Sharing Energy Storage Systems under Net Metering and Time-of-Use Pricing

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Abstract

Sharing economy has become a socio-economic trend in transportation and housing sectors. It develops business models leveraging underutilized resources. Like those sectors, power grid is also becoming smarter with many flexible resources, and researchers are investigating the impact of sharing resources here as well that can help to reduce cost and extract value. In this work, we investigate sharing of energy storage devices among individual households in a cooperative fashion. Coalitional game theory is used to model the scenario where utility company imposes time-of-use (ToU) price and net metering billing mechanism. The resulting game has a non-empty core and we can develop a cost allocation mechanism in the core with easy to compute analytical formula. A mechanism for sharing the excess energy under the peer to peer network (P2P) is also developed. Thus sharing electricity generated by storage devices among consumers can be effective in this set-up. Our simulation results also validate the theoretical claim.

Keywords: energy storage, sharing economy, net metering, ToU price, coalitional games, P2P network.

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1. Introduction

The concept of sharing economy was first proposed by Marcus Felson and Joe L. Spaeth [1]. It means sharing of resources and services between the owners and users, which maximizes utilization of resources to meet the requirements of all parties involved [2]. Sharing economy with successful business set-ups has been groundbreaking in transportation and housing sectors over the last decade. Uber, Ola cabs, Zoomcar, Airbnb, and HomeToGo are some examples of companies in different countries that use sharing economy for their businesses [3, 4]. Sharing economy has huge potential in smart grid applications as well [5, 6, 7] due to introduction of flexible resources in order to cater to the variability associated with deep renewable penetration. In the last few years, there has been investigation of sharing economy using various resources in smart grid like solar PV energy [8], hydrogen energy [9], battery storage energy [10], multiple energy systems [11].

The use of energy storage systems continues to increase in residential and large-scale sectors. The major advantages that are driving the increased use of storage devices are system peak shaving, arbitrage, load management, storing excess wind and solar generation, etc. [12]. A study is conducted in [13] comparing the cost and utilization of individual and shared energy storage operations with various parameter settings in a residential community with time-varying prices. It is found that the shared energy storage is an economical and effective way to solve the problems of peak-demand and variability of renewable energy.

The sharing economy of energy storage leads to the formation of a P2P network. In [14], a P2P market model is proposed with sharing of individual household storage units taking into account the strategic behaviors of participants using the Karush-Kuhn-Tucker optimality condition; a mixed-integer linear program is used as the algorithm for implementation, providing fair sharing. In [15], a business model for energy storage trading in a small neighborhood of multiple households with a common energy storage system is considered, the capacity of which is shared among the households by an auction mechanism,
and the method is implemented using genetic algorithm. In [16], different energy allocation mechanisms are compared for private energy storage and joint community storage in a residential community. Using a mixed integer linear programming model, an aggregator or a third party energy management service provider selects the allocation scheme based on the characteristics and number of households, energy storage system capacity, the impact on the costs, storage utilization, and fairness to the community. In all the above-mentioned works [14, 15, 16], optimization is used to solve the formulated problems.

Game theory is an analytical framework that studies complex interactions among independent and rational players and devises strategies that can guarantee certain performance requirements under realistic assumptions [17]. Stackelberg game models are studied for sharing of energy storage in residential communities in [18, 19]. Non-cooperative game models with Nash equilibrium solution are developed in [20, 21, 22, 23, 24, 25]. An energy storage sharing framework to provide strategies for the allocation of both energy and power capacity is developed in [20]. A multi-period game theoretic model is proposed that takes into account the possibility of shifting electricity demand, production, storage, and selling energy between the users and the providers in [21]. A double-auction market model is designed in [22] that allows the incorporation of power markets with multiple buyers and sellers, allowing the strategic sale of energy depending on the current market state. An advanced energy storage allocation method is proposed based on the interactions among multiple agents during an energy transaction process in a distribution system in [23]. In all of the above sharing models [14, 15, 16, 18, 19, 20, 21, 22, 23, 24, 25], only real-time dynamic pricing is considered, which is difficult to implement in a practical system.

The time-of-use (ToU) pricing policy allows users to alter their electricity consumption schedules to different time periods in a day, and it has a simple design that is easy for consumers to understand [26]. Games with a sharing mechanism for a single peaked time-of-use pricing scheme are formulated and analyzed [27, 28, 29, 30, 31]. In [27], a sharing mechanism design using Nash equilibrium with two coupled games, namely the capacity decision game and the
aggregator user interaction game is solved. In [28], storage investment decisions of a collection of users is formulated as a non-cooperative game. A cooperative energy storage business model based on the sharing mechanism is studied in [30] to maximize the economic benefits with fair cost allocation for all users. Two scenarios are considered in [31]: one where consumers have already invested in individual storage devices, and another where a group of consumers are interested in investing in joint storage capacity and operate using cooperative game theory. A coalition game model for P2P energy trading with both solar and energy storage units for a ToU pricing is developed and analyzed in [32].

Along with the ToU pricing policy, utility companies across the world are also introducing innovative billing mechanisms using which consumers can sell their excess energy back to the grid [33]. Net metering is one such popular billing mechanism [34]. Many states in the US have a net metering policy [35]. A few works have studied the benefits of sharing energy under net metering policy [36] [37]. Still, the benefits of sharing energy in a system that uses net metering billing mechanism along with time-of-use pricing have not been explored so far. In this paper, we consider a set of households with storage units interested in sharing their excess energy among peers. We first prove that the electricity cost of the household operating under a time-of-use pricing policy can be further reduced by introducing a net metering billing mechanism. We then show using the coalitional game theory that sharing the energy of electrical storage units in a P2P network will bring down the electricity costs even further. The formulated coalitional game is profitable and stable. We formulate a mechanism for excess energy sharing. A cost allocation rule is also developed that distributes the joint electricity cost of the coalition among users. So the formation of a coalition is very effective in this scenario.

The rest of the paper is organized as follows. Section 2 presents the mathematical formulation of the proposed model. In Section 3 we discuss the main theoretical results of the cooperative game model. In Section 4 we present the developed sharing mechanism, and in Section 5 we analyse the model with real-world data. Finally, conclusions are drawn in Section 6.
2. Problem Formulation

We consider a set of households as consumers of electricity indexed by $i \in \mathcal{N} = \{1, 2, ..., N\}$. The region where the households are situated have time-of-use electricity price. Each day is divided into two fixed continuous periods: peak $(h)$ and off-peak $(l)$. The price of electricity $(\lambda)$ purchased from the grid is represented by $\lambda_h$ during peak period and $\lambda_l$ during off-peak period. The daily electricity consumption of a household during the peak and off-peak periods are $X_i$ and $Y_i$ respectively. The daily electricity consumption cost of a household without any storage investment and with time-of-use pricing is

$$J_u(i) = \lambda_h X_i + \lambda_l Y_i$$  \hspace{1cm} (1)

Now we assume that each consumer has invested in an energy storage device with capacity $B_i$. We consider the storage devices to be ideal ones. The consumers plan to charge the storage during off-peak period and use it during peak period. The resulting daily consumption cost of the household is

$$J_v(i) = \lambda_h (X_i - B_i)^+ + \lambda_l Y_i + \lambda_l \min\{B_i, X_i\}$$  \hspace{1cm} (2)

where $(x)^+ = \max\{x, 0\}$ for any real number $x$. It is straightforward to see that $J_v(i) \leq J_u(i)$. But the storage also has a capital cost. Storage devices of each house might be made using different technologies and they were also acquired at different times. As a result, each consumer has a different daily capital cost $\lambda_b$ amortised over its lifespan. We assume the values of $\lambda_b$ gives each house an arbitrage opportunity. Thus the daily cost of each household having storage device under time-of-use pricing mechanism [28] is

$$J_w(i) = \lambda_b B_i + \lambda_h (X_i - B_i)^+ + \lambda_l Y_i + \lambda_l \min\{B_i, X_i\}$$  \hspace{1cm} (3)

and $J_w(i) \leq J_u(i)$. Next, we assume that net metering billing mechanism is introduced in our set-up. Under net metering billing mechanism, the house is compensated for the net power generation at price $\mu$ at the end of a billing period. Otherwise, the house would be required to pay the net consumption
at price $\lambda$ for the deficit power consumed from the grid. The price of selling electricity back to the grid $\mu$ for peak and off-peak periods are $\mu_h$ and $\mu_l$ respectively. We consider the following pricing conditions.

\begin{align*}
\lambda_h &\geq \mu_h \\
\lambda_l &\geq \mu_l \\
\mu_h &\geq \lambda_l
\end{align*}

Under this scenario \[38\], the daily cost of the household is

$$J(i) = \lambda_b B_i + \lambda_h (X_i - B_i)^+ - \mu_h (B_i - X_i)^+ + \lambda_l (Y_i + B_i)$$ (7)

**Theorem 1.** The cost of electricity consumption of a household is less under net metering along with TOU pricing compared to under only TOU pricing and no net metering.

**Proof.** The condition \[6\] ensures that it is cost effective to sell any extra electricity available in the storage at the end of peak period to the grid and charge the entire storage during off-peak taking electricity from the grid. The cost effectiveness can be shown by mathematics as follows.

For $X_i \geq B_i$,\n
$$J(i) = \lambda_b B_i + \lambda_h (X_i - B_i) + \lambda_l (Y_i + B_i),$$

$$J_w(i) = \lambda_b B_i + \lambda_h (X_i - B_i) + \lambda_l (Y_i + B_i).$$

So $J(i) = J_w(i)$.

For $X_i < B_i$,\n
$$J(i) = \lambda_b B_i + \mu_h (X_i - B_i) + \lambda_l (Y_i + B_i),$$

$$J_w(i) = \lambda_b B_i + \lambda_l (Y_i + X_i).$$

As $\mu_h \geq \lambda_l$, $J_w(i) \geq J(i)$. \hfill \blacksquare
Thus a consumer with storage can take the advantage of time-of-use price as well as net metering. Next, we investigate the benefits of sharing of energy from residential storage units in the community of households. The consumers aggregate their storage units and they use the aggregated storage capacity to store energy during off-peak periods that they will later use or sell during peak periods. By aggregating their storage units, the unused capacity of some consumers may be used by others, producing cost savings for the group. The price of selling or buying excess energy stored by all the consumers is assumed to be $p$. We analyze this scenario using cooperative/coalitional game theory\cite{39}. Fig. 1 illustrates the proposed grid-connected residential community with P2P network.

![Figure 1: Schematic of grid-connected community with peer-to-peer network.](image)

We define the coalitional game as $G(\mathcal{N}, J)$ with finite number of consumers from the set $\mathcal{N}$, each having value function $J$ which is actually the daily cost of electricity consumption. The consumers participate in the game to minimise the joint cost and cooperatively share this cost. A coalition is any subset of consumers $\mathcal{S} \subseteq \mathcal{N}$ where $\mathcal{N}$ is the grand coalition. $X_S = \sum_{i \in \mathcal{S}} X_i$ denotes the
aggregated peak-period consumption, \( Y_S = \sum_{i \in S} Y_i \) is the joint off-peak period consumption, and the joint storage capacity is \( B_S = \sum_{i \in S} B_i \). The daily cost of a coalition \( S \) is given by

\[
J(S) = \sum_{i \in S} \lambda_b B_i + \lambda_h (X_S - B_S)^+ - \mu_h (B_S - X_S)^+ + \lambda_l (Y_S + B_S)
\] (8)

3. Theoretical Results for the Coalitional Game

In this section, we develop the theoretical results for our game. For the cooperation to be advantageous the game must be proved to be subadditive, i.e., for a pair of coalitions \( S, T \subset \mathcal{N} \) which are disjoint, i.e., \( S \cap T = \emptyset \), they should satisfy the condition \( J(S) + J(T) \geq J(S \cup T) \).

Theorem 2. The cooperative game \( G(\mathcal{N}, J) \) for sharing of storage energy is subadditive.

Proof. As per definition, the expressions of \( J(S) \), \( J(T) \), and \( J(S \cup T) \) are as given below,

\[
J(S) = \sum_{i \in S} \lambda_b B_i + \lambda_h (X_S - B_S)^+ - \mu_h (B_S - X_S)^+ + \lambda_l (Y_S + B_S),
\]

\[
J(T) = \sum_{i \in T} \lambda_b B_i + \lambda_h (X_T - B_T)^+ - \mu_h (B_T - X_T)^+ + \lambda_l (Y_T + B_T),
\]

and

\[
J(S \cup T) = \sum_{i \in S \cup T} \lambda_b B_i + \lambda_h (X_S - B_S + X_T - B_T)^+ - \mu_h (B_S - X_S + B_T - X_T)^+ + \lambda_l (Y_S + B_S + Y_T + B_T).
\]

We can identify four possible cases, (i) \( X_S \geq B_S \) and \( X_T \geq B_T \), (ii) \( X_S \geq B_S \), \( X_T < B_T \) and \( X_S + X_T \geq B_S + B_T \), (iii) \( X_S \geq B_S \), \( X_T < B_T \) and \( X_S + X_T < B_S + B_T \), and (iv) \( X_S < B_S \) and \( X_T < B_T \).
When $X_S \geq B_S$, $X_T \geq B_T$, 

$$J(S) = \sum_{i \in S} \lambda_i b_i + \lambda_i (X_S - B_S) + \lambda_i (Y_S + B_S),$$

$$J(T) = \sum_{i \in T} \lambda_i b_i + \lambda_i (X_T - B_T) + \lambda_i (Y_T + B_T),$$

and

$$J(S \cup T) = \sum_{i \in S \cup T} \lambda_i b_i + \lambda_i (X_S - B_S + X_T - B_T) + \lambda_i (Y_S + B_S + Y_T + B_T).$$

As $X_S + X_T \geq B_S + B_T$, we can see that $J(S \cup T) = J(S) + J(T)$. Similarly we can show for $X_S < B_S$ and $X_T < B_T$.

When $X_S \geq B_S$, $X_T < B_T$ and $X_S + X_T \geq B_S + B_T$, 

$$J(S) = \sum_{i \in S} \lambda_i b_i + \lambda_i (X_S - B_S) + \lambda_i (Y_S + B_S),$$

$$J(T) = \sum_{i \in T} \lambda_i b_i - \mu_i (B_T - X_T) + \lambda_i (Y_T + B_T),$$

$$J(S \cup T) = \sum_{i \in S \cup T} \lambda_i b_i + \lambda_i (X_S - B_S + X_T - B_T) + \lambda_i (Y_S + B_S + Y_T + B_T),$$

and

$$J(S) + J(T) = \sum_{i \in S} \lambda_i b_i + \sum_{i \in T} \lambda_i b_i + \lambda_i (X_S - B_S) - \mu_i (B_T - X_T)$$

$$+ \lambda_i (Y_S + B_S + Y_T + B_T).$$

Comparing $J(S \cup T)$ with $J(S) + J(T)$, we can see that $J(S \cup T) \leq J(S) + J(T)$. Similarly we can show for $X_S \geq B_S$, $X_T < B_T$ and $X_S + X_T < B_S + B_T$.

Thus, in all four cases it is proved that $J(S \cup T) \leq J(S) + J(T)$.

The cooperative game $G(\mathcal{N}, J)$ for sharing of storage energy is subadditive and hence the joint investments of all players in a coalition is never greater than
the sum of individual player cost. Therefore, cooperation is advantageous to
the players in the game. But we also need to check if the game is stable. In this
game, once the grand coalition is formed, players should not break it and be
more profitable by forming coalition with a subset of players. Mathematically,
the condition is called balancedness [40]. In the next theorem, we will show that
our cooperative game is balanced.

**Theorem 3.** The cooperative game $G(N, J)$ for sharing of storage energy is
balanced.

**Proof.** Let $\alpha$ be a positive number.

$$J(\alpha S) = \sum_{i \in S} \lambda_b(i) B_i + \lambda_h(\alpha X_S - \alpha B_S)^+ - \mu_h(\alpha B_S - \alpha X_S)^+$$

$$+ \lambda_l(\alpha Y_S + \alpha B_S)$$

$$= \alpha \sum_{i \in S} \lambda_b(i) B_i + \alpha \lambda_h(X_S - B_S)^+ - \alpha \mu_h(B_S - X_S)^+ + \alpha \lambda_l(Y_S + B_S)$$

$$= \alpha \left[ \sum_{i \in S} \lambda_b(i) B_i + \lambda_h(X_S - B_S)^+ - \mu_h(B_S - X_S)^+ + \lambda_l(Y_S + B_S) \right]$$

This shows us that $J(\alpha S) = \alpha J(S)$, therefore $J$ is a positive homogeneous
function. Let $\alpha$ be any balanced map such that $\alpha : 2^N \to [0, 1]$. For a balanced
map, $\sum_{S \subseteq 2^N} \alpha(S) 1_S(i) = 1$ where $1_S$ is an indicator function of set $S$, i.e., $1_S(i) = 1$ if $i \in S$ and $1_S(i) = 0$ if $i \notin S$. As the cost $J$ is a homogeneous function and
the game is also subadditive, so we can write,

$$\sum_{S \subseteq 2^N} \alpha(S) J(S) = \sum_{S \subseteq 2^N} J(\alpha(S) X_S, \alpha(S) Y_S, \alpha(S) B_S)$$

$$\geq J \left( \sum_{S \subseteq 2^N} \alpha(S) X_S, \sum_{S \subseteq 2^N} \alpha(S) Y_S, \sum_{S \subseteq 2^N} \alpha(S) B_S \right)$$

$$= J \left( \sum_{i \in N} \sum_{S \subseteq 2^N} \alpha(S) 1_S(i) X_i, \sum_{i \in N} \sum_{S \subseteq 2^N} \alpha(S) 1_S(i) Y_i, \sum_{i \in N} \sum_{S \subseteq 2^N} \alpha(S) 1_S(i) B_i \right)$$

$$= J(X_N, Y_N, B_N) = J(N)$$

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where $J(N)$ is the cost of the grand coalition defined as

$$J(N) = \sum_{i \in N} \lambda_b B_i + \lambda_h (X_N - B_N)^+ - \mu_h (B_N - X_N)^+ + \lambda_l (Y_N + B_N)$$

This shows that the game $G(N, J)$ is balanced.

Thus the game is profitable and stable. A grand coalition will be formed and consumers will not break the coalition rationally.

Now, the joint cost of the grand coalition needs to be allocated to the individual agents. Let us discuss about cost allocation in general. Let $\xi_i$ denote the cost allocation for consumer $i \in S$. For coalition $S$, $\xi_S = \sum_{i \in S} \xi_i$ is the sum of cost allocations of all members of the coalition. The cost allocation is said to be an imputation if it is simultaneously efficient ($J(S) = \xi_S$) and individually rational ($J(i) \geq \xi_i$) [41]. Let $I$ denote the set of all imputations. The core, $C$ of the coalition game $G(N, J)$ [41] includes all cost allocations from set $I$ such that cost of no coalition is less than the sum of allocated costs of all consumers. In mathematical notations, the definition is as follows:

$$C = \{ \xi \in I : J(S) \geq \xi_S, \forall S \in 2^N \}$$

According to Bordareva-Shapley value theorem [40], the coaltional game has a non-empty core if it is balanced. Since our game is balanced, the core is non-empty and hence it is possible to find a cost allocation that is in the core of the coalition game. In this paper, we develop a cost allocation $\xi_i$ with analytical formula that is straightforward to compute.

$$\xi_i = \begin{cases} 
\lambda_b B_i + \lambda_h (X_i - B_i) + \lambda_l (Y_i + B_i) & \text{if } X_N \geq B_N \\
\lambda_b B_i - \mu_h (B_i - X_i) + \lambda_l (Y_i + B_i) & \text{if } X_N < B_N 
\end{cases}$$

**Theorem 4.** The cost allocation $\xi_i, i \forall N$ belongs to the core of the cooperative game $G(N, J)$.

**Proof.** The cost of the grand coalition is

$$J(N) = \begin{cases} 
\sum_{i \in N} \lambda_b B_i + \lambda_h (X_N - B_N) + \lambda_l (Y_N + B_N) & \text{if } X_N \geq B_N \\
\sum_{i \in N} \lambda_b B_i - \mu_h (B_N - X_N) + \lambda_l (Y_N + B_N) & \text{if } X_N < B_N 
\end{cases}$$
The cost of an individual household without joining the coalition is

\[
J(i) = \begin{cases} 
\lambda_b B_i + \lambda_h (X_i - B_i) + \lambda_l (Y_i + B_i) & \text{if } X_i \geq B_i \\
\lambda_b B_i - \mu_h (B_i - X_i) + \lambda_l (Y_i + B_i) & \text{if } X_i < B_i 
\end{cases}
\]

For \(X_N \geq B_N\),

\[
\sum_{i \in N} \xi_i = \sum_{i \in N} \lambda_b B_i + \lambda_h (X_N - B_N) + \lambda_l (Y_N + B_N) = J(N)
\]

For \(X_N < B_N\),

\[
\sum_{i \in N} \xi_i = \sum_{i \in N} \lambda_b B_i - \mu_h (B_N - X_N) + \lambda_l (Y_N + B_N) = J(N)
\]

So \(\sum_{i \in N} \xi_i = J(N)\) and the cost allocation \((\xi_i : i \in N)\) satisfies the budget balance.

We now need to prove that cost allocation is individually rational i.e., \(\xi_i \leq J(i)\) for all \(i \in N\).

For \(X_N \geq B_N\),

\[
\xi_i = \lambda_b B_i + \lambda_h (X_i - B_i) + \lambda_l (Y_i + B_i),
\]

If \(X_i \geq B_i\),

\[
J(i) = \lambda_b B_i + \lambda_h (X_i - B_i) + \lambda_l (Y_i + B_i) = \xi_i.
\]

If \(X_i < B_i\),

\[
J(i) = \lambda_b B_i - \mu_h (B_i - X_i) + \lambda_l (Y_i + B_i),
\]

\[
\xi_i = J(i) - (\lambda_h - \mu_h) (B_i - X_i),
\]

\[
\therefore \xi_i = J(i) - (\lambda_h - \mu_h) (B_i - X_i)^+.
\]
For $X_N < B_N$,

$$\xi_i = \lambda_b B_i - \mu_h (B_i - X_i) + \lambda_l (Y_i + B_i),$$

If $X_i < B_i$,

$$J(i) = \lambda_b B_i - \mu_h (B_i - X_i) + \lambda_l (Y_i + B_i) = \xi_i.$$

If $X_i \geq B_i$,

$$J(i) = \lambda_b B_i + \lambda_h (X_i - B_i) + \lambda_l (Y_i + B_i),$$

$$\xi_i = J(i) - (\lambda_h - \mu_h) (X_i - B_i),$$

$$\therefore \xi_i = J(i) - (\lambda_h - \mu_h) (X_i - B_i)^+. \quad (1)$$

This proves individual rationality of the cost allocation. Thus the cost allocation is an imputation. Now, in order to prove that the imputation $\xi_i$ belongs to the core of the cooperative game, we need to prove that the $\sum_{i \in S} \xi_i \leq J(S)$ for the coalition $S \subseteq N$.

If $X_N \geq B_N$,

$$\sum_{i \in S} \xi_i = \sum_{i \in S} \lambda_b B_i + \lambda_h (X_S - B_S) + \lambda_l (Y_S + B_S),$$

$$= J(S) - (\lambda_h - \mu_h) (B_S - X_S)^+. \quad (2)$$

If $X_N \leq B_N$,

$$\sum_{i \in S} \xi_i = \sum_{i \in S} \lambda_b B_i - \mu_h (B_S - X_S) + \lambda_l (Y_S + B_S),$$

$$= J(S) - (\lambda_h - \mu_h) (X_S - B_S)^+. \quad (3)$$

We can observe that $\sum_{i \in S} \xi_i \leq J(S)$ for any $S \subseteq N$ and therefore the cost allocation $\xi_i$ is in the core. \hfill \blacksquare

4. Sharing Mechanism

In this section, we discuss the mechanism that is used for energy sharing among the storage units which are forming the coalition. We have considered
that the houses in the residential community are interconnected by a P2P network through which they can share energy between them. We have developed a sharing mechanism in order to properly distribute the energy between the houses for an appropriate price so that the cost allocations, $\xi_i$ remain in the core, $\mathcal{C}$. The price ($p$) for sharing of energy between the peer-to-peer network is defined by

\[
p = \begin{cases} 
\lambda_h & \text{if } X_N \geq B_N \\
\mu_h & \text{if } X_N < B_N
\end{cases}
\]

When a house wants to sell or buy from the utility, we denote the price as

\[
g = \begin{cases} 
\lambda_h & \text{if } X_i \geq B_i \\
\mu_h & \text{if } X_i < B_i
\end{cases}
\]

We examine the conditions of a house with respect to the community conditions and discuss how sharing of energy would take place and what the cost savings would be. When a house is in deficit of energy ($D_i$), it would either buy the required energy from the P2P network for a price, $p$, or buy from the grid for a price $g$. When a house has excess energy ($E_i$), it would either sell the excess energy to the P2P network for a price, $p$, or sell to the grid for a price $g$. We denote $G_i$ as the cost savings achieved by sharing of energy in the P2P network.
If $X_N \geq B_N$,
\[ p = \lambda_h. \]

If $X_i < B_i$,
\[ g = \mu_h, \]
\[ E_i = B_i - X_i, \]
\[ pE_i > gE_i, \]
\[ G_i = (p - g)E_i = (\lambda_h - \mu_h)E_i, \]
\[ \therefore \xi_i < J(i). \]

If $X_i \geq B_i$,
\[ g = \lambda_h, \]
\[ D_i = B_i - X_i, \]
\[ pD_i = gD_i, \]
\[ G_i = (g - p)D_i = (\lambda_h - \lambda_h)D_i = 0, \]
\[ \therefore \xi_i = J(i). \]

We consider a condition when the combined peak-period consumption is more than the combined storage capacity ($X_N > B_N$). In this condition, if all houses have their individual peak-period consumption more than their storage capacities ($X_i > B_i$), there would be no sharing of energy in the P2P network and therefore no cost savings. Sharing of energy and cost savings will only occur if one or more houses have excess storage energy ($X_i < B_i$). In such cases, the houses whose consumption is more than their storage capacities ($X_i > B_i$) will first utilize the excess storage energy ($\sum_{i \in N} E_i$) from the other houses for the price $p = \lambda_h$, and will buy the remaining energy ($\sum_{i \in N} D_i - \sum_{i \in N} E_i$) from the grid for the same price $g = \lambda_h$, thus they would not have any cost savings. The houses whose consumption is less than their capacities ($X_i < B_i$), will sell their excess energy for the price $p = \lambda_h$ in the P2P network instead of selling to the grid for the price $g = \mu_h$, therefore they would have cost savings of $(\lambda_h - \mu_h)E_i$. 

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If $X_N < B_N$,

\[ p = \mu_h. \]

If $X_i < B_i$,

\[ g = \mu_h, \]
\[ E_i = B_i - X_i, \]
\[ pE_i = gE_i, \]
\[ G_i = (p - g)E_i = (\mu_h - \mu_h)E_i = 0, \]
\[ \therefore \xi_i = J(i). \]

If $X_i \geq B_i$,

\[ g = \lambda_h, \]
\[ D_i = B_i - X_i, \]
\[ pD_i < gD_i, \]
\[ G_i = (g - p)D_i = (\lambda_h - \mu_h)D_i, \]
\[ \therefore \xi_i < J(i). \]

We consider another condition when the combined peak-period consumption is lower than the combined storage capacity ($X_N < B_N$). In this condition, if all houses have their individual peak-period consumption less than their storage capacities ($X_i < B_i$), there would be no sharing of energy in the P2P network and thus no cost savings. Sharing of energy and cost savings will only occur if one or more houses have deficit storage energy ($X_i > B_i$). In such cases, the houses whose consumption is less than their storage capacities ($X_i < B_i$) will first sell their excess storage energy to the other houses which are in deficit ($\sum_{i \in N} D_i$) for the price $p = \mu_h$, and will sell the remaining energy ($\sum_{i \in N} E_i - \sum_{i \in N} D_i$) to the grid for the same price $g = \mu_h$, therefore, they would not make any savings in cost. The houses whose consumption is more than their capacities ($X_i > B_i$), will buy the required energy from the P2P network for the price $p = \mu_h$ instead of buying from the grid for the price $g = \lambda_h$, therefore they would have cost.
5. Simulation Study

5.1. Data Analysis

We consider a group of five houses from the Pecan Street project of 2016 in Austin, Texas \footnote{42} with consumer codes 4373, 4767, 781, 6063, 2199 as houses 1 to 5 respectively. We take the consumption data of each house for an entire year and divide it into peak-periods from 8 hrs to 22 hrs and off-peak periods from 22 hrs to 8 hrs.

\begin{table}[h]
\centering
\caption{Statistical Summary of Daily Total of Load Consumption in Peak-Period}
\begin{tabular}{lcccc}
\hline
Household & 1 & 2 & 3 & 4 & 5 \\
\hline
mean & 35.31 & 34.91 & 17.07 & 17.90 & 9.86 \\
std & 13.65 & 19.86 & 8.13 & 11.22 & 4.54 \\
min & 3.58 & 7.51 & 3.02 & 4.03 & 3.18 \\
25\% & 25.78 & 18.39 & 11.21 & 8.30 & 6.10 \\
50\% & 34.03 & 30.09 & 15.69 & 14.22 & 9.00 \\
75\% & 45.13 & 48.76 & 22.29 & 28.00 & 13.26 \\
max & 69.63 & 93.90 & 48.34 & 50.02 & 27.50 \\
\hline
\end{tabular}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{peak_period_load_consumption}
\caption{Boxplots of the peak-period load consumption of five households.}
\end{figure}
Table 1 shows the statistical summary of the daily total load consumption of all five houses for the peak period. They are also graphically represented using box plots in Fig. 2. Houses 1 and 2 have higher consumption with an average of 35 kWh compared to the rest of the houses, while Houses 3 and 4 have moderate consumption with an average of 17 kWh, and House 5 has the lowest consumption with an average of 9 kWh.

In Fig. 3 we can observe the 24 hr load consumption of all five houses. House 1 has a high consumption period from 12 hrs to 22 hrs, with the mean peak consumption around 0.75 kWh from 17 hrs to 20 hrs. House 2 has a high consumption period from 16 hrs to 24 hrs with the mean peak consumption of around 0.75 kWh from 18 hrs to 22 hrs. House 3 has a high consumption
period from 17 hrs to 2 hrs with the mean peak consumption of around 0.5 kWh from 20 hrs to 24 hrs. House 4 has a high consumption period from 13 hrs to 22 hrs with the mean peak consumption around 0.35 kWh from 14 hrs to 19 hrs. House 5 has peak consumption period from 17 hrs to 24 hrs with the mean peak consumption around 0.25 kWh from 19 hrs to 22 hrs. Thus we can see that only Houses 1 and 2 have common mean peak values and mean peak consumption periods, while Houses 3 and 5 have somewhat similar mean peak consumption periods but differ in their mean peak values. House 4 has a different mean peak value and mean peak consumption period and is not similar to any other house. In Fig. 4 we can observe that all five houses have higher peak period consumption during the summer months from June to September and lower peak period consumption during the winter months from December to February.

![Box plots of peak period consumption for each month in a year of five households.](image)

Figure 4: Box plots of peak period consumption for each month in a year of five households.
5.2. Results and Discussion

We consider that the utility has set the buying price for peak and off-peak periods as \(54e/kWh\) and \(22e/kWh\), and the selling price for peak and off-peak periods as \(30e/kWh\) and \(13e/kWh\), respectively. We consider that all five houses purchase energy storage units independently and randomly. Thus, the storage capacity of each house is different and is selected without the use of any optimization algorithm. For a battery lifespan of 10 years, the amortized cost of storage unit per day for all five houses is considered to be 8.84\$/kWh, 8.92\$/kWh, 8.64\$/kWh, 8.57\$/kWh, 8.73\$/kWh respectively.

### Table 2: Sharing Mechanism for Day 1

| House 1 | House 2 | House 3 | House 4 | House 5 | Total |
|---------|---------|---------|---------|---------|-------|
| \(X_i\) \(\text{(kWh)}\) | 43.76 | 69.22 | 13.39 | 26.57 | 9.47 | 162.41 |
| \(B_i\) \(\text{(kWh)}\) | 19 | 22 | 34 | 48 | 27 | 150 |
| Cond. | \(X_1 > B_1\) | \(X_2 > B_2\) | \(X_3 < B_3\) | \(X_4 < B_4\) | \(X_5 < B_5\) | \(X_N > B_N\) |
| \(E_i\) \(\text{(kWh)}\) | 0 | 0 | 20.61 | 21.43 | 17.53 | 59.57 |
| \(D_i\) \(\text{(kWh)}\) | 24.76 | 50.22 | 0 | 0 | 0 | 74.98 |
| \(u(i)\) \(\text{($)}\) | 13.37 | 27.11 | -6.18 | -6.43 | -5.26 | 22.61 |
| \(\zeta(i)\) \(\text{($)}\) | 13.37 | 27.11 | -11.12 | -11.57 | -9.47 | 8.32 |
| \(G_i\) \(\text{($)}\) | 0 | 0 | 4.94 | 5.14 | 4.21 | 14.29 |

In Table 2 and 3, we present the sharing mechanism for day 1 and day 158 in the year respectively. The combined total storage capacity of all five houses is 150 kWh. On day 1, the combined total peak-period consumption of all five houses is 162.41 kWh which is more than their combined storage capacities \((X_N > B_N)\). Houses 1 and 2 have their individual peak period consumption more than their individual storage capacity \((X_i > B_i)\) with combined deficit energy \((\sum_{i \in N} D_i)\) of 74.98 kWh. Houses 3, 4, and 5 have their individual peak period consumption less than their individual storage capacity \((X_i < B_i)\) with combined excess energy \((\sum_{i \in N} E_i)\) of 59.57 kWh. As the combined deficit is more than the combined excess \((\sum_{i \in N} D_i > \sum_{i \in N} E_i)\), the houses which are in a deficit of 74.98 kWh of energy in total will first buy from the houses which have excess
storage energy of 59.57 kWh. The remaining energy \( \sum_{i \in N} D_i - \sum_{i \in N} E_i \) of 15.41 kWh is bought from the grid. In both cases, the buying is price 54c/kWh. Therefore, the houses which are buying energy from the P2P network do not make a profit. Only the houses which are selling energy to the P2P network make a profit as the selling price to the grid is 30c/kWh. Thus, the combined savings (\( \sum_{i \in N} G_i \)) is $14.29.

| House 1 (kWh) | House 2 (kWh) | House 3 (kWh) | House 4 (kWh) | House 5 (kWh) | Total |
|---------------|---------------|---------------|---------------|---------------|-------|
| 30.54         | 31.18         | 12.68         | 9.57          | 14.05         | 98.01 |
| B_i (kWh)     | 19            | 22            | 34            | 48            | 27    | 150   |
| Cond.         | X_1 > B_1     | X_2 > B_2     | X_3 < B_3     | X_4 < B_4     | X_5 < B_5 | X_N < B_N |
| E_i (kWh)     | 0             | 0             | 21.32         | 38.43         | 12.95 | 72.17 |
| D_i (kWh)     | 11.54         | 9.18          | 0             | 0             | 0     | 21.34 |
| u(i)($)       | 6.23          | 4.96          | -6.39         | -11.53        | -3.89 | -10.62 |
| \xi($)        | 3.46          | 2.75          | -6.39         | -11.53        | -3.89 | -15.59 |
| G_i($)        | 2.77          | 2.21          | 0             | 0             | 0     | 4.98  |

On day 158, the combined total peak-period consumption of all five houses is 98.01 kWh, which is less than their combined storage capacities (\( X_N < B_N \)). Houses 1 and 2 have their individual peak period consumption more than their individual storage capacity (\( X_i > B_i \)) with combined deficit energy (\( \sum_{i \in N} D_i \)) of 21.34 kWh. Houses 3, 4, and 5 have their individual peak period consumption less than their individual storage capacity (\( X_i < B_i \)) with combined excess energy (\( \sum_{i \in N} E_i \)) of 72.17 kWh. As the combined excess is greater than the combined deficit (\( \sum_{i \in N} E_i > \sum_{i \in N} D_i \)), the houses which are in excess of 72.17 kWh of energy in total will first sell to the houses which have deficit energy of 21.34 kWh in total. The remaining energy (\( \sum_{i \in N} E_i - \sum_{i \in N} D_i \)) of 51.99 kWh is sold to the grid. In both cases, the selling is price 30c/kWh. Therefore, the houses which are selling energy to the P2P network do not make a profit. Only the houses which are buying energy from the P2P network make a profit as the buying price from the grid is 54c/kWh. Thus, the combined savings (\( \sum_{i \in N} G_i \)) is $21.
$4.98.

We compute the electricity cost of the household without storage using equation (1) and with storage using (2). We then compute the cost allocations given by equation (6) and compare the cost savings with and without sharing using equation (2). The monthly cost of all houses are tabulated for with no storage, with storage, and with sharing of storage in Tables 4 to 8 and also the savings and percentage of savings with sharing are computed.

|                   | Cost ($) | No Storage | with Storage | Savings with sharing | % Savings with sharing |
|-------------------|----------|------------|--------------|----------------------|------------------------|
| **January**       | 418.81   | 293.66     | 257.38       | 36.29                | 12.36                  |
| **February**      | 418.89   | 293.46     | 257.11       | 36.34                | 12.38                  |
| **March**         | 440.98   | 325.12     | 269.72       | 55.40                | 17.04                  |
| **April**         | 566.13   | 434.11     | 343.38       | 90.74                | 20.90                  |
| **May**           | 600.65   | 473.42     | 375.78       | 97.64                | 20.62                  |
| **June**          | 713.38   | 581.37     | 519.67       | 61.71                | 10.61                  |
| **July**          | 952.62   | 816.21     | 794.75       | 21.46                | 2.63                   |
| **August**        | 877.87   | 741.46     | 672.45       | 69.01                | 9.31                   |
| **September**     | 5763.35  | 631.33     | 547.62       | 83.71                | 13.26                  |
| **October**       | 542.41   | 416.19     | 336.06       | 80.13                | 19.25                  |
| **November**      | 405.49   | 288.18     | 246.60       | 41.58                | 14.43                  |
| **December**      | 3493.48  | 360.16     | 305.44       | 54.72                | 15.19                  |
| **Total for one year** | 7194.07  | 5634.66    | 4925.95      | 728.72               | 12.89                  |
Table 5: Cost Analysis for House 2

| Cost ($) | No Storage with Storage | with sharing of storage | Savings with sharing | % Savings with sharing |
|----------|-------------------------|-------------------------|----------------------|-----------------------|
| January  | 353.72                  | 235.31                  | 225.42               | 9.89                  | 4.20                  |
| February | 264.97                  | 172.64                  | 169.80               | 2.84                  | 1.64                  |
| March    | 314.28                  | 212.18                  | 198.25               | 13.94                 | 6.57                  |
| April    | 341.66                  | 235.47                  | 217.85               | 17.62                 | 7.48                  |
| May      | 656.48                  | 501.68                  | 420.00               | 2.84                  | 1.64                  |
| June     | 1001.34                 | 849.01                  | 771.91               | 13.94                 | 6.57                  |
| July     | 1111.60                 | 954.19                  | 933.06               | 21.13                 | 2.21                  |
| August   | 957.19                  | 799.79                  | 730.42               | 69.37                 | 8.67                  |
| September| 812.49                  | 661.59                  | 609.18               | 52.41                 | 7.92                  |
| October  | 601.44                  | 449.43                  | 378.24               | 71.19                 | 15.84                 |
| November | 319.17                  | 218.70                  | 203.08               | 15.63                 | 7.14                  |
| December | 466.81                  | 327.23                  | 290.81               | 36.41                 | 11.13                 |
| Total for one year | 7201.13 | 5620.22 | 5148.01 | 472.21 | 8.40 |

Table 6: Cost Analysis for House 3

| Cost ($) | No Storage with Storage | with sharing of storage | Savings with sharing | % Savings with sharing |
|----------|-------------------------|-------------------------|----------------------|-----------------------|
| January  | 184.88                  | 123.05                  | 123.05               | 0.00                  | 0.00                  |
| February | 199.00                  | 135.65                  | 135.65               | 0.00                  | 0.00                  |
| March    | 222.42                  | 153.66                  | 153.66               | 0.00                  | 0.00                  |
| April    | 316.90                  | 222.93                  | 220.98               | 1.95                  | 0.87                  |
| May      | 275.58                  | 199.70                  | 194.23               | 5.48                  | 2.74                  |
| June     | 418.97                  | 292.64                  | 244.13               | 48.51                 | 16.58                 |
| July     | 522.33                  | 362.49                  | 294.32               | 68.16                 | 18.80                 |
| August   | 438.23                  | 304.51                  | 260.42               | 44.09                 | 14.48                 |
| September| 397.68                  | 275.71                  | 234.94               | 40.77                 | 14.79                 |
| October  | 334.39                  | 237.81                  | 234.88               | 2.93                  | 1.23                  |
| November | 246.22                  | 171.12                  | 171.12               | 0.00                  | 0.00                  |
| December | 240.11                  | 158.14                  | 158.14               | 0.00                  | 0.00                  |
| Total for one year | 3796.69 | 2637.41 | 2425.52 | 211.89 | 8.03 |
We observe that Houses 1 and 2 save costs by sharing for all months. In contrast, Houses 3, 4, and 5 save costs by sharing only in the summer months (June to September) and have zero to negligible savings during the rest of the months. Houses 1 and 2 have their peak-period consumption greater than their storage capacities for most days, and Houses 3, 4, and 5 have their peak-period consumption lower than their storage capacities for most days. Only during the summer months the total consumption of all houses is greater than the combined storage capacity for most days. In such conditions, only the houses with storage capacities greater than their peak-period consumption make a profit through sharing. For the rest of the months, we have a combined storage capacity greater than the combined peak-period consumption for most days. In such conditions, only the houses with storage capacities less than their peak-period consumption make a profit through sharing.

Table 7: Cost Analysis for House 4

|          | Cost ($) | No Storage | with Storage | Savings with sharing | % Savings with sharing |
|----------|----------|------------|--------------|----------------------|------------------------|
| January  | 179.56   | 122.69     | 122.69       | 0.00                 | 0.00                   |
| February | 145.29   | 100.39     | 100.39       | 0.00                 | 0.00                   |
| March    | 160.72   | 109.43     | 109.43       | 0.00                 | 0.00                   |
| April    | 190.56   | 126.82     | 126.82       | 0.00                 | 0.00                   |
| May      | 264.09   | 170.00     | 163.10       | 6.89                 | 4.06                   |
| June     | 481.69   | 303.16     | 236.84       | 66.32                | 21.88                  |
| July     | 611.36   | 382.39     | 286.55       | 95.85                | 25.07                  |
| August   | 531.06   | 336.65     | 274.36       | 62.30                | 18.50                  |
| September| 496.31   | 310.36     | 264.15       | 46.21                | 14.89                  |
| October  | 323.84   | 205.55     | 200.04       | 5.51                 | 2.68                   |
| November | 174.32   | 118.37     | 118.37       | 0.00                 | 0.00                   |
| December | 178.86   | 121.23     | 121.23       | 0.00                 | 0.00                   |
| Total for one year | 3737.67 | 2407.05 | 2123.97 | 283.08 | 11.76 |
Table 8: Cost Analysis for House 5

| Month       | Cost ($) | No Storage | Storage with sharing of storage | Savings with sharing | % Savings with sharing |
|-------------|----------|------------|----------------------------------|----------------------|------------------------|
| January     | 111.49   | 75.94      | 75.94                            | 0.00                 | 0.00                   |
| February    | 87.53    | 61.64      | 61.64                            | 0.00                 | 0.00                   |
| March       | 106.82   | 74.32      | 74.32                            | 0.00                 | 0.00                   |
| April       | 135.02   | 90.98      | 90.98                            | 0.00                 | 0.00                   |
| May         | 160.35   | 108.28     | 104.60                           | 3.68                 | 3.40                   |
| June        | 227.82   | 153.43     | 99.92                            | 53.51                | 34.87                  |
| July        | 296.66   | 196.98     | 116.07                           | 80.91                | 41.08                  |
| August      | 253.65   | 168.75     | 119.41                           | 49.35                | 29.24                  |
| September   | 236.49   | 155.58     | 118.56                           | 37.01                | 23.79                  |
| October     | 185.46   | 121.87     | 118.19                           | 3.68                 | 3.02                   |
| November    | 115.96   | 78.53      | 78.53                            | 0.00                 | 0.00                   |
| December    | 119.97   | 81.23      | 81.23                            | 0.00                 | 0.00                   |
| Total for one year | 2037.21 | 1367.52    | 1139.38                          | 228.14               | 16.68                  |

Table 9: Comparative Analysis for all 5 Houses

|                | House 1    | House 2    | House 3    | House 4    | House 5    | Total       |
|----------------|------------|------------|------------|------------|------------|-------------|
| Total cost with storage | 5654.66    | 5620.22    | 2637.41    | 2407.05    | 1367.52    | 17686.9     |
| Total cost with sharing of storage | 4925.95    | 5148.01    | 2425.52    | 2123.97    | 1139.38    | 15762.8     |
| Cost savings   | 728.71     | 472.207    | 211.886    | 283.083    | 228.143    | 1924.04     |
| % Savings      | 12.89      | 8.40       | 8.03       | 11.76      | 16.68      | 10.88       |

Table 9 presents the comparative cost analysis for all five houses, and the cost savings are represented graphically in Fig. 5. The combined total electricity consumption cost for a period of one year for all households with storage is $17,686.9. This cost reduces to $15,762.8 with the sharing of storage energy through the P2P network, providing cost savings of $1924.04 i.e. 10.86% of savings. All costs also include the capital costs considered for the given period of one year. We can observe that House 5 has the highest savings of 16.68% through selling its excess energy in the P2P network. This house has excess...
storage energy and has the lowest consumption compared to all other houses for most days in a year. House 5 has the second highest savings of 12.89% through only buying energy from the P2P network. This house has a deficit of storage energy and has the highest consumption compared to all other houses for most days in a year. House 2 also has higher peak-period consumption than its storage capacity, and it buys energy from the P2P network for most days in a year, making savings of 8.40%. Houses 3 and 4 have their storage capacities higher than their peak-period consumption and sell their excess energy to the P2P network for most days in a year, resulting in savings of 8.03% and 11.76% respectively.

6. Conclusion

In this paper, we presented the sharing of electrical storage energy among a group of residential houses in a community under net metering and time of use pricing mechanism. We used cooperative game theory to model the sharing in a peer-to-peer network, and the game was shown to be profitable and stable. We developed a sharing mechanism and a cost allocation rule such that all houses would profit through either buying from or selling to the P2P network. Thus, our results show that sharing of storage in a cooperative way provides cost savings for all the houses in the community. We presented a case study using

Figure 5: % Savings with and without sharing of storage of five households.
load consumption data of one year for five houses and investigated how sharing operates. The results show a clear reduction in costs for all the households through sharing electrical storage energy in the P2P network. In our future work, we will extend the results to residential houses with combined solar PV panels and storage units. We will also investigate sharing of renewable energy for different pricing mechanisms.

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