Smart Networks

Incentives in Electricity Distribution

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Ninth Annual CMU Conference On The Electricity Industry
February 4 - 5, 2014, Pittsburgh, PA

Outline

1. Introduction
   - Competition and Cooperation
   - Modeling strategic incentives
2. Model I: Incentives for demand shaping
3. Model II: Incentives to fight electric theft
4. Discussion
   - Summary
   - Questions?

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Large scale modern distribution system: Features

Complex, data rich environments with

- advanced communications
- advanced computational capabilities
- heterogeneous networked nodes
- multiple times scales
- multiple parties with conflicting interests

Today's talk: Models of two different problems Interplay of Control and Incentives

Model I. Electricity Demand Shaping via Randomized Rewards

- Daily demand fluctuations
- Possibility of cooperation with customers

Model II. Electricity Theft Management

- Regulated distributor
- Dishonest customer

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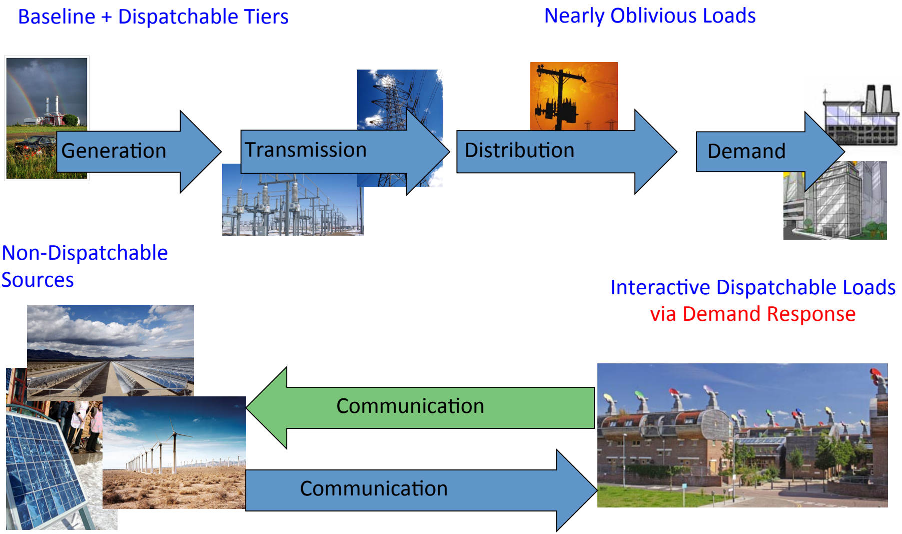
Towards an “aware” energy infrastructure



Courtesy: Prof. David Culler – ActionWebs project (UC Berkeley)

Demand Response

- Partly shiftable/reducible demand
- FERC Order # 745 [2011]
  - Provides certain level of compensation to DR providers for participating in wholesale markets

    "demand response resource must be compensated for the service it provides to the energy market at the market price for energy, referred to as the locational marginal price (LMP)"
  - Prof. William Hogan (Harvard): Order # 745 is anticompetitive & amounts to "an application of regulatory authority to enforce a buyer's cartel"
  - Question: Is DR viable for US residential consumers? Could they produce negawatts?

Motivations for Demand Management

- Sources of demand fluctuations
  1. variability of user demand (with time of the day)
  2. randomness of demand (in each specific time)
- Demand variability negatively affects
  - production costs (utilities, & transmission and generation)
  - reliability and security (of electric grid)
- Demand management:
  - peak-time (high demand) off-peak time (low demand) $\Rightarrow$
  - need in mechanisms to “shape” (flatten) demand

But a well known caveat:

DR via conventional price mechanisms is problematic

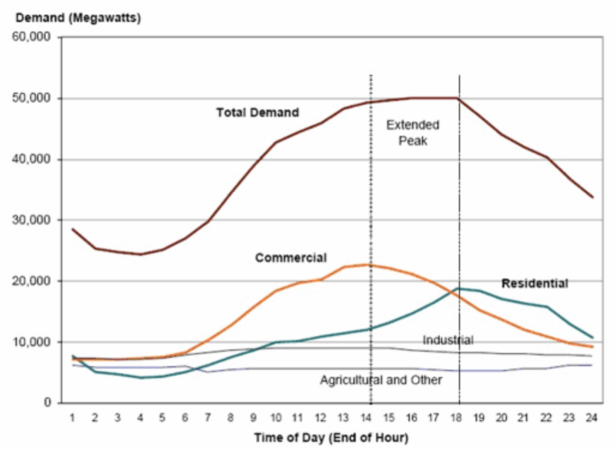
Mechanisms of Demand Management

- Pricing [Chen, Jiang & Low (2011)] (review)
  - real-time prices are volatile ==>
    closed-loop feedback system could be very volatile or even unstable [Roozbehani, Dahleh & Mitter (2012)]
  - *ceteris paribus*, user utility decreases [if the risk of demand fluctuations is shifted to users]
  - negative effects on privacy & security
- Direct load control [Ma, Callaway, & Hiskens (2012)] (review)
  - main application: reduction of minor fluctuations
  - may negatively affect quality of service [QoS]
- Random (probabilistic) rebates [Schwartz, Hamidou, Amin, & Sastry (2012)]
  - user participation is volunteer
  - users and utility share risks of demand variability
  - each user bears risk at the cheapest for him time(s)

Daily Demand Pattern

- Demand for electricity is not uniform throughout the day

We will focus on residential demand



Probabilistic Pricing as Lottery

Main Idea:

PROBABILISTIC REWARD ≈ LOTTERY

- i.e., our mechanism can be
  interpreted as a lottery
  implemented via lottery
  possible use of "pure" random rewards (no "high stake" lottery)

- Total rebate R is fixed
- Rebate of a participating user

$$\frac{\text{this user's shifted demand}}{\text{total shifted demand}} \times R$$

- Do users produce negawatts?

Incentive Design via Lotteries: Literature Review

Literature

- lottery-based scheduling for system processes
  [Waldspurger & Weihl (1994)]
- lotteries for roads decongestion
  [Merugu, Prabhakar & Rama (2009)]
- lottery for public “good” provision [Morgan (2000)]
- lottery for public “bad” reduction (network congestion management)
  [Loiseau, Schwartz, Musacchio & Amin (2011)]

Public "goods" and "bads"

Two distinct cases: public goods and public bads

(i) goods [*positive* externalities]
(ii) bads [*negative* externalities]

For efficiency one should: *subsidize* public "goods" and *tax* public "bads"

Positive externalities (*"goods"*)

PBC
Info / news sharing (web)

Negative externalities (*"bads"*)

network congestion; highway congestion
pollution
reliability of electricity

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Notation

User i utility is quasi-linear [standard]

$$U_i = w_i + h_i(G),\ h_i'(\cdot) > 0 \text{ and } h_i''(\cdot) < 0$$

$i = \{1, \ldots, n\}$ [usually n is large]
n – number of users [users are *risk-neutral*]
h_i – describes user i preferences for public good

Generalizable to quasi-concave [also standard]

$$U_i = w_i H(G) + h_i(G),\ H(\cdot) > 0$$

G – level of provision of public good [money]
w_i – wealth of user i [money]

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Basic setup [Morgan (2000)]

No lottery [public good contributions are voluntary]

User i contribution $x_i \in [0, w_i]$ max expected utility

$$EU_i = w_i + h_i(x(n)) - x_i,$$

$x(n) := \sum_{i=1}^{n} x_i$ - sum of all contributions

here $G = x(n)$

Lottery [fixed-prize raffle]

User i bet x_i max expected utility

$$EU_i = w_i + h_i(x(n) - R) - x_i + R\frac{x_i}{x(n)},$$

here $G = x(n) - R$

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Fixed-prize raffle: Equilibrium Properties

I. Equilibrium is unique ‣ Th 1 Morgan (2000) and

$$G^V < G^L < G^*.$$

II. There exists a finite aggregate user wealth and fixed-prize R^*, s.t. G^L is within ε from G^* ‣ Th 2 Morgan (2000)

III. Lotteries finance only socially *desirable* goods ‣ Th 3 Morgan (2000)

$$G^L > 0 \quad \text{iff} \quad G^* > 0.$$

[comp. with voluntary contributions: G^V could be zero even if $G^* > 0$]

IV. Fixed-prize raffle is outcome-equivalent to a fixed rebate R, with individual i rebate share $\frac{x_i}{x(n)}$ ‣ Remark 1 Morgan (2000)

Lotteries for public "bads"

Could lotteries alleviate over-provision of public "bads"?

- Q1: Why lotteries, not taxes (or prices)?
- Q2: Financing lotteries: who and how?

Lotteries for "bads" and "goods": the key differences

- Contributions are non-monetary
  - users reduce peak-time consumption (negawatts)
  - but negawatts are ill-defined
- Addressing lottery cancelations
  - the need to assure enough negawatts

Objective of Electric utility

Short-term utility profit maximization (standard):

$$\Pi = \max_{Q_2} \left[E \left[Q \times p - \underbrace{c_0(Q^{\max}, \sigma)}_{\text{[network costs]}} - \underbrace{\{c_1 Q_1 + c_2 Q_2 + c_3 Q_3\}}_{\text{[electricity costs]}} \right] \right]$$

at $(t+1)$ utility chooses Q_2, given history ($\mathbf{Q}^t$ and $\mathbf{c}^t$), s.t.

$$Q^d = Q^s = Q$$

and

$$Q = Q_1 + Q_2 + Q_3;$$

$$Q_3 = [Q - Q_1 - Q_2]_+$$

from the data:

$$c_1 < c_2 \ll c_3.$$

Model Summary

- Two states of demand: peak (near capacity) and off-peak
  - s_i – state of user i (reflects user preference for shifting)
  - x_i – shifted demand of user i; $x_i \in [0, q_i]$
  - p – user price
  - $c(Q^{\max}, \sigma)$ – utility cost of network management
  - $Q^{\max}$ – max demand; σ – its variance
  - Q – shiftable demand; q_i – per user i shiftable demand
  - $\hat{Q}$ – non-shiftable demand; $\hat{q}_i$ – per user i non-shiftable demand
- User i chooses x to max $u_i = u_i(s_i, x_1, \ldots, x_n, R_n)$

$$u_i = w(s_i) + \left[h\left(s_i, \frac{1}{n} \left\{ \sum_{j=1}^{n} x_j - R_n \right\} \right) - x_i + R_n \frac{x_i}{\sum_{j=1}^{n} x_j} \right].$$

- Utility chooses R_n to max its profit Π

$$\Pi(R_n) = (Q_n + \hat{Q}_n) \times p - R_n - c(Q^{\max}, \sigma)$$

Model Summary: Mean Field

Mean field limit

$$r = \liminf R_n / n \text{ and } m = \liminf \left[\sum_{j=1}^{n} x_j \right] / n$$

- s – state of a user (reflects user preference for shifting)
- x – shifted demand for user in state s; $x \in [0, q_i]$
- c_m – per user utility cost of network management
- q^{max} – per user max peak demand

- User in state s chooses shift of demand x to off-peak

$$u(s, x, m, r) = w(s) + \left[h(s, m - r) - x + r\frac{x}{m} \right]$$

- Utility chooses r to max its per user profit $\pi(r)$

$$\pi(r) = (q + \hat{q}) \times p - r - c_m(q^{max}, \sigma)$$

Equilibrium with Lottery: Intuition

Driving forces of the equilibrium

Trade-offs of increasing R

	Users	Utility
Incentives	Higher reward Higher shifted demand	Higher expense on R Lower management cost
Payoffs	Non-lower	Unclear (Non-monotone)

Will utility and users trade negawatts?

Summary: Setting & Results

A mean field game of utility and users

- sequential game; utility moves first
- utility choice is rebate R
- user choice is shifted usage
- user participation is volunteer
- users care about public good h [grid reliability & security]
- flatter user demand = lower utility cost of network maintenance

Main results

- Under realistic conditions, in equilibrium $R \neq 0$
- All parties are better-off w/ lottery

Advantages (over plain-vanilla pricing)

- No real-time info exchanges of users and utility
- Utility and users share risks of demand/cost fluctuations.

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Indian Blackout of 2012

Control + Incentive issues:

1. Overdraw by utilities
2. High loading
3. Weak transmission
4. Mis-operation of protection systems

- 620*M* people without power
- 10x severe that US blackout of 2003

Electricity Theft: India

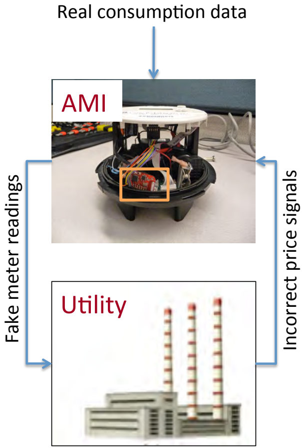
A man stands on a stepladder to fix tangled overhead electric power cables at a residential area in Noida, India, June 1, 2011 (Parivartan Sharma/Courtesy Reuters).

World Bank Reports: $\sim 30 - 50\%$ electricity is stolen in some

Electricity Theft: Brazil

Persistent theft in some areas, but not others. Why?

Advanced Metering Infrastructures

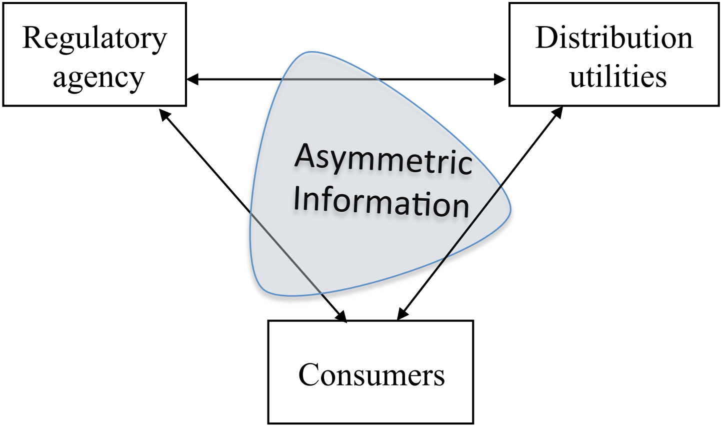


Attackers

- Fraudulent consumers: Minimize energy bill while not being detected
- No game theoretic models! [so far]

- $\downarrow$ Monitoring costs
- $\uparrow$ IT insecurities

Regulated electricity distribution: players



All parties have hidden (private) information

E.g: distributor knows his costs & consumer demand better than

Sequential (Stackelberg) game: Consumer model

Large # of Consumers (Followers)

- Each consumer: Max his utility $U(\theta)$, where θ is consumer type
- Consumer chooses how much electricity he will

pay for $q_B(\theta)$ & steal $q_U(\theta)$

Consumed quantity = Billed + Unbilled (theft/fraud, billing errors)

$$q(\theta) = q_B(\theta) + q_U(\theta)$$

When the amount $q_U(\theta)$ is stolen

- $\rho(e)$ – probability of detection, where e distributor effort [investment in monitoring technology (AMIs)]
- $F^r(q_U)$ – penalty (fine schedule) if the theft is detected [w.p. $\rho(e)$]
- No penalty if the theft is undetected [w.p. $(1 - \rho(e))$]

Sequential (Stackelberg) game: Distributor model

Distribution utility (Leader)

- Max profit π^m , s.t. regulatory constraints
- Distribute $Q = Q_U + Q_B$ quantity of electricity.
- Distributor choices:
  - e – monitoring effort level [investment in AMIs]
  - T – tariff (pricing schedule) $T(q_B)$ for $q_B(\theta)$
- Tariff
  - Flate-rate (for farmers)
  - Linear two-part tariffs (possibly type dependent) [standard]
  - Nonlinear (e.g., upcoming flexible pricing schemes)

Regulated distributor

Price-cap (or incentive) regulatory regime

- Tariff rate could increase, on average, at a specified rate
- Only average prices are controlled by regulator, and distributor is free to choose the pattern of relative prices s.t. constraints
- Distributor has incentives to minimize operating costs
- Our claim: Price-cap regulation can fail to incentivize distributor to invest in monitoring/enforcement efforts at socially optimal levels

Game

Distributor: Leader [chooses: Q and e]

$$\hat{\pi} = \max_{Q \geq 0, e \geq 0} R - C(e, Q) - \psi(e) \text{ s.t.}$$
$$R = \bar{p}Q \quad \text{and} \quad R \leq R(Q)$$

- $C(e, Q)$ – aggregate cost function
- $\psi(e)$ – cost of deploying AMIs
- $R(Q)$ – revenue
- $\bar{p}$ – *price cap* chosen by the regulator

Consumers: Followers [choose: q_B and q_U]

$$v(\theta) \equiv \max_{q_B \geq 0, q_U \geq 0} [\theta u(q_B + q_U) - T(q_B) - \rho(e) F^r(q_U)]$$

Price-cap regulation: main result

1. Regulator sets price-cap $\bar{p}$ while ignoring Q_S (total stolen electricity)
   - Profit: $\hat{\pi}$
   - Level of investment $\hat{e}$
2. Regulator sets price cap $\bar{p}$ while accounting Q_S
   - Profit: $\tilde{\pi}$
   - Level of investment $\tilde{e}$

Theorem: $\exists\ \bar{p}$, s.t. $\hat{\pi} > \tilde{\pi}$ and $\hat{e} \leq \tilde{e}$

Main results

A game-theoretic model of distribution utility and consumers

- Sequential game; distributor moves first
- Consumer choice is an amount of electricity to steal
- Consumer steals less when (i) fines are higher (ii) detection prob. is higher
- Distribution utility invests more in monitoring when (i) costs of monitoring lower (ii) user stealing higher

Conclusions

- Regulated distributors: suboptimal investment in monitoring
- Low monitoring $=$ High theft

Incentives + Control

- Distributors: via regulatory reform [Incentives]
- Customers: via increase of fines, shaming [Control]

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Electricity Distribution System: effects of technological advances

Increase in BOTH: conflict and cooperation

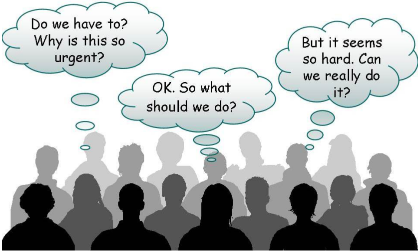
- Cooperation (*driven by technological complementarities*)
- Competition (*driven by availability of numerous substitutes*)

The role of Central Authority: improving incentives and control

- Higher competition & conflict ⇔ *Importance of resolving conflicts*
- Threats of security failures ⇔ *Important to invest in security*
- Threats of faults ⇔ *Important to investing in demand management*

Thank you for your attention

Questions are guaranteed in life.



... Answers aren't.