Chapter 3

A Cooperative Game Analysis of Peer-to-Peer Energy Transactions: Foundation of Virtual Community

3.1 Introduction

This chapter presents a decentralized P2P energy-sharing framework that involves a profit-based battery energy storage system (BESS) and a group of buildings (a community) equipped with renewable energy sources (RES). This work compares incentive-based and hourly price-based mechanisms for energy trading. A Generalized Nash Bargaining is used for the distribution of economic benefit and the Alternating Direction Method of Multipliers (ADMM) is used to implement decentralization in the optimization process. The load-shifting scheme is used to implement demand-side management. The contribution of this chapter can be summarised as follows.

1. A building-to-building (B2B) framework is developed to reduce the cost for each player (member) of the community considering a community battery energy storage system (CBESS) as a player along with the buildings.

2. Hong's 2m point estimate method-based stochastic model is used to cope with the uncertainties of renewable generation.

3. Both price and incentive-based mechanisms are compared for evaluating the P2P energy-sharing model.

4. An algorithm is developed based on the ADMM to determine the power profiles of each building, and the incentives, and the prices of internal transactions in a decentralized manner.

3.2 System modelling and problem formulation

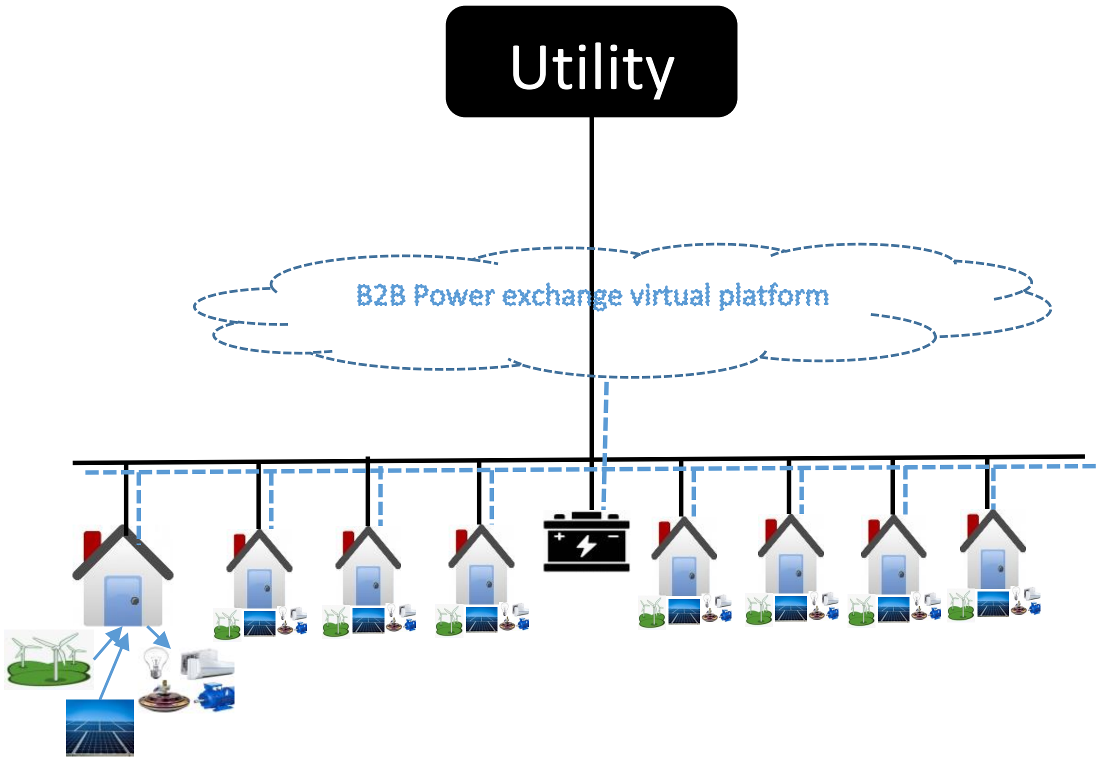


Figure 3.1: SYSTEM MODEL FOR B2B ENERGY TRADING

A community of n players (members) consisting of $(n-1)$ number of buildings and one community battery energy storage system (CBESS) is considered in this chapter. The $(n-1)$ buildings are equipped with renewable generations (including both solar and wind energy generation resources), load-shifting capability, and advanced metering systems. The n^{th} element of this community is a profit-based community battery energy storage system (CBESS). All are connected as shown in Figure3.1. In addition to all of the above, it is assumed that there is a cloud computing platform to facilitate the P2P transactions wherein a player does not have access to the data of other players.

The cost function of each element in this community is given by,

$$C_b = C_b^0 + \sum_{\substack{b'=1 \\ b'\neq b}}^{n} C_{i,j}^{b2b}. \tag{3.1}$$

The C_b^0 of $(n-1)$ number of buildings in this community is given by,

$$C_b^0 = \sum_{t=1}^{T} (C_{i,t}^U + C_{i,t}^{fl}), \tag{3.2}$$

and for n^{th} element of this community i.e. CBESS,

$$C_b^0 = \sum_{t=1}^{T} (C_{i,t}^U + C_{i,t}^{bat}). \tag{3.3}$$

Here,

$$C_{i,t}^U = (\Lambda_t^{im} + \epsilon^{CE}) P_{i,t}^b - \Lambda_t^{ex} P_{i,t}^s, \tag{3.4}$$

$$C_{i,t}^{fl} = \Lambda^{dis} (P_{i,t}^{ls} - L_{i,t})^2, \tag{3.5}$$

$$C_{i,t}^{bat} = \Lambda^{UTI} (P_t^{ch} + P_t^{dis}). \tag{3.6}$$

All the power profiles are denoted by P, and the respective price is denoted by Λ. The cost due to trade with utility $C_{i,t}^U$ is given by (3.4), where ϵ^{CE} is the tax corresponding to carbon emission, Λ_t^{im} and Λ_t^{ex} are price for power exchange with the utility. The cost, $C_{i,t}^{fl}$, corresponding to dissatisfaction due to scheduling of flexible load is given by (3.5), where Λ^{dis} is the parameter used for the consumer's dissatisfaction arose due to the load shifting from $L_{i,t}$ to $P_{i,t}^{ls}$. The CBESS has an additional cost of battery degradation, $C_{i,t}^{bat}$, due to repetitive charging and discharging, as given in (3.6). The term $C_{i,j}^{b2b}$ in (3.1), will be equal to $\pi_{i,j}$ in incentive-based mechanism whereas this will be equal to $\sum_{t=1}^{T} P_{i,j,t}^{b2b} \rho_{i,j,t}^{b2b}$ in price-based mechanism.

The objective function is subjected to the following constraints.

$$P_{i,t}^b \geq 0, \tag{3.7a}$$

$$P_{i,t}^s \geq 0, \tag{3.7b}$$

$$L_{i,t}^{min} \leq P_{i,t}^{ls} \leq L_{i,t}^{max}, \tag{3.8}$$

$$\sum_{t=1}^{T} P_{i,t}^{ls} \geq \epsilon^{LS} \sum_{t=1}^{T} L_{i,t}, \tag{3.9}$$

$$P_{i,j,t}^{b2b} + P_{j,i,t}^{b2b} = 0, \tag{3.10}$$

$$\pi_{i,j} + \pi_{j,i} = 0, \tag{3.11}$$

$$\rho^{b2b}_{i,j,t} - \rho^{b2b}_{j,i,t} = 0, \tag{3.12}$$

$$P^{s}_{i,t} - P^{b}_{i,t} - \sum_{b'=1}^{n} P^{b2b}_{i,j,t} \leq R_{i,t} - P^{ls}_{i,t}, \tag{3.13}$$

$$P^{ch^{min}}_{t} \leq P^{ch}_{t} \leq P^{ch^{max}}_{t}, \tag{3.14}$$

$$P^{dis^{min}}_{t} \leq P^{dis}_{t} \leq P^{dis^{max}}_{t}, \tag{3.15}$$

$$SOC^{min}_{t} \leq SOC_{t} \leq SOC^{max}_{t}, \tag{3.16}$$

$$SOC_{t} = (1 - \eta^{loss})SOC_{t-1} + \eta^{ch} P^{ch}_{t} - \frac{1}{\eta^{dis}} P^{dis}_{t},\ and \tag{3.17}$$

$$P^{s}_{i,t} - P^{b}_{i,t} - \sum_{b'=1}^{n} P^{b2b}_{i,j,t} + P^{dis}_{t} - P^{ch}_{t} = 0. \tag{3.18}$$

The flexible loads can only be shifted within the permissible limits, as shown in (3.8). The ϵ^{LS} in (3.9) indicates the fraction of load supplied i.e. load after curtailment. The building-to-building (B2B), building-to-CBESS, and CBESS-to-building are the internal transactions for a community. Constraints corresponding to P2P power exchange, incentive exchange and price of P2P energy exchange are given by (3.10), (3.11), and (3.12), respectively. The constraints (3.10)-(3.12) are the coupling constraints in P2P trading. If the element b of the community is importing power from the element b', then $P^{b2b}_{i,j,t}$ will be positive, else negative. Similarly, if element b of the community pays to the element b', then $\pi_{i,j}$ will be positive, else negative. But hourly price, $\rho^{b2b}_{i,j,t}$, will always be positive. The load balancing constraint for buildings is represented by (3.13). The maximum and minimum limits on the charging/discharging power and state-of-charge (SOC) of CBESS are imposed by (3.14), (3.15), and (3.16), respectively. Equation (3.17) defines the relationship between the present and previous hour of SOC levels and the charging/discharging status of CBESS. η^{ch} and $\frac{1}{\eta^{dis}}$ are the charging and discharging efficiencies, respectively, while η^{loss} is the parameter related to the self-discharging of the battery. The power balance equation of CBESS is given by (3.18). Constraints (3.7), (3.8) and (3.13) are related to buildings, while constraints (3.14)-(3.18) are related to CBESS. This framework doesn't need any separate constraints to prevent simultaneous charging and discharging or buying and selling to the grid, as explained in Appendix III.

3.3 Methodology

This work uses the Nash bargaining-based cooperative game theory for P2P energy trading. Hong's 2m point estimate method (PEM) is used to cope with the uncertainties of RESs.

Hong's 2m PEM provides the expected value of energy trading between players considering the uncertainties of RESs. The problem described in section 3.2 has some coupling variables such as $P^{b2b}_{i,j,t}$, $\pi_{i,j}$, and $\rho^{b2b}_{i,j,t}$, and can be solved using ADMM in a decentralized manner. The expected strategies of all players, i.e., the first moment of random variables, will be used in the Nash bargaining based energy trading.

3.3.1 Nash bargaining and ADMM

The problem of the above system can be formulated using a cooperative game where all the elements of the community, including the CBESS, are the players and all the strategies are given by $\mathbb{E}(P)$, where, $P \in \{P^{b}_{i,t}, P^{s}_{i,t}, P^{ls}_{i,t}, P^{ch}_{t} P^{dis}_{t}, \pi_{i,j}, P^{b2b}_{i,j,t}\}$. The main aim of P2P trading can be defined as,

$$\mathbb{E}(C_b^{with\ b2b}) \leq \mathbb{E}(C_b^{w/o\ b2b}). \tag{3.19}$$

Using Generalised Nash Bargaining (GNB), the problem can be formulated as,

$$\max_{\mathbb{E}(P)} \prod_{b=1}^{n} (\mathbb{E}(C_b^{w/o\ b2b}) - \mathbb{E}(C_b^{with\ b2b})), \tag{3.20}$$

subjected to (γ, 3.10,3.11), where $\gamma \in \{$(3.7) to (3.9) and (3.13) to (3.18)$\}$. This maximization function aims to maximize the collective difference in cost between scenarios without P2P energy trading and with P2P energy trading for all participants. The product of these individual differences is used to emphasize that, in cooperative games, participants collaborate to maximize mutual benefits.This can be re-written as,

$$\min_{\mathbb{E}(P)} \sum_{b=1}^{n} -log(\mathbb{E}(C_b^{w/o\ b2b}) - \mathbb{E}(C_b^{with\ b2b}) + 1), \tag{3.21}$$

subjected to (γ, 3.10,3.11). Equations (3.10),(3.11), and (3.12) are the coupling constraints. The above problem is solved in a decentralized way using ADMM. The coupling constraints can be dealt with the help of new auxiliary variables $\sigma^{\pi}_{i,j}$, $\sigma^{\rho}_{i,j,t}$ and $\sigma^{P}_{i,j,t}$ such that,

$$\sigma^{\pi}_{i,j} = \pi_{i,j}, \tag{3.22}$$

$$\sigma^{\pi}_{i,j} + \sigma^{\pi}_{j,i} = 0, \tag{3.23}$$

$$\sigma^{\rho}_{i,j,t} = \rho^{b2b}_{i,j,t}, \tag{3.24}$$

$$\sigma^{\rho}_{i,j,t} - \sigma^{\rho}_{j,i,t} = 0, \tag{3.25}$$

$$\sigma^P_{i,j,t} = \mathbb{E}(P^{b2b}_{i,j,t}), \tag{3.26}$$

$$\sigma^P_{i,j,t} + \sigma^P_{j,i,t} = 0. \tag{3.27}$$

The expression (3.21) can be re-written in the augmented Lagrangian form as,

$$\mathcal{L}(\mathbb{E}(P), \sigma, \omega) = \sum_{b=1}^{n} -log(\mathbb{E}(C_b^{w/o\ b2b}) - \mathbb{E}(C_b^{with\ b2b}) + 1) + \frac{\delta_1}{2} \sum_{b=1}^{n} \sum_{\substack{b'=1 \\ b' \neq b}}^{n} (\pi_{i,j} - \sigma^{\pi}_{i,j} + \frac{\omega^{\pi}_{i,j}}{\delta_1})^2 + \frac{\delta_2}{2} \sum_{t=1}^{T} \sum_{b=1}^{n} \sum_{\substack{b'=1 \\ b' \neq b}}^{n} (\mathbb{E}(P^{b2b}_{i,j,t}) - \sigma^P_{i,j,t} + \frac{\omega^P_{i,j,t}}{\delta_2})^2, \tag{3.28}$$

where δ_1 and δ_2 are penalty parameters, and $\omega^{\pi}_{i,j}$ and $\omega^P_{i,j,t}$ are dual multipliers.

An algorithm for this two-step optimization is given in Algorithm 1 for solving the incentive-based energy-sharing optimization problem. In the first step, the strategies will be optimized wherein $\{P^b_{i,t}, P^s_{i,t}, P^{ls}_{i,t}, P^{ch}_t P^{dis}_t, \pi_{i,j}, P^{b2b}_{i,j,t}\}$ are decided/optimized by using 3.28. Then in step 2 the auxiliary variables are updated by the minimizing the following lagrangian function.

$$\mathcal{L}(\sigma, \omega) = \frac{\delta_1}{2} \sum_{b=1}^{n} \sum_{\substack{b'=1 \\ b' \neq b}}^{n} (\pi_{i,j} - \sigma^{\pi}_{i,j} + \frac{\omega^{\pi}_{i,j}}{\delta_1})^2 + \frac{\delta_2}{2} \sum_{t=1}^{T} \sum_{b=1}^{n} \sum_{\substack{b'=1 \\ b' \neq b}}^{n} (\mathbb{E}(P^{b2b}_{i,j,t}) - \sigma^P_{i,j,t} + \frac{\omega^P_{i,j,t}}{\delta_2})^2, \tag{3.29}$$

Once all the variables (strategies and auxiliary) are obtained, the dual multipliers are updated as shown in steps 8 and 9. Finally, the penalty parameters, δ_1 and δ_2, are updated with the help of primal and dual residuals. Here, τ and ν are given parameters. This algorithm is for incentive-based energy sharing model. For an hourly price-based energy sharing, the same algorithm will be used by replacing $\pi_{i,j}$ with $\rho^{b2b}_{i,j,t}$ and modifying it accordingly. (3.28) will also be modified with the help of (3.24) and (3.25).

3.4 Simulation Results

The single line diagram (SLD) of the B2B energy trading diagram is shown below (Figure 3.2). The buildings are grouped into virtual communities as can been from this diagram. Here a community of three buildings is considered, all of which have different load profiles (Figure 3.3(a)) and renewable generations (Figure 3.3(b)). In Figure 3.3(b), the solar power generation (SPG) and wind power generation (WPG) data are given for the rated capacity of 125kW and 100kW, respectively. The rated capacities of load, RESs, and battery are summarised in Table 3.1. Along with the buildings, a profit-based CBESS is also present. The maximum charging

Algorithm 1: Algorithm for optimizing P2P energy sharing using a cooperative game approach and ADMM to distribute energy efficiently among participants by solving the optimization problem iteratively.

Initialize tolerance, $\delta(1), \tau, \nu, \omega(1) = 0, \kappa = 1$
Do
  For each player
    $\min_{\mathbb{E}(P)\in\gamma} \mathcal{L}(\mathbb{E}(P), \sigma(\kappa), \omega(\kappa))$ {First Step}
  Update $\sigma(\kappa+1)$:
    $\min_{\sigma\in(3.23,3.27)} \mathcal{L}(\mathbb{E}(P(\kappa+1)), \sigma, \omega(\kappa))$ {Second Step}
  Update $\omega(\kappa+1)$:
    $\omega^{\pi}(\kappa+1) = \omega^{\pi}(\kappa) + \delta_1(\kappa)(\pi_{i,j}(\kappa+1) - \sigma^{\pi}_{i,j}(\kappa+1))$
    $\omega^{P}(\kappa+1) = \omega^{P}(\kappa) + \delta_2(\kappa)(\mathbb{E}(P^{b2b}_{i,j,t}(\kappa+1)) - \sigma^{P}_{i,j,t}(\kappa+1))$
  Calculate primal and dual residuals
    $\lambda^P_1 = ||\pi_{i,j}(\kappa+1) - \sigma^{\pi}_{i,j}(\kappa+1)||$
    $\lambda^P_2 = ||\mathbb{E}(P^{b2b}_{i,j,t}(\kappa+1)) - \sigma^{P}_{i,j,t}(\kappa+1)||$
    $\lambda^D_1 = ||\sigma^{\pi}_{i,j}(\kappa+1) - \sigma^{\pi}_{i,j}(\kappa)||$
    $\lambda^D_2 = ||\sigma^{P}_{i,j,t}(\kappa+1) - \sigma^{P}_{i,j,t}(\kappa)||$
  If $\lambda^P > \frac{1}{\tau}\lambda^D$, then
    $\delta(\kappa+1) = \nu\delta(\kappa)$
  else if $\lambda^P < \tau\lambda^D$, then
    $\delta(\kappa+1) = \frac{1}{\nu}\delta(\kappa)$
  else
    $\delta(\kappa+1) = \delta(\kappa)$
  end if
  $\kappa = \kappa + 1$
while $||\omega(\kappa+1) - \omega(\kappa)|| > tolerance$

and discharging power of CBESS is 50 kW/h. The maximum and minimum SOC level limits are 90% and 20%, respectively. The value of other parameters used is mentioned in Table 3.2. Load curtailment is not considered in this work, i.e., $\epsilon^{LS} = 1$. The consumer's dissatisfaction parameter Λ^{dis} is assumed as $0.03\$/kW^2$. The load shift is limited to $\pm10\%$. The utility price is considered to be time-varying (Figure 3.4(b)) with ϵ^{CE} equal to $0.05\$/kW$. A desktop with a Core $i3$ 1.20 GHz processor with 4 GB RAM is used to implement the code, and GAMS/CONOPT4 solver is used for optimization.

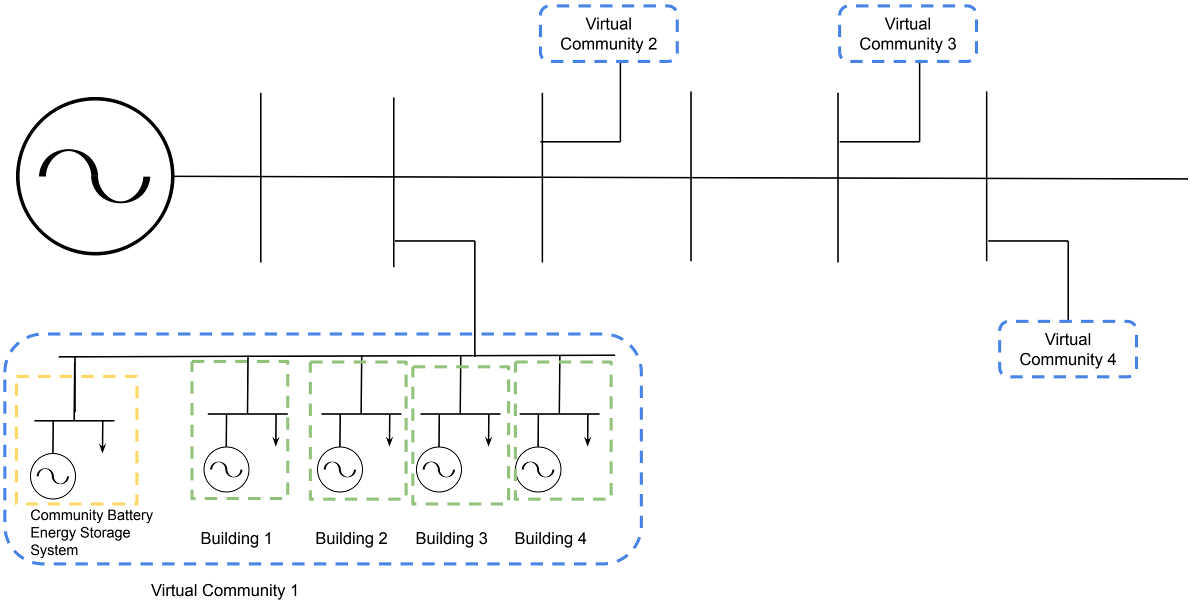


Figure 3.2: Single line diagram (SLD) for the system

Table 3.1: Rated Capacities of Loads, RESs, and Battery

	Rated Load (kW)	SPG (kW)	WPG (kW)	Battery (kW)
Build 1	125	125	100	-
Build 2	125	125	100	-
Build 3	100	100	50	-
CBESS	-	-	-	200

Table 3.2: Values of Parameters used

Parameters	Λ^{UTI}	η^{loss}	η^{ch}	η^{dis}	δ	τ	ν
Value	$0.06\$/kW$	0.5%	96%	94.3%	0.002	0.02	2

Each building in the B2B energy trading framework can be considered as a node in the equivalent circuit (Figure 3.2). This is because

- Each building has its own load, renewable energy generation, and potentially a battery energy storage system (BESS), making it a distinct entity in terms of power flow.

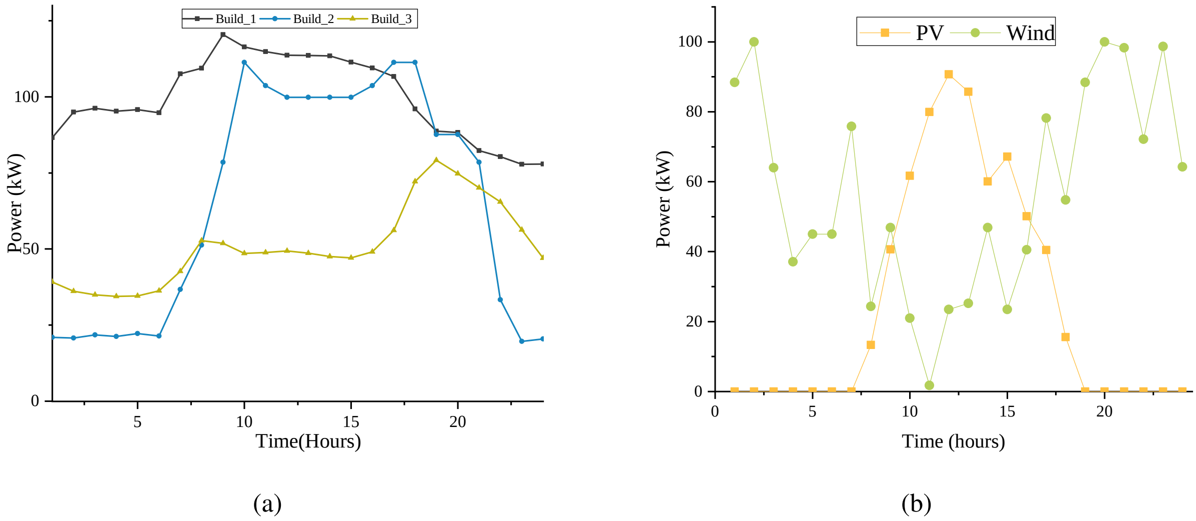


Figure 3.3: (a) Load profile of the buildings, and (b) Data for renewable generation of the buildings.

- The interaction between buildings (energy exchange) can be represented as power flows between nodes in an electrical network.
- The community battery energy storage system (CBESS) acts as an additional node that interacts with all buildings.

The introduction of B2B energy trading significantly reduces costs for all participants by enabling surplus renewable energy to be shared among buildings. The CBESS further enhances cost savings by storing surplus energy during low-demand periods and discharging it during peak demand. This equivalent circuit representation effectively models the B2B energy trading framework, with each building considered as a node. This abstraction highlights the interactions between buildings and their shared resources (CBESS), enabling detailed analysis of power flows and cost optimization.

Three different cases are considered(i) without B2B energy trading, (ii) B2B energy trading with incentives mechanism, and (iii) B2B energy trading with hourly pricing mechanism.

Table 3.3 shows the expected energy cost of the buildings for all three cases. The cost function of the buildings reduces with B2B energy trading compared to without B2B energy trading, irrespective of the incentive/pricing scheme used. The expected energy cost of $Building$ 1, $Building$ 2, and $Building$ 3 reduced by 22.60%, 187%, and 44.03%, respectively. The expected profit of CBESS increases by 19.54 %. The difference in the total cost between the incentive and hourly pricing mechanism is not much. However, the execution time for energy scheduling with the incentive mechanism is 102.730 seconds, whereas with the hourly-pricing mechanism, the execution time for energy scheduling is 150.675 seconds.

Table 3.3: TOTAL ENERGY COST ($) OF EACH BUILDING WITHOUT B2B ENERGY SHARING AND WITH B2B ENERGY SHARING

	Build 1	**Build 2**	**Build 3**	**CBESS**	**Total**
$\mathbb{E}(C^{w/o\ B2B})$	118.66	13.95	59.57	1.34	193.51
$\mathbb{E}(C^{with\ B2B}_{incentive})$	91.84	-12.23	33.34	-24.85	88.10
$\mathbb{E}(C^{with\ B2B}_{price})$	92.28	-12.41	33.19	-25.00	88.07

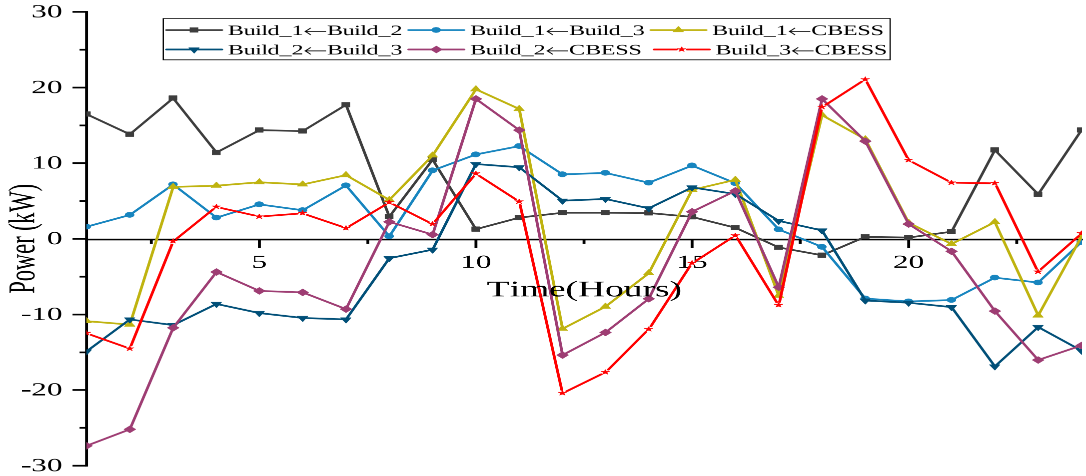
The B2B energy trading incentives are shown in Table 3.4. As shown in Table 3.4, $Building$ 1 always incentivizes (pays to) other buildings and CBESS because, most of the time, $Building$ 1 imports power from other buildings and CBESS. The B2B energy sharing profile is depicted in Figure 3.4(a). The CBESS always receives incentives from all buildings because CBESS stores excess renewable energy from buildings as well as imports energy from utilities during low tariff periods; and uses this stored energy to sell it back to buildings during high tariff periods. Thus, the incentives corresponding to CBESS are negative.

The hourly price for B2B sharing is depicted in Figure 3.4(b). In the case of the pricing mechanism for B2B sharing, it is observed that the prices lie between the utility rates of export and import. This fact motivates the participants toward B2B energy trading.

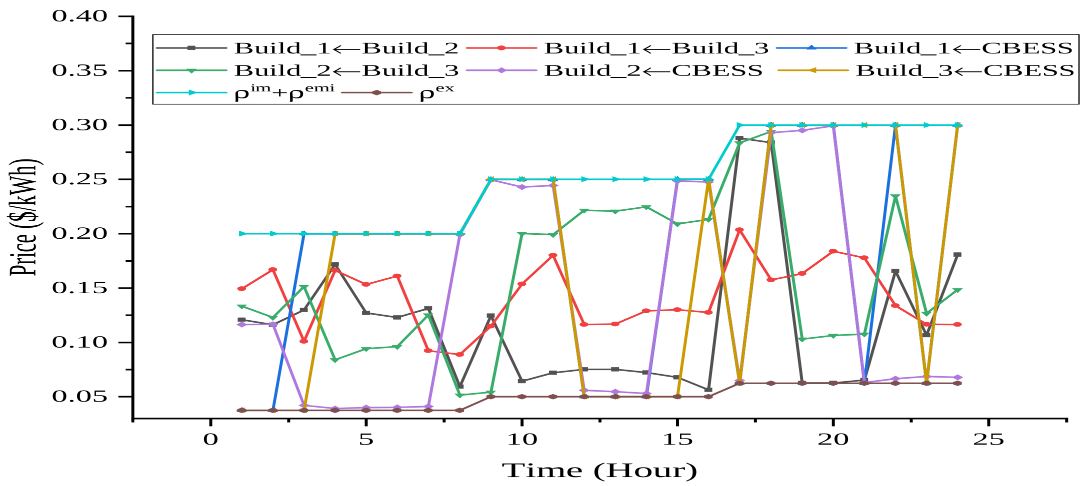
Table 3.4: INCENTIVES FOR B2B ENERGY TRADING IN $

	Incentive (pay), $
$C^{b2b}_{1,2}$	20.43
$C^{b2b}_{1,3}$	9.35
$C^{b2b}_{2,3}$	-11.08
$C^{b2b}_{1,CBESS}$	30.21
$C^{b2b}_{2,CBESS}$	9.35
$C^{b2b}_{3,CBESS}$	20.86

The energy exchange with utility is shown in Figure 3.5. From the figure, it is observed that the energy import and export decrease in case of B2B energy trading. The surplus energy of a building is used to supply the other energy-deficient buildings or to store the energy in CBESS.



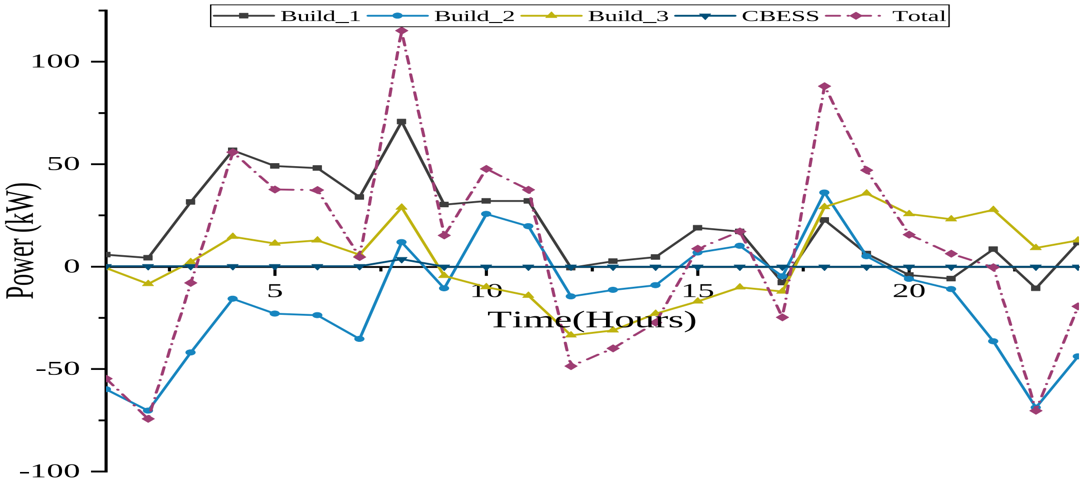
(a)



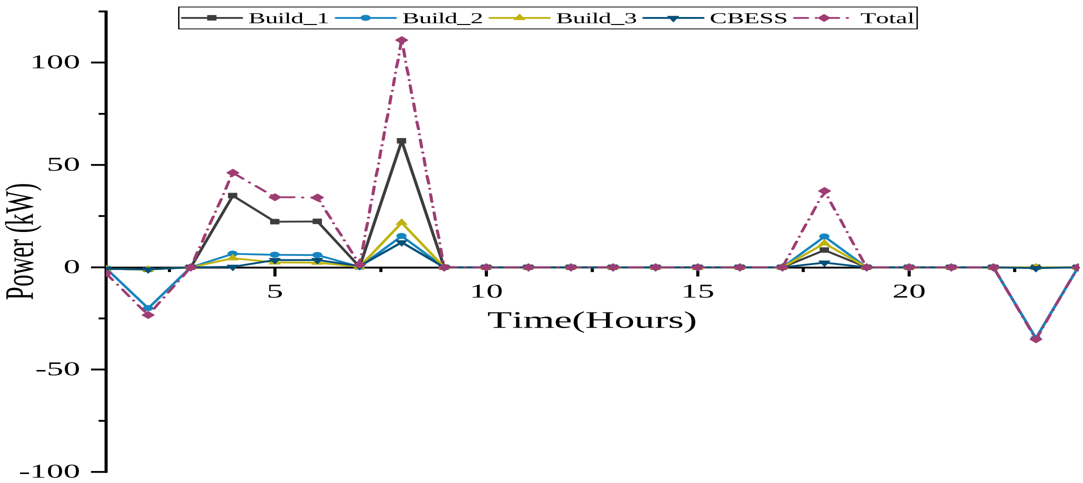
(b)

Figure 3.4: (A) B2B ENERGY SHARING PROFILE, AND (B) HOURLY-PRICE FOR B2B ENERGY SHARING.

For example, *Building* 2 has surplus power during 1:00-7:00 hours, 12:00-14:00 hours, and 20:00-24:00 hours. In case of no B2B energy exchange, *Building* 2 exports this surplus power to the utility. But in the case of B2B sharing, *Building* 2 exports this surplus power to other buildings and CBESS. As shown in Figure 3.5(b), the power exchange with utility is zero during 9:00-17:00 and 19:00-22:00 hours. CBESS supplies to the buildings during 9:00-11:00 hours, 15:00-16:00 hours, and 18:00-21:00 hours, while imports energy during 12:00-14:00 hours and 17:00 hours due to the availability of surplus energy in the community. Based on this energy exchange, the charging/discharging profile of CBESS is shown in Figure 3.6. Thus, the CBESS helps increase RES utilization in favor of the community in B2B sharing mode.



(a)



(b)

Figure 3.5: Power exchange with utility (a) Without B2B energy trading, and (b) With B2B energy trading.

A comprehensive sensitivity analysis is conducted on the proposed stochastic model by varying the mean values of the uncertainty data. Specifically, five scenarios have been examined: Base case (0% change in mean), 5% decrease in mean, 10% decrease in mean, 5% increase in mean, and 10% increase in mean, respectively. For each scenario, the total cost is calculated both with and without B2B energy trading through pricing mechanism. The results are presented in Table 3.5, demonstrating the model's performance across different uncertainty levels.

Preliminary results indicate that B2B energy trading consistently reduces total costs across all scenarios, suggesting the robustness of the proposed model. This analysis provides valuable insights into the model's behavior under varying levels of uncertainty and strengthen the validity

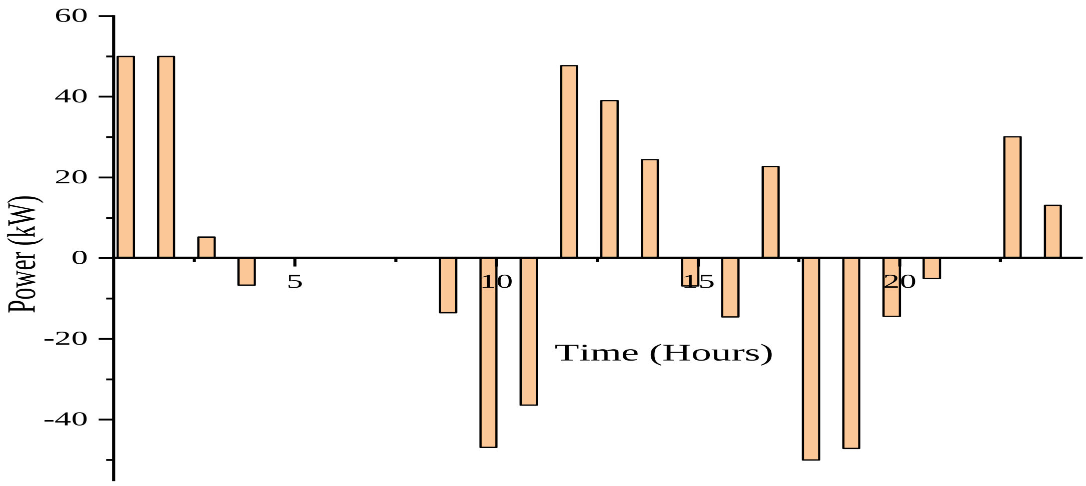


Figure 3.6: Charging and discharging power profile of CBESS

of the conclusions drawn from the stochastic framework.

Table 3.5: Sensitivity analysis of the proposed stochastic model

		Build1	**Build2**	**Build3**	**CBESS**	**Total**	**Percentage Decrease**
Case 1 (μ)	**Cost without B2B**	167.1236	36.96736	84.37675	1.328233	289.7959	25.86984878
	Cost with B2B (Price)	148.382	18.22421	65.63521	-17.4152	214.8262	
Case 2 (0.95μ)	**Cost without B2B**	187.4214	50.57768	91.51644	1.328233	330.8438	20.08964978
	Cost with B2B (Price)	170.8057	33.95916	74.90055	-15.287	264.3784	
Case3 (0.9μ)	**Cost without B2B**	208.3448	65.0854	99.24413	1.328233	374.0026	15.80007766
	Cost with B2B (Price)	193.5704	50.31416	84.47101	-13.4457	314.9099	
Case 4 (1.05μ)	**Cost without B2B**	148.0539	24.64487	77.44371	1.328233	251.4707	32.09458114
	Cost with B2B (Price)	127.8694	4.468996	57.26757	-18.8437	170.7622	
Case 5 (1.1μ)	**Cost without B2B**	130.1332	13.91172	70.71208	1.328233	216.0852	38.37478325
	Cost with B2B (Price)	109.3971	-6.81583	49.98016	-19.3985	133.163	

3.5 Summary

An energy management framework using the Nash bargaining method has been proposed in this chapter. The cooperative game is designed with CBESS as an additional participant. Further Hong's 2m point estimate method for stochastic modeling is used to deal with the inherent uncertainties of solar and wind generation. A comparative analysis of incentive-based and price-based mechanisms are also performed. Both mechanisms gave almost the same costs. The main difference lies in the execution time of these mechanisms. The incentive-based mechanism is comparatively faster and can be used when hourly rates are not required.

This chapter contributes valuable insights into cooperative game theory applications in P2P energy sharing among a group of buildings, offering effective strategies for incentivization. However, when the number of buildings increases the computational complexity also increases. The buildings considered in this model are assumed to be in close proximity allowing the distribution network parameters to be neglected. This assumption renders this model to be impractical when the buildings are not close to each other. However, in further chapters, a practical model has been developed considering the network parameters.