Transactive energy coordination mechanism for community microgrids supplying multidwelling residential apartments

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Abstract: A transactive energy coordination mechanism is proposed in this study where community microgrids are supplying power to multi-dwelling residential apartments. The proposed transactive energy coordination mechanism coordinates the energy sharing among apartments based on the energy profile of the community microgrid where the excess energy is traded with non-contributing apartments. The proposed coordination mechanism is embedded within an energy management controller which uses the energy profile and determines the valuation of energy. A choice factor along with the bound on electricity prices is also incorporated to calculate the bidding price and a double-sided auction mechanism is considered for the bidding purpose. The utility maximisation approach is used to clear the market. Different scenarios based on the flexibility in the pricing strategy are considered to evaluate the performance of the proposed transactive energy coordination mechanism. The potential economic benefits of the proposed scheme are also analysed which clearly demonstrate that it is beneficial for all participants.

1 Introduction

The maintenance of the supply–demand balance with intermittent renewable energy sources (RESs) in low-voltage power distribution networks is an ongoing issue. Generally, the energy management system or controller is used for coordinating the supply–demand balance in small microgrids where solar photovoltaic (PV) systems are mainly used to supply power and battery energy storage systems (BESSs) are used to store excess energy after fulfiling load demands. The integration of RESs in distribution networks enables two-way communications for the coordination of energy sharing. In a microgrid setting, there could be some residences which do not have access to RESs and the energy management controller can be used to share the excess energy among such residences from where prosumers will gain some benefits. The transactive coordination scheme is an emerging approach to match the supply–demand which requires two-way communication where decisions associated with balancing the supply–demand are made locally [1]. Furthermore, the transactive coordination approach is envisioned to bring a distribution centric paradigm shift in the way the demand-supply balance is managed [2] and hence, it is essential to develop a coordination mechanism for community microgrids which are used to supply apartment buildings in order to investigate underlying benefits.

Local energy markets, i.e. markets at distribution ends rely on exchanging economic signals associated with the supply and demand in order to facilitate a market mechanism which benefits not only the grid but also provides incentives to end-users [3]. Peer-to-peer (P2P) energy transactions and community energy sharing schemes are considered as key points for energy management controllers in power distribution systems including microgrids [4]. The P2P energy trading scheme incentivizes small-scale prosumers to participate in the market for selling excess energy to their neighbours [5]. Different game-theoretic approaches are used in order to facilitate the P2P energy trading among prosumers in a neighbourhood microgrid environment [6] where interactions among different parties (i.e. sellers and buyers) are modelled as a Stackelberg game. In these energy trading games, the energy trading prices of sellers are fixed in a non-cooperative manner whereas buyers are involved through evolutionary games to purchase energy from the market. A holistic P2P energy trading pattern for the smart grid is proposed in [7] where various agents representing prosumers, suppliers and generators maximise their utilities to facilitate the coordination among participants. The P2P energy trading problem among prosumers is addressed in [8] through an economic dispatch model and solved using the relaxed consensus and innovation method. All these energy trading schemes maximise social welfare while satisfying individual preferences. However, these schemes are developed for small-scale single-owner owned facilities and the energy trading scenario for resources in a central location (e.g. community microgrids) needs to be treated differently.

In community-based microgrids, several prosumers invest to form microgrids where all resources are located centrally and benefits of microgrids are shared among prosumers through shared market protocols (SMPs). For such community microgrids, there will be some participants who directly invest while some others will not. However, all participants can be benefitted as investors can earn money by selling excess energy to others and similarly, non-investors could save in their electricity bills by purchasing electricity in a cheaper price. In [9], it is revealed through Monte-Carlo simulation studies that the community solar PV system is more efficient than an analogous individual rooftop system. Similarly, community-scale BESSs are more beneficial than their applications in individual households in terms of the profitability and performance [10]. The apartment building with a centralised solar PV and BESS-based power supply system can be considered as a special case of the community microgrid which has the huge potential to leverage the benefits through the transactive energy coordination mechanism if the market is properly designed.

The major challenges for energy trading among different apartments from a community microgrids are: (i) different preferences of different apartment dwellers, (ii) cost-benefit sharing among owners and tenants and (iii) unequal financial contribution of different apartments. However, these are not the case for owner-owned individual microgrids. Several community energy storage models are developed in [11] which can be used for local energy markets though there is no indication about the energy sharing and trading mechanisms for such local energy markets. The performance of a community microgrid with shared solar PV and BESSs serving a multi-apartment building is assessed in [12] through a computational framework. In this microgrid, the excess energy is stored into the BESS instead of feeding back to the grid in order to increase the self-sufficiency. However, the potential of the energy trading is discouraged in [12] just by mentioning the high investment cost without providing any analysis to support this

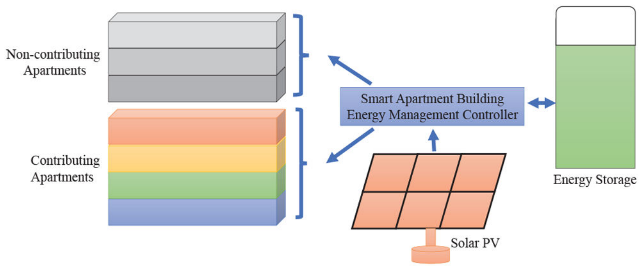

Fig. 1 *A community microgrid for a residential apartment building with a smart apartment building energy management controller*

statement and hence, it is worth to analyse the structure of the local energy market to extract the full benefits of the transactive energy trading mechanism.

Game-theoretic approaches provide a way to investigate the market structure and analyse the utility of participants from the local energy trading. Various auction methods incorporating game theories are extensively used for the energy management in microgrids. The example of such an energy management process can be seen in [13] where buyers initiate the energy transaction by revealing their demands in the form of a procurement auction and the demand is satisfied by purchasing from sellers with lower asking prices. Another auction-based energy trading mechanism is demonstrated in [14] which has the ability to successfully consider the day-ahead and real-time energy markets. A modified Vickrey auction mechanism is deployed in [15] for the energy management in various common spaces within a microgrid where some portions of the distributed energy storage devices are acquired to meet the demand. Different auction mechanisms are analysed for different pricing structures in [16, 17], optimal bidding in [18, 19], distributed solutions in [20, 21], and market efficiency in [22, 23]. However, these approaches do not cover the energy trading among different apartments which are supplied by a community microgrid where both sellers and buyers bid to win the auction.

The involvement of both sellers and buyers in the auction process is known as the double-sided auction as both buyers and sellers can bid which is a kind of an SMP. A continuous double auction mechanism is proposed in [24] where the traders with different approaches to risk bid by anticipating the equilibrium market price. However, there is no bound for pricing in this auction mechanism which makes the process inefficient as well as not attractive. For example, a local energy market with such an auction mechanism may have the bid price lower than the feed-in tariff from the buyer and higher than the utility rate from sellers which make it difficult to achieve the market equilibrium. Moreover, the buyers [24] with different approaches to the risk bid based on the market history and this approach does not consider the demand and supply situation. Here, the consideration of market history during the bidding process might be beneficial when there is ample supply. However, it is essential to consider the supply–demand balance in the case of the scarcity of the supply with the high competition for energy. A double auction mechanism is used in [25] for the market clearing process to trade energy among different agents without any value discovery mechanism. Another double auction-based approach is used in [26] for facilitating energy transactions among multiple microgrids where both sellers and buyers discover the value of energy. However, the social optimality is not guaranteed in [26] though this is important for matching the traded energy among buyers and sellers. A social optimal solution is proposed in [27] which is achieved by enabling a central controller to match the energy trade among sellers and buyers. Different performance metrics are also presented in [27] to compare different energy management systems and two double auction-based energy management schemes are contrasted while neglecting the relationship between the valuation of energy and payoff. Therefore, it is essential to develop a transactive energy coordination mechanism which overcomes all limitations of existing works as highlighted in this paper.

The transactive energy market framework for the owner-occupied single house is analysed in [28, 29]. However, it is essential to address the energy management issues and challenges associated with multi-dwelling apartment buildings [30, 31] which use shared RESs and BESSs. Two energy allocation and pricing models are compared in [30] where the first model considers the utility maximisation of the apartment for different fixed values of market prices and the second model deals with a non-cooperative approach providing more control of market prices to the owners of PV and BESSs. The proposed models in [30] are based on the knowledge of consumers' willingness-to-pay (WTP) which is a private value. When the private valuation of the buyer is known to the seller, the market becomes inefficient due to the lack of competition. Moreover, the buyers do not have an option to bid in such models. Furthermore, the energy trading approaches in [22, 30] do not provide any bound on the market price which might lead the market being either the owner centric or consumer centric.

Based on the literature review, the main limitations of existing approaches including the double-sided auction can be summarised as follows:

- The bidding strategy works based on different risk models, i.e. the attitude of buyers in terms of taking risks and the bidding is done based on the market history instead of the current situation in the market.
- The privacy of bidders is not preserved as the seller knows the private valuation of all buyers.
- The absence of bounds on the market price might result in a market that is skewed towards either buyers or sellers.
- The bidding price is set by the market and buyers do not have any option to select their own prices.

All these limitations mainly affect the value discovery, flexibilities in the pricing bound and social optimality. Furthermore, the benefits of all participants within the existing transactive energy trading framework are not revealed.

This paper proposes a new transactive energy coordination mechanism which alleviates the limitations associated with the value discovery, flexible pricing bounds, and social optimality. In the proposed transactive energy trading mechanism, the energy trading problem is formulated for multi-dwelling apartments which are supplied by community microgrids. In this framework. consumers are empowered through their participation in the bidding process. Consumers usually bid within a price bound set by the market to eliminate the market power. A specific bidding function is introduced to capture the choice of different consumers while bidding in the market. The bidding is based on the current market condition which does not require any historical information. The proposed framework is embedded on an energy management controller which receives signals associated with energy profiles from microgrids. Non-contributing apartments determine the valuation of energy using the comparative factors and start the bidding process based on the pre-defined pricing strategy and choice factors. The pricing strategy and choice factors are used to ensure social optimality. A double-sided auction mechanism is used to finalise the bidding price and finally, the market is cleared based on the utility maximisation of all participants. The effectiveness of the proposed scheme is evaluated on a community microgrid supplying power to 15 apartments in a building where 10 apartments contribute to the microgrid while 5 apartments do not contribute. The economic benefits of the proposed scheme are analysed and it is found that the transactive energy coordination mechanism is beneficial for all participants.

2 Overview of the community microgrid for energy trading

The proposed community microgrid supplies power to a multi-dwelling building where some owners of apartments within this building invest in this microgrid while others do not contribute. By considering this, apartments within the building can be categorised as contributing and non-contributing apartments as shown in Fig. 1. All contributing apartments invest in solar PV and BESS in the community microgrid as shown in Fig. 1. However, all apartments (i.e. both contributing and non-contributing) enjoy the benefit of microgrids although priorities are given to contributing apartments.

For example, the energy generated from the PV system and energy stored into the BESS is first used for contributing apartments, as these apartments are primary investors for microgrids. The optimal utilisation of the solar PV and BESS system is ensured before sharing the excess energy among non-contributing apartments. The distributed optimisation scheme as presented in [28] is used in this paper where the central controller ensures the optimum utilisation of both the solar PV and BESS where the optimisation scheme considers multiple time periods. The excess energy, after sharing energy among all contributing apartments, is shared and traded among non-contributing apartments with a price lower than the utility rate. Fig. 1 also shows a smart apartment building management controller which coordinates energy sharing and trading activities among all apartments. This energy management controller has a salient feature, called contributing factor which is used to calculate the benefits from the community microgrid for all contributing apartments. The contributing factor (Γ_i) for a particular ith apartment is actually the ratio of the investment cost (C_i) made by the apartment and the total investment cost (C_t) which can be written as follows:

$$\Gamma_i = \frac{C_\mathrm{i}}{C_\mathrm{t}} \tag{1}$$

The energy allocations among all contributing apartments are done based on the social optimality while non-contributing apartments involve in an auction process to procure the energy through the energy management controller. The auction mechanism is embedded within the energy management controller through which buyers and sellers bid in the market to trade energy. In the beginning, the energy management controller estimates the overall energy generation and allocates energy to contributing apartments based on the social optimality. This controller also provides an estimation of excess energy and broadcasts this information to buyers. Interested buyers then bid through the controller where the bidding of buyers is followed by a private valuation of the energy demand compared with the energy excess. After receiving the bids from the seller and buyers, the energy management controller uses a double-sided auction mechanism for allocating energy. The overall energy sharing and trading within the proposed framework are discussed in the following section.

3 Proposed energy sharing and trading mechanism

The energy sharing among contributing apartments are straightforward as this is done using corresponding contribution factors based on the available energy from the solar PV unit and BESS. For this purpose, the energy management controller is used which actually acts as an agent. At the same time, this controller initiates the auction process for non-contributing apartments where the overall energy sharing process starts by announcing the average energy excess per buyer. Afterwards, buyers make a valuation of their own energy demands and participate in the auction process for bidding according to these valuations. The energy management controller employs a double-sided auction scheme after receiving bids from all buyers. However, the overall energy management process requires different signals, the pricing strategy and energy valuation before the market can be cleared through the auction-based mechanism. All these are discussed in the following subsections.

3.1 Signals from the energy management controller

As mentioned earlier, the energy management controller estimates the amount of the total energy excess ($\tilde{E}_\mathrm{e}$) for a time interval (Δt) and announces the amount of the average energy excess ($\tilde{E}_\mathrm{avg}$) for a non-contributing apartment within this interval. It is worth to note that all expressions presented through different variables in this paper are considered for the time interval (Δt) and hence, the use of Δt with these variables is avoided for the brevity. If N_nc represents the total number of non-contributing apartments in a building where the community microgrid is supplying power, the average estimated energy excess can be written as follows:

$$\tilde{E}_\mathrm{avg} = \frac{\tilde{E}_\mathrm{e}}{N_\mathrm{nc}} \tag{2}$$

The auction process relies on the estimated energy excess and the number of non-contributing apartments. $\tilde{E}_\mathrm{avg}$ is considered as a primary signal for the non-contributing apartments from the energy management controller. This signalling initiates the auction process. After this, it is essential to perform the valuation of the energy and setting the energy pricing strategy before starting the bidding.

3.2 Valuation of energy

The energy sharing process involves the valuation of energy as all buyers valuate their own demands before their participation in energy trading. Based on the received estimated energy excess information from the energy management controller, each non-contributing apartment compares the energy demand (E_l) with the average estimated energy excess ($\tilde{E}_\mathrm{avg}$) as represented by the following equation:

$$\tau = E_l - \tilde{E}_\mathrm{avg} \tag{3}$$

where τ is a comparative factor and the valuation of energy can be calculated by multiplying this factor with the utility tariff. It is worth to note that E_l indicates the energy demand of an apartment at any instant and it varies with time. Since the value of the comparative factor can either be positive (when $E_l > \tilde{E}_\mathrm{avg}$) or negative (when $E_l < \tilde{E}_\mathrm{avg}$), the valuation of energy might also be either positive or negative. The bidding amount of the non-contributing apartment depends on the valuation which is a private value to the apartment owner or its tenant. The pricing strategy is another important factor for trading energy within the proposed framework which is discussed in the following subsection.

3.3 Pricing strategy

The market price for energy trading with non-contributing apartments is bounded by the feed-in (r_fd) and utility (r_uy) prices. The reasoning behind the bound on the market price is that a market price higher than the utility price but lower than the feed-in price would result in an infeasible market structure because of the fact that contributing apartments can sell the excess energy to the utility grid with the feed-in tariff and similarly, non-contributing apartment can purchase energy from the utility grid with the utility rate. Hence, the proposed bound on the asking price makes the energy market more attractive for both contributing and non-contributing apartments and this bound is used in the proposed auction-based energy trading mechanism.

There are chances that the cost or approach of procuring energy from the proposed community microgrid may not be at the satisfaction levels of buyers. Moreover, the desired amount of energy for non-contributing apartments may not be available within a specific market interval. As a result, the demand for such non-contributing apartments is generally flexible in terms of procuring energy from the local energy market. Thus, it is essential to focus on the choices of non-contributing apartments while formulating the decision-making strategy of energy trading for the community microgrid. In the proposed auction-based energy trading mechanism, the bidding strategy for non-contributing apartments (i.e. buyers) is formulated through a choice function. The choice function depends on the valuation of energy along with the bound on the market price which considers both the demand flexibility and energy excess (i.e. the available supply for non-contributing apartments). Based on these, the proposed bidding strategy for buyers is discussed in the following subsection.

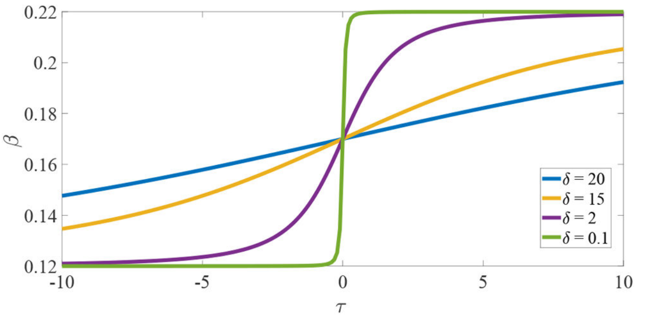

Fig. 2 *Mapping of bidding for different choice factors within the valuation range of* -10 *to 10*

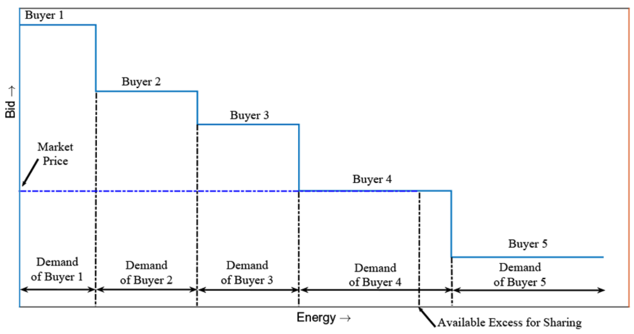

Fig. 3 *Bidding of different buyers and market clearing mechanism*

3.4 Bidding strategy of buyers

At this point, all non-contributing apartments need to translate their valuation of energy in the form of bidding prices. Generally, the bidding price (β) is proportional to the valuation of energy where non-contributing apartments with higher positive valuations would bid closer to the utility rate (r_{uy}) in order to become a successful bidder as they need more energy. Similarly, non-contributing apartments with negative valuations would bid closer to the feed-in tariff (r_{fd}). The relationships among the bidding price, the valuation of energy, the utility rate and the feed-in tariff can be expressed through the following function:

$$\beta = \frac{r_{\text{uy}} - r_{\text{fd}}}{2} \frac{\tau/\delta}{\sqrt{1 + (\tau/\delta)^2}} + \frac{r_{\text{uy}} + r_{\text{fd}}}{2} \qquad (4)$$

where δ is the choice factor of the apartment for selecting the dynamic range of the bidding price. This choice factor is associated with the demand flexibility which defines the maximum amount of the load demand that can be shed, i.e. $E_{\text{m}} - E_l$ during any particular market interval. The choice factor could be any positive value and the selection of a choice factor from the high range would result in a lower bid value while the selection of a choice factor from the lower range would give a higher bid value. As a result, the buyer with more demand flexibility would choose a value of the choice factor from the higher range as compared to the buyer with the less demand flexibility whose choice factor is selected from the lower range. Here, the range of the suggested choice factor for any buyer is not provided to protect the privacy of consumers. Note that the choice factor is a private value and any buyer can change it without revealing to the energy management controller. The saturation characteristics of the bidding functions in equation (4) are shown in Fig. 2 for different values of the choice factor and these characteristics are portrayed by the by the pivotal term, $(\tau/\delta)/\sqrt{1 + (\tau/\delta)^2}$. The first term in equation (4), $(r_{\text{uy}} - r_{\text{fd}})/2$ scales the saturation curve to $[+(r_{\text{uy}} - r_{\text{fd}})/2, \; -(r_{\text{uy}} - r_{\text{fd}})/2]$. Finally, the shifting factor $(r_{\text{uy}} + r_{\text{fd}})/2$ is utilised to eliminate the negative portion of the saturation curve and fit the curve to the dynamic range of the market price $[r_{\text{uy}}, \, r_{\text{fd}}]$ as the bidding price needs to be bounded by the utility tariff and the feed-in tariff.

The energy bid of a buyer $m \in \mathscr{M}$ comprises the bidding price (β_{m}) along with the maximum energy demand (E_{m}). Here, E_{m} represents the maximum energy demand of an apartment, i.e. the maximum load which is usually constant. Hence, the energy bid is the maximum energy that the buyer is interested to procure from the community microgrid through the participation in the proposed energy trading framework. However, the energy bid is not necessarily the same as the desired load demand as it is flexible. The energy bid of buyer m can be written as

$$b_{\text{m}} \equiv (\beta_{\text{m}}, E_{\text{m}}) \in \mathscr{B}_{\text{m}} = (r_{\text{fd}}, r_{\text{uy}}) \times (0, \infty), \quad \forall m \in \mathscr{M} \qquad (5)$$

The bid profile for all buyers can be represented as follows

$$\mathbf{b} \equiv (b_{\text{m}}, m \in \mathscr{M}) \quad \text{with} \quad m = 1, 2, \ldots, M \qquad (6)$$

where M is the number of buyers. By considering the bid profile of all buyers, the market-clearing process is discussed in the following subsection.

3.5 Market-clearing process

The energy management controller clears the market based on received bids ($\boldsymbol{b}$) from all buyers. Since different buyers have different bidding prices based on their valuations of energy, an auction-based scheme is suitable for analysing such energy markets. The proposed auction-mechanism is formulated in a generalised way which has the ability to deal with any number of sellers and buyers although the energy trading scenario in this work includes single sellers and multiple buyers. The proposed auction-based mechanism is risk free for all participants as the market price is bounded through the pricing strategy where no one loses anything by the participation in the auction for energy trading as all bids outside the bound of the bidding price are automatically rejected.

Due to the nature of the microgrid structure, there is only one seller and the number of buyers is normally more than one. In double-sided auctions, there are more than one seller and the buyer where bids are obtained from both parties. Hence, the proposed energy trading scheme can be considered as a special case of a double-sided auction with only one seller. However, the proposed auction-scheme is independent of the number of participants. In this auction-based energy trading framework, the energy allocation problem can be solved by formulating an optimisation problem for the energy management controller. An illustration of the market-clearing process for the community microgrid is shown in Fig. 3 where Buyer 1 to Buyer 3 are able to purchase energy from the market within the demonstrated market interval as these buyers bid with a price higher than the market price. From Fig. 3, it can also be seen that Buyer 4 can procure only some portion of the energy shortage as Buyer 4 is the least bidded winning buyer and the energy excess is exhausted. Moreover, Buyer 5 will loose the auction and cannot purchase energy as the bidding price is much lower than the market price.

The energy management controller aims to maximise the utility of all buyers and sellers by allocating energy in an optimal way. Let $E_{n,m}$ represent energy allocation to buyer m and $r_{n,m}$ represent the market price for sharing energy from seller n to buyer m during any particular market interval. The utility of the buyer can be represented as follows:

$$\mathscr{U}_{\text{m}} = \sum_{m=1}^{M} (\beta_{\text{m}} - r_{n,m}) E_{n,m} \qquad (7)$$

where M is the total number of buyers. Similarly, the utility of the seller can be represented as follows:

$$\mathscr{U}_n = \sum_{n=1}^{N} (r_{n,m} - r_n) E_{n,m} \qquad (8)$$

where N is the total number of sellers and r_n is the asking price of the seller $n \in \mathscr{N}$.

The optimisation problem can be formulated as follows:

$$\max_{E_{n,m}} \sum_{m=1}^{M} \sum_{n=1}^{N} E_{n,m}(\beta_{\mathrm{m}} - r_n) \tag{9}$$

From equation (9), someone might think that it is a single-stage and deterministic linear equation. However, this is not the case as this represents an objective function for any particular time interval (Δt) where buyers bid with different bidding prices and sellers also ask for different prices within this interval in order to ensure the double-sided auction.

This optimisation problem is a solved subject to the supply balance constraint as represented by the following equation:

$$\sum_{n=1}^{N} E_{n,m} \le \tilde{E}_{\mathrm{e}} \tag{10}$$

Moreover, the demand is also bounded by the following constraint

$$\sum_{m=1}^{M} E_{n,m} \le E_{\mathrm{m}} \tag{11}$$

Finally, the energy allocation variables must be non-negative as represented in the following:

$$E_{n,m} \ge 0 \tag{12}$$

The solutions of the optimisation problem under these constraints compute the energy allocations for potential buyers such that the overall social optimality is achieved. For the particular case in this work, the number of seller is 1, i.e. $N = 1$. The proposed energy trading scheme is analysed through some simulation results in the following section.

4 Simulation results

This section includes analytical results depicting some cases in order to validate the effectiveness of the developed auction-based energy trading mechanism. In this work, it is considered that the community microgrid supplying a building which comprises of 15 individual apartments. Only ten apartments have invested in the community microgrid out of these 15 apartments while five apartments have not invested. Hence, the numbers of financially contributing apartments (FCAs) are ten which are identified through FCA1 to FCA10 and similarly, the numbers of financially non-contributing apartments (FNCAs) are five which are defined through FNCA1 to FNCA5. The average load demand for the community microgrid is 100 kWh per day which is actually the total load demand for all 15 houses in the building while the sizes of the solar PV and the BESS are 27 kW and 30 kWh, respectively.

This energy trading model works based on the energy shortage and excess information of buyers and sellers, respectively. The uncertainties in RESs will significantly affect the outcomes of energy trading. In fact, there are uncertainties in loads and customers' participation in the market. The focus of this paper is to develop the mechanism based on the formulation of problems for buyers and sellers where this mechanism uses readily available energy shortage and excess information. Thus, the uncertainties in RESs, loads and customers' participation do not affect the original algorithm as it has been developed in a generalised way and it can easily be implemented for the real-time operation of community microgrids. Moreover, the uncertainties in the power generation from PV units and loads are taken into consideration in the yearly input data which are used to demonstrate the energy sharing in this paper. For the actual implementation in microgrid test beds, any existing uncertainty modelling techniques can be incorporated without the loss of generality.

For starting the energy trading with the auction-based scheme, the energy excess over a particular time interval (i.e. market interval) is considered as 4kWh which is the leftover amount after fulfilling the load demands of all FCAs. In this work, the market interval is considered as 60 min but it could be any time interval. With this energy excess information, the energy management controller announces the average excess energy of $4\,\mathrm{kWh}/5 = 0.8\,\mathrm{kWh}$ to all FNCAs. Table 1 shows the energy demand for all FNCAs during this market interval from where it can be seen that FNCA5 has the highest demand while the demand is the lowest for FNCA3. Hence, the valuation of energy will be the highest for FNCA5 and the lowest for FNCA3. In this particular interval, the utility rate is considered as 0.3$/kWh while the feed-in tariffs assumed as 0.1 $/kWh. The calculation of bidding prices is also affected by the choice factor and the choice factors for different FNCAs are also shown in Table 1. All these factors are randomly considered in this paper though these can be calculated by incorporating FNCAs' behaviours such as energy consumption patterns, willingness to buy energy from RESs, etc. Table 1 shows the final bids for all FNCAs from where it can be seen that FNCA1 bids in the market with the highest prices, i.e. 0.1774 $/kWh although its valuation of energy equals to that of FNCA4 and lower than that of FNCA5. This is due to the lower value of the choice factor for FNCA1 as compared to that of FNCA4 and FNCA5 which means that FNCA1 has a more tighter range of the choice factor while FNCA5 is more flexible for bidding.

The auction mechanism is applied through the energy management controller after receiving bids from all FNCAs and the controller determines the market-clearing prices. In this market clearing process, the bids from buyers are used to produce a demand curve where bidding prices of all FNCAs are placed in descending order. The bidder for which the cumulative demand matches the available energy excess would be the least bidding buyer who can purchase energy from the energy market. Table 2 illustrates the market clearing process for the considered market interval from where it can be seen that three apartments (FNCA1, FNCA2 and FNCA5) fully purchase their demand from the market as the cumulative demand is less than the available energy excess while FNCA4 only purchases a small portion of energy (0.4 kWh) from the market at a rate 0.1730$/kWh. Hence, the market-clearing price for this interval is 0.1730$/kWh.

Finally, the energy management controller allocates the energy to successful FNCAs as per the results of the auction process. The optimum energy allocated to different FNCAs along with the utility for this specific market interval is shown in Fig. 4 where the total utility of the community microgrid is 0.69$. In this time interval, FNCA3 does not win the bid and hence, there is no utility from this apartment which can also be seen from Fig. 4.

During the considered market interval, the developed energy trading framework is compared with an existing method as presented in [30] though it is not exactly similar as it is developed

Table 1 Calculation of bids for FNCAs in a specific market interval

Buyer ID	E_{m}, kWh	$\tilde{E}_{\mathrm{avg}}$, kWh	τ, kWh	Factor δ	Bid, $/kWh
FNCA1	1.1	0.8	0.3	2	0.1774
FNCA2	1.0	0.8	0.2	2	0.1750
FNCA3	0.6	0.8	-0.2	3	0.1667
FNCA4	1.1	0.8	0.3	5	0.1730
FNCA5	1.5	0.8	0.7	10	0.1735
total	5.3	4.0			

Table 2 Demonstration of the market clearing process

Non-contributing buyer ID	Bids in descending order,$/kWh	Demand of buyer, kWh	Cumulative demand of buyer, kWh	Comparison with energy excess
FNCA1	0.1774	1.1	1.1	< 4
FNCA2	0.1750	1.0	2.1	< 4
FNCA5	0.1735	1.5	3.6	< 4
FNCA4	0.1730	1.1	4.7	> 4
FNCA3	0.1667	0.6	5.3	> 4

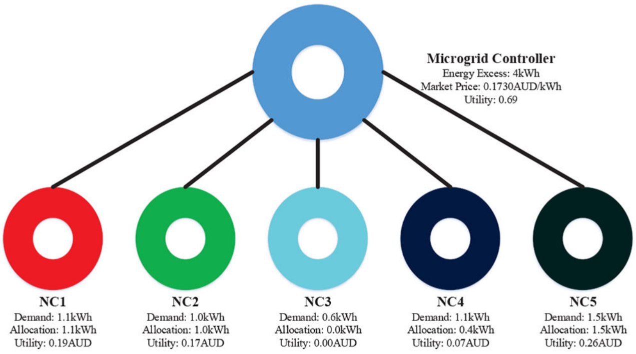

Fig. 4 *Optimum energy allocation among different FNCAs*

Table 3 Comparison of the transactive energy sharing models

ID for FNCAs	WTP, $/kWh	Proposed approach			Existing approach [30]		
		Traded energy, kWh	Consumer surplus, $	Owner surplus, $	Traded energy, kWh	Consumer surplus, $	Owner surplus, $
FNCA1	0.3000	1.1000	0.1349	0.1951	0.0000	0.0000	0.0000
FNCA2	0.3450	1.0000	0.1700	0.1750	0.8000	0.0000	0.2760
FNCA3	0.3500	0.0000	0.0000	0.0000	0.6000	0.0000	0.2100
FNCA4	0.4490	0.4000	0.1104	0.0692	1.1000	0.0000	0.4939
FNCA5	0.4600	1.5000	0.4298	0.2603	1.5000	0.0000	0.6900

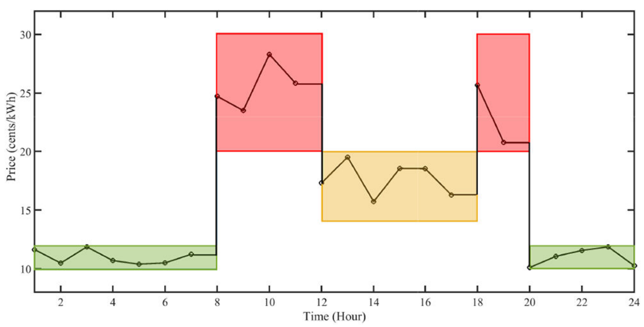

Fig. 5 *Variations in prices during different time intervals of a day*

Table 4 Tariff structures

Rate,$/kWh	Time of the day		
	Off-peak (8 pm–8 am)	Shoulder (12 pm–6 pm)	Peak (8 am–12 pm) and (6 pm–8 pm)
utility	0.12	0.20	0.30
feed-in	0.10	0.14	0.20

for optimizing the surpluses of consumers (i.e. buyers) and owners (i.e. sellers). Three different pricing models are considered in [30] where the first pricing models consider the market price as zero while the second one considers the utility rate as the market price and the third model considers the WTP by consumers as the market price. The first two pricing models as presented in [30] do not have any existence in the practical energy market and hence, these methods are not considered for the comparison. Since the third pricing model empowers the consumer, it is used here for comparing the result with the proposed scheme. The results are compared in terms of the traded energy, consumer surplus and owner surplus. In the beginning, it is essential to calculate the WTP which is done based on the approach as discussed in [30] and the values of the WTP for FNCAs are shown in Table 3 which are different from each other. The consumer and owner surpluses are also calculated based on the approach presented in [30] where the WTP is used as the market price and hence, the consumer surplus becomes zero as shown in Table 3. However, this is not the case for the developed energy trading model as the bidding price is the market price. Therefore, the consumer surplus does not become zero if the energy trading occurs which can also be seen from Table 3. From Table 3, it can be seen that the amount of traded energy is the same for both approaches, i.e. 4 kWh. Furthermore, Table 3 shows that there are only surpluses for owners when the existing method is used and this is not a general case. However, the newly developed energy trading scheme includes the surpluses for both owners and consumers which are the cases for the energy trading of microgrids in the real-time condition. Hence, the developed scheme is more practical and empowers all participants.

Another case study is also performed to analyse the versatility or demonstrate the generalisation of the developed auction-based energy trading mechanism. In this case study, the variations in the utility and feed-in rate are considered during the different periods of the day as shown in Fig. 5. According to the pricing strategy, there are upper as well as lower bounds and in this case study, the upper bound is considered as the time-varying utility price while the lower bound is the time-varying feed-in rate as shown in Fig. 5. The tariff structures during the different periods of the day are shown in Table 3 from where it can be seen that there are three different periods: off-peak, shoulder and peak for which the electricity prices vary. From Fig. 5 and Table 4, it can be seen that the variation in market prices are too high during the peak hours while this is so narrow during the off-peak period. Since there will be no power generation from solar PV system during the off-peak hours (though there could be a very small generation in the early morning which will be mostly used by FCAs), there are fewer chances of trading energy during this period. However, there could be some trading if the energy stored into the BESS is more than sufficient for FCAs.

The developed energy trading mechanism is employed on the community microgrid for sharing and trading energy among FNCAs. The total energy sharing between the community microgrid and FNCAs during different intervals in a day is shown in. Fig. 6 which clearly illustrates that the highest amount of energy is shared during peak sunny hours. Hence, the overall grid reliance of the building is also low during these peak sunny hours. Fig. 6 shows that there are some energy sharing from the BESS during the night time. However, the amount of shared energy is lower than any other period of the day and hence, the grid reliance is high.

The overall benefit of the community microgrid is assessed for all houses in the building in terms of different factors such as the grid dependency, yearly bill savings, yearly connection fees, yearly earnings and payback period. All these factors are shown in Table 5 for both FCAs and FNCAs. From Table 5, it can be seen that the reduction in the grid dependency for FCAs is two times higher than

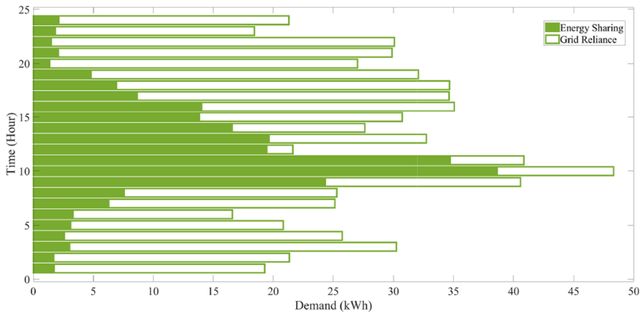

Fig. 6 *Energy shared in the microgrid during different market intervals of a day with variations in prices*

Table 5 Overall benefits of the community microgrid

	FCAs	FNCAs
grid dependency reduction, %	80	40
bill savings, $/y	970	939
reduction in the connection fee, $/y	345	345
earnings from energy sharing, $/y	305	—
payback period, y	7	—

FNCAs though FNCAs save slightly lower than FCAs in their electricity bills. However, FNCAs do not save anything in their connection fees and do not earn any money while FCAs save a significant amount of money in their connection fees and earn money by selling energy to FNCAs. Furthermore, the payback period is seven years which is calculated by considering 4% interest rate for the investments of FCAs on the PV and BESS. This clearly shows that FCAs receive their return on investments within the warranty period of the solar PV and BESS.

From different case studies, it is clear that the developed energy trading mechanism is useful for all participants and the microgrid structure is economically feasible.

5 Conclusion

A transactive energy coordination scheme is developed for multi-dwelling apartment buildings which consume power from community microgrids. The energy management controller is used to coordinate the energy transactions among all non-contributing apartments based on a bidding process. An auction mechanism is developed based on the energy excess information, the price bound and a choice factor which is used for this bidding process. The energy excess information is translated in the form of the energy valuation and the price bound is set based on the utility and feed-in rates. The choice factors are used to define the willingness of buyers to participate in the bidding process. The developed coordination mechanism is employed on a test system from where it can be concluded that it works under any pricing strategy and choice factors. The economic analysis clearly shows that the developed mechanism offers benefit to all participants and ensures the return on investment for all contributing apartments within the warranty period.

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