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RESEARCH ARTICLE

An Effective Pricing Mechanism for Electricity Trading Considering Customer Preference and Reserved Price in Direct P2P Electricity Market Under Uncertainty in Grid Supply

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ABSTRACT Meeting electricity demand by the generation of electricity from locally distributed energy sources has gained much success over the years. Among different frameworks for such renewable generation and consumption, peer-to-peer (P2P) markets have proved to be an efficient solution. As the pricing mechanism is an integral part of P2P markets, optimal price determination for electricity trading that ensures the profitability of the participants is the key to success in such markets. In addition to profitability, the pricing mechanism should be able to incorporate users' reserved prices and grid supply uncertainty to be implementable in developing countries. To achieve this objective and based on participants' preferences, an effective game-theoretic model is proposed to formulate the trading pairs among consumers and sellers. Then, keeping in view the participants' reserved prices for electricity trading, an effective and novel method based on the game-theoretic approach is proposed to determine the electricity price in the direct P2P electricity market. The proposed model is evaluated on a market having 22 participants. Among these, 11 participants act as electricity consumers, and the other 11 act as sellers. Simulation results show that the proposed algorithm is more effective as it further reduces the electricity bills for consumers from 5% to 8% and increases the revenues of sellers from 13% to 15% as compared to other proposed mid-range auction and uniform pricing models.

INDEX TERMS Pricing mechanism, peer-to-peer market, game theory, consumers, small-scale sellers.

NOMENCLATURE

EU^t	Electricity trading units.
Δ_{ses}	Preference list of SESs.
r	Total allowable round.
$\theta_{i,j}$	Trading Electricity amount from $ec_i \rightarrow ses_j$.
$\theta_{j,i}$	Trading Electricity amount from $ses_j \rightarrow ec_i$.
$N_{S}ec \rightarrow ses$	Numerical score of the offered price to the proposed price.
$C_{ses,ec}$	Contract Pair.
EC	Electricity consumer.
ROP	Reserved offered price.
SI	Satisfaction Index.
P2P	Peer-to-peer.
Δ_{ec}	Preference list of ECs.
t	Current round.
E_{req}	Electricity required by consumers.
$\alpha_t(t/r)^{c_i^j}$	Consensus environment.
$N_{S}ses \rightarrow ec$	Numerical score of the proposed price to the offered price.

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E_{bill}	Electricity Bill.
γ	Grid availability factor.
SES	Small-scale electricity seller.
RPP	Reserved proposed price.
DRES	Distributed renewable energy sources.
SW	Social Welfare.

I. INTRODUCTION

Energy in the form of electricity is vital for any nations' economic growth and is now widely accepted as a valuable human commodity [1]. The total electricity demand has increased by 2.5% over the last year and it is expected to reach 1000 EJ by 2050 [2], [3]. With a massive increase in demand, many regions of the world especially the South Asia region has undergone electricity shortage which not only affects the standard of living in these regions but also deteriorates the economic condition of several South Asian countries [4]. In order to meet the increase in electricity demand, many developed countries are also struggling to make necessary arrangements and trying to mitigate the expected electricity shortage. For this purpose, several reforms are undertaken, such as, expanding the electricity generation capacity of existing plants and acquiring new sites for installing new generation plants. However, keeping the global warming threats and reduction in CO_2 emission for a green and healthy environment [5], [6], these reforms may not remain active for use in practice. Consequently, policymakers should reconsider their policies and recommendations.

Public awareness of electricity utilization can be an effective way to alert the consumers about the limited source of electricity generation [4]. However, the lack of buying power of consumers to change their existing high electricity consumption appliances to the new smart electricity consumption devices may also fail this strategy. Moreover, the consumers who belong to the high socioeconomic class may not agree to reduce their electricity consumptions [7], [8]. In this precarious scenario, a shift from conventional electricity generation to any modern electricity generation networks may be needed. For this purpose, many developed countries are using distributed renewable energy sources (DRES) to shift their traditional unidirectional electricity framework to the new distributed bidirectional electricity framework [9].

Peer-to-Peer electricity trading [10] is one of the types of new distributed electricity framework. In this framework, many consumers have deployed their own DRES to produce their green electricity [11], [12]. In the case of excess electricity, these consumers are encouraged to trade with their neighbors hence changing their role from consumers only to the small-scale electricity sellers [13]. This promotes the sharing economy among not only the peers but also an efficient way to meet the local demand of consumers by employing renewable local generation [10]. Regulators give many incentives to DRES owners to encourage this sharing economy process, such as the abolition of grid costs, delivery levy, and so on [14].

P2P electricity trading markets based on their infrastructure can be classified into three main types. (i) Community-based P2P electricity market: It requires a centralized authority known as a community manager or market operator to activate and supervise the trading activities among the peers. This type of market has been reported in studies [9], [10], [15], [16], [17]. (ii) Full P2P market: This type of market does not include any intermediator inside the market to activate the trading activities. Moreover, it provides full freedom to each consumer and seller to select their trading partner. Examples of such market can be found in [18], [20], and [21]. (iii) Hybrid P2P market: It is a mixture of the above two types where some trading activities are performed under the supervision of the market operator while some activities are performed in the absence of the operator. Examples of such markets can be found in [22] and [23].

Many countries are deploying pilot projects for P2P electricity trading integrated with the smart grid to meet local demand and supply of electricity. Examples of pilot projects include the SonnenCommunity in Germany [24], Vandebron in Netherlands [25], and Piclo in UK [26]. These pilot projects have focused on providing incentives and tariffs to electricity customers from the perspective of electricity suppliers. The success of the P2P electricity trading market is heavily dependent on the active and increased involvement of the consumers and sellers. Financial benefits for both consumers and small-scale sellers can be used as an effective way to motivate them to increase their involvement in the electricity market [10].

For this purpose and to promote the benefits of the P2P electricity market by highlighting the savings in electricity bills for consumers and increase in revenues of small-scale electricity sellers, researchers proposed different pricing mechanisms. A mid-range or average pricing technique has been proposed in [16], [17], and [27]. A supply-demand ratio (SDR) based pricing technique has been proposed in [28] and [29]. Vickrey-based auction mechanism has been proposed in [31]. A flat rate and feed-in-tariff-based pricing technique has been proposed in [30]. In these works, centralized authority is used to manage the trading activities. Moreover, the preferences of consumers and sellers are not considered.

For direct P2P electricity trading, a pricing mechanism that is based on the iterative double auction method has been proposed in [32] and an average pricing technique is proposed in [33]. A Blockchain-based double auction method has been proposed in [34] and [35]. A rule-based iterative pricing algorithm (RIP) has been proposed in [19]. In these works, the preferences of the participants are not discussed. Moreover, the reserved prices for both consumers and sellers are also not discussed.

In addition, due to the prevalence of blackout occurrences, the electricity system has witnessed a dramatic development in recent years, affecting the reliable operation of the grid and inflicting major economic losses [37], [38]. The planned and unplanned grid outages, which may be caused by bad weather, maintenance purpose, component failure, or other uncontrollable reasons, also affect electricity users. Considering the outage or uncertainty in grid supply, a preference-based pricing method has been proposed in [39]. This proposed model only handles the preferences of the consumers towards the selection of electricity supply source, i.e., grid or P2P market. Whereas, the preferences among the selection of consumers and sellers along with their reserved prices are not discussed. Moreover, the proposed method does not count the grid charges. A double-side auction-based pricing model that considers grid supply outage has been proposed in [40]. In this proposed method, neither the grid charges nor the participants' preferences are considered. Furthermore, in this proposed system, the final trading price is higher than the grid prices, thus increasing the sellers' revenues and deteriorating the consumers' savings. This proposed model also does not consider the reserved prices of the participants. A two-stage pricing model has been proposed in [41], which allows the consumers to reduce their electricity bills and increases the sellers' revenues by accessing the better prices in a day-ahead electricity market. This proposed model does not provide any information about the preferences of the participants. Moreover, grid outages along with grid charges are also not discussed in this proposed method. Based on the interaction among consumers and sellers, a game-theoretic-based pricing method has been proposed [36]. This proposed system also does not discuss the participants' preferences and grid supply uncertainty. Moreover, the reserved prices of the participants are not considered.

II. MOTIVATIONS AND OBJECTIVES

Based on the above-discussed literature it is worth noting that an optimal price determination will have a significant effect on the energy market participants. An effective pricing mechanism motivates participants and serves as a solid foundation for the p2p energy trading market.. In P2P energy trading markets, several buyers and sellers are interacting with each other's therefore, a model is imperatively needed in the P2P energy trading market that reflects the true preferences towards the selection of trading partner and determines the energy trading price while keeping their reserved prices in an account. The main contributions of this paper are as follows:

1) A model is proposed that considers the uncertainty in grid supply and motivates the consumers and sellers to participate in the P2P electricity trading market by increasing their utilities, i.e., saving electricity bills for consumers and increasing revenues for sellers.
2) A modified game-theoretic framework is proposed for stable contract formulation.
3) A novel method is proposed for developing a consensus algorithm to determine the electricity price for the trading pair considering their reserved values and participants' preferences.
4) This proposed model also works effectively to distribute the electricity among the participants when there is an imbalance between the demand and supply of electricity in the absence of grid supply.

The proposed work uses a few assumptions which are given below:

1) All energy participants use the smart meter in their homes.
2) participants have no prior information about the grid outage.
3) The proposed P2P energy trading market considers a small community where the participants are located nearby to each other's therefor transmission and distribution losses can be considered as negligible [43]
4) It is assumed that a small-scale energy seller's reserved price includes all the exclusive prices such as cost of renewable generation setup, transmission cost, battery, and its associated constraints cost. Further, no battery constraints are used in the proposed model.

The rest of the paper is organized as follows: Section II describes the motivation and objective of the proposed work. Section III describes the proposed model along with consumers' and small-scale sellers' models. Section IV discusses the proposed game for trading pair formulation. Section V discusses proposed game formulation for consensus algorithm and the Nash Equilibrium used for the consensus algorithm to determine the electricity trading price among the pair. Section VI discusses the results. In Section VII, the conclusion and future work will be discussed.

III. PROPOSED MODEL

This paper considers a community that consists of several electricity consumers (ECs) who demand electricity (E_{req}) to fulfill their routine works and the proprietors of renewable energy sources (RESs) who wish to sell their excess electricity (E_{sur}) beyond their usage. Hence, these act as small-scale electricity sellers (SESs) as shown in Fig.(1). The community microgrid is assumed to have limited storage capacity and is connected to the main grid. It is assumed that the electricity supply is not available for 24 hours from the main grid and peers have no prior information about the grid outage. This paper considers a case where there is an uncertainty in electricity supply from the grid.

The proposed work develops a consensus algorithm to determine the electricity trading price among the peers without the involvement of any intermediator. It forms a direct P2P electricity trading market. For this purpose, at every time slot 't' all electricity consumers (ECs) select their preferred sellers (SESs) to whom they intend to trade electricity along with their reservation price. Similarly, the SESs will also select their preferred ECs considering their reserved price for electricity trading. Based on preference lists of ECs and SESs, a stable trading pair which will be briefly discussed in Section IV is formed. This trading pair reflects the true preferences of both ECs and SESs. Then, a consensus algorithm that is developed for the trading pair will be briefly discussed in Section IV determines the electricity trading price. The grid

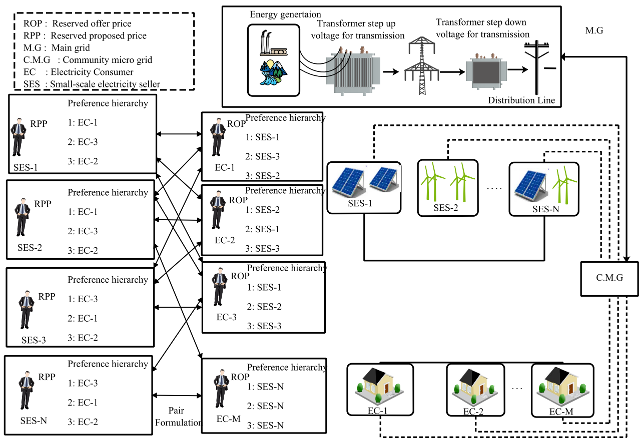


FIGURE 1. Proposed model.

will impose a small fee on all SESs. This is considered as the grid charge. The advantage that sellers and buyers receive by exchanging a certain quantity of energy in the P2P energy trading market is known as social welfare. In the sellers' case, it is the total profit a seller gets by trading all its energy minus the cost of generating that energy. In the buyers' case, it is the utility a buyer gets by consuming that energy minus the cost of buying that energy [21]. The objective function of the proposed model is to maximize the social welfare (SW) among the market participants by increasing the savings of electricity bills for the consumers and increasing the revenues for the SESs.

$$\begin{aligned} f &= max(SW)_{\forall i,j \in ec_i, ses_j} \\ s.t\ E_{req_i} &= 0 \quad \forall i \in ec_i \\ E_{sur_j} &= 0 \quad \forall j \in ses_j \end{aligned} \tag{1}$$

The proposed work is based on the following assumptions: (i) all consumers and small scale sellers inform the system about the upper and lower bound of prices as reserved prices. (ii) All consumers and sellers prefer to participate in the P2P electricity trading market rather than trading with the grid. (iii) Grid charges are imposed on sellers to boost the saving of the consumers.

A. CONSUMERS' MODELING

In the P2P electricity market, EC can interact with several SESs to trade electricity to fulfill their demands. The selection among the various SESs depends upon several factors such as price, amount, distance, and product differentiation, i.e., acquiring electricity either from the grid, Photovoltaic panels (PV), wind, biomass, and trading preference with the neighbors. In the P2P electricity trading market, ECs can purchase electricity either from the grid or from peers. Generally, the electricity trading price offered by peers in the P2P electricity market is lower than the grid import price (P_{imp}) [10]. Therefore, ECs would want to trade electricity with peers on a prior basis so that their electricity bills can be reduced. Furthermore, in the direct P2P electricity market, ECs have the freedom to choose their SESs to promote a green energy environment and enhance society values and social welfare among the peers. In the proposed system, each consumer chooses the preferred small-scale seller. The preferred list for SESs of an ec_i can be expressed as $\Delta_{ec_i} = ses_1 \prec ses_2 \prec ses_3 \prec, \ldots, \prec ses_n$.

In the proposed system, each consumer uses some reserved offer price (ROP) which reflects the range of minimum and maximum buying capacity of a consumer ec_i. In the proposed system the reserved offer price (ROP) will further have two prices $ROP_{\gamma=1}$ and $ROP_{\gamma=0}$ where $ROP_{\gamma=1}$ represents the reserved offer price when the grid is available and $ROP_{\gamma=0}$ represents the reserved offer price when the grid is not available.

Furthermore, in the proposed system, an EC_i can interact with several energy sellers SES_j to fulfil his/her electricity needs if his/her electricity need cannot be met with one peer. If E_{req_i} is the demand of an electricity consumer EC_i and let $\theta_{i,j}, \theta_{i+1,j}, \theta_{i+2,j}, \ldots, \theta_{i=n,j}$ be the amount of electricity in which a consumer EC_i trades with his/her preferred small-scale seller $SES_j, SES_{j+1}, SES_{j+2}, \ldots, SES_{j=n}$ at the trading price $Tp_1, Tp_2, Tp_3, \ldots, Tp_n$. The electricity bill for a consumer EC_i can be found as:

$$E_{bill} = \sum_{j=1}^{N} \theta_{i,j} \times Tp_{i,j} \tag{2}$$

The satisfaction index (SI) of a consumer with respect to the obtained electricity in the P2P electricity market is an important characteristic that motivates the peers to increase their participation in the P2P electricity trading market. Consumers' SI can vary from [0 − 1] depending on the amount of electricity he/she obtained in the P2P electricity trading market. The SI with respect to the allocated electricity of a consumer EC_i can be calculated as:

$$SI_i = \frac{E_{obtained}}{E_{dem}} \tag{3}$$

B. SMALL-SCALE ELECTRICITY SELLERS' MODELING

Distributed energy resources (DERs) create a new model in the electricity generation industry. These DERs may include photovoltaic panels (PV), rooftop wind turbines, small hydro, biomass, fuel cells, etc. Based on the installed capacity, these DERs can be classified as micro, mini, small, medium, and large DERs. However, for domestic usage, micro to medium DERs can be used effectively in the P2P electricity market. Such proprietors of DERs can be called small-scale electricity sellers (SESs) in the P2P electricity market. In the proposed system, similar to the consumer a small-scale seller can trade his/her surplus electricity to a number of consumers if his/her surplus electricity is not used up in one contract. If E_{sur_j} is the surplus of a electricity consumer SES_j and let $\theta_{j,i}, \theta_{j+1,i}, \theta_{j+2,i}, \ldots, \theta_{j=n,i}$ be the amount of electricity which a small-scale seller SE_j trades with his/her preferred consumer $EC_i, EC_{i+1}, EC_{i+2}, \ldots, EC_{i=n}$ at the trading price $Tp_1, Tp_2, Tp_3, \ldots, Tp_n$. The revenue for a small scale seller SES_j can be found as:

$$Revenue = (\sum_{i=1}^{N} \theta_{j,i} \times Tp_{j,i}) - Grid\ fee \quad (4)$$

In the proposed system, the grid fee is assumed to apply only to the sellers as used in [16]. In the P2P electricity trading market, the SESs intend to increase their revenues. Generally, in the P2P electricity trading market, the buying price offered by the grid (P_{exp}) to SESs is lower than the price offered by peers [10]. Therefore, SESs will always try to trade their excess electricity with the peers. Similar to ECs, SESs will also have the freedom to select their preferred trading peers. For this purpose, each seller will also form a preference list that reflects the preferred electricity consumers for electricity trading. The preference list for ECs of a ses_i can be expressed as $\Delta_{ses_i} = ec_1 \prec ec_2 \prec ec_3 \prec, \ldots, \prec ec_n$.

Like consumers, each seller also has some reserved purchase price (RPP) for electricity trading. RPP reflects the maximum and minimum range of purchase price at which each seller intends to trade their surplus electricity. Further, RPP is classified as $RPP_{\gamma=1}$ or $RPP_{\gamma=0}$.

IV. PROPOSED GAME FOR TRADING PAIR FORMULATION

Freedom to select trading partners is one of the main characteristics of the direct P2P electricity trading market [10]. For this purpose, with reference to the proposed game [16], a modification is made to form a trading pair. The proposed game starts at time 't'. Every EC and SES select their preferred candidates for electricity trading in the form of descending order of preference. These preference lists are supposed to be hidden from each other. The objective of this game is to form a trading pair that reflects the true preference of both consumers and small-scale sellers.

Formally, a game Ξ among the market participants can be expressed as:

$$\Xi = \langle N, A, U \rangle \quad (5)$$

where, N represents the number of players comprising $EC = \{ec_1, ec_2, ec_3, \ldots, ec_n\}$ and $SES = \{ses_1, ses_2, ses_3, \ldots, ses_m\}$ as a disjoint set such that $ec_i \bigcap ses_i = 0$, A is the action profile of the players and it contains the preference lists for both EC and SES as strategies i.e., $A = \{\Delta_{ec_i}, \Delta_{ses_i}\}$; and $U : A_1 \times A_2 \times A_3, \times, \ldots, \times A_n \rightarrow R$ is the i^{th} player utility.

Each $ses_i \in SES$ has a utility match u_{ij}^{ses} with $ec_i \in EC \cup \phi$, where ϕ represents no match. Similarly, for each $ec_j \in EC$, u_{ij}^{ec} is the match utility from matching to $ses_i \in SES \cup \phi$. We denote $U^{ses} = (u_{ij}^{ses})_{i \in SES, j \in EC}$ as a small-scale seller and consumer pair for electricity trading. Moreover, a strict preference for a SES ses_i, $u_{ij}^{ses} \neq u_{ij'}^{ses}$ for an $j, j' \in EC \cup \phi$ and for any EC ec_j, $u_{ij}^{ec} \neq u_{ij'}^{ec}$ for any $i, j \in SES \cup \phi$. Match utilities are strictly positive for all $ses_i \in SES$ and $ec_j \in EC$, $u_{ij}^{SES} > 0$ for all $ec_j \in EC$ and $ses_i \in SES$, $u_{ij'}^{EC} > 0$. All ECs and SESs prefer to be matched over remaining unmatched.

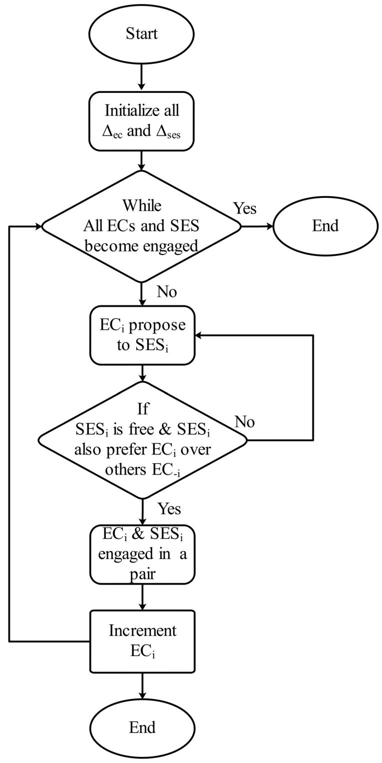


FIGURE 2. Flow-chart for the pair formulation.

Therefore for any $ses_i \in SES$, a ECs are acceptable where $u_{ij}^{ses} > u_{i\phi}^{ses}$ and for any $ec_j \in EC$, a SESs $ses_i \in SES$ are acceptable where $u_{ij}^{ec} > u_{\phi j}^{ec}$.

Fig.2 represents the flow-chart for the pair formulation in the proposed work.

V. PROPOSED GAME FORMULATION FOR CONSENSUS ALGORITHM

Generally, in the P2P electricity trading market, the trading price of electricity is relatively low for ECs with respect to the grid import rate of electricity and also high for SESs with respect to the grid export rate [16]. The proposed game starts at time 't' when the grid issues its export rate (P_{exp}) and import rate (P_{imp}) for electricity trading. With respect to this pricing signal, all ECs and SESs will place their offered and proposed prices together with their reserved values. These reserved prices reflect the maximum and minimum buying and seller capacity of ECs and SESs respectively. Further, these reserved prices are assumed to be kept hidden from each other.

Formally, a game Ξ' among the market participants can be expressed as:

$$\Xi' = \langle N, A, U \rangle \quad (6)$$

where N is the number of players i.e., ECs and SESs. A is the action profile and strategies of the players and it contains the offered and proposed prices of the EC and SES and U is the utility of a player.

TABLE 1. Preference list of buyers and sellers.

Consumers' Preference List (Δ_{ec_i})		Small-scale sellers' Preference List (Δ_{ses_i})	
ec_1	$1 \prec 2 \prec 3 \prec 4 \prec 5 \prec 6 \prec 7 \prec 8 \prec 9 \prec 10 \prec 11$	ses_1	$4 \prec 1 \prec 2 \prec 3 \prec 5 \prec 6 \prec 7 \prec 8 \prec 9 \prec 10 \prec 11$
ec_2	$10 \prec 11 \prec 8 \prec 7 \prec 6 \prec 3 \prec 4 \prec 2 \prec 1 \prec 5 \prec 9$	ses_2	$3 \prec 2 \prec 1 \prec 4 \prec 5 \prec 7 \prec 8 \prec 9 \prec 11 \prec 10 \prec 6$
ec_3	$8 \prec 7 \prec 9 \prec 10 \prec 11 \prec 5 \prec 4 \prec 3 \prec 2 \prec 1 \prec 6$	ses_3	$2 \prec 4 \prec 3 \prec 5 \prec 7 \prec 10 \prec 11 \prec 6 \prec 8 \prec 9 \prec 1$
ec_4	$3 \prec 5 \prec 6 \prec 7 \prec 8 \prec 9 \prec 11 \prec 10 \prec 2 \prec 1 \prec 4$	ses_4	$5 \prec 6 \prec 7 \prec 8 \prec 9 \prec 10 \prec 11 \prec 2 \prec 3 \prec 1 \prec 4$
ec_5	$5 \prec 8 \prec 7 \prec 10 \prec 11 \prec 2 \prec 1 \prec 6 \prec 4 \prec 3 \prec 9$	ses_5	$5 \prec 7 \prec 8 \prec 9 \prec 11 \prec 6 \prec 3 \prec 2 \prec 1 \prec 10 \prec 4$
ec_6	$6 \prec 8 \prec 9 \prec 7 \prec 10 \prec 11 \prec 2 \prec 3 \prec 1 \prec 4 \prec 5$	ses_6	$10 \prec 11 \prec 8 \prec 7 \prec 6 \prec 9 \prec 5 \prec 3 \prec 2 \prec 1 \prec 4$
ec_7	$8 \prec 7 \prec 10 \prec 11 \prec 9 \prec 6 \prec 4 \prec 1 \prec 2 \prec 3 \prec 5$	ses_7	$4 \prec 3 \prec 1 \prec 5 \prec 6 \prec 8 \prec 9 \prec 10 \prec 11 \prec 7 \prec 2$
ec_8	$9 \prec 11 \prec 10 \prec 2 \prec 1 \prec 3 \prec 4 \prec 7 \prec 6 \prec 5 \prec 8$	ses_8	$5 \prec 8 \prec 9 \prec 10 \prec 11 \prec 2 \prec 3 \prec 4 \prec 6 \prec 1 \prec 7$
ec_9	$11 \prec 9 \prec 10 \prec 7 \prec 6 \prec 8 \prec 5 \prec 3 \prec 1 \prec 2 \prec 4$	ses_9	$11 \prec 10 \prec 8 \prec 9 \prec 7 \prec 6 \prec 4 \prec 2 \prec 1 \prec 3 \prec 5$
ec_{10}	$6 \prec 2 \prec 3 \prec 1 \prec 8 \prec 11 \prec 10 \prec 9 \prec 7 \prec 5 \prec 4$	ses_{10}	$7 \prec 5 \prec 4 \prec 3 \prec 9 \prec 10 \prec 11 \prec 2 \prec 1 \prec 8 \prec 6$
ec_{11}	$3 \prec 4 \prec 6 \prec 8 \prec 7 \prec 1 \prec 2 \prec 11 \prec 10 \prec 9 \prec 5$	ses_{11}	$9 \prec 5 \prec 6 \prec 2 \prec 1 \prec 3 \prec 4 \prec 7 \prec 10 \prec 11 \prec 8$

As the objective of the ECs is to minimize their electricity bill and maximize their utility function during the negotiation process. Consumers' ec_i initial offered price to ses_j can be written as:

$$ec_i \rightarrow sec_j(EU_i^t) = \{x_t^{ec_i \rightarrow sec_j}(EU_i^t)\}_{j=1}^m \tag{7}$$

where (EU_i^t) presents the electricity trading units in which the price is to be determined and $x_t^{ec_i \rightarrow sec_j}$ is the offered price of a buyer $ec_i \in EC$ to a small-scale seller $ses_j \in SES$ at t.

$$[x_t^{ec_i \rightarrow sec_j}(EU_i^t)_{\gamma=1} = \min(ROP) + \alpha_t(\max(ROP) - \min(ROP))] \tag{8}$$

And

$$[x_t^{ec_i \rightarrow sec_j}(EU_i^t)_{\gamma=0} = \max(ROP) + \alpha_t(\max(ROP) - \min(ROP))] \tag{9}$$

where $\alpha_t = (t/r)^{c_i^j}$ is the consensus environment which is based on a specific number of negotiation rounds. On this initial offered price from EC, the SES proposed price can be written as:

$$ses_j \rightarrow ec_i(EU_i^t) = \{x_t^{ses_j \rightarrow ec_i}(EU)_i^t\}_{i=1}^m \tag{10}$$

where

$$[x_t^{ses_j \rightarrow ec_i}(EU_i^t)_{\gamma=1} = \max(RPP) - \alpha_t(\max(RPP) - \min(RPP))] \tag{11}$$

and

$$[x_t^{ses_j \rightarrow ec_i}(EU_i^t)_{\gamma=0} = \min(RPP) - \alpha_t(\max(RPP) - \min(RPP))] \tag{12}$$

On reception of SESs proposed price, the proposed consensus algorithm evaluates the numerical score for both the ECs' and SESs' offered and proposed prices. The numerical score for ECs' offered price at time 't' can be found as:

$$N_S(EU)_t^{ec_i \rightarrow ses_j} = \sum_{j=1}^{m} N_S(x_t^{ec_i \rightarrow ses_j}(EU_i^t)) \times W_i^j \tag{13}$$

where

$$N_S(x_t^{ec_i \rightarrow ses_j}(EU_i^t))_{\gamma=1} = \frac{\max(ROP) - x_t^{ec_i \rightarrow ses_j}(EU_i^t)}{\max(ROP) - \min(ROP)} \tag{14}$$

and

$$N_S(x_t^{ec_i \rightarrow ses_j}(EU_i^t))_{\gamma=0} = \frac{x_t^{ec_i \rightarrow ses_j}(EU_i^j) - \min(ROP)}{\max(ROP) - \min(ROP)} \tag{15}$$

Similarly, the numerical score to evaluate the SESs' proposed price at time 't' can be found as:

$$N_S(EU_t^{ses_j \rightarrow ec_i}) = \sum_{i=1}^{m} N_S(x_t^{ses_j \rightarrow ec_i}(EU_i^t)) \times W_i^j \tag{16}$$

where

$$N_S(x_t^{ses_j \rightarrow ec_i}(EU_i^t))_{\gamma=1} = \frac{(x_t^{ses_j \rightarrow ec_i}(EU_i^t)) - \min(RPP)}{\max(RPP) - \min(RPP)} \tag{17}$$

and

$$N_S(x_t^{ses_j \rightarrow ec_i}(EU_i^t))_{\gamma=0} = \frac{\max(RPP) - x_t^{ses_j \rightarrow ec_i}(EU_i^j)}{\max(RPP) - \min(RPP)} \tag{18}$$

If at the given time 't', the score of ECs' is greater than or equal to the SESs' score, then this proposed price will be selected as the trading price among the trading pair of EC and SES. However, if ECs' score is less than the SESs' score, the consensus algorithm will offer the next price to the SES. This subsequent offered price by the EC can be written as:

$$(x_t^{ec_i \rightarrow ses_j}(EU)_i^t)_{\gamma=1} = x_{t-1}^{ec_i \rightarrow ses_j}(EU)_i^t + \alpha_t(\max(ROP) - x_{t-1}^{ec_i \rightarrow ses_j}(EU)_i^t) \tag{19}$$

$$(x_t^{ec_i \rightarrow ses_j}(EU)_i^t)_{\gamma=0} = x_{t-1}^{ec_i \rightarrow ses_j}(EU)_i^t + \alpha_t(x_{t-1}^{ec_i \rightarrow ses_j} \times (EU)_i^t - \min(ROP)) \tag{20}$$

On this subsequent offered price, the counter proposal from a SES can be written as:

$$(x_t^{ses_j \rightarrow ec_i}(EU)_i^t)_{\gamma=1} = x_{t-1}^{ses_j \rightarrow ec_i}(EU)_i^t - \alpha_t(x_{t-1}^{ses_j \rightarrow ec_i} \times (EU)_i^t - \min(RPP)) \tag{21}$$

$$(x_t^{ses_j \rightarrow ec_i}(EU)_i^t)_{\gamma=0} = x_{t-1}^{ses_j \rightarrow ec_i}(EU)_i^t - \alpha_t(\min(RPP) - x_{t-1}^{ses_j \rightarrow ec_i}(EU)_i^t) \tag{22}$$

The process will continue until the ECs' score on their offered prices will be equal to or greater than the SESs' proposed price. This leads the game towards the stable condition known as Nash Equilibrium. The proposed game is also used to distribute electricity among a trading pair.

Let (A, f) be the action profiles of a consumer $ec_i \in EC$ and $ses_j \in SES$ and f is the function that translates the action profile of the players to their expected payoff. According to the formal definition of Nash-equilibrium the expected payoff or utility function f_c of a player $ec_i \in EC$ if he chooses the strategy as a_{i*} and the other player a small-scale seller, chooses the strategy a_j then his expected payoff function (f_c) should be greater than or equal to the expected payoff function (f_c) if he chooses another strategy as a_i. Using the formal definition of Nash-Equilibrium it can be written as:

$$\forall_{i,j} \in EC, SES : f_c(a_{i*}, a_i) \geq f_c(a_i, a_j) \tag{23}$$

Algorithm 1 represents the pseudocode for finding the Nash Equilibrium for the proposed game.

Algorithm 1 Pseudocode for Finding Nash Equilibrium

1) Initialize the minimum and maximum range for ECs' ROP.
2) Initialize the minimum and maximum range for SESs' RPP.
3) Consumer evaluates the value of c_i^j and identifies the values of t_{tot} and r depending upon the consensus environment.
4) Consumer initially generates the offered price (ec_i, ses_i) and becomes engaged $(P_{offered} = x_t^{ec_i \rightarrow ses_j}(EU)_i^t)$ and submit to the small-scale seller.
5) Small-scale seller generates the proposed price $(P_{pro} = x_t^{ses_j \rightarrow ec_i}(EU)_i^t)$
6) Consumer evaluates its score $N_S(EU_t^{ses_j \rightarrow ec_i})$
7) Consumer does the following calculations.

if $t = t_{end}$ or $t = r$ **then**
  Compute $N_S(EU_{tend}^{ec_i \rightarrow ses_j})$.
  if $N_S(EU_t^{ses_j \rightarrow ec_i}) \geq N_S(EU_{tend}^{ec_i \rightarrow ses_j})$ **then**
    Accept it as a trading price.
  else
    Reject the proposed price.
  end if
else
  Generate $x_{t+1}^{ec_i \rightarrow ses_j}(EU_i^t)$.
  if $N_S(EU)_t^{ses_j \rightarrow ec_i} \geq N_S(x_{t+1}^{ec_i \rightarrow ses_j}(EU)_i^t)$ **then**
    Accept it as a trading price.
  else
    Submit $x_{t+1}^{ec_i \rightarrow ses_j}(EU)_i^t$, $t = t + 1$; go to Step 6.
  end if
end if

VI. RESULTS AND DISCUSSION

This section presents the simulation results for the proposed consensus algorithm to determine the electricity trading price in the P2P electricity trading market. For this purpose, we assume a total of 22 players as market participants. Among these 22 players, 11 players are acting as ECs and 11 players are acting as SESs. Among these SESs, six sellers are assumed to be equipped with storage capacity and the others are assumed without storage capacity. The ECs' load demand, SESs' surplus electricity data along with import and export electricity rate and grid charges are applicable to the sellers are obtained from [16]. The grid availability with

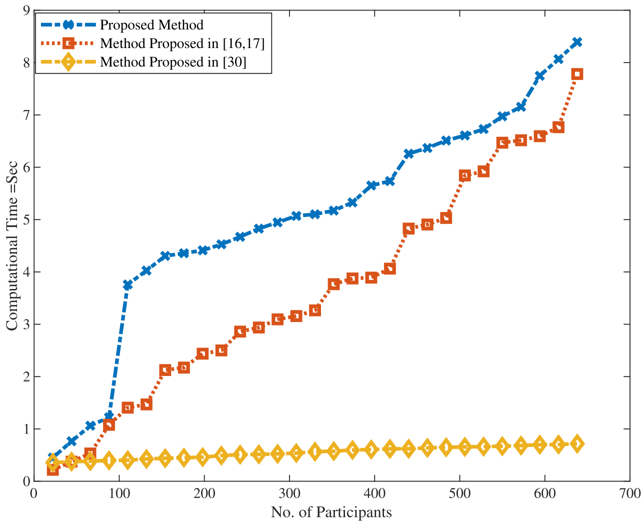


FIGURE 3. Scalability analysis.

8-hours outage in a day is assumed arbitrary. The ECs' and SESs' preferences are selected arbitrarily and presented in Table 1. Further, it is assumed that the grid can store only 90kW electricity at time 't'. The price of the grid import rate of the stored electricity is assumed to be 11.5 c/kWh. To show the effectiveness of the proposed model, we take a random time slot at time $t = 5$ with grid availability $\gamma = 1$. The electricity required by ECs, E_{req}, and the surplus electricity, E_{sur}, from SESs are given as:

$$E_{req}(kWh) = \{7.6774, 9.9088, 4.9540, 0.6008, 2.7455, \times 2.4272, 1.0550, 0.4194, 0.5149, 1.2775, \times 1.8731\} \tag{24}$$

$$E_{sur}(kWh) = \{2.6324, 1.8548, 3.8437, 1.0780, 2.6438, \times 6.5318, 8.4248, 12.9793, 0.9068, 14.1599, \times 3.7128\} \tag{25}$$

The first step of the proposed system is to make trading pairs based on preferences of both ECs and SESs. For this purpose, let us take the preference list of EC ec_3 and demonstrate how the proposed flow-chart presented in Fig.2 works. From Table 1, the preference list of ec_3 is given as $\Delta_{ec_3} = \{8 \prec 7 \prec 9 \prec 10 \prec 11 \prec 5 \prec 4 \prec 3 \prec 2 \prec 1 \prec 6\}$.

From the preference list, it can be seen that ec_3 wants to make an electricity trading pair with ses_8. But the preference list of ses_8 presented in Table 1 shows that ses_8 gives high preference to ECs $(5, 8, 9, 10, 11, 2)$ over ec_3. Therefore, a trading pair among $(ec_3$ & $ses_8)$ cannot be formed. The next potential candidate in the list of ec_3 is ses_7. Again evaluating the preference list of ses_7, it can be seen that ses_7 prefers to trade electricity with ec_4 over ec_3. Therefore, a pair between $(ec_3$ & $ses_7)$ will not be formed. The next potential candidate in the list of ec_3 is ses_9. The preference list of ses_9 reflects that the seller, ses_9 prefers to trade electricity with consumers

TABLE 2. Offered and proposed prices.

$(ses_1 \leftrightarrows ec_1)$	$(ROP)_{\gamma=1} = (6.2, 7), (ROP)_{\gamma=0} = (9, 11)$	
	$(RPP)_{\gamma=1} = (6.0, 7), (RPP)_{\gamma=0} = (9.5, 11)$	T_p = 6.1512 c/kWh
$(ses_2 \leftrightarrows ec_3)$	$(ROP)_{\gamma=1} = (6.3, 6.9), (ROP)_{\gamma=0} = (9.8, 10.8)$	
	$(RPP)_{\gamma=1} = (6.5, 6.9), (RPP)_{\gamma=0} = (9.2, 10.9)$	T_p = 6.5605 c/kWh
$(ses_3 \leftrightarrows ec_2)$	$(ROP)_{\gamma=1} = (6.25, 7.0), (ROP)_{\gamma=0} = (9.4, 10.5)$	
	$(RPP)_{\gamma=1} = (6.1, 7), (RPP)_{\gamma=0} = (9.4, 10.4)$	T_p = 6.2361 c/kWh
$(ses_4 \leftrightarrows ec_7)$	$(ROP)_{\gamma=1} = (6.3, 7.0), (ROP)_{\gamma=0} = (9.2, 10.89)$	
	$(RPP)_{\gamma=1} = (6.28, 7), (RPP)_{\gamma=0} = (9.4, 10.89)$	T_p = 6.3889 c/kWh
$(ses_5 \leftrightarrows ec_5)$	$(ROP)_{\gamma=1} = (6.1, 7.0), (ROP)_{\gamma=0} = (9.6, 11)$	
	$(RPP)_{\gamma=1} = (6, 7), (RPP)_{\gamma=0} = (9.0, 11)$	T_p = 6.1512 c/kWh
$(ses_6 \leftrightarrows ec_4)$	$(ROP)_{\gamma=1} = (6.31, 6.8), (ROP)_{\gamma=0} = (9.2, 10.8)$	
	$(RPP)_{\gamma=1} = (6.2, 7), (RPP)_{\gamma=0} = (9.6, 11)$	T_p = 6.4907 c/kWh
$(ses_7 \leftrightarrows ec_{10})$	$(ROP)_{\gamma=1} = (6.5, 7), (ROP)_{\gamma=0} = (9.0, 11)$	
	$(RPP)_{\gamma=1} = (6.45, 7), (RPP)_{\gamma=0} = (9.5, 10.8)$	T_p = 6.5332 c/kWh
$(ses_8 \leftrightarrows ec_8)$	$(ROP)_{\gamma=1} = (6.5, 7), (ROP)_{\gamma=0} = (9.0, 11)$	
	$(RPP)_{\gamma=1} = (6.45, 7), (RPP)_{\gamma=0} = (9.5, 10.8)$	T_p = 6.5332 c/kWh
$(ses_9 \leftrightarrows ec_{11})$	$(ROP)_{\gamma=1} = (6.31, 6.8), (ROP)_{\gamma=0} = (9.2, 10.8)$	
	$(RPP)_{\gamma=1} = (6.0, 7), (RPP)_{\gamma=0} = (9.5, 11)$	T_p = 6.3210 c/kWh
$(ses_{10} \leftrightarrows ec_6)$	$(ROP)_{\gamma=1} = (6.5, 7), (ROP)_{\gamma=0} = (9, 11)$	
	$(RPP)_{\gamma=1} = (6.45, 7), (RPP)_{\gamma=0} = (9.5, 10.8)$	T_p = 6.5332 c/kWh
$(ses_{11} \leftrightarrows ec_9)$	$(ROP)_{\gamma=1} = (6.31, 6.8), (ROP)_{\gamma=0} = (9.2, 10.8)$	
	$(RPP)_{\gamma=1} = (6.2, 7), (RPP)_{\gamma=0} = (9.6, 11)$	T_p = 6.3210 c/kWh

TABLE 3. Price determination between (ec_8 & ses_8).

Time round (r)	Consumers' (ROP)	Sellers' (RPP)	Score ($ses_8 \rightarrow ec_8$)	Score ($ec_8 \rightarrow ses_8$)	$NS_{SES \rightarrow EC_{t=t}} \geq NS_{EC \rightarrow SES_{t=t+1}}$
t=1	6.5050	6.9450	0.4250	-	Not met
t=2	6.5050	6.8460	0.7400	1.8401	Not met
t=3	6.5676	6.7272	1.1180	1.6153	Not met
t=4	6.6368	6.6163	1.4708	1.2939	Not met
t=5	6.7276	6.5332	1.7354	0.9171	met

TABLE 4. Electricity bills for consumers over one-year simulated data.

Consumers' ID	Proposed Method bill	Method Proposed in [16], [17]	Saving w.r.t [16], [17]	Method Proposed in [30]	Saving w.r.t [30]
ec_1	667783.9462	724559.754	8.5021%	724569.4156	8.5035%
ec_2	869406.5149	919739.8343	5.7893%	930552.1382	7.0330%
ec_3	800915.4834	836954.9547	4.4997%	843420.9442	5.3071%
ec_4	106367.6144	110513.3002	3.8975%	111853.6808	5.1576%
ec_5	367539.7497	398410.8612	8.3993%	397359.0096	8.1132%
ec_6	589339.1037	619957.533	5.1953%	622488.9946	5.6249%
ec_7	135637.6653	144124.1826	6.2567%	144852.0653	6.7933%
ec_8	60369.91725	63507.66729	5.1975%	63762.69162	5.6199%
ec_9	114902.1065	121161.7591	5.4478%	122621.7761	6.7184%
ec_{10}	212441.4188	223441.5373	5.1779%	224346.1863	5.6037%
ec_{11}	322020.3674	339550.8472	5.4439%	341755.7659	6.1286%

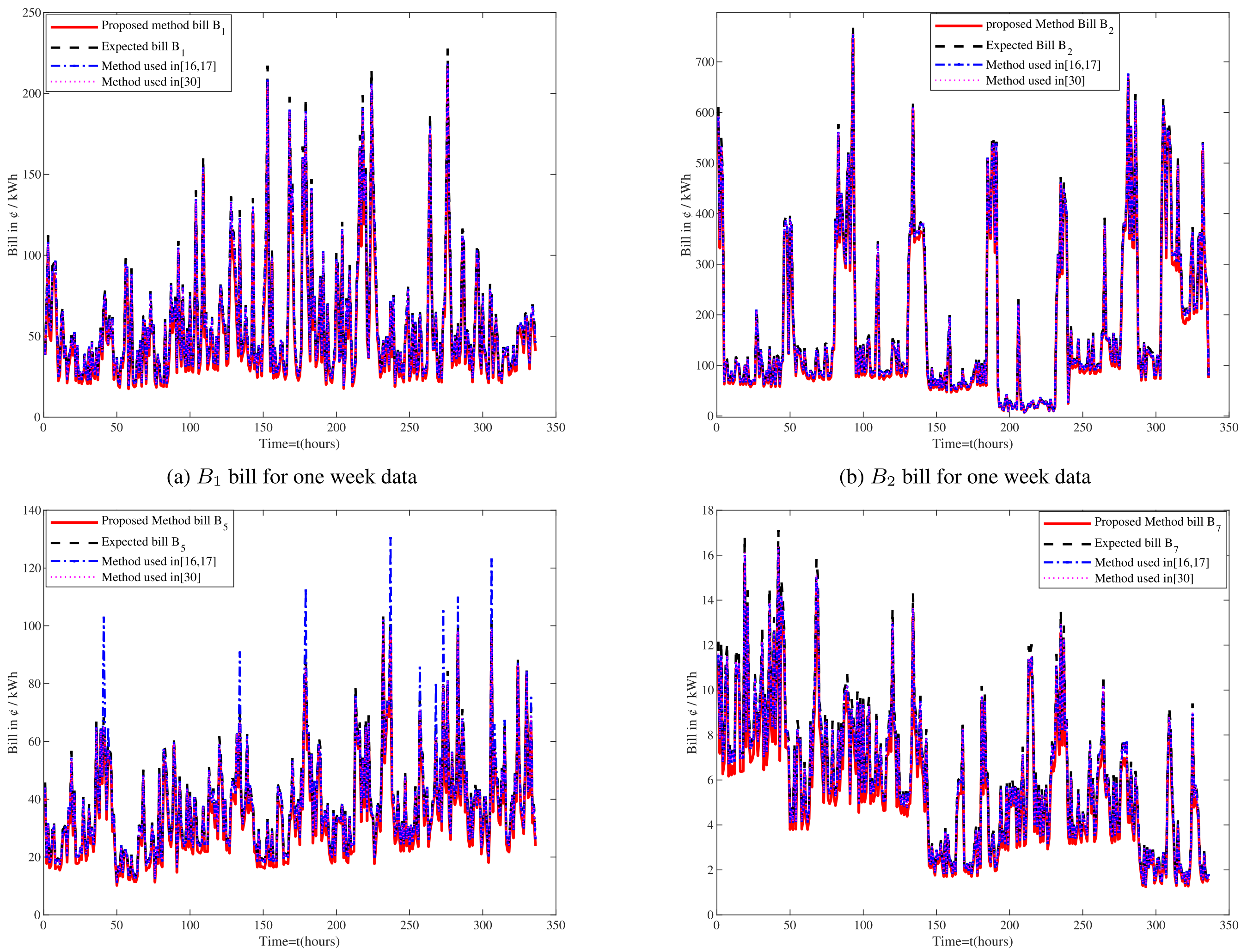
(11, 10, 8, 9, 7, 6, 4, 2, 1) rather than ec_3. Therefore pairing with this candidate is also not possible. The next potential candidate in the list of ec_3 is ses_{10}. This seller gives high preferences to consumers (7, 5, 4) over ec_3. The next potential candidate in the list of ec_3 is ses_{11}. This seller gives high preferences to consumers (9, 5, 6, 2, 1) over ec_3. The next potential candidate in the list of ec_3 is ses_5. This seller gives high preferences to consumers (5, 7, 8, 9, 11, 6) over ec_3. The next potential candidate in the list of ec_3 is ses_4. This seller gives high preferences to consumers (5, 6, 7, 8, 9, 10, 11, 2) over ec_3. Therefore, the trading pair with this seller is also not possible. The next potential candidate in the list of ec_3 is ses_3. This seller gives high preferences to the consumers (2, 4) over ec_3. The next potential candidate in the list of ec_3 is ses_2. This seller, ses_2, gives high priority to ec_3. Therefore, a stable trading pair among (ec_3 & ses_2) which reflects the true preferences for both the EC and SES is formulated.

It can be seen from Fig 9 that the proposed method increases the satisfaction index of the consumers more as compared to the method used in [42].

The process will continue for all other ECs and SESs until all participants are matched into trading pairs. The trading pairs along with their offered and proposed prices are represented in Table 2. The next objective is to develop a consensus algorithm among a pair to determine the price for electricity trading. For this purpose, we pick a random pair ($ses_8 \rightarrow ec_8$) to demonstrate how the proposed Algorithm 1 is used to determine the electricity price. Since for the given

TABLE 5. Revenues for sellers over one-year simulated data.

Sellers' ID	Proposed Method revenue	Method Proposed in [16], [17]	Increase w.r.t [16], [17]	Method Proposed in [30]	Increase w.r.t [30]
ses_1	335829.7747	275000	18.1132%	320000	4.7136%
ses_2	207675.5034	164000	21.0306%	192000	7.5480%
ses_3	467544.5558	389000	16.7993%	448000	4.1802%
ses_4	170755.3113	135000	20.9395%	135000	5.7130%
ses_5	308483.0361	247000	19.9307%	287000	6.9640%
ses_6	351815.0947	235000	33.2035%	267000	24.1078%
ses_7	871577.6329	702000	19.4564%	740000	15.0964%
ses_8	511658.8839	269000	47.4259%	324000	36.6765%
ses_9	95511.2573	74500	21.9987%	89700	6.0843%
ses_{10}	1505562.33	1250000	16.974%	1250000	12.3251%
ses_{11}	181027.742	153573.579	15.1657%	153573.579	13%



(a) B_1 bill for one week data

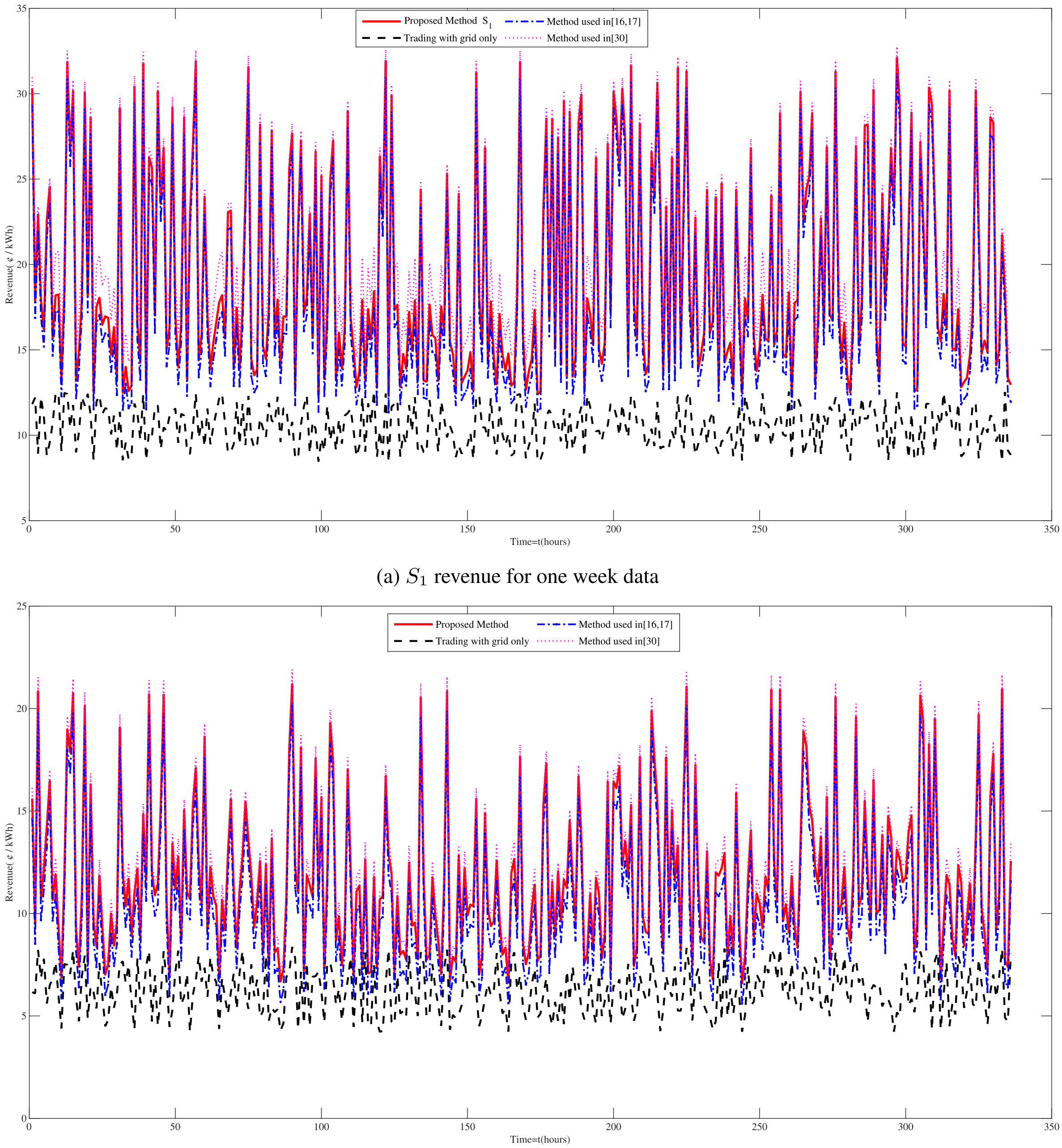
(b) B_2 bill for one week data

(c) B_5 bill for one week data

(d) B_7 bill for one week data

FIGURE 4. Electricity bills for buyers of one week simulated data.

time slot, the grid availability $\gamma = 1$, therefore, the values for the off-grid price will not be used for this time slot. From Table 2, the range of $ec_8's$ offered price is taken as ($ROP = 6.5 - 7$) and the range of $ses_8's$ proposed price is taken as ($RPP = 6.45 - 7$). A total of ten rounds ($r = 10$) is assumed in the consensus algorithm when determining the trading price. Following Eq.(8) the $ec_8's$ offered price at time '$t = 1$' will be ($ROP = 6.5050$). At this offered price, the ses_8 proposed price following the Eq.(11) will be ($RPP = 6.9450$). Since at these prices the condition described at step-7(a) in Algorithm 1 cannot be met therefore $ec_8's$ will reject this proposed price and offer a new price ($ROP = 6.5248$) at



(a) S_1 revenue for one week data

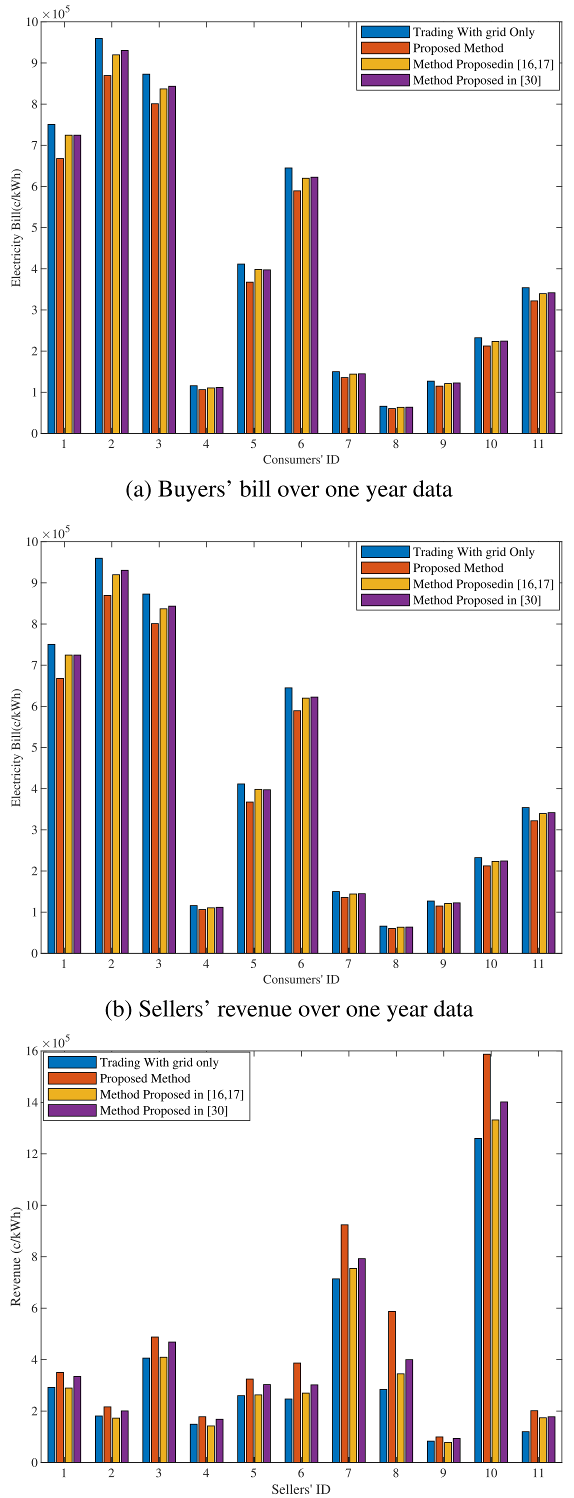
(b) S_2 revenue for one week data

FIGURE 5. Revenues graphs over one week dataset.

'$t = 2$' and compute Eq.(14). On receiving this new offered price and after the Eq.(17) calculation the ses_8's new proposed price at '$t = 2$' will be ($RPP = 6.8460$). Again at these prices, the condition for selecting the trading price is not met. Hence ec_8 will offer a new price to ses_8. The process will continue until the condition described in step-7 (a) in Algorithm 1 is met. The overall process with respect to time 't' for determining the trading price is given in Table 3.

Knowing the numerical values of (E_{req}) and (E_{sur}) in a pair from Table 2, it can be seen that some pairs have a mismatch between the asked demand and available surplus e.g., in a pair $ses_1 \rightarrow es_1$ where EC demand is (7.6774 kWh) and SES available surplus is 2.6324 kWh. Therefore, after trading with this peer, the proposed algorithm will make the next pair according to its preference.

Fig. 3 presents the scalability analysis of the proposed model to the models used in [16], [17], and [30]. From Fig. 3 it can be seen that the proposed system scalability is lesser than the others used in [16], [17], and [30]. However, by comparing the revenues and electricity bills from Tables (4 and 5) it



(a) Buyers' bill over one year data

(b) Sellers' revenue over one year data

(c) Sellers' revenue over one year data without grid charges

FIGURE 6. Bill and revenues graphs over one year dataset.

TABLE 6. Preference list of buyers and sellers at $t = 3$.

Consumers' Preference List (Δ_{ec_i})		Small-scale sellers' Preference List (Δ_{ses_i})	
ec_1	$2 \prec 3 \prec 4 \prec 5 \prec 8 \prec 9 \prec 10 \prec 11 \prec 1 \prec 7 \prec 6$	ses_1	$7 \prec 8 \prec 5 \prec 4 \prec 2 \prec 1 \prec 9 \prec 11 \prec 10 \prec 6 \prec 3$
ec_2	$2 \prec 5 \prec 4 \prec 7 \prec 8 \prec 10 \prec 9 \prec 11 \prec 1 \prec 3 \prec 6$	ses_2	$8 \prec 7 \prec 5 \prec 3 \prec 2 \prec 9 \prec 1 \prec 11 \prec 10 \prec 6 \prec 4$
ec_3	$8 \prec 7 \prec 9 \prec 10 \prec 11 \prec 5 \prec 4 \prec 3 \prec 2 \prec 1 \prec 6$	ses_3	$4 \prec 8 \prec 6 \prec 7 \prec 2 \prec 1 \prec 9 \prec 10 \prec 11 \prec 5 \prec 3$
ec_4	$10 \prec 8 \prec 9 \prec 1 \prec 3 \prec 4 \prec 6 \prec 7 \prec 2 \prec 5 \prec 11$	ses_4	$7 \prec 8 \prec 5 \prec 4 \prec 2 \prec 6 \prec 3 \prec 11 \prec 10 \prec 1 \prec 9$
ec_5	$8 \prec 10 \prec 9 \prec 1 \prec 3 \prec 4 \prec 11 \prec 7 \prec 2 \prec 5 \prec 6$	ses_5	$6 \prec 5 \prec 8 \prec 2 \prec 4 \prec 7 \prec 3 \prec 10 \prec 11 \prec 9 \prec 1$
ec_6	$9 \prec 8 \prec 10 \prec 3 \prec 1 \prec 4 \prec 6 \prec 7 \prec 2 \prec 5 \prec 11$	ses_6	$8 \prec 11 \prec 10 \prec 6 \prec 7 \prec 5 \prec 9 \prec 2 \prec 3 \prec 1 \prec 4$
ec_7	$6 \prec 8 \prec 9 \prec 1 \prec 3 \prec 4 \prec 10 \prec 2 \prec 7 \prec 11 \prec 5$	ses_7	$5 \prec 2 \prec 3 \prec 4 \prec 6 \prec 9 \prec 8 \prec 10 \prec 7 \prec 11 \prec 1$
ec_8	$2 \prec 8 \prec 9 \prec 5 \prec 4 \prec 3 \prec 6 \prec 7 \prec 11 \prec 1 \prec 10$	ses_8	$4 \prec 9 \prec 8 \prec 11 \prec 10 \prec 2 \prec 5 \prec 3 \prec 6 \prec 1 \prec 7$
ec_9	$7 \prec 9 \prec 8 \prec 2 \prec 3 \prec 4 \prec 10 \prec 6 \prec 1 \prec 5 \prec 11$	ses_9	$9 \prec 10 \prec 8 \prec 11 \prec 6 \prec 7 \prec 4 \prec 1 \prec 2 \prec 3 \prec 5$
ec_{10}	$9 \prec 10 \prec 8 \prec 1 \prec 3 \prec 7 \prec 5 \prec 4 \prec 2 \prec 6 \prec 11$	ses_{10}	$6 \prec 5 \prec 4 \prec 9 \prec 3 \prec 10 \prec 11 \prec 2 \prec 8 \prec 1 \prec 7$
ec_{11}	$11 \prec 8 \prec 9 \prec 3 \prec 1 \prec 5 \prec 6 \prec 7 \prec 2 \prec 4 \prec 10$	ses_{11}	$5 \prec 9 \prec 2 \prec 6 \prec 4 \prec 3 \prec 1 \prec 10 \prec 7 \prec 11 \prec 8$

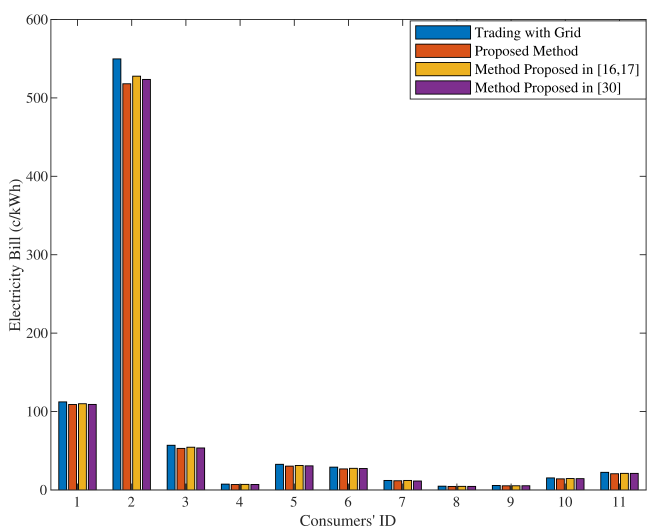


FIGURE 7. Electricity bill of consumers at $t = 3$.

can ensure that the proposed system is more beneficial to the participants.

Fig. 4 and Fig. 5 present the revenues and electricity bills of some sellers and consumers using one week of simulated data by varying demand, generation, prices and compared with the methods proposed in [16], [17], and [30].

TABLE 7. Contract formulation Stage-1.

ses_i	Δses_i	$C_{ses,ec}$	Demand	Surplus	Demand Left	Surplus Left	Trading Price
1	7,~~8,5,4,2,1,9,11,10,6,3~~	1,7	1.0538	2.1270	0	1.0731	11.1220
2	8,~~7,5,3,2,9,1,11,10,6,4~~	2,8	0.4183	1.9578	0	1.5395	10.7186
3	~~4,8,6,7,2,1,~~9~~,10,11,5,3~~	3,9	0.4958	3.5537	0	3.0578	10.6647
4	~~7,8,5,4,2,6,3,~~11~~,10,1,9~~	4,11	1.9542	1.4602	0.4940	0	10.5674
5	~~6,5,8,~~2~~,4,7,3,10,11,9,1~~	5,2	47.8029	2.7472	45.0557	0	10.6034
6	~~8,11,10,6,7,5,9,2,~~3~~,1,4~~	6,3	4.9540	6.0000	0	1.0459	10.6976
7	~~5,1,3,4,6,9,8,~~10~~,7,11,2~~	7,10	1.3348	9.0000	0	7.6651	10.6034
8	4,~~9,8,11,10,2,5,3,6,1,7~~	8,4	0.6454	12.9078	0	12.2624	10.6976
9	~~9,10,8,11,6,7,4,1,2,3,~~5	9,5	2.8437	0.4018	2.4419	0	10.6034
10	6,~~5,4,9,3,10,11,2,8,1,7~~	10,6	2.5299	13.9490	0	11.4190	10.6034
11	~~5,9,2,6,4,3,~~1~~,10,7,11,8~~	11,1	9.7653	4.6757	5.0896	0	10.7883

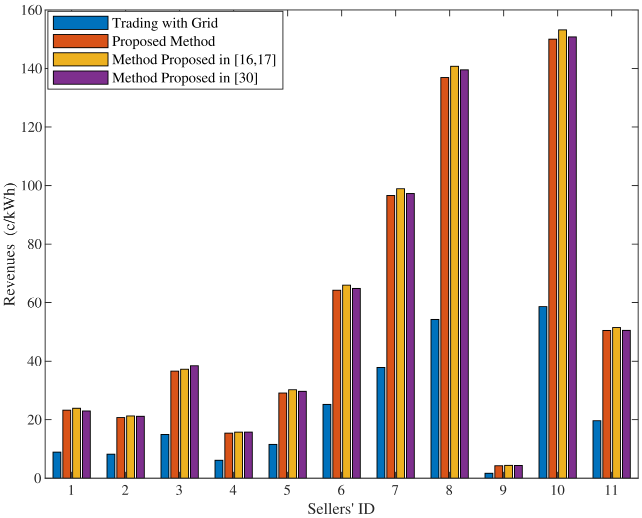


FIGURE 8. Revenue of sellers at $t = 3$.

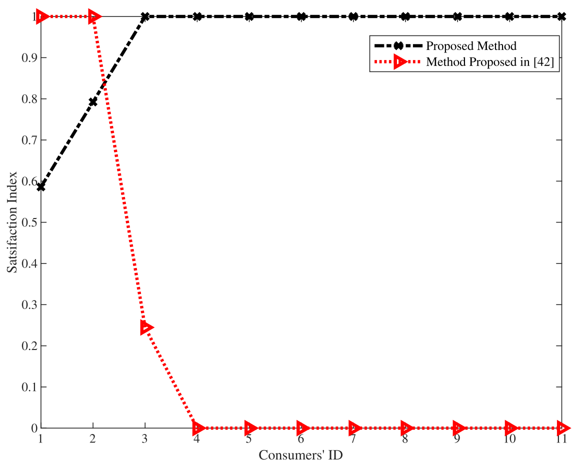


FIGURE 9. Satisfaction index $t = 3$.

The experiment is performed over the one-year dataset with varying prices, demand, and surplus and the simulated results is presented in Fig. 5. Tables (5 & 6) present the percentage savings in electricity bills for the consumers and percentage increase in revenues for the sellers with respect to methods proposed in [16], [17], and [30]. It can be seen that the proposed model further reduces the electricity bills of the consumers by 5% to 8% and increases the revenues of the sellers from 13% to 15% when compared to other proposed algorithms in [16], [17], and [30].

TABLE 8. Contract formulation Stage-2.

ses_i	Δses_i	$C_{ses,ec}$	Demand	Surplus	Demand Left	Surplus Left	Trading Price
7	5,~~1,11,2~~	7,5	2.4419	7.6651	0	5.2232	10.6976
8	11,~~2,5,1~~	8,11	0.4940	12.2624	0	11.7684	10.6034
10	~~5,11,~~2~~,1~~	10,2	45.0557	11.4190	33.6366	0	10.7883
6	~~11,5,2,~~1	6,1	5.0896	1.0459	4.0437	0	10.7883

VII. CONCLUSION

A growing number of participants in the P2P electricity trading market ensures the success of the P2P trading market. Increase in the involvement of the participants in the P2P electricity trading market ensures success. Moreover, an effective pricing scheme that increases the utilities of participants while considering their reserved prices further incentives them to take part in trading activities. For this purpose, based on the game-theoretic framework, an effective pricing scheme that considers participants' reserved prices for determining the electricity trading price is proposed. It can be seen that the proposed algorithm is more effective as compared to those of others as it further reduces the electricity bill of consumers from 5% to 8% and increases the revenues of the sellers from 13% to 15% when compared to other proposed algorithms. Compared with the other state of art methods, the proposed method is more effective as it brings more savings and profitability for consumers and sellers with a marginal increase in the iteration time. However, several factors have been ignored in this proposed method, such as network constraints and battery constraints. Furthermore, blockchain can be deployed to make the model more secure for financial transactions and minimum sharing of peers' information.

APPENDIX. ANOTHER EXAMPLE I.E., WHEN DEMAND IS GREATER THAN SUPPLY AND GRID IS NOT AVAILABLE

To show the effectiveness of the proposed model, we take a random time slot at time $t = 3$ with grid availability $\gamma = 0$. The electricity required by ECs, E_{req}, and the surplus electricity, E_{sur}, from SESs, are given as:

$$E_{req}(kWh) = \{9.7654, 47.8030, 4.9540, 0.6454, 2.8437, \times 2.5299, 1.0538, 0.4183, 0.4958, 1.3348, \times 1.9542\} \quad (26)$$

$$E_{sur}(kWh) = \{2.1270, 1.9578, 3.5537, 1.4602, 2.7472, \times 6.0000, 9.0000, 12.9078, 0.4018, 13.9490, \times 4.6757\} \quad (27)$$

The list of preferences for all consumers and small scale sellers at time $t = 3$ is presented in Table 6.

For analyzing the working principle of the proposed game for contract formulation, we pick a random EC ec_4 and from Table 6 its preference list is taken as $\Delta_{ec_4} = \{10 \prec 8 \prec 9 \prec 1 \prec 3 \prec 4 \prec 6 \prec 7 \prec 2 \prec 5 \prec 11\}$.

For a better understanding of the proposed game contract formulation model, we discuss the contract formulation in different stages. At the start of the game (stage-1), by evaluating the preference list of ec_4, it can be seen that the ec_4 wants to perform electricity trading pairing with ses_{10}. But the preference list of ses_{10} presented in Table 6 shows that ses_{10} gives high preference to ECs 6, 5 over ec_4. Therefore, a trading pair among (ec_4 *and* ses_{10}) cannot form. The next potential candidate in the preference list of ec_4 is ses_8. By evaluating the preference list of ses_8, it can be seen that ses_8 gives a high preference to ec_4 over all other consumers. Therefore, a stable trading pair between (ec_4 *and* ses_8) which reflects the true preferences for both the EC and SES, is formulated.

Following the method described above, a further contract formulation at Stage-2 is presented in Table 8. From Table 7 it can be seen that at the end of Stage-1, the demand and surplus of several ECs and SESs is zero. Hence this is not included in the second stage of the contract formulation as presented in Table 8.

From Tables 7 and 8 it can be seen that all ECs demand except ec_2 *and* ec_1 are zero.Whereas, all SESs surplus except (ses_1, ses_2, ses_3, ses_7, ses_8) are zero. By examining the preferences list of these sellers it can be seen that these sellers prefer ec_2 over ec_1. Therefore, all these sellers trade their surplus electricity to consumer ec_2 which results the net remaining demand of ec_2 as 9.9285kWh and ec_1 as 4.0437kWh. These consumers will obtained this amount of electricity from the grid storage.

Figs 7 and 8 present the electricity bills and revenues for all consumers and sellers at time $t = 3$.

The proposed game used for contract formulation to determine the electricity trading price also helps to distribute the electricity among the peers to increase the consumers' satisfaction index, especially when grid supply is not available, and there is an imbalance between the demand asked by the consumers and surplus offered by the sellers. For this purpose, Fig 9 presents the satisfaction index for all consumers at time $t = 3$. To compare the satisfaction index of the proposed method with the other state of art methods such as the work proposed in [42]. We assume that consumers are treated as those in a standalone microgrid and based on their electricity demand, the sorted values for electricity demand set is given as:

$$E_{req}(kWh) = \{47.8030, 9.7654, 4.9540, 2.8437, 2.5299, \times 1.9542, 1.3348, 1.0538, 0.6454, 0.4958, \times 0.4183\} \quad (28)$$

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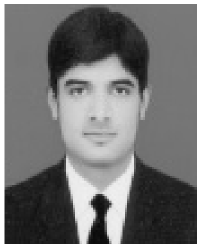

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