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RESEARCH ARTICLE

A Scalable and Computational Efficient Peer-to-Peer Energy Management Scheme

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ABSTRACT Peer-to-peer (P2P) trading is essential in maximising the benefits of renewable integration. The paper proposes a novel framework for economic benefit through P2P trading among buildings at different geographical locations. The number of transactions is reduced by grouping the buildings into virtual communities (VCs) based on their geographical locations. A non-cooperative game is formulated and solved in a decentralised manner for the energy management of individual buildings, building-to-building (B2B) energy exchange, building-to-community (B2C) energy exchange, energy management of the respective VC, and community-to-community (C2C) energy exchange. Load shifting is used to incorporate demand-side management. Cloud computing-based proposed algorithm is used for determining the energy profile and prices for each internal transaction (B2B, B2C, and C2C) separately to encourage the participation of each building by benefiting them appropriately and avoiding privacy/security issues normally arising in any data-centric framework. A shareable battery energy storage system (BESS) is also assumed to be present in each VC. Load shifting is used in the modelling of buildings to incorporate demand-side management.

INDEX TERMS BESS, decentralized optimization, demand response, generalized Nash equilibrium, peer-to-peer energy sharing.

NOMENCLATURE

ϵ^{CE}	Charges due to carbon emission.
ϵ^{LC}	Load curtailment factor.
$P^{ch}_{n,h}$,$P^{dis}_{n,h}$	Charging/discharging power of battery.
η^{loss}_{n}	Self-discharge related parameter of the battery of VC n.
Λ^{dis}_{h}	Weighted coefficient for discomfort due to load shifting at hour h.
Λ^{im}_{h}, Λ^{ex}_{h}	Price of power import/export from/to utility.
Λ^{UTI}	Battery utilization cost.
μ,ν	Given constants.
σ,ω,δ	Auxiliary variables, dual multipliers, penalty parameters respectively.
$d^{c2c}_{n,m}$	distance between VC n and VC m.
i,j,n,m,h	Indices $\in \mathbb{N}$.
K_d	Cost coefficient of distance.
$L^{max}_{n,i,h}$,$L^{min}_{n,i,h}$	Maximum/minimum limit for load shifting.
N^{b}_{n}	Number of buildings in the VC n.
N^{c}	Number of VCs.
$P^{b2b}_{n,i,j,h}$,$\pi^{b2b}_{n,i,j,h}$	Power imported by building i from building j and the respective payment.
$P^{b2c}_{n,i,h}$,$\pi^{b2c}_{n,i,h}$	Power imported by building i from its VC n and the respective payment.
$P^{c2c}_{n,m,h}$,$\pi^{c2c}_{n,m,h}$	Power imported by VC n from VC m and the respective payment.
η^{ch}_{n},η^{dis}_{n}	Charging/discharging efficiency of the battery of VC n.
$P^{b}_{n,i,h}$,$P^{s}_{n,i,h}$	Power import/export from/to utility.
$P^{ls}_{n,i,h}$,$L_{n,i,h}$	Shifted load and Actual load respectively.
$P^{max}_{n,i}$,$P^{min}_{n,i}$	Power exchange limit of building i from VC n.

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$P_n^{ch_{max}}$,$P_n^{ch_{min}}$	Maximum/minimum limit for charging power of the battery of VC n.
$P_n^{dis_{max}}$,$P_n^{dis_{min}}$	Maximum/minimum limit for discharging power of the battery of VC n.
q^{xb},$q^{\pi b}$	Current power/price strategy set of buildings.
q^{xc},$q^{\pi c}$	Current power/price strategy set of VCs.
$R_{n,i,h}$	Total renewable generation by building i of VC n.
$toll_1$,$toll_2$	Tolerances.
SOC_n^{max},SOC_n^{min}	Maximum/minimum limit for SOC of the battery of VC n.
$SOC_{n,h}$	State of charge of the battery of the VC n at hour h.
PR,DR	Primal and dual residuals.

I. INTRODUCTION

Nowadays many buildings are equipped with renewable energy sources (RESs) and battery energy storage system (BESS) facilities to reduce the energy demand from the utility grid, giving rise to the concept of (nearly) zero energy buildings (ZEBs) [1]. Several studies on optimised models of nearly ZEB solutions have been reported in the literature [2], [3]. BESS, used to reduce power fluctuations of RESs, can be installed either by individual buildings on their own or can be installed jointly for a group of buildings [4], [5]. In comparison with the individual BESS, the shared BESS gives more profit by incorporating the idle resources and removing the individual ownership [5]. The net energy cost of buildings can also be reduced by using demand-side management, i.e., shifting the load from high electricity price periods to low price periods [6]. However, the load shift may cause discomfort to the consumers residing in the buildings, which is accounted for by adding a penalty charge to the cost function. Instead of selling excess energy to the grid, buildings can share it among themselves for better economic benefits. Such an energy exchange is usually referred to as Peer-to-Peer (P2P) energy sharing.

The P2P framework proposed in [7] uses the concept of energy community and involves a community manager for trading. A local trading centre (LTC) is proposed in [8] that manages the P2P market. In [8], two different types of LTCs, profit and non-profit-oriented, have been studied. A demand-side management system has been introduced in [9] for coordinated P2P energy sharing.

The main drawback with these frameworks is the presence of centralised agents or centralised optimisation, which raises concerns related to data privacy for prosumers.

Decentralized approaches have been adopted in the literature for privacy-preserving energy-sharing frameworks. A Stackelberg-Nash game, proposed in [10] for P2P energy sharing, preserves the privacy of the participants with the help of an operation model based on enhanced Benders decomposition. A two-stage distributed optimisation model, based on cooperative game theory, is proposed in [11] for P2P energy sharing in a small community. In the first stage, it is decided whether to participate or not in P2P energy sharing with the help of their social utility function, and power profiles are calculated if they decide to participate. The associated payment of P2P sharing is calculated in the second stage. For designing a P2P energy-sharing framework, game theory proves to be an effective tool [12].

P2P energy trading among a large number of participants (buildings) leads to an increase in computational complexity and consequently the requirement for a robust communication infrastructure along with privacy concerns also increases. Further, the P2P energy-sharing model proposed in these works assumes the buildings to be geographically close, which, in practice, may not be the case.

A flexible energy strategy with a multi-energy coupling matrix is used in [13]. In [13], the authors discussed prosumers' multiple roles, i.e., buyer or seller. A game theoretic model is presented in [14] where sellers play a non-cooperative game for price competition, and buyers are involved in an evolutionary game for seller selection competition. In [15], a two-level energy market was proposed. The first level deals with intra-community trading, while the second deals with the transactions between the utility and the community controller. BESS has not been considered in the market proposed in [15]. The optimization model proposed in [16] has the objective of social welfare maximisation of sellers and buyers. However, sellers and buyers are predefined for a time period. A Stackelberg game is proposed in [17] where sellers' pricing problem is dealt with in the upper level, and buyers' purchasing problem is dealt with in the lower level. The blockchain-based framework [17] doesn't consider the demand response and energy storage system that is usually present in practical applications.

References [13], [14], [15], [16], [17], and [18] classify the prosumers as sellers or buyers at the beginning itself depending upon the available excess energy. But for each time period, the prosumer should have the autonomy to choose the role of seller or buyer or both because demand responsive load, BESS and other participants' strategies may motivate the prosumer to switch roles.

In addition to energy scheduling, P2P trading involves price/incentive distribution among participants to motivate them to engage in P2P energy trading. A dynamic pricing model for P2P energy sharing is proposed in [19] that is based on the supply and demand ratio (SDR) and is bounded by the feed-in tariffs. A dynamic pricing mechanism based on the modified SDR method is used in [20] with the help of a compensating factor for encouraging energy sharing. For incentive distribution, a mid-market rate (MMR) method was proposed in [21]. Based on the surplus power available to the prosumers, the trading price can be set using the MMR method [22].

The use of the SDR and MMR methods needs the participants to share their energy profiles. These methods cannot be applied without compromising data privacy.

Based on the above literature survey, certain research gaps have been identified. The scalability and maintaining privacy at the same time is an issue in the approaches suggested in the above works. When the number of participants increases, the computational complexity increases [23], and thereby the communication burden also increases. For P2P energy sharing, the buildings are assumed to be geographically close [6], [14]. If the buildings considered are geographically distant from each other, then loss coefficients must be considered. The pricing schemes suggested in the above work either don't guarantee fair benefits to all the participants or require participants to share their energy profiles, compromising their data privacy. The prosumers, in the existing literature, are classified into sellers and buyers at the beginning itself. A prosumer should have the autonomy to select the role of seller or buyer or both dynamically. In the P2P energy-sharing framework, most of the work uses a simplified model of buildings. In real life, the buildings have smart equipment and smart metering system that enables them to incorporate demand-side management.

In view of the aforementioned limitations, this paper proposes a decentralised P2P energy-sharing framework that uses the concept of Virtual communities (VCs) to tackle the issue of scalability. The proposed framework has been realised as P2P energy sharing between nearby buildings and between buildings located geographically far away to account for energy losses. A charge is also added for long-distance energy sharing. The proposed two-level P2P framework considers a realistic model of buildings which can endogenously decide their role (buyer or seller or both) to maximise their profits. The pricing scheme proposed in this work guarantees the fair distribution of economic benefits of the P2P energy framework. The contribution of this paper can be summarised as follows.

- Cloud computing-based decentralised P2P energy sharing framework is developed to reduce the energy cost of all buildings. The power exchanges and prices corresponding to the P2P transactions are determined in a decentralised way using the proposed algorithm based on a non-cooperative game.
- The proposed framework uses the concept of virtual communities connected through a computing cloud for P2P energy trading between nearby and geographically distant buildings. The network loss is incorporated by adding penalty charges based on inter-community distances.
- The proposed framework does not require the surplus or the deficit energy status of each participant in advance for P2P energy sharing. The roles of prosumers are decided endogenously.
- The data privacy of each prosumer is preserved by cloud computing-based decentralised framework without any prerequisite information about their energy status.

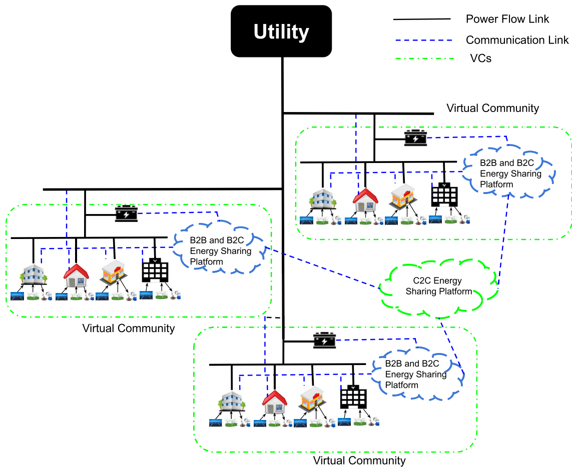


FIGURE 1. Peer-to-Peer energy sharing framework.

This paper is organised as follows. Section II-A describes the system model. The problem formulation is discussed in Section II. The methodologies used and process flow are described in section III. In Section IV, simulation results are presented to demonstrate the effectiveness of the proposed approach. Finally, conclusions are given in section V.

II. PROBLEM FORMULATION

A. SYSTEM MODEL

As shown in Figure 1, several buildings are clustered based on geographical distances to form virtual communities (VCs). Each VC has a BESS shared with the building of that VC. These VCs are a hypothetical group of buildings and BESS that are connected through a computing cloud. For the buildings of a VC, it is considered non-profit-based, but for other VCs, it is considered a profit-based community. The concept of VCs helps in taking advantage of P2P energy sharing among buildings with a less computational and communication burden. Also, a shareable BESS is easy to manage with a VC cloud. The buildings consist of RESs, i.e. solar photovoltaic (SPV) and wind power generators (WPG), flexible load, a local energy management system and advanced metering infrastructure. The buildings are connected to the utility through the local distribution network. In addition, a secure platform for information sharing and cloud computing is present in each community for building-to-building (B2B) and building-to-community (B2C) energy and price sharing. Similarly, a secure platform is used for community-to-community (C2C) energy and price sharing. The communication infrastructure is assumed to be robust in this model.

B. COST MODEL OF BUILDINGS

The cost function for building i of VC n, $C^{b}_{n,i}$, comprises the cost of power exchange with the utility ($C^{u}_{n,i,h}$), the cost of discomfort experienced by the consumer in shifting load ($C^{ls}_{n,i}$), cost of B2B energy sharing ($C^{b2b}_{n,i,h}$) and cost of B2C energy sharing ($C^{b2c}_{n,i,h}$), i.e.,

$$C^{b}_{n,i} = \sum_{h=1}^{24}(C^{u}_{n,i,h} + C^{ls}_{n,i,h} + C^{b2b}_{n,i,h} + C^{b2c}_{n,i,h}) \tag{1}$$

1) EXCHANGE WITH THE UTILITY

Each building i of VC n can trade with the utility. The respective cost function at hour h is given by

$$C^{u}_{n,i,h} = (\Lambda^{im}_{h} + \epsilon^{CE})P^{b}_{n,i,h} - \Lambda^{ex}_{h}P^{s}_{n,i,h}. \tag{2}$$

2) LOAD SHIFTING

The consumer's discomfort due to load shifting [6] is added as a penalty to the cost function:

$$C^{ls}_{n,i} = \Lambda^{dis}_{h}(P^{ls}_{n,i,h} - L_{n,i,h})^2 \tag{3}$$

The quantum of load shift is constrained as follows:

$$L^{min}_{n,i,h} \leq P^{ls}_{n,i,h} \leq L^{max}_{n,i,h}, \tag{4}$$

$$\sum_{h=1}^{24} P^{ls}_{n,i,h} = \epsilon^{LC}\sum_{h=1}^{24} L_{n,i,h}. \tag{5}$$

Here, $\epsilon^{LC} = 1$ for no load curtailment and $\epsilon^{LC} < 1$ for load curtailment.

3) B2B AND B2C ENERGY EXCHANGE

The cost of intra-VC B2B energy exchange is given by:

$$C^{b2b}_{n,i,h} = \sum_{\substack{j=1\\ j\neq i}}^{N^{b}_{n}} \pi^{b2b}_{n,i,j,h}P^{b2b}_{n,i,j,h}, \tag{6}$$

The cost of B2C energy exchange is given by:

$$C^{b2c}_{n,i,h} = \pi^{b2c}_{n,i,h}P^{b2c}_{n,i,h}. \tag{7}$$

Here, $P^{b2b}_{n,i,j,h} > 0$ when i^{th} building is importing from j^{th} building, while $P^{b2b}_{n,i,j,h} < 0$ when exporting to j^{th} building. Similarly, $P^{b2c}_{n,i,h} > 0$ when i^{th} building is importing from the VC and $P^{b2c}_{n,i,h} < 0$ when it is exporting to the community. Constraints related to B2B and B2C sharing are as follows:

$$P^{b2b}_{n,i,j,h} + P^{b2b}_{n,j,i,h} = 0, \tag{8}$$

$$\pi^{b2b}_{n,i,j,h} = \pi^{b2b}_{n,j,i,h}, \tag{9}$$

$$\Lambda^{ex}_{h} \leq \pi^{b2b}_{n,i,j,h} \leq \Lambda^{im}_{h}, \tag{10}$$

$$\Lambda^{ex}_{h} \leq \pi^{b2c}_{n,i,h} \leq \Lambda^{im}_{h}. \tag{11}$$

Here, (8) and (9) are constraints for B2B transactions. While (10) and (11) are used to encourage more B2B and B2C transactions than transactions with utility. The load balance is given as follows:

$$P^{s}_{n,i,h} - P^{b}_{n,i,h} - \sum_{\substack{j=1\\ j\neq i}}^{N^{b}_{n}} P^{b2b}_{n,i,j,h} - P^{b2c}_{n,i,h} = R_{n,i,h} - P^{ls}_{n,i,h}, \tag{12}$$

$$P^{min}_{n,i} \leq P^{s}_{n,i,h} - P^{b}_{n,i,h} - \sum_{\substack{j=1\\ j\neq i}}^{N^{b}_{n}} P^{b2b}_{n,i,j,h} - P^{b2c}_{n,i,h} \leq P^{max}_{n,i}. \tag{13}$$

Here, (13) ensures the power exchange limits of the buildings. Let $\gamma_b :=[P^{b} \geq 0, P^{s} \geq 0,$ (4), (5), (8) to (13)].

C. COST MODEL OF VIRTUAL COMMUNITY

The VC charges/discharges the common BESS participates in C2C transactions. The cost function for the VC n is given by:

$$C^{c}_{n} = \sum_{h=1}^{24}(C^{Bat}_{n,h} + C^{c2c}_{n,h}). \tag{14}$$

1) BATTERY ENERGY STORAGE SYSTEM (BESS)

In this paper, the BESS utilization cost is considered, while the installation cost of the BESS is not incorporated. Thus, the cost of the BESS is given by:

$$C^{Bat}_{n,h} = \Lambda^{UTI}(P^{ch}_{n,h} + P^{dis}_{n,h}), \tag{15}$$

$$P^{ch_{min}}_{n} \leq P^{ch}_{n,h} \leq P^{ch_{max}}_{n}, \tag{16}$$

$$P^{dis_{min}}_{n} \leq P^{dis}_{n,h} \leq P^{dis_{max}}_{n}, \tag{17}$$

$$SOC_{n,h} = (1 - \eta^{loss}_{n})SOC_{n,h-1} + \eta^{ch}_{n}P^{ch}_{n,h} - \eta^{dis}_{n}P^{dis}_{n,h} \tag{18}$$

$$SOC^{min}_{n} \leq SOC_{n,h} \leq SOC^{max}_{n}. \tag{19}$$

Constraints (16) and (17) impose maximum and minimum limits on the charging and discharging power of the BESS. The state of charge (SOC) update equation is defined by (18). The SOC level is constrained by (19).

2) C2C ENERGY EXCHANGE

The C2C energy exchange cost includes the cost of inter-VC energy exchanges and penalties based on inter-VC distances. The penalty only applies to VCs exporting energy to other VCs. The cost function is as follows:

$$C^{c2c}_{n,h} = \sum_{\substack{m=1\\ m\neq n}}^{N^{c}} \pi^{c2c}_{n,m,h}P^{c2c}_{n,m,h} + \sum_{\substack{m=1\\ m\neq n}}^{N^{c}} K_{d}d^{c2c}_{n,m}P^{c2c^{aux}}_{n,m,h}. \tag{20}$$

Here, the auxiliary variable, $P^{c2c^{aux}}_{n,m,h}$, is used to penalise only power export such that $P^{c2c^{aux}}_{n,m,h} \geq -P^{c2c}_{n,m,h}$ and $P^{c2c^{aux}}_{n,m,h} \geq 0$. The objective $C^{c2c}_{n,h}$ is subjected to the following constraints.

$$P^{c2c}_{n,m,h} + P^{c2c}_{m,n,h} = 0, \tag{21}$$

$$\pi^{c2c}_{n,m,h} = \pi^{c2c}_{m,n,h}, \tag{22}$$

$$\Lambda^{ex}_{h} \leq \pi^{c2c}_{n,m,h} \leq \Lambda^{im}_{h}, \tag{23}$$

$$P^{dis}_{n,h} - P^{ch}_{n,h} + \sum_{\substack{m=1\\ m\neq n}}^{N^{c}} P^{c2c}_{n,m,h} = \sum_{i=1}^{N^{b}_{n}} P^{b2c}_{n,i,h}. \tag{24}$$

Here (21)-(23) are C2C power exchange and price related constraints. In (24), network losses and other losses are neglected. If $P^{c2c}_{n,m,h} > 0$ then n^{th} VC is importing from m^{th} VC and if $P^{c2c}_{n,m,h} < 0$ then n^{th} VC is exporting to m^{th} VC.

The VC is considered a non-profit entity for its buildings. Hence, payments received or made by a VC will be distributed among the buildings within the VC as follows:

$$\sum_{h=1}^{24}(C^{Bat}_{n,h} + C^{c2c}_{n,h}) = \sum_{h=1}^{24}\sum_{i=1}^{N^b_n}\pi^{b2c}_{n,i,h}P^{b2c}_{n,i,h}. \tag{25}$$

Let γ_c :=[(16) to (19), (21) to (25)].

III. METHODOLOGY

A. SCHEDULING ENERGY PROFILES

1) NON-COOPERATIVE GAME

A non-cooperative game is used for scheduling energies of various buildings and VCs. Let ψ denote the non-cooperative game, which comprises:

(i) Players: All buildings and VCs are players in the game.

(ii) Strategies: For buildings, the strategy is denoted by: $x^b_{n,i,h} := (P^b_{n,i,h}, P^s_{n,i,h}, P^{ls}_{n,i,h}, P^{b2b}_{n,i,j,h}, P^{b2c}_{n,i,h})$ and $\pi^b_{n,i,h}$:=$(\pi^{b2c}_{n,i,h}$,$\pi^{b2b}_{n,i,j,h})$ such that both are within the feasible set γ_b. For VCs, the strategy is denoted by: $x^c_{n,h} := (P^{ch}_{n,h}, P^{dis}_{n,h}, P^{c2c}_{n,m,h})$ and $\pi^c_{n,h} := (\pi^{c2c}_{n,m,h})$ such that both are within the feasible set γ_c.

(iii) Cost function (CF): The main goal is to minimise the cost function for all the buildings of all the VCs. So, here the cost function is $C^b_{n,i}$.

For the game ψ, let z^*_p be the generalised nash equilibrium (GNE) of player 'p' where z_p is the strategy of the player 'p' such that: $z_p \in (x^b_{n,i,h}, \pi^b_{n,i,h}, x^c_{n,h}, \pi^c_{n,h})$. This is only possible if CF$(z^*_p, z^*_{-p}) \leq$ CF(z_p, z^*_{-p}) where z_{-p} is the strategy of other players except the player 'p'. To find the GNE, a regularised Nikaido-Isoda-function (also known as NI-function) is used [24]. The NI function is denoted by $\phi(z, q)$, where q has the same dimensions as z. Thus, the regularised NI function is given by:

$$\phi(z, q)= \sum_{p}^{players} [CF(z_p, z_{-p}) - CF(q_p, z_{-p})] - \frac{\rho}{2}||z - q||^2_2. \tag{26}$$

The above function denotes the total gains of a player if it switches from its current strategy z_p to q_p regardless of other players' strategies. Here ρ is a known parameter. Let τ be the gain maximizer function such that:

$$\tau(z, q) = \underset{q\in(\gamma_b,\gamma_c)}{\arg\max}\, \phi(z, q). \tag{27}$$

$$\tau(z, q) = \underset{q\in(\gamma_b,\gamma_c)}{\arg\max} \sum_{p}^{players} [CF(z_p, z_{-p}) - CF(q_p, z_{-p})] - \frac{\rho}{2}||z - q||^2_2. \tag{28}$$

The first term represents the current strategy which can be ignored. Therefore,

$$\tau(z, q) = \underset{q\in(\gamma_b,\gamma_c)}{\arg\min} \sum_{p}^{players} [CF(q_p, z_{-p})] + \frac{\rho}{2}||z - q||^2_2. \tag{29}$$

The cost function is $C^b_{n,i}$. So, using (1), we can write:

$$\tau(z, q) = \underset{q\in(\gamma_b,\gamma_c)}{\arg\min} \sum_{h=1}^{24}\sum_{n=1}^{N^c}\sum_{i=1}^{N^b_n}[C^u_{n,i,h} + C^{ls}_{n,i,h} + C^{b2b}_{n,i,h} + C^{b2c}_{n,i,h}] + \frac{\rho}{2}||z - q||^2_2. \tag{30}$$

According to (8) and (9), there will be no effect on the total cost of the B2B ($C^{b2b}_{n,i,h}$) in the above equation. Thus,

$$\tau(z, q) = \underset{q\in(\gamma_b,\gamma_c)}{\arg\min} \sum_{h=1}^{24}\sum_{n=1}^{N^c}\left[\sum_{i=1}^{N^b_n}(C^u_{n,i,h} + C^{ls}_{n,i,h}) + \sum_{i=1}^{N^b_n} C^{b2c}_{n,i,h}\right] + \frac{\rho}{2}||z - q||^2_2. \tag{31}$$

According to (25), $\sum_{i=1}^{N^b_n} C^{b2c}_{n,i,h}$ in the above equation can be replaced as:

$$\tau(z, q) = \underset{q\in(\gamma_b,\gamma_c)}{\arg\min} \sum_{h=1}^{24}\sum_{n=1}^{N^c}\left[\sum_{i=1}^{N^b_n}(C^u_{n,i,h} + C^{ls}_{n,i,h}) + (C^{Bat}_{n,h} + C^{c2c}_{n,h})\right] + \frac{\rho}{2}||z - q||^2_2. \tag{32}$$

Here, $C^{c2c}_{n,h}$ will consist only of the penalty charged based on the distance between the VCs. There will be no effect on the actual cost of importing/exporting power because of (21, 22). Thus,

$$\tau(z, q) = \underset{q\in(\gamma_b,\gamma_c)}{\arg\min} \sum_{h=1}^{24}\sum_{n=1}^{N^c}\left[\sum_{i=1}^{N^b_n}(C^u_{n,i,h} + C^{ls}_{n,i,h}) + C^{Bat}_{n,h} + C^{c2c^{distance}}_{n,h}\right] + \frac{\rho}{2}||z - q||^2_2. \tag{33}$$

It is observed from (33), that there is no reasonable solution for $\pi^b_{n,i,h}$ and $\pi^c_{n,h}$ using above method. Therefore, the solutions will be found separately in III-B, while only the energy profiles are found as follows:

$$\tau(z, q) = \underset{q\in(\gamma_b,\gamma_c)}{\arg\min} \sum_{h=1}^{24}\sum_{n=1}^{N^c}\left[\sum_{i=1}^{N^b_n}(C^u_{n,i,h} + C^{ls}_{n,i,h}) + C^{Bat}_{n,h} + C^{c2c^{distance}}_{n,h}\right] + \frac{\rho}{2}||z^{xb} - q^{xb}||^2_2 + \frac{\rho}{2}||z^{xc} - q^{xc}||^2_2. \tag{34}$$

To find the GNE of the game, $\tau(z, q)$ is solved iteratively to get the best response z^*_p such that $\phi(z^*, q) = 0$.

2) DECENTRALIZATION

In the proposed framework, finding the GNE of the non-cooperative game, described in section III-A1, involves building level and VC level problems with their coupling constraints. The building level and VC level are also coupled. Algorithm 1 uses alternating direction method of multipliers (ADMM) [25] in a nested manner to solve the problem described in (34). Based on nested ADMM, Algorithm 1 is proposed for a decentralised solution by decoupling the coupled constraints using the auxiliary variables ($\sigma^{b2b}_{n,i,j,h}$,$\sigma^{b2c}_{n,i,h}$,$\sigma^{c2c}_{n,m,h}$) as follows:

$$\sigma^{b2b}_{n,i,j,h} = P^{b2b}_{n,i,j,h}, \tag{35}$$

$$\sigma^{b2b}_{n,i,j,h} + \sigma^{b2b}_{n,j,i,h} = 0, \tag{36}$$

$$\sigma^{b2c}_{n,i,h} = P^{b2c}_{n,i,h}, \tag{37}$$

$$P^{dis}_{n,h} - P^{ch}_{n,h} + \sum_{\substack{m=1\\m\neq n}}^{N^c} P^{c2c}_{n,m,h} = \sum_{i=1}^{N^b_n} \sigma^{b2c}_{n,i,h}, \tag{38}$$

$$\sigma^{c2c}_{n,m,h} = P^{c2c}_{n,m,h}, \tag{39}$$

$$\sigma^{c2c}_{n,m,h} + \sigma^{c2c}_{m,n,h} = 0. \tag{40}$$

Thus, constraints (8), (24), and (21) are replaced by constraints (35, 36), (37, 38), and (39, 40), respectively. The augmented Lagrangian becomes:

$$\begin{aligned}
&\mathcal{L}(q,\sigma,\omega)\\
&= \sum_{h=1}^{24}\sum_{n=1}^{N^c}\Bigg[\sum_{i=1}^{N^b_n}(C^u_{n,i,h} + C^{ls}_{n,i,h} + \sum_{\substack{j=1\\j\neq i}}^{N^b_n}\frac{\delta_1}{2}(q^{xb^{b2b}}_{n,i,j,h}\\
&\quad -\sigma^{b2b}_{n,i,j,h} + \frac{\omega^{b2b}_{n,i,j,h}}{\delta_1})^2 + \frac{\delta_2}{2}(q^{xb^{b2c}}_{n,i,h} - \sigma^{b2c}_{n,i,h} + \frac{\omega^{b2c}_{n,i,h}}{\delta_2})^2) + C^{Bat}_{n,h}\\
&\quad + C^{c2c^{distance}}_{n,h} + \frac{\delta_3}{2}(q^{xc^{c2c}}_{n,m,h} - \sigma^{c2c}_{n,m,h} + \frac{\omega^{c2c}_{n,m,h}}{\delta_3})^2\Bigg]\\
&\quad + \frac{\rho}{2}||z^{xb} - q^{xb}||^2_2 + \frac{\rho}{2}||z^{xc} - q^{xc}||^2_2.
\end{aligned} \tag{41}$$

(41) is split into four parts as follows:

- For building i of VC n,

$$\begin{aligned}
&F_1(q^{xb},\sigma^{b2b},\sigma^{b2c})\\
&\quad = \sum_{h=1}^{24}[C^u_{n,i,h} + C^{ls}_{n,i,h}\\
&\qquad + \sum_{\substack{j=1\\j\neq i}}^{N^b_n}\frac{\delta_1}{2}(q^{xb^{b2b}}_{n,i,j,h} - \sigma^{b2b}_{n,i,j,h} + \frac{\omega^{b2b}_{n,i,j,h}}{\delta_1})^2\\
&\qquad + \frac{\delta_2}{2}(q^{xb^{b2c}}_{n,i,h} - \sigma^{b2c}_{n,i,h} + \frac{\omega^{b2c}_{n,i,h}}{\delta_2})^2] + \frac{\rho}{2}||z^{xb} - q^{xb}||^2_2.
\end{aligned} \tag{42}$$

- For B2B auxiliary variable update of VC n,

$$\begin{aligned}
F_2(q^{xb},\sigma^{b2b}) &= \sum_{h=1}^{24}\sum_{i=1}^{N^b_n}\sum_{\substack{j=1\\j\neq i}}^{N^b_n}\frac{\delta_1}{2}(q^{xb^{b2b}}_{n,i,j,h} - \sigma^{b2b}_{n,i,j,h}\\
&\quad + \frac{\omega^{b2b}_{n,i,j,h}}{\delta_1})^2.
\end{aligned} \tag{43}$$

- For VC n,

$$\begin{aligned}
&F_3(q^{xb},q^{xc},\sigma^{b2c},\sigma^{c2c})\\
&= \sum_{h=1}^{24}[\sum_{i=1}^{N^b_n}(\frac{\delta_2}{2}(q^{xb^{b2c}}_{n,i,h} - \sigma^{b2c}_{n,i,h}\\
&\quad + \frac{\omega^{b2c}_{n,i,h}}{\delta_2})^2) + C^{Bat}_{n,h} + C^{c2c^{distance}}_{n,h} + \sum_{\substack{m=1\\m\neq n}}^{N^c}\frac{\delta_3}{2}(q^{xc^{c2c}}_{n,m,h}\\
&\quad - \sigma^{c2c}_{n,m,h} + \frac{\omega^{c2c}_{n,m,h}}{\delta_3})^2] + \frac{\rho}{2}||z^{xc} - q^{xc}||^2_2.
\end{aligned} \tag{44}$$

- For C2C auxiliary variable update,

$$\begin{aligned}
F_4(q^{xc},\sigma^{c2c}) &= \sum_{h=1}^{24}\sum_{n=1}^{N^c}\sum_{\substack{m=1\\m\neq n}}^{N^c}[\frac{\delta_3}{2}(q^{xc^{c2c}}_{n,m,h}\\
&\quad - \sigma^{c2c}_{n,m,h} + \frac{\omega^{c2c}_{n,m,h}}{\delta_3})^2].
\end{aligned} \tag{45}$$

The entire process is explained in Algorithm 1. First, the base strategies are initialized, followed by the minimization of objective functions and updating of the decoupling variables in steps. At the beginning of the iteration, buildings optimise their strategy (step 14), and then their B2B decoupling variables are updated (step 16). After this, each VC will optimise their strategy and update the B2C decoupling variables (step 20). At the end of the iteration, C2C decoupling variables are updated (step 25). The penalty parameters are updated with the help of their respective primal residuals (PR) and dual residuals (DR). In the end, the base strategies are updated using the relaxation method [26] in step 37. The process is repeated until the tolerance is achieved, as shown in step 39. The results of this program will be $x^b_{n,i,h} := (P^b_{n,i,h}, P^s_{n,i,h}, P^{ls}_{n,i,h}, P^{b2b}_{n,i,j,h}, P^{b2c}_{n,i,h})$ and $x^c_{n,h} := (P^{ch}_{n,h}, P^{dis}_{n,h}, P^{c2c}_{n,m,h})$, which will be used for payment distribution described in the next section.

B. PAYMENT DISTRIBUTION OF VARIOUS ENERGY SHARING PROFILES

For the calculation of $\pi^b_{n,i,h} := (\pi^{b2c}_{n,i,h}, \pi^{b2b}_{n,i,j,h})$ and $\pi^c_{n,h} := (\pi^{c2c}_{n,m,h})$ in this work, Algorithm 1 is modified as described below.

1) C2C PRICE

The price for each inter-VC energy sharing is computed. The computed price is distributed among the buildings within

Algorithm 1

1 Initialize ρ, $toll_1$, $toll_2$, d=1
2 For each VC,
3 For each building,
4 Initialize $z^{xb}(1) := (P^b(1), P^s(1), P^{ls}(1), P^{b2b}(1), P^{b2c}(1))$
5 End for.
6 Initialize $z^{xc}(1) := (P^{ch}(1), P^{dis}(1), P^{c2c}(1))$
7 End for.
8 Repeat
9 Intialise k=1, $\sigma(1) = 0$, and $\omega(1) = 0$
10 Set $\delta(1)$, μ, ν
11 Repeat
12 For each VC,
———-*Building level*———
13 For each building,
14 $\min_{q^{xb} \in \gamma_b} F_1(q^{xb}, \sigma^{b2b}(k), \sigma^{b2c}(k))$
15 End for.
———-*Intra-VC level*———-
16 Update σ^{b2b}: $\min_{\sigma^{b2b} \in \{(35),(36)\}} F_2(q^{xb}(k+1), \sigma^{b2b})$
17 $\omega_1(k+1) = \omega_1(k) + \delta_1(k)(q^{xb^{b2b}}(k+1) - \sigma^{b2b}(k+1))$
18 $PR_1 = ||q^{xb^{b2b}}(k+1) - \sigma^{b2b}(k+1)||$
19 $DR_1 = ||\sigma^{b2b}(k+1) - \sigma^{b2b}(k)||$
———-*VC level*———-
20 $\min_{\substack{\sigma^{b2c} \in \{(37),(38)\} \\ q^{xc} \in \gamma_c}} F_3(q^{xb}(k+1), q^{xc}, \sigma^{b2c}, \sigma^{c2c}(k))$
21 $\omega_2(k+1) = \omega_2(k) + \delta_2(k)(q^{xb^{b2c}}(k+1) - \sigma^{b2c}(k+1))$
22 $PR_2 = ||q^{xb^{b2c}}(k+1) - \sigma^{b2c}(k+1)||$
23 $DR_2 = ||\sigma^{b2c}(k+1) - \sigma^{b2c}(k)||$
24 End for.
———-*Inter-VC level*———
25 Update σ^{c2c}: $\min_{\sigma^{c2c} \in \{(39),(40)\}} F_4(q^{xc}(k+1), \sigma^{c2c})$
26 $\omega_3(k+1) = \omega_3(k) + \delta_3(k)(q^{xc^{c2c}}(k+1) - \sigma^{c2c}(k+1))$
27 $PR_3 = ||q^{xc^{c2c}}(k+1) - \sigma^{c2c}(k+1)||$
28 $DR_3 = ||\sigma^{c2c}(k+1) - \sigma^{c2c}(k)||$
———-*Penalty-parameter update*———-
29 Do for (PR_1, DR_1, δ_1),(PR_2, DR_2, δ_2), and (PR_3, DR_3, δ_3)
30 If $PR < \mu DR$, then $\delta(k+1) = \frac{\delta(k)}{\nu}$
31 elseif $PR > \frac{DR}{\mu}$ then $\delta(k+1) = \nu\delta(k)$
32 else $\delta(k+1) = \delta(k)$
33 End do.
34 k=k+1
35 Until $||\{||\omega_1(k) - \omega_1(k-1)|| + ||\omega_2(k) - \omega_2(k-1)|| + ||\omega_3(k) - \omega_3(k-1)||\}|| < toll_2$
36 Updating the strategies:
37 $z(d+1) = \frac{1}{k+1} z(d) + \frac{k}{k+1} q(k)$
38 d=d+1
39 Until $||z(d) - q(k)|| < toll_1$

the VC as described in III-B2. The game ψ is redefined as follows:

(i) Players: All VCs will be players in the game.
(ii) Strategies: The strategies will include only $\pi^c_{n,h} := (\pi^{c2c}_{n,m,h})$ such that they are within the feasible set γ_c.
(iii) Cost function (CF): Here, every VC will try to reduce its cost as mentioned in (14). All the other parameters are either given or calculated from this equation, except for $\pi^{c2c}_{n,m,h}$. Therefore, the cost function for n^{th} VC becomes:

$$CF_n = \sum_{h=1}^{24} \sum_{\substack{m=1 \\ m \neq n}}^{N^c} \pi^{c2c}_{n,m,h} P^{c2c}_{n,m,h}. \tag{46}$$

$\pi^{c2c}_{n,m,h}$ should be such that:

$$C^b_{n,i} + C^c_n \leq \underbrace{(C^b_{n,i} + C^c_n)}_{\substack{assuming \\ no\ c2c}}. \tag{47}$$

Therefore, the profit is more if C2C transactions take place. As earlier, (29) is modified as follows:

$$\tau(z, q) = \underset{q \in \{(22),(23),(47)\}}{\arg\min} \sum_{p}^{players} [CF_p(q_p, z_{-p})] + \frac{\rho}{2}||z - q||_2^2. \tag{48}$$

$$\tau(z, q) = \underset{q \in \{(22),(23),(47)\}}{\arg\min} \sum_{h=1}^{24} \sum_{n=1}^{N^c} \sum_{\substack{m=1 \\ m \neq n}}^{N^c} [q^{\pi_c}_{n,m,h} P^{c2c}_{n,m,h}] + \frac{\rho}{2}||z^{\pi_c} - q^{\pi_c}||_2^2. \tag{49}$$

Here, $z_p \in (\pi^{c2c}_{n,m,h})$ and 'q' have the same dimensions as that of 'z'. An auxiliary variable $\sigma^{c2c}_{n,m,h}$ is used to deal with the coupled constraint (22), such that:

$$\sigma^{c2c}_{n,m,h} = \pi^{c2c}_{n,m,h}, \tag{50}$$
$$\sigma^{c2c}_{n,m,h} = \sigma^{c2c}_{m,n,h}. \tag{51}$$

The modified augmented Lagrangian becomes:

$$\mathcal{L}^{\pi^c}(q, \sigma, \omega) = \sum_{h=1}^{24} \sum_{n=1}^{N^c} \sum_{\substack{m=1 \\ m \neq n}}^{N^c} [q^{\pi_c}_{n,m,h} P^{c2c}_{n,m,h} + \frac{\delta_3}{2}(q^{\pi_c}_{n,m,h} - \sigma^{c2c}_{n,m,h} + \frac{\omega^{c2c}_{n,m,h}}{\delta_3})^2] + \frac{\rho}{2}||z^{\pi_c} - q^{\pi_c}||_2^2. \tag{52}$$

In Algorithm 1, remove steps (3-5, 13-19, and 21-23), and the rest of the steps is modified as follows.
In step 6, initialize $z^{\pi_c}(1)$.
In step 20, for VC n, do

$$\min_{q^{\pi_c} \in \{(22),(23),(47)\}} F_3(q^{\pi_c}, \sigma^{c2c}(k)). \tag{53}$$

Here,

$$F_3 = \sum_{h=1}^{24} \sum_{\substack{m=1 \\ m \neq n}}^{N^c} [q^{\pi_c}_{n,m,h} P^{c2c}_{n,m,h} + \frac{\delta_3}{2}(q^{\pi_c^{c2c}}_{n,m,h} - \sigma^{c2c}_{n,m,h} + \frac{\omega^{c2c}_{n,m,h}}{\delta_3})^2] + \frac{\rho}{2}||z^{\pi_c} - q^{\pi_c}||_2^2.$$

In step 25, update σ^{c2c} by

$$\min_{\sigma^{c2c} \in \{(50),(51)\}} F_4(q^{\pi_c^{c2c}}(k+1), \sigma^{c2c}). \tag{54}$$

Here,

$$F_4 = \sum_{h=1}^{24} \sum_{n=1}^{N^c} \sum_{\substack{m=1 \\ m \neq n}}^{N^c} [\frac{\delta_3}{2}(q^{\pi_c^{c2c}}_{n,m,h} - \sigma^{c2c}_{n,m,h} + \frac{\omega^{c2c}_{n,m,h}}{\delta_3})^2]. \tag{55}$$

By applying the above modification in Algorithm 1, we will get $\pi^{c2c}_{n,m,h}$ for each VC. The same will be distributed among the buildings within the VC.

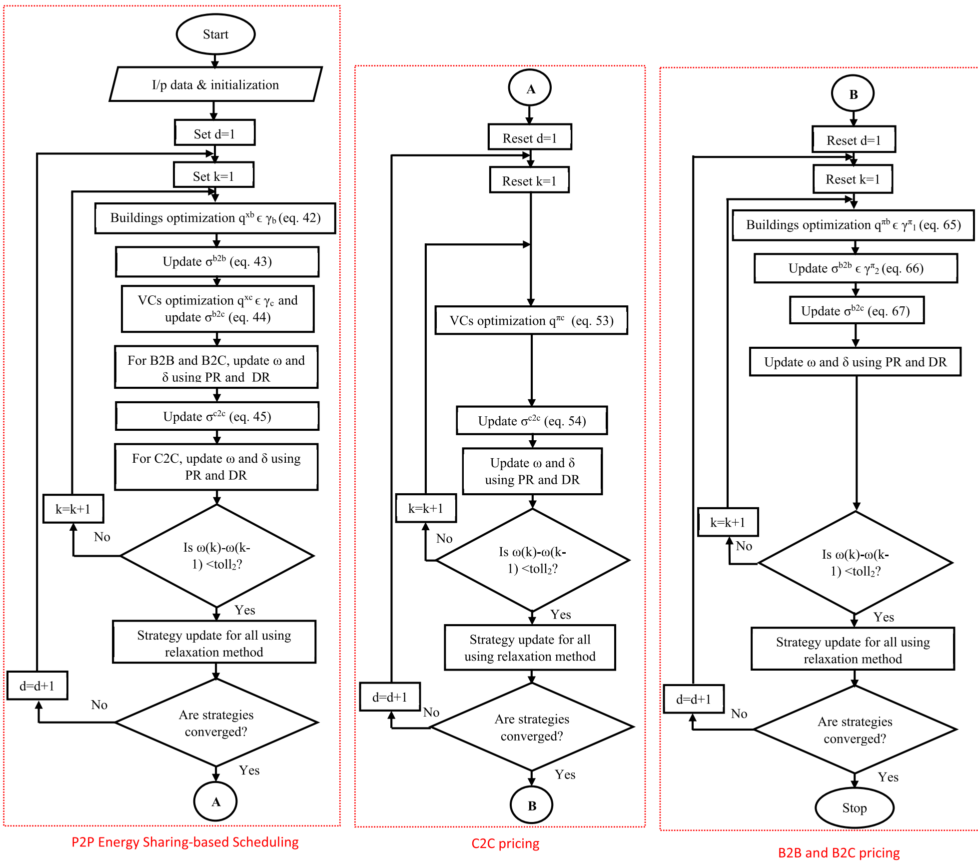


FIGURE 2. **Flowchart of proposed energy sharing framework.**

2) B2C AND B2B PRICE

All the energy profiles and prices for C2C transactions were calculated earlier, which will be used to compute B2C and B2B prices. A modified version of Algorithm 1 is again used. The game ψ is redefined as follows:

(ii) Players: All buildings are players in the game.

(ii) Strategies: The strategies will include only $\pi^{b}_{n,i,h} := (\pi^{b2c}_{n,i,h}, \pi^{b2b}_{n,i,j,h})$ such that they are within the feasible set γ_b.

(iii) Cost function (CF): Every building will try to minimise cost. Other parameters are already calculated except $(\pi^{b2c}_{n,i,h}$ and $\pi^{b2b}_{n,i,j,h})$. Thus for i^{th} building of n^{th} VC,

$$CF_{n,i} = \sum_{h=1}^{24} [\pi^{b2c}_{n,i,h} P^{b2c}_{n,i,h} + \sum_{\substack{j=1\\ j\neq i}}^{N^b_n} \pi^{b2b}_{n,i,j,h} P^{b2b}_{n,i,j,h}]. \quad (56)$$

This $\pi^{b2c}_{n,i,h}$ and $\pi^{b2b}_{n,i,j,h}$ should be such that

$$C^{b}_{n,i} \leq \underset{\substack{assuming\\ no\ b2c\ and\ no\ b2b}}{C^{b}_{n,i}} \quad (57)$$

Therefore, B2C and B2B transactions increase profits. Let γ^{π}_{1} :=[(10), (11), (57)] and γ^{π}_{2} :=[(9), (25)]. As earlier, (29) is modified as follows:

$$\tau(z, q) = \underset{q \in \{\gamma^{\pi}_{1}, \gamma^{\pi}_{2}\}}{\arg\min} \sum_{p}^{players} [CF_p(q_p, z_{-p})] + \frac{\rho}{2}||z - q||^2_2, \quad (58)$$

$$\tau(z, q) = \underset{q \in \{\gamma^{\pi}_{1}, \gamma^{\pi}_{2}\}}{\arg\min} \sum_{h=1}^{24} \sum_{n=1}^{N^c} \sum_{i=1}^{N^b_n} \{q^{b2c}_{n,i,h} P^{b2c}_{n,i,h} + \sum_{\substack{j=1\\ j\neq i}}^{N^b_n} q^{b2b}_{n,i,j,h} P^{b2b}_{n,i,j,h}\} + \frac{\rho}{2}||z^{\pi^{b2b}} - q^{\pi^{b2b}}||^2_2 + \frac{\rho}{2}||z^{\pi^{b2c}} - q^{\pi^{b2c}}||^2_2. \quad (59)$$

Here, $z^{\pi^b} \in (\pi^b_{n,i,h}, \pi^b_{n,i,j,h})$ and 'q' have the same dimensions as that of 'z'. Auxiliary variables $\sigma^{b2c}_{n,i,h}$ and $\sigma^{b2b}_{n,i,j,h}$ are used to handle the coupled constraint γ^{π}_{2}:

$$\sigma^{b2b}_{n,i,j,h} = \pi^{b2b}_{n,i,j,h}, \quad (60)$$

$$\sigma^{b2b}_{n,i,j,h} = \sigma^{b2b}_{n,j,i,h}, \quad (61)$$

$$\sigma^{b2c}_{n,i,h} = \pi^{b2c}_{n,i,h}, \quad (62)$$

$$(C^{Bat}_{n,h} + C^{c2c}_{n,h}) = \sum_{i=1}^{N^b_n} \sigma^{b2c}_{n,i,h} P^{b2c}_{n,i,h}. \quad \forall n \quad (63)$$

TABLE 1. Comparison of all the cases.

		C1				C2				C3				Total Sum
		B1	B2	B3	Sum	B1	B2	B3	Sum	B1	B2	B3	Sum	
$Cost$	Case1	104.80	90.22	105.17	300.18	106.93	13.16	6.08	126.17	53.48	214.44	147.83	415.76	842.11
	Case2	90.94	84.58	92.88	268.40	81.38	-3.58	-21.41	56.38	53.49	193.91	138.46	385.86	710.64
	Case3	86.68	78.65	86.21	251.54	72.30	-7.58	-35.04	29.68	36.12	178.49	119.32	333.92	615.14
	Case4	85.10	81.06	88.66	254.81	76.96	-5.89	-27.40	43.67	42.98	185.63	129.74	358.34	656.83
P^b	Case1	477.38	415.17	477.89	1370.44	405.79	102.50	112.39	620.68	223.23	886.23	584.53	1693.99	3685.11
	Case2	381.12	379.74	387.74	1148.60	86.64	55.40	55.64	197.68	342.67	625.56	517.98	1486.22	2832.50
	Case3	331.61	329.32	336.52	997.44	119.96	76.69	69.91	266.57	212.08	470.86	387.10	1070.04	2334.05
	Case4	320.96	317.70	326.42	965.08	81.68	52.90	53.76	188.34	263.10	529.13	446.86	1239.08	2392.50
P^s	Case1	54.27	95.62	135.79	285.69	35.40	265.83	518.57	819.79	166.35	32.46	169.05	367.86	1473.34
	Case2	5.76	11.53	19.34	36.63	30.09	130.57	204.15	364.81	46.64	13.72	76.46	136.83	538.26
	Case3	0.00	0.44	2.00	2.45	0.03	0.84	0.92	1.79	8.39	1.63	17.55	27.57	31.81
	Case4	0.00	0.00	0.00	0.00	0.00	5.64	23.72	29.36	22.70	6.42	39.39	68.51	97.87
P^{b2b}_{im}	Case2	87.62	32.10	45.84	165.55	210.02	56.24	20.78	287.03	2.59	152.40	47.98	202.97	655.55
	Case3	92.15	35.28	47.91	175.34	257.95	68.77	19.76	346.48	5.97	177.32	49.19	232.48	754.30
	Case4	92.45	35.70	47.77	175.92	259.98	67.38	20.53	347.89	4.19	171.92	48.56	224.67	748.48
P^{b2b}_{ex}	Case2	53.61	55.99	55.95	165.55	15.23	102.77	169.03	287.03	141.56	2.61	58.88	203.06	655.64
	Case3	55.27	58.80	61.26	175.33	14.64	119.42	212.46	346.52	149.61	4.63	78.21	232.45	754.30
	Case4	55.22	58.61	62.12	175.94	14.99	121.89	210.93	347.82	144.26	5.82	74.55	224.63	748.38
P^{b2c}_{im}	Case2	72.07	57.83	72.86	202.77	164.23	46.58	58.87	269.68	17.32	125.11	60.22	202.65	675.09
	Case3	122.09	107.36	124.30	353.75	122.42	48.98	62.82	234.22	115.10	279.29	199.48	593.87	1181.85
	Case4	129.76	113.33	131.06	374.14	146.65	54.97	69.46	271.07	74.13	215.15	137.24	426.52	1071.73
P^{b2c}_{ex}	Case2	58.33	82.61	89.06	230.00	45.17	88.20	168.29	301.66	117.51	32.96	75.35	225.82	757.47
	Case3	67.47779	93.16155	103.3708	264.01	115.27	237.51	345.29	698.07	118.27	67.44	124.53	310.24	1272.32
	Case4	64.84	88.58	101.03	254.45	102.93	211.05	315.27	629.24	117.59	50.19	103.23	271.00	1154.69

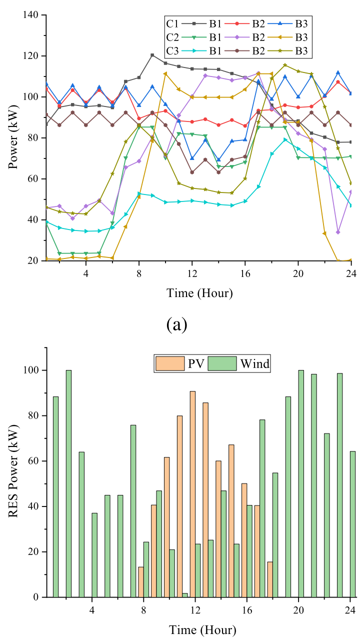


FIGURE 3. (a) Load profile of buildings in all communities, (b) RES power generation.

The modified augmented Lagrangian becomes:

$$\mathcal{L}^{\pi^b}(q,\sigma,\omega) = \sum_{h=1}^{24}\sum_{n=1}^{N^c}\sum_{i=1}^{N_n^b}[q^{b2c}_{n,i,h}P^{b2c}_{n,i,h} + \sum_{\substack{j=1\\ j\neq i}}^{N_n^b} q^{b2b}_{n,i,j,h}P^{b2b}_{n,i,j,h} + \sum_{\substack{j=1\\ j\neq i}}^{N_n^b}\frac{\delta_1}{2}(q^{\pi^{b2b}}_{n,i,j,h} - \sigma^{b2b}_{n,i,j,h} + \frac{\omega^{b2b}_{n,i,j,h}}{\delta_1})^2 + \frac{\delta_2}{2}(q^{\pi^{b2c}}_{n,i,h} - \sigma^{b2c}_{n,i,h} + \frac{\omega^{b2c}_{n,i,h}}{\delta_2})^2] + \frac{\rho}{2}||z^{\pi^{b2b}} - q^{\pi^{b2b}}||_2^2 + \frac{\rho}{2}||z^{\pi^{b2c}} - q^{\pi^{b2c}}||_2^2. \quad (64)$$

TABLE 2. Community-to-community power exchange.

		C1	C2	C3
P^{C2C}_{im}	Case3	316.2523	176.2641	482.0041
	Case4	221.878	105.9789	267.3148
P^{C2C}_{ex}	Case3	197.3159	607.631	169.5414
	Case4	71.04568	436.5601	87.52149

In Algorithm 1, remove steps related to the VC's optimisation, i.e. remove steps (6 and 25-28) and modify accordingly. In Step 4, initialize z^{π^b}. In step 14, for building i of VC n do

$$\min_{q^{\pi^b}\in\gamma_1^\pi} F_1(q^{\pi^b}, \sigma^{b2b}(k), \sigma^{b2c}(k)). \quad (65)$$

Here,

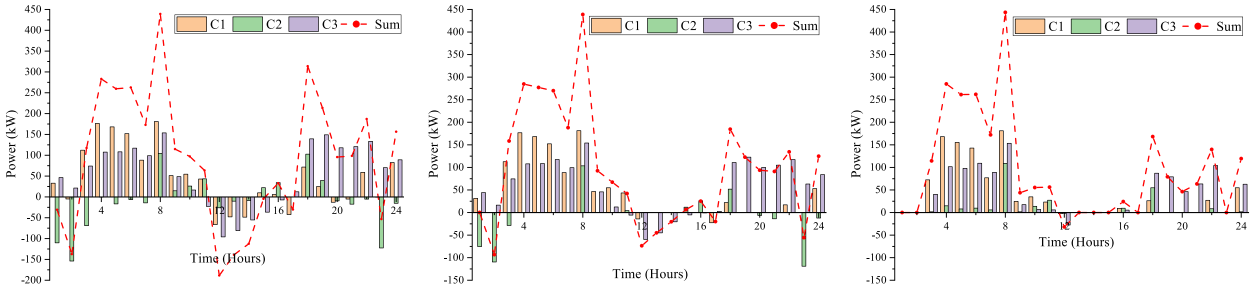
$$F_1 = \sum_{h=1}^{24}[q^{b2c}_{n,i,h}P^{b2c}_{n,i,h} + \sum_{\substack{j=1\\ j\neq i}}^{N_n^b} q^{b2b}_{n,i,j,h}P^{b2b}_{n,i,j,h} + \sum_{\substack{j=1\\ j\neq i}}^{N_n^b}\frac{\delta_1}{2}(q^{\pi^{b2b}}_{n,i,j,h} - \sigma^{b2b}_{n,i,j,h} + \frac{\omega^{b2b}_{n,i,j,h}}{\delta_1})^2 + \frac{\delta_2}{2}(q^{\pi^{b2c}}_{n,i,h} - \sigma^{b2c}_{n,i,h} + \frac{\omega^{b2c}_{n,i,h}}{\delta_2})^2] + \frac{\rho}{2}||z^{\pi^{b2b}} - q^{\pi^{b2b}}||_2^2 + \frac{\rho}{2}||z^{\pi^{b2c}} - q^{\pi^{b2c}}||_2^2.$$

In step 16, for each VC n, update σ^{b2b} by

$$\min_{\sigma^{b2b}\in\{\gamma_2^\pi\}} F_2(q^{\pi^{b2b}}(k+1), \sigma^{b2b}). \quad (66)$$

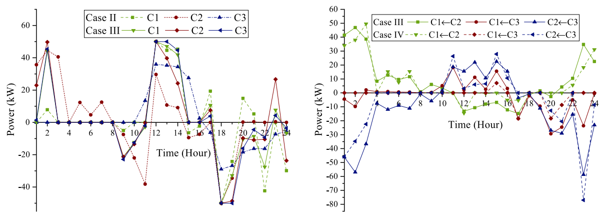
Here,

$$F_2 = \sum_{h=1}^{24}\sum_{i=1}^{N_n^b}\sum_{\substack{j=1\\ j\neq i}}^{N_n^b}\frac{\delta_1}{2}(q^{\pi^{b2b}}_{n,i,j,h} - \sigma^{b2b}_{n,i,j,h} + \frac{\omega^{b2b}_{n,i,j,h}}{\delta_1})^2.$$



(a) (b) (c)

FIGURE 4. **Building to Utility Power Exchange (a) *Case I*, (b) *Case II*, (c) *Case III*.**



(a) (b)

FIGURE 5. **(a) The charging and discharging power of VC's battery, (b) C2C Net Power Exchange.**

In step 20, for each VC n, do

$$\min_{\sigma^{b2c} \in \{\gamma_2^{\pi}\}} F_3(q^{\pi^{b2c}}(k+1), \sigma^{b2c}). \tag{67}$$

where,

$$F_3 = \sum_{h=1}^{24} \sum_{i=1}^{N_n^b} [\frac{\delta_2}{2}(q_{n,i,h}^{\pi^{b2c}} - \sigma_{n,i,h}^{b2c} + \frac{\omega_{n,i,h}^{b2c}}{\delta_2})^2]. \tag{68}$$

Thus, all the energy schedules and the respective prices for various energy-sharing schedules are computed. All the discussed steps of P2P energy sharing and the corresponding price determination are summarised in the flowchart as depicted in Figure 2.

IV. SIMULATION RESULTS

In this work, nine (09) buildings having different load profiles (Figure 3(a)) and renewable generations (Figure 3(b)) are considered. The buildings are clustered into three (3) VCs (C1, C2, and C3), each comprising three (03) buildings. In Figure 3(b), the SPV and WPG data are given for the rated capacity of 125kW and 100kW, respectively. All buildings in C1 and buildings 2 and 3 in C2 have 125 kW, and 100 kW of SPV and WPG installed capacity, respectively. SPV and WPG installed capacities are 100 kW and 50 kW, respectively, in all other buildings. Each VC has a BESS of 200kW. The SOC level is to be maintained in [20%,90%]. The charging and discharging power is limited to 50kW for all the BESSs. η^{ch} and η^{dis} are 96% and 106%, respectively. η^{loss} and the BESS utilization cost is equal to 0.5% and 0.06\$/kW, respectively. A time-varying energy price (Figure 8) is considered for energy exchange (import and export) with the utility. The charge for carbon emission is 0.05\$/kW. Since no load curtailment is done, the load curtailment factor is 1. The coefficient of discomfort is $0.03\$/kW^2$. The load can be shifted up to ±10%. Other parameters are $\rho = 0.01$, $\sigma = 0.02$, $toll_1 = 0.01$, $toll_2 = 0.001$, $\mu = 0.02$, and $\nu = 2$. The code is implemented on a laptop with a Core $i3$ 1.20 GHz processor with 4 GB RAM. GAMS/CONOPT4 solver is used for optimization.

To show the effectiveness of the proposed P2P framework, four different cases are considered:

Case I (Base case): In this case, all the buildings manage their energy to meet their load demand. Buildings can exchange energy with the utility only.

Case II: In this case, B2B and B2C transactions are considered.

Case III: In an extension to the second case, C2C transactions are also considered.

Case IV: This case is similar to *Case III*. In addition, penalty charges based on the distance between VCs are considered in C2C transactions.

Table 1 shows the summary of results for all the cases. In *Case I*, the cost function of each building is the highest, and the energy exchange with utility is also the highest among all cases. In *Case II*, the cost function of each building is reduced compared to the base case due to B2B transactions and BESS. As shown in Figure 3(a), all buildings in a VC have different load profiles. Due to this, buildings have different surplus/deficit power in a time interval. Therefore, intra-VC B2B transactions can occur at a price lying between the utility buying and selling price. Also, BESS is used in B2C transactions. In *case II*, the energy cost decreases from 300.18\$, 126.17\$, and 415.76\$ to 268.40\$, 56.38\$, and 385.86\$ for C1, C2, and C3, respectively. The reduction is enhanced further in *case III* by C2C transactions. The cost function is the lowest in *case III* among all the cases. In *case III*, buildings have more opportunities to exchange energy with buildings of other VCs through C2C transactions. In *case IV*, the cost function has increased compared to *case III* because of the penalty charges (due to distances). But, still, the cost function is less compared to *case I* and *case II*.

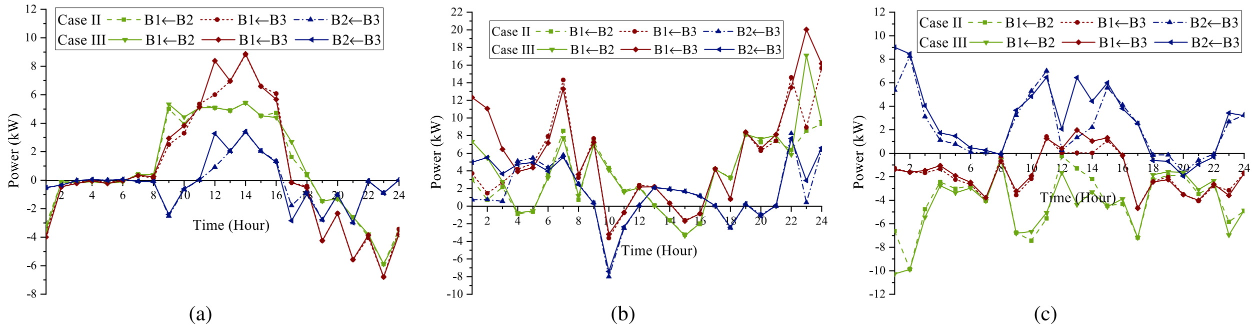


FIGURE 6. B2B Power Exchange for *case II* and *case III* (a) Community 1, (b) Community 2, (c) Community 3.

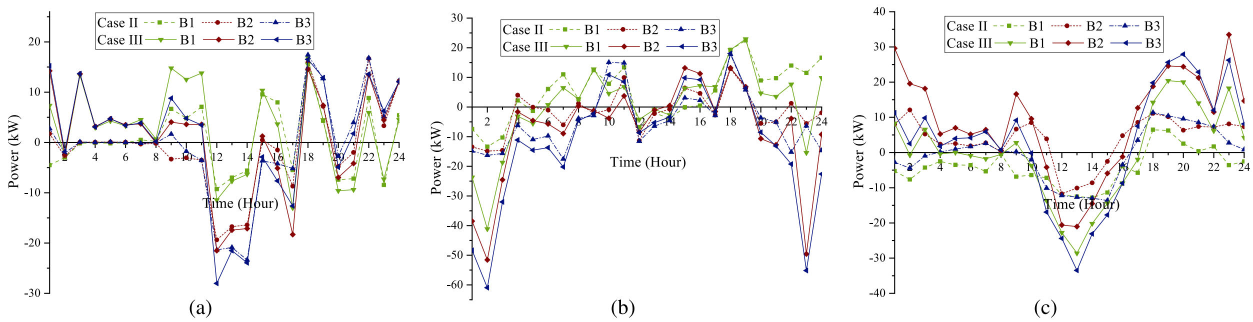


FIGURE 7. B2C Power Exchange (a) Community 1, (b) Community 2, (c) Community 3.

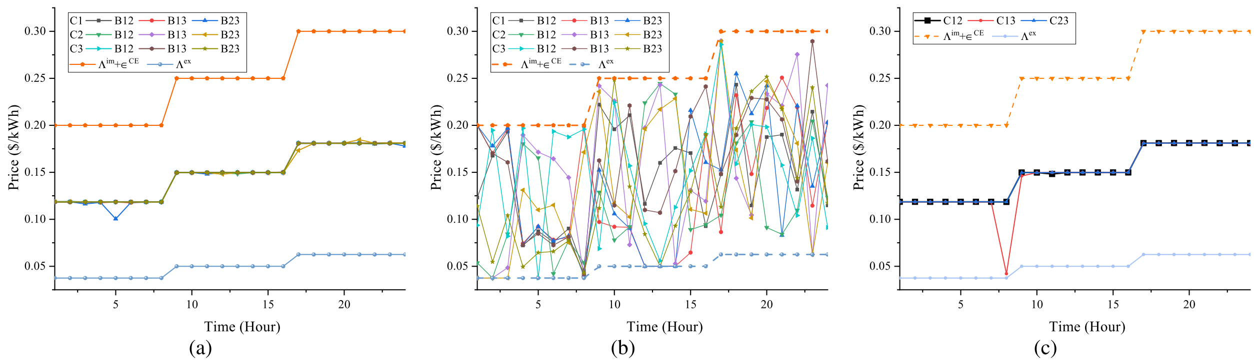


FIGURE 8. Price for internal transactions for *case III* (a) B2B, (b) B2C, (c) C2C.

Table 1 shows that the total power imported from the utility reduces in *case II* and *case III* compared to *case I*. The same holds for the total power exported to the utility. Around $12^{th}-15^{th}$ hours, the power exported by the buildings to the utility in *case I* (Figure 4(a)) is used for B2B (Figure 6) and B2C (Figure 7) trading in *case II* and *case III*. Figure 5(a) shows that the VC's BESS is getting charged at the same time when buildings are exporting to the utility in *case I* (Figure 4(a)), i.e., during $12^{th}-15^{th}$ hours. When the utility electricity price is high, energy stored in BESS is used during $18^{th}-21^{th}$ hours. Due to the availability of C2C trading in *case III*, the power exchange in B2C transactions has increased compared to *case II* (Figure (7)).

In Figure 6(a), for C1, the power exchanged in B2B transactions is almost the same in *case II* and *case III* except for $11^{th}-13^{th}$ hours. During this time interval, the variation in *case II* and *case III* is quite visible for C3 (Figure 6(c)). In table 1, for each case, it is seen that the total power imported through B2B transactions is equal to the total power exported through B2B transactions. This validates equation (8). The power imported or exported during B2C transactions, in *case II* is much less than in *case III* or *case IV* (Table 1). This is because, in *case II*, the B2C transactions imply using the BESS only. Furthermore, this overall B2C power is slightly less in *case IV* compared to *case III*.

Table 2 shows the total power imported and exported separately in C2C trading in *case III* and *case IV*. Due to the penalty imposed (based on distance) in *case IV*, the imported/exported power decreases compared to *case III*. In (Figure 5(b)), the net power exchanged in

C2C transactions is depicted for *case III* and *case IV*. For *case III*, the equation (24) can easily be verified from Figure 5(a), 7(b) and 5(b). During $12^{th} - 14^{th}$ hours, for C2, the power imported from C2C transactions (Figure 5(b)), and the power imported from all the buildings inside C2 through B2C transactions (Figure 7(b)) is used for charging the VC's BESS as shown in Figure 5(a). After 18^{th} hour, C3 is importing from the other two VCs (Figure 5(b)) and is discharging its BESS (Figure 5(a)). The power from the BESS and C2C trading are then transferred to buildings of C3 through B2C transactions (Figure 7(c)). Therefore, B2B, B2C and C2C energy sharing provides an opportunity to take advantage of the demand diversity of all buildings in all the VCs and to utilize RESs and BESSs more effectively.

The energy management of buildings and VCs depends on the energy exchange prices. In *case I*, the buildings have to exchange energy at utility prices. But in *case II* and *case III* energy exchange is possible at a price between the settled price of VCs and the utility price, as shown in Figure 8. Due to this energy sharing at a price between the settled price of VCs and the utility price, there is a reduction in energy exchange with the grid resulting in lower energy costs for buildings as shown in Table 1. Further, the energy exchange profile and BESS charging profiles are also different for *case II* and *case III* due to more opportunities for energy sharing in *case III* as compared to *case II*, as shown in Figure 5 and Figure 7.

In Figure 8, the prices for all the internal transactions are shown. As expected, the prices are between the utility prices to encourage the buildings to participate in the P2P sharing framework. In Figure 8(a) and Figure 8(c), at 5^{th} hour and 8^{th} hour, respectively, a slight variation is observed in prices. But the respective power component is zero as shown in 6(a) and Figure 5(b), respectively. This means that variation has no significance. Thus, the prices for B2B (Figure 8(a)) and B2C (Figure 8(c)) are almost identical for all the buildings. But a vast variation is observed in B2C prices (Figure 8(b)). This is because the VC's cost is distributed to the buildings through these prices according to equation (25). The B2C prices depend on the contribution of buildings in B2C transactions.

V. CONCLUSION

A novel decentralised P2P energy management scheme has been proposed for virtual communities comprising several buildings equipped with RESs and load-shifting systems. The energy management scheme includes B2B, B2C, and C2C energy trading, optimal BESS scheduling, and demand side management. A non-cooperative game theoretic approach is used in a decentralised manner making the players a seller/buyer/both endogenously. Numerical results elucidate the proposed framework's effectiveness in minimising the cost function for each building. The grouping of buildings into virtual communities reduces the number of transactions, enhances the scalability of the system, and improves computational efficiency. Future research intends to incorporate the stochastic load and renewable generation models to make the proposed framework more effective.

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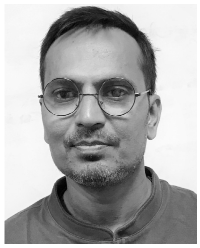

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