Shared Economy for Battery Storage

A Game Theoretic Approach

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Power grid

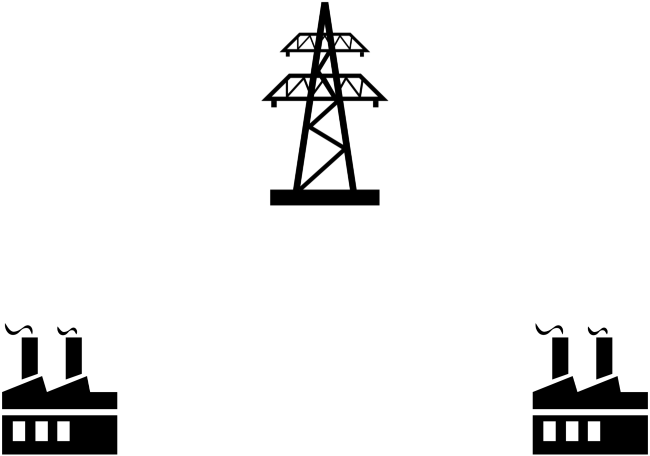
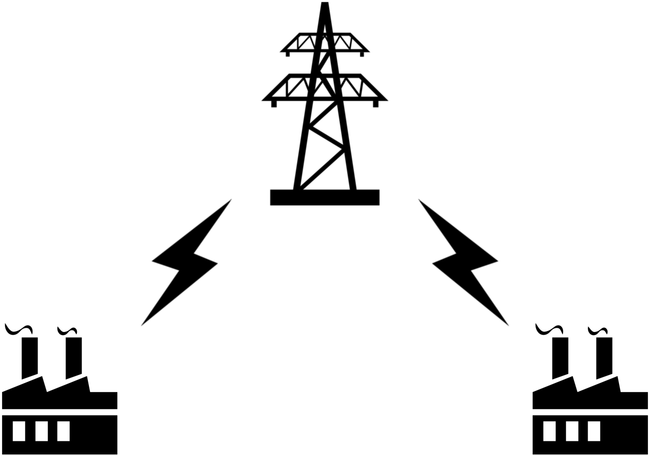


Figure 1: Power grid (Traditional transactions)

Power grid



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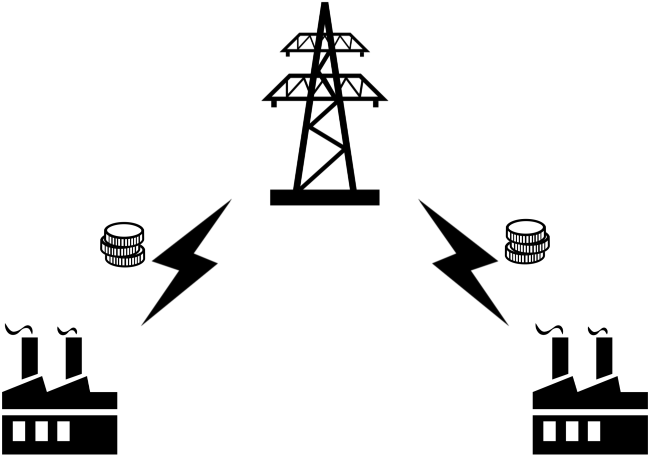

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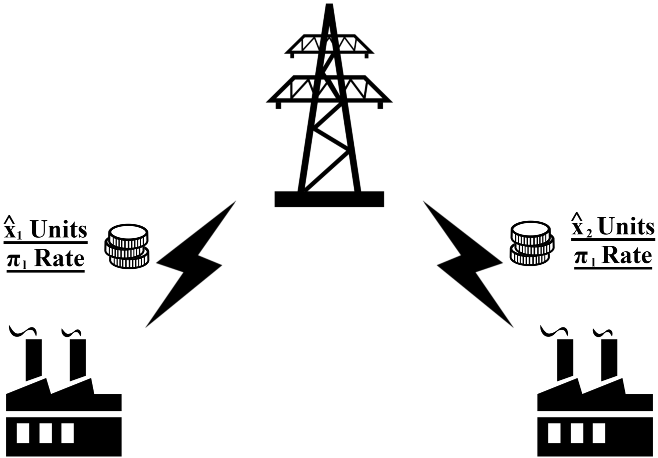
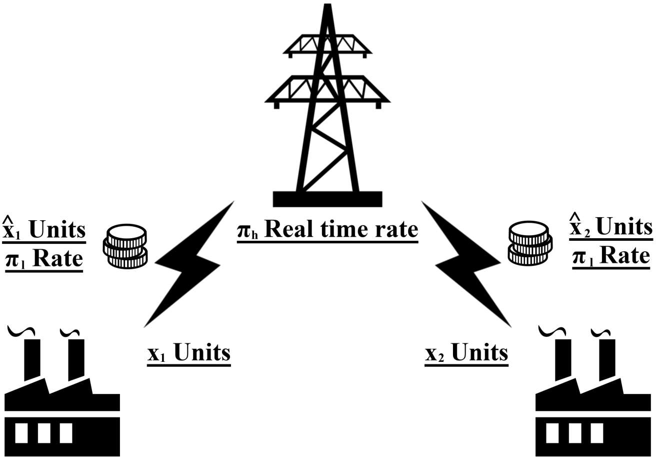


Figure 1: Power grid (Slot ahead pricing scheme)

Power grid



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Power grid

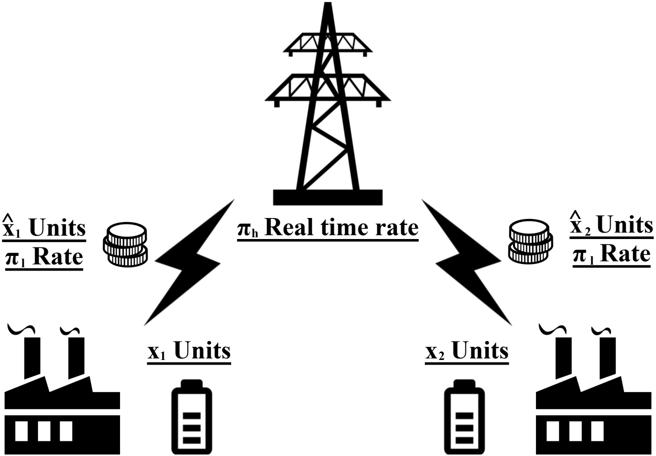

Figure 1: Power grid (Batteries to prevent exposure to real time market)

Power grid

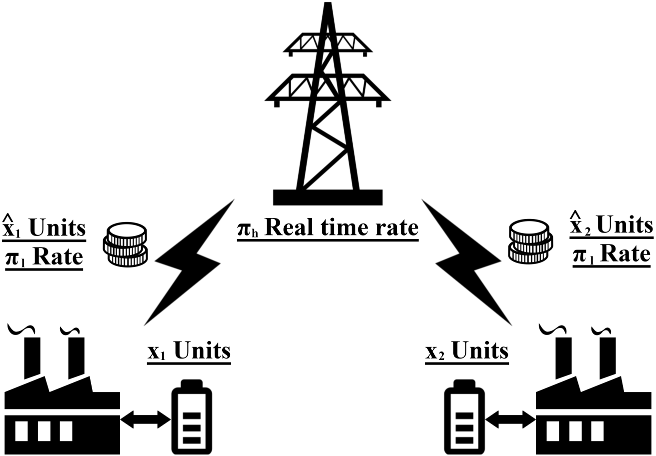

Figure 1: Power grid (Batteries to prevent exposure to real time market)

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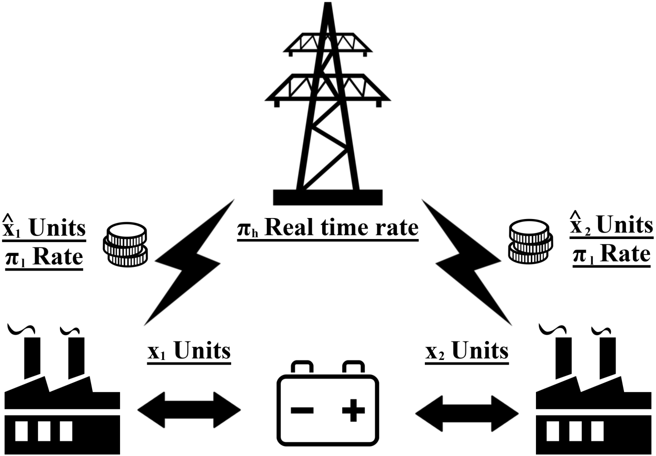

Figure 1: Power grid (Shared battery storage)

Overview

- Game theory
  - Cooperative/Coalition games
  - Utility allocation, Core
- Shared economy for battery storage
  - Risk avoidance
  - Expected cost minimization
- Solar energy aggregation and coalition formation
- Future works

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Game theory

Simultaneous games

$$\langle \mathcal{N}, (Strategy_i)_{i \in \mathcal{N}}, (Utility_i)_{i \in \mathcal{N}} \rangle \quad (1)$$

where,

$$\begin{aligned}
\mathcal{N} &: \text{Set of players} \\
Strategy_i &: \text{Strategy set available to player i} \\
\times_{i \in \mathcal{N}} Strategy_i &: \text{Strategy profile} \\
Utility_i &: \text{Utility function for player i}
\end{aligned}$$

Modeling of strategic interaction amongst multiple players.

Prisoner's dilemma

		P1	
		D	C
P2	D	(2,2)	(0,3)
	C	(3,0)	(1,1)

Table 1: Matrix form representation of prisoner's dilemma game
Remarks: Utilities represent reduction in jail term

Modeling of strategic interaction amongst multiple players.

Prisoner's dilemma

		P1	
		D	**C**
P2	**D**	(2,2)	(0,3)
	C	(3,0)	(1,1)*

Table 1: Matrix form representation of prisoner's dilemma game
Remarks: Utilities represent reduction in jail term

*Equilibrium (Security strategy)

Modeling of strategic interaction amongst multiple players.

Prisoner's dilemma

		P1	
		D	**C**
P2	**D**	$(2,2)^{+}$	(0,3)
	C	(3,0)	$(1,1)^{*}$

Table 1: Matrix form representation of prisoner's dilemma game
Remarks: Utilities represent reduction in jail term

**Equilibrium (Security strategy)*, $^{+}$*Welfare maximization*

Cooperative/Coalition games with transferrable utility

A cooperative game with transferrable utility is defined by a tuple $(\mathcal{N}, v)$, where $v : 2^{\mathcal{N}} \to \mathbb{R}$, with $v(\phi) = 0$.

Core

Set of all allocation which are feasible and stable.

Game theory

Example: Core of a coalition game

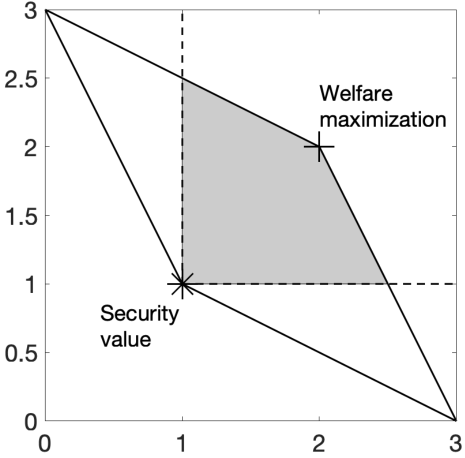

Figure 2: Core of Prisoner's dilemma game

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Risk avoidance [1]

Notation

$$\mathcal{N} = \{1, 2, \ldots, N\} : \text{Consumers}$$

$$\mathcal{T} = \{1, 2, \ldots, T\} : \text{Partition of time slots each of duration } \Delta T$$

$$\mathbf{x}_i(t) = \hat{x}_i(t) + x_i(t) : \text{Average + deviated electricity consumption}$$

where $x_i(t)'s$ are i.i.d. random variable $\forall i, t$

$$s_i(t) : \text{Battery state of charge at time } t \; \forall i \in \mathcal{N}$$

$$s_i = s_i^{max} : \text{Capacity of battery storage } \forall i \in \mathcal{N}$$

$$\mathbb{E}\left[x_i(t)\right] = 0; \; \forall \; i \in \mathcal{N}, \; \forall t$$

$$\Sigma_{ij} = \mathbb{E}\left[x_i(t) x_j(t)\right] = \rho_{ij}\sigma_i\sigma_j$$

$$\Sigma = \{\Sigma_{ij}\}_{1 \leq i,j \leq N} : \text{Covariance matrix}$$

Risk avoidance [1]

Pricing scheme

Existence of slot ahead market to purchase $\hat{x}_i$ amount of electricity at nominal cost π_l. Excess real time purchase is at higher cost π_h.

Risk avoidance [1]

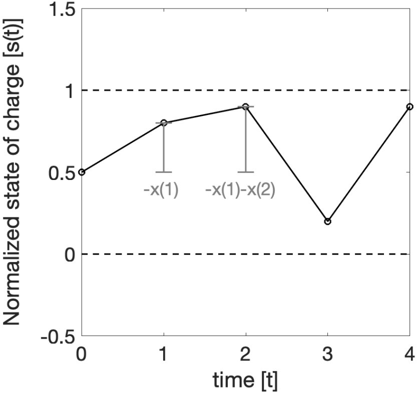
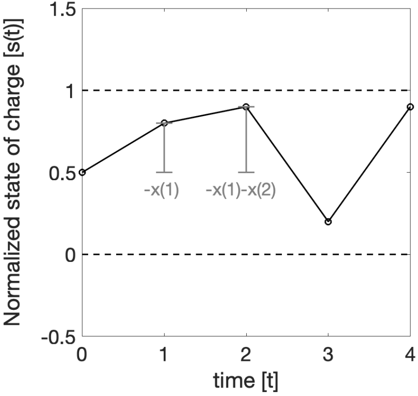


Figure 3: No exposure to real time market

Risk avoidance [1]



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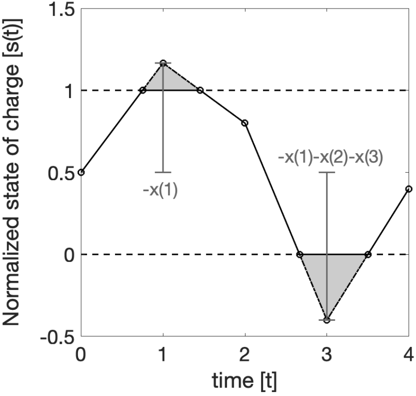

Figure 4: Exposure to real time market

Risk avoidance [1]

Optimization model (Single player)

Battery storage sizing (Single player)

$$\min_{s}(ks + c_0)$$
$$s.t.\ p^c = \mathbb{P}\left(\max_{t\in\mathcal{T}} \|s(t-1) - x(t) - s(0)\| \geq \frac{s^{max}}{2}\right) \leq \theta \qquad (2)$$

where,

s^{max} : Battery storage size

k : Unit price for storage capacity

c_0 : Cost of installation of inverter

Bound on battery size

$$s^{max} \geq \frac{2\sqrt{T}\sigma}{\sqrt{\theta}} \qquad (3)$$

Risk avoidance [1]

Optimization model (N-players)

Battery storage sizing (N-players)

$$\min_{s_{\mathcal{N}}}(ks_{\mathcal{N}} + c_0)$$
$$s.t.\ p_i^c \leq \theta \ \forall \ i \tag{4}$$

where,

$s_{\mathcal{N}}^{max}$: Shared battery storage size

k : Unit price for storage capacity

c_0 : Cost of installation of inverter

Bound on battery size

$$s_{\mathcal{N}}^{max} \geq \frac{2\sqrt{T\mathbb{1}'\Sigma\mathbb{1}}}{\sqrt{\theta}} \tag{5}$$

Benefits of shared storage

Sharing of storage minimizes overall cost.

Cost allocation

$$\pi_c(i) = \frac{\sum_{j \in \mathcal{N}} \rho_{ij} \sigma_i \sigma_j}{\mathbb{1}' \Sigma \mathbb{1}} \times \textit{Total cost} \tag{6}$$

Fair division

Cost allocation scheme given by (6) is in the core of the game.

Expected cost minimization [2][3]

Pricing scheme
Each day is divided into two periods - peak (rate π_h) and off-peak (rate π_l). Availability of fully charged battery at the start of day.

Expected cost minimization [2][3]

Optimization model

Cost function

$$J(\mathbf{x}_{\mathcal{S}}, C_{\mathcal{S}}) = \pi_{\mathcal{S}} C_{\mathcal{S}} + \pi_l \mathbb{E}\left[\min\left\{C_{\mathcal{S}}, \mathbf{x}_{\mathcal{S}}\right\}\right] + \pi_h \mathbb{E}\left[(\mathbf{x}_{\mathcal{S}} - C_{\mathcal{S}})^+\right] \quad (7)$$

where,

$\mathcal{N} \supset \mathcal{S}$: Subset of participants

$\sum_{i \in \mathcal{S}} \mathbf{x}_i = \mathbf{x}_{\mathcal{S}}$: Aggregated peak consumption of $\mathcal{S}$

$\pi_{\mathcal{S}}$: Daily cost of storage

π_h, π_l : Peak/Off-peak period price of electricity

Expected cost minimization [2][3]

Results

Optimal battery size

CDF of $\mathbf{x}_{\mathcal{S}}$ at optimum battery size satisfies

$$F_{\mathcal{S}}(C_{\mathcal{S}}^*) = \frac{\pi_h - \pi_l - \pi_{\mathcal{S}}}{\pi_h - \pi_l} \tag{8}$$

Cost allocation

Existence of a stable cost allocation scheme given by,

$$\pi_{\mathcal{N}}(i) := \pi_l \mathbb{E}\left[x_i\right] + \pi_{\mathcal{N}} \mathbb{E}\left[x_i | \mathbf{x}_{\mathcal{N}} \geq C_{\mathcal{N}}^*\right] \tag{9}$$

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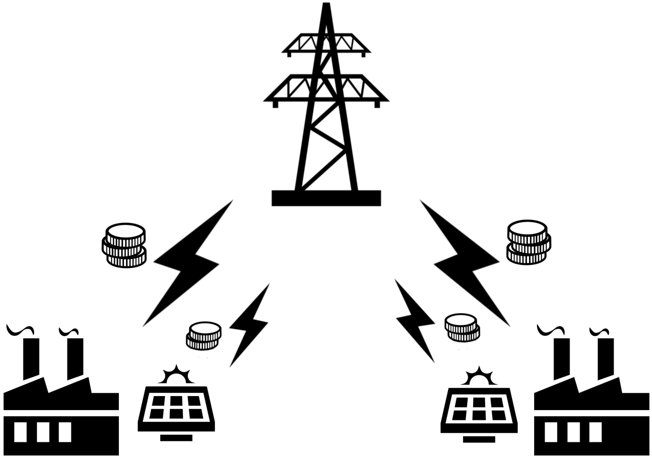

Figure 3: Solar energy aggregation

Solar energy aggregation and coalition formation [4]

Problem statement

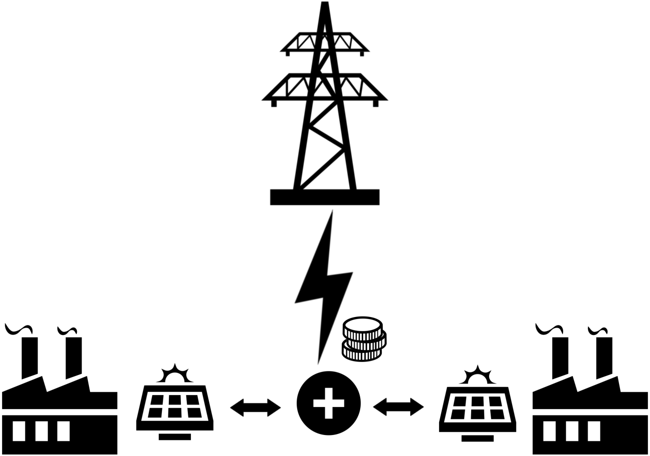

Figure 3: Solar energy aggregation

Feed-in-tariff (FiT) scheme
$\lambda(A_2 + A_3) - \mu(A_1 + A_2)$

Net metering (NM) scheme
$\lambda(A_3 - A_1)^+ - \mu(A_1 - A_3)^+$

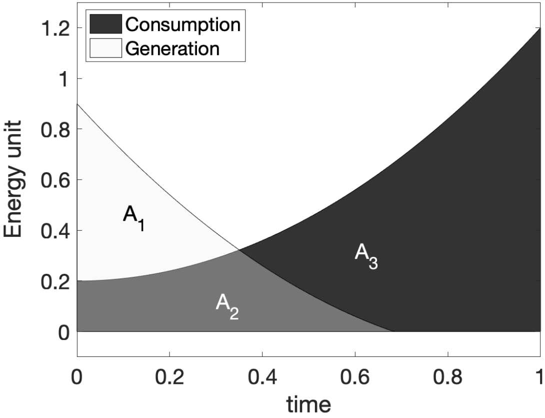

Figure 3: Energy profile

Feed-in-tariff

Cost function for FiT is coperation neutral.

Reason:

$$\sum_{i \in \mathcal{N}} (x_i - y_i) = \sum_{i \in \mathcal{N}} x_i - \sum_{j \in \mathcal{N}} y_i$$

Net metering

Cost function for NM is subadditive and has a non-empty core iff $\lambda \geq \mu$.

Reason:

$$\sum_{i \in \mathcal{N}} (x_i - y_i)^+ \geq \left(\sum_{i \in \mathcal{N}} (x_i - y_i) \right)^+$$

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Future works

- Dynamic peak pricing
  - Best strategy to minimize cost
- Self-utilization of renewable energy
  - Shared battery economy and freeloaders
- Technology, distributed ledger and smart contracts

Reference

C. Wu, J. Porter, and K. Poolla. “Community storage for firming”. In: *2016 IEEE International Conference on Smart Grid Communications (SmartGridComm)*. Nov. 2016, pp. 570–575. DOI: 10.1109/SmartGridComm.2016.7778822.

P. Chakraborty et al. “Sharing Storage in a Smart Grid: A Coalitional Game Approach”. In: *IEEE Transactions on Smart Grid* (2018), pp. 1–1. ISSN: 1949-3053. DOI: 10.1109/TSG.2018.2858206.

D. Kalathil et al. “The Sharing Economy for the Electricity Storage”. In: *IEEE Transactions on Smart Grid* (2018), pp. 1–1. ISSN: 1949-3053. DOI: 10.1109/TSG.2017.2748519.

P. Chakraborty, E. Baeyens, and P. P. Khargonekar. “Analysis of Solar Energy Aggregation under Various Billing Mechanisms”. In: *CoRR* abs/1708.05889 (2017). arXiv: 1708.05889. URL: http://arxiv.org/abs/1708.05889.