma"] \arrow[dr, dashed, "h"'] & & \mathscr{D} \\
& \mathscr{M} \arrow[ur, "f"'] &
\end{tikzcd}$$

$\mathscr{E}$: Environment space.

$\mathscr{D}$: Allocation space.

γ: Goal function.

h: Tâtonnement process to obtain equilibrium message.

$\mathscr{M}$: Message space.

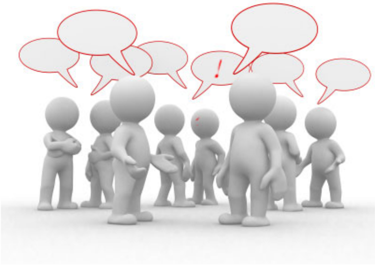
f: Outcome function.

The rule typically consists of the messages that users are allowed to use to communicate and a function which maps each message to an allocation (the amount of resource that everyone receives/and the tax (subsidy) everyone pays (receives)).

Mechanism Design - Implementation Theory

The specification of $(\mathscr{M}, f)$ and the realization of an environment e (which defines the utility functions and topology) induces a game $(\mathscr{M}, f, e)$ that players voluntarily participate in.

$$(\mathcal{M}, f, e) \longrightarrow$$



$$\longrightarrow m^*$$

The optimal resource allocation is computed from the equilibrium message, m^* as $f(m^*)$.

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Generation Expansion Planning

- Previously: Electricity industry regulated by government
  - Monopoly (vertically integrated)

- Currently: competitive wholesale market
  - Generation and transmission operated by different entities
  - In both of the above markets we have an oligopoly.

- Generation expansion not a reliable investment because of uncertainty

Generation Expansion Planning

- Uncertainty
    - highly variant demand
    - uncertain market share for new strategic entrants
    - unreliable transmission expansion
- Firms' strategic investment on generation expansion closely related to how the electricity market is going to run
- Our approach: generation expansion as a static mechanism design problem

Generation Expansion Planning – Model

- Time horizon T
- Independent system operator (ISO)
  - ISO runs the market for electricity trade at every $t = 1, 2, \ldots, T$
- N strategic energy producers, $N > 3$
  - Every producer i makes a decision about its generation expansion C_i at time 0
- Consumers represented by their aggregate demand (non-strategic)
  - Demand D_t, $t = 1, 2, \ldots, T$ is given, common knowledge

Generation Expansion Planning – Model

- Private information
  - Each producer faces an expansion cost $L_i(C_i)$, $L_i(\cdot) \in \mathscr{L}_i$
  - Each producer i has a cost $\hat{c}_i(e_i)$ of producing energy e_i, $\hat{c}_i(\cdot) \in \hat{\mathscr{C}}_i$
- Each producer receives $\tau_t^i(e_{i,t})$ amount of money at time t for the energy $e_{i,t}$ it produces at t
- Producer i's utility over time horizon T

$$\sum_{t=1}^{T} \tau_t^i(e_{i,t}) - \sum_{t=1}^{T} \hat{c}(e_{i,t}) - L_i(C_i)$$

- Consumers' utility over time horizon T

$$\sum_{t=1}^{T} u(D_t) - \sum_{t=1}^{T} \sum_{i=1}^{N} \tau_t^i(e_{i,t})$$

Generation Expansion Planning – Model

- ISO is social welfare maximizer
  - Maximizes the sum of the consumers' and producers' utilities

- Constraints
  - Produced energy $e_i = \sum_{i=1}^{N} e_{i,t}$ at t must meet demand D_t
  - $e_{i,t} \leqslant C_i,\ i = 1, 2, \ldots, N,\ t = 1, 2, \ldots, T$ (capacity constraints)
  - Network constraints, power flow equations

Generation Expansion Planning – Objective

- ISO's objective
  Design a mechanism/incentive scheme that has the following features
  - Voluntary participation
    Producers voluntarily participate in the energy production process
  - Budget balance
  - The generation capacity expansion C_i, $i = 1, 2, \ldots, N$ and energy production $e_{i,t}$, $i = 1, 2, \ldots, N$, $t = 1, 2, \ldots, T$, corresponding to all Nash equilibria (NE) of the game induced by the mechanism are solutions of the corresponding centralized optimization problem

Generation Expansion Planning – Research Plan

- Proceed in two steps
    - Constraints imposed by power flow equations not present
    - Constraints imposed by power flow equations present

- Without network constraints, we have the solution.

- Open problem when network constraints are included.

Generation Expansion Planning – Features

- Solution concept NE
  - Non-Bayesian modeling of private information
  - No pdf on $\mathscr{L}_i$, $\mathscr{C}_i$, $i = 1, 2, \ldots, N$
- Theory of mechanism design provides positive results
  - Implementation in NE possible
- Theory of mechanism design provides guidelines for the discovery of efficient mechanisms
- Used guidelines to achieve efficient coordination among strategic producers

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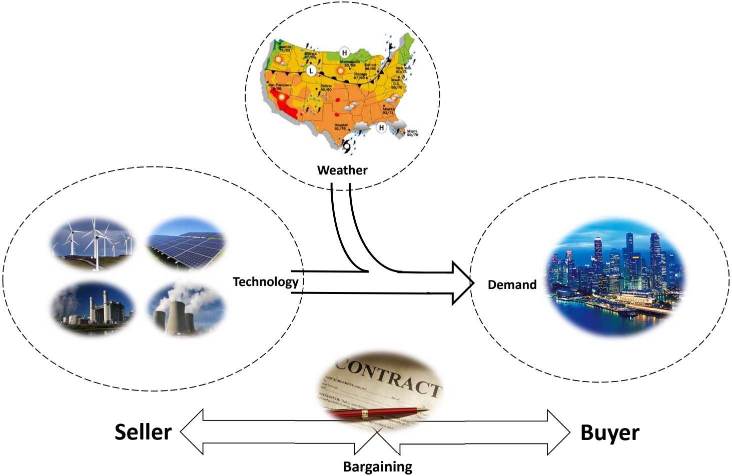
Renewable Energy Integration



Weather

Technology

Demand

Seller

Buyer

Bargaining

Renewable Energy Integration

- Electricity generation from renewable resources under development.
- Plan: generate 20% of electricity from modern renewable resources
- Due to intermittent nature of modern renewable resources, integration into the current designed infrastructure for conventional energy generation is a challenging problem
- Currently, renewable generators paid at fixed rate, receive subsidy, do not take any risk
  - No strategic behavior, no competition among renewable generators.

Renewable Energy Integration

- Increase in share of renewable generation increases competition among renewable generators, results in strategic behavior
- Study energy procurement from a strategic seller with hybrid generation (renewable and conventional generation)
- First attempt to integrate renewable and conventional energy production within the context of an energy procurement problem

Renewable Energy Integration – Model

- One strategic buyer
    - Buyer's utility: $V(q) - t$
        - q: amount of procured energy
        - t: payment to seller

- One strategic seller with conventional and renewable generators
    - Private information
        - θ: conventional generator's technology, $\theta \in \Theta$
        - γ: renewable generator's technology, $\gamma \in \Gamma$

- Common knowledge
    - Γ, Θ: common knowledge
    - $f(\gamma, \theta)$: common knowledge

Renewable Energy Integration – Model

- Seller's utility
  - $t - \theta \max[0, q - g(\gamma, w)]$
  - $g(\gamma, w)$: renewable energy produced
  - w: weather
  - f_W: pdf on W, common knowledge
  - θ: production cost of conventional energy
  - zero production cost of renewable energy

- Buyer has all bargaining power
  - Buyer is mechanism designer

Renewable Energy Integration – Objective

- Buyer's objective
  - Design a mechanism $(\Gamma \times \Theta, q, t)$, $q : \Gamma \times \Theta \to \mathbb{R}_+$, $t : \Gamma \times \Theta \to \mathbb{R}_+$ to

$$\max_{q,t} \mathbb{E}_{\gamma,\theta,W} \left[V(q(\gamma,\theta)) - t(\gamma,\theta) \right] \qquad \text{(Buyer's expected utility)}$$

  - Constraints
    - Incentive compatibility (IC)
      Truth-telling maximizes the seller's expected utility
    - Voluntary participation (VP)

$$\mathbb{E}_W \left[t(\gamma,\theta) - \theta \left(q(\gamma,\theta) - g(\gamma,\theta) \right)^+ \right] \geqslant 0, \text{ for all } (\gamma,\theta) \in \Gamma \times \Theta$$

Renewable Energy Integration – Research

- Solution of problem complete
  - Nonlinear pricing scheme that out-performs best linear pricing scheme
    - Loss of efficiency

- Extensions
  - Incorporated start-up cost
  - Initial VP constraint is interim
    - Solved problem with ex-post VP constraint

- One strategic buyer, many strategic sellers, open problem

Renewable Energy Integration – Features

- Solution concept: Bayesian Nash Equilbrium (BNE)
  - Bayesian modeling of seller's private information $(\gamma, \theta) \in \Gamma \times \Theta$, pdf $f_{\Gamma,\Theta}(\gamma, \theta)$ on $\Gamma \times \Theta$

- Theory of mechanism design provides negative/impossibility results
  - Impossible to design efficient, incentive compatible, individually rational, and budget balanced mechanisms

- Theory of mechanism design provides guidelines for the discovery of optimal incentive compatible and individually rational mechanisms

- Used guidelines to specify nonlinear pricing scheme

Conclusion

- Discussed new research challenges due to market restructuring and smart grid
- Illustrated merits of mechanism design approach for incentive regulation
- Generation expansion planning
  - Instance where mechanism design provides positive results and guidelines for discovery of efficient , budget balanced, individually rational mechanisms
- Renewable energy integration
  - Instance where mechanism design gives impossibility results and provides guidelines for the discovery of optimal (but not efficient) incentive compatible and individually rational mechanisms

Open Problems

- Generation expansion problems with network constraints
- Generation expansion problems with elastic demand
- Dynamic generation expansion problems
- Renewable energy integration problems with one or many buyers and many sellers
- Dynamic mechanism design guided by
  - Energy markets
  - Cyber-security problems

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