The Sharing Economy for Grid2050

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Shared Electricity Services

- The New Sharing Economy
  - cars, homes, services, ...
  - business model: exploit underutilized resources
  - huge growth: \$40B in 2014 $\rightarrow$ \$110B in 2015

- What about the grid?
  - what products/services can be shared?
  - what technology infrastructure is needed to support sharing?
  - what market infrastructure is needed?
  - is sharing good for the grid?

Three Opportunities

- ex 1: Shared Storage
  - firms face ToU prices
  - install storage C, excess is shared
- ex 2: Sharing Distributed Generation
  - homes install PV
  - excess generation is sold to others
  - net metering isn't really sharing ...
    price of excess is fixed by utility, not determined by market condn
- ex 3: Sharing Demand Flexibility
  - utilities recruit flexible customers
  - flexibility can be modeled as a virtual battery
  - battery capacity is shared

Challenges for Sharing in the Electricity Sector

- Power tracing
  electricity flows according to physical laws undifferentiated good
  cannot claim x KWh was sold by i to firm j
- Regulatory obstacles
  early adopters will be behind-the-meter single PCC to utility
  firms can do what they wish outside purvue of utility
- Paying for infrastructure
  fair payment to distribution system owners
  many choices: flat connection fee, usage proportional charge, ...

Sharing Electricity Storage

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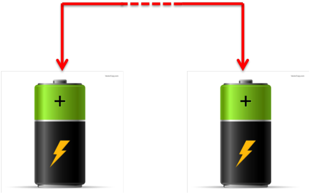
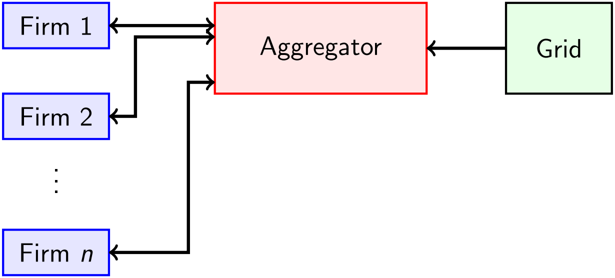
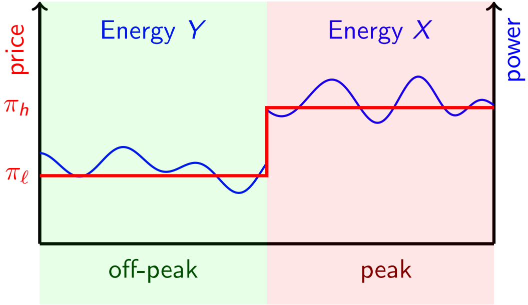


Set-up



- n firms, facing time-of-use pricing
- Ex: industrial park, campus, housing complex
- firm k invests in storage C_k for arbitrage
- unused stored energy is traded with other firms
- AGG manages trading & power transfer
- collective deficit is bought from Grid

ToU Pricing and Storage



- random consumption X, Y
- $F(x) =$ CDF of X
- value of storage: firm can move some purchase from peak to off-peak

Consumption Model

- Energy demand for firm k is random

  X_k in peak period, CDF $F_k(\cdot)$
  Y_k in off peak period

- Collective peak period demand

$$X_c = \sum_k X_k, \quad \text{CDF } F_c(\cdot)$$

Prices and Arbitrage

π_s	capital cost of storage amortized per day over battery lifetime
π_h	peak-period price
π_ℓ	off-peak price
π_δ	difference $\pi_h - \pi_\ell$

- Comments
  - today $\pi_s \approx 20$¢, but falling fast
  - need $\pi_\delta > \pi_s$ to justify storage investment for arbitrage alone
  - rarely happens today, but many more opportunities tomorrow ...
  - ex: PG&E A6 tariff ... $\pi_\delta \approx 25$¢$> \pi_s = 20$¢
- Arbitrage constant

$$\gamma = \frac{\pi_\delta - \pi_s}{\pi_\delta} \qquad \gamma \in [0, 1]$$

Assumptions

1. Firms are price-takers for ToU tariff ...
   consumption is not large enough to influence π_h, π_ℓ
2. Demand is inelastic ...
   savings from using storage do not affect statistics of X_k, Y_k
3. Storage is lossless, inverters are perfectly efficient
   temporary assumption
4. All firms decide on their storage investment simultaneously
   temporary assumption

No Sharing: Firm's Decision

- Daily cost components for firm k

$\pi_s C_k$	amortized cost for storage
$\pi_h(X_k - C_k)_+$	peak period: use storage first, buy deficit from grid
$\pi_\ell \min\{C_k, X_k\}$	off-peak: recharge storage

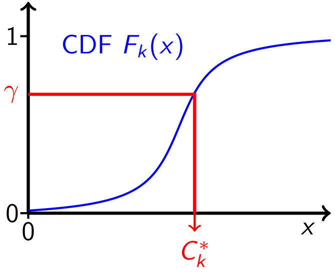
- Expected cost

$$J_k(C_k) = \pi_s C_k + \mathbb{E}\left[\pi_h(X_k - C_k)_+ + \pi_\ell \min\{C_k, X_k\}\right]$$

Theorem

Stand alone firm
Optimal storage investment

$$\begin{aligned} C_k^* &= \arg min_{C_k} J_k(C_k) \\ &= F_k^{-1}(\gamma) \end{aligned}$$



Discussion

- Without sharing, firms make sub-optimal investment choices:
  - firms may over-invest in storage!
    not exploiting other firms storage, if γ is large
  - or under-invest!
    not taking into account of profit opportunities, if γ is small
- More precisely:
  - optimal storage investment for collective

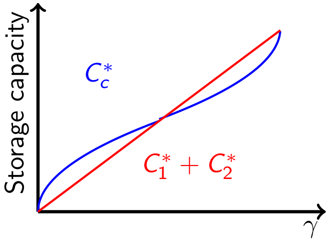
$$C_c^* = F_c^{-1}(\gamma), \quad \sum_k X_k = X_c \sim F_c(\cdot)$$

  - total optimal investment for stand-alone firms $\sum_k C_k^*$
  - under-investment $C_c^* > \sum_k C_k^*$
    over-investment: $C_c^* < \sum_k C_k^*$

Example: Two Firms

- $X_1, X_2 \sim U[0,1]$, independent
- individual investments: $C_k^* = F_k^{-1}(\gamma) = \gamma$
- collective investment: $C_c^* = F_c^{-1}(\gamma)$ where $X_c = X_1 + X_2$

$$C_c^* = \begin{cases} \sqrt{2\gamma} & \text{if } \gamma \in [0, 0.5] \\ 2 + \sqrt{2 - 2\gamma} & \text{if } \gamma \in [0.5, 1] \end{cases}$$



Sharing Storage

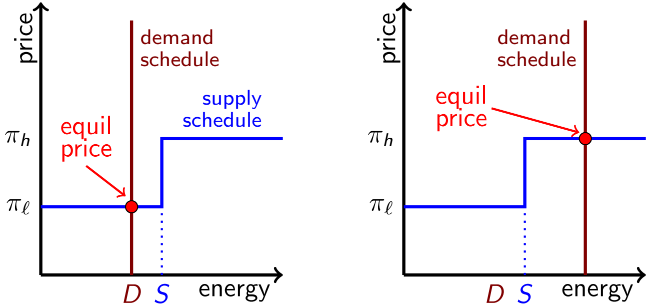
- Firm k has surplus energy in storage $(C_k - X_k)^+$
  - can be sold to other firms who might have a deficit
  - willing to sell at acquisition price π_ℓ
- Supply and demand
  - collective surplus: $S = \sum_k (C_k - X_k)^+$
  - collective deficit: $D = \sum_k (X_k - C_k)^+$
- Spot market for sharing storage
  - if $S > D$ firms with surplus compete
    energy trades at the price floor π_ℓ
  - if $S < D$ firms with deficit must buy some energy from grid
    energy trades at price ceiling π_h

Spot Market

- Market clearing price

$$\pi_{eq} = \begin{cases} \pi_l & \text{if } S > D \\ \pi_h & \text{if } S < D \end{cases}$$

- Random, depends on daily market condns



Firm's Decisions Under Sharing

- Expected cost for firm k

$$J_k(C_k \mid C_{-k}) = \pi_s C_k + \pi_l C_k + \mathbb{E}[\pi_{eq}(X_k - C_k)^+ - \pi_{eq}(C_k - X_k)^+]$$

- Storage Sharing Game
  - players: n firms, decisions: storage investments C_k
  - optimal investment C_k^* depends on the investment of other firms
- Expected cost for collection of firms $\sum_k J_k$
  - simplifies to: $J_c(C_c) = \pi_s C_c + \pi_g \mathbb{E}[(X_c - C_c)^+]$
  - like a single firm without sharing
- Social Planner's Problem

$$\min_{C_c} J_a(C_c) \qquad \text{solution:} \quad C_c^* = F_c^{-1}(\gamma)$$

Firm's Decisions Under Sharing

Theorem

(a) Storage Sharing Game admits unique Nash Equilibrium

(b) Optimal storage investments:

$$C_k^* = \mathbb{E}[X_k \mid X_c = C_c], \;\; \text{where } C_c = \sum_k C_k^*, \; F(C_c) = \gamma$$

(c) Nash equilibrium supports the social welfare

(d) Equilibrium is coalitional stable – no subset of firms will defect

(e) Nash equilibrium is also the (unique) cooperative game equilibrium

Not a competitive equilibrium: firms account for their influence on π_{eq}

$$\mathbb{E}[X] = m, \mathrm{cov}(X) = \Lambda \quad \Longrightarrow \quad C^* \approx m + \frac{\Lambda \mathbf{1}}{\mathbf{1}^T \Lambda \mathbf{1}} (C_c^* - \mathbf{1}^T m)$$

Lossy Storage

- More realistic storage model
  - charging efficiency $\eta_i \approx 0.95$
  - discharging efficiency $\eta_o \approx 0.95$
  - daily leakage ϵ (holding cost)
- Storage parameters modify arbitrage constant

Theorem

Optimal investment of collective is

$$C_a^* = \frac{1}{\eta_o} \cdot F_a^{-1}(\gamma), \quad \textit{where } \gamma = \frac{\pi_h \eta_o \eta_i - \pi_\ell - \eta_i \pi_s}{\pi_h \eta_o \eta_i - \pi_\ell (1 - \epsilon)}$$

Sequential Investment Decisions

- Collective of n firms have optimally invested C^n in storage
- Now firm F_{n+1} want to join the club
- Optimal investment of new collective is C^{n+1}

Theorem

Optimal storage investment is extensive, i.e. increases as new firms join

$$C^{n+1} \geq C^n$$

- Who benefits?
  - F_{n+1} is better off by joining
  - collective is bettor off when F_{n+1} joins
  - but firms in the collective may not individually benefit! – need side payments

Joining the Club

- Optimal ownership redistributes when F_{n+1} joins

$$C^n = (\alpha_1, \cdots, \alpha_n) \quad \rightarrow \quad C^{n+1} = (\beta_1, \cdots, \beta_n, \beta_{n+1})$$

- Actions
  - new firm F_{n+1} pays the collective $\pi_s \beta_{n+1}$
  - receives rights and revenue stream for β_{n+1} units of storage
  - collective invests in $C^{n+1} - C^n$ additional storage
  - internal exchange of money and storage ownership within collective

Physical Implementation

- Firms may monetize storage in many ways
  - ToU price arbitrage
  - shielding from critical peak prices
  - local voltage support
- We have considered *energy sharing* ...
  ignored when the energy is to be traded within peak period
- Physical trading of power requires some coordination
  - Stanford's PowerNET
  - 3-phase inverter
  - control of charging/discharging
  - comm module to coordinate charge/discharge schedule
- Storage location and management
  - centralized, managed by AGG, leasing model (needs 1 inverter)
  - distributed, located at firms (needs n inverters)

Market Implementation

Theorem

No pure storage play:

$$X_k \equiv 0 \implies C_k^* = 0$$

Therefore AGG is in a neutral financial position

- Privacy and market clearing
  - to determine its investment C_k^*, firm k need knowledge of collective investment and statistics
  - informed by neutral AGG
  - AGG determines clearing price π_{eq} each day
- Other market choices?
  - bulletin board for P2P bilateral trades
  - matching market hosted by AGG

Sharing PV Generation

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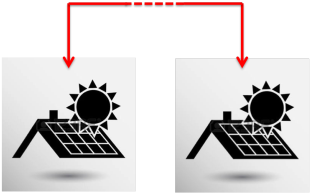
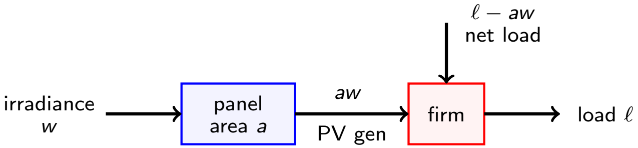


Set-up

- n homes or firms, indexed by k
- time slots $t = 1, \cdots, T$

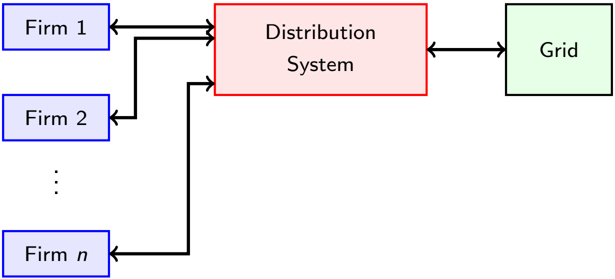
$\ell_k(t)$	random load of firm k in slot t
$w_k(t)$	random irradiance $\mathrm{KW/m^2}$ at firm k in slot t
a_k	panel area, decision variable
$a_k w_k(t)$	generation from PV in slot t



- Notation: Average Expectation

$$\overline{\mathbb{E}}[x \mid y] = \frac{1}{T}\sum_{t=1}^{T}\mathbb{E}[x(t) \mid y(t)]$$

Set-up and Prices



- firms invest in PV
- surplus gen shared among firms
- collective deficit bought from grid
- collective surplus sold to grid

π_s	capital cost of PV per m^2 amortized over T time slots
π_g	grid electricity price
π_{nm}	net-metering price

Sharing PV Generation

- Firm k has surplus energy $(a_k w_k - \ell_k)^+$
  - can be sold to firms who have a deficit, or sold to grid
  - price floor π_{nm}
- Supply and demand
  - collective surplus: $S = \sum_k (a_k w_k - \ell_k)^+$
  - collective deficit: $D = \sum_k (\ell_k - a_k w_k)^+$
- Spot market for sharing PV generation
  - runs in each time slot
  - if $S > D$ firms with surplus compete
    energy trades at the price floor π_{nm}
  - if $S < D$ firms with deficit must buy some energy from grid
    energy trades at price ceiling π_g

Clearing Price for Shared PV Generation

- Clearing price in spot market

$$\pi_{eq} = \begin{cases} \pi_{nm} & \text{if } S > D \\ \pi_g & \text{if } S < D \end{cases}$$

- Random, depends on market condns in time slot t
- Define random sequences for $t = 1, \cdots, T$

$$\begin{array}{c|ll} L & = \sum_k \ell_k(t) & \text{collective load} \\ G & = \sum_k a_k w_k(t) & \text{collective PV generation} \end{array}$$

- Market clearing price simplifies to

$$\pi_{eq} = \begin{cases} \pi_{nm} & \text{if } G > L \\ \pi_g & \text{if } G < L \end{cases}$$

Cost Functions and Decision Problems

- Cost components for firm k in time slot t

$\pi_s a_k$	amortized cost of PV panels
$\pi_{eq}(\ell_k - a_k w_k)^+$	deficit bought from other firms or grid
-$\pi_{eq}(\ell_k - a_k w_k)^-$	surplus sold to other firms or grid

- Expected cost for firm k
  depends on investment decisions a_{-k} of other firms

$$J_k(a_k \mid a_{-k}) = \pi_s a_k + \overline{\mathbb{E}}\left[\pi_{eq}(\ell_k - a_k w_k)\right]$$

- Firm k decision problem

$$\min_{a_k} J(a_k \mid a_{-k})$$

- Social Planner's problem

$$\min_{a_1, \cdots a_n} J_c = \sum_k J_k$$

Common Irradiance

Theorem

Assume $w_k = w$ for all firms.

(a) *Unique Nash equilbrium*

(b) *Total PV investment A solves*

$$0 = \pi_s - \pi_g \cdot p \cdot \mathbb{E}\{w \mid X > 0\} - \pi_{nm} \cdot (1-p) \cdot \mathbb{E}\{w \mid X < 0\}$$

where $p = Pr(L > Aw)$

(c) *Optimal investment of firm k is*

$$\frac{a_k}{A} = \frac{\overline{\mathbb{E}}\{\ell_k \mid L = Aw\}}{\overline{\mathbb{E}}\{L \mid L = Aw\}}$$

(d) *Supports social welfare !!*

- a_k is proportional to expected load ℓ_k conditioned on $L = Aw$

Diverse Irradiance

- bound maximum PV area investment for firm k

$$0 \leq a_k \leq m_k$$

- else, problem is ill-posed
  only most favorable location invests in PV
  all others invest $a_k = 0$

- firms influence clearing price π_{eq}

- Cournot competition

Theorem

(a) Unique Nash equilbrium

(b) Does not support social welfare

Deep Penetration

- bound maximum PV area investment for firm k $\quad 0 \leq a_k \leq m_k$
- large number of firms
  no single firm can influence statistics of clearing price π_{eq}
- asymptotically perfect competition

Theorem

(a) Unique Nash equilibrium

(b) Optimal investments – threshold policy

$$a_k = \begin{cases} m_k & \text{if} \quad \mathbb{E}\left[w_k | L > G\right] > \theta \\ 0 & \text{else} \end{cases}$$

(c) Supports social welfare

$\overline{\mathbb{E}}\left[w_k \mid L > G\right]$ measures merit of site k

Computing Threshold θ

- θ is the unique solution of

$$\theta = \frac{\pi_s}{\pi_g p}, \quad p = \Pr\{L > G\}$$

- bisection search

1	start with selected firms	$\mathbb{S}$
2	compute PV gen of selected firms	$G = \sum_{k \in \mathbb{S}} a_k w_k$
3	compute prob of collective deficit	$p = \Pr\{L > G\}$
4	update threshold	$\theta = \frac{\pi_s}{\pi_g p}$
5	update selected firms	$\mathbb{S} \leftarrow \{k : \overline{\mathbb{E}}[w_k \mid L > G] > \theta\}$

Synthetic Example

- 1000 homes, max panel area = 8 m^2
- Irradiance data from SolarCity, load data from NREL
- $\pi_g = 0.17$ \$ per KWh
- $\pi_s = 0.006$ \$ per m^2h ($\approx$ 3.2¢ per watt levelized cost, no subsidy)

- Two cases:
  - status quo: net metering with annual cap
  - sharing with $\pi_{nm} = 0$: no net metering
- Results:
  - 7% more PV panel area, 10% more production from PV
  - 3.2 % lower end-user electricity costs lower
  - under status quo
    homes with good PV production & low load underinvest
    homes with poor PV production & high load overinvest
  - sub-optimal investment decisions fixed by sharing

The 50% Subsidy

- Assume quadratic generator cost curves (linear price)

$$\pi_g = \alpha \cdot X \qquad \text{PV generation influences grid price } \pi_g$$

Theorem

Common irradiance $w_k = w$, quadratic generation costs, single bus.

(a) Unique Nash equilibrium

(b) Does not support social welfare

(c) Suppose all firms receive 50% solar subsidy $\pi_s \to 0.5\pi_s$ then Nash equilibrium supports social welfare

- Who pays for the subsidy? not sure ...
- Diverse irradiance?
  - conjecture is that subsidy should depend on location
  - favorable PV locations receive larger subsidy

Utopia in Grid2050

- What if ...
  - Solar PV is universal ... homes, businesses, industry
  - Everyone shares
  - Utilities own the wires ... transmission and distribution assets
  - Large generators supply collective net load $X = (L - G)^+$
- Research agenda:
  - analyze the economics of this utopia
  - revisit utility business model
  - emissions? effective price of electricity?
  - sensitivity to PV prices, penetration, ...
  - inform policy
  - argue that Sharing in the Electricity Sector benefits everyone ...