COOPERATIVE GAME THEORY BASED PEER TO PEER ENERGY TRADING ALGORITHM

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Abstract

The energy sector is undergoing a paradigm shift to integrate the increasing volume of embedded renewable energy generation and creating local energy communities or LECs that have been an essential component in increasing the same. Peer to Peer (P2P) energy trading is one of the alternatives to curb the surplus energy flow and would also help in maintaining a dynamic balance between supply and demand in the power grid. In this paper, we propose a P2P energy trading mechanism with distributed solar photovoltaic, community battery storage, and electric vehicle charging points. Game theory is the most widely used approach for P2P energy trading because of its characteristic of solving complicated interactions between provider and receiver. In the present work, we have considered a coalition based cooperative game theory framework whose objective is to maximize the total profit of the coalition. The simulation framework of this mechanism has been tested on a local energy community with 100 households having 50 consumers and 50 prosumers creating a win-win approach for both consumers and prosumers (users able to generate and consume simultaneously). Various trading scenarios have been proposed in this paper depending on geographical location, maximum energy demand, and maximum energy generated. These trading scenarios have been tested on a low voltage model to check their feasibility for a real network. The best operational performance priority at each timeslot with solar PV and community storage has also been analysed.

1 Introduction

The energy sector is undergoing a paradigm shift to integrate the increasing volume of embedded renewable generation with challenges like unpredictability and intermittency. According to [1], the EU set ambitious energy and climate targets of integrating renewables by 32%, cutting greenhouse gas emissions by 40%, and increasing energy efficiency by 32.5%. This shift is converting consumers into prosumers – an entity that manages multiple resources and is capable of generating as well as consuming energy simultaneously. Prosumers will be able to purchase energy from the main grid when there is not enough power to fulfil the demand. On the other hand, at the time of surplus energy, they can also sell the energy to other consumers or inject it back into the main grid. The set of prosumers and consumers in a network forms a local energy community (LEC) that is capable to operate in grid-connected mode or isolated mode. However, many distribution networks are not designed to accommodate reverse power flows that happen with an increase in distributed energy resources. This can potentially jeopardize the reliability of the power system by increasing the bus voltage. Therefore, potential solutions are provided in the present work to avoid such circumstances.

Peer to Peer (P2P) energy trading [2] is one of the alternatives to curb the surplus energy flow and would help in maintaining a dynamic balance between supply and demand in the power grid. This trading model also known as the transactive grid will potentially permit the prosumers to make more profit as compared to buying/selling to the grid. Thus, reducing the load & dependence on the power grid creates a win-win approach by selecting a trading price such that it is cheaper than the time of use (TOU) tariff and more expensive than the feed-in tariff (FIT). One of the most significant advantages of P2P is a better utilization of power network benefits and reduction of distribution and transmission losses as trading is happening between shorter distances. Furthermore, the financial gain of prosumers is increased due to the negotiated price with the help of P2P energy trading. Game theory [3] is one of the most widely used approaches for P2P energy trading because of its characteristic of solving complicated interactions between provider and receiver. Mainly, there are two types of game theory i.e. non-cooperative game theory and cooperative game theory. In the present work, we have considered a cooperative game theory framework whose objective is to maximize the total profit of the coalition. Therefore, to provide the same access and anonymity to all peers, a secured technology like blockchain [4]can be implemented in the network.

A comparison of five different Distributed Energy Resources (DER) P2P trading projects including some pilot projects and commercial projects with the future development and challenges are explained in [5]. An energy trading platform providing advantages like openness, reliability, and robustness, where energy flows just like data packets into the Internet in a smart grid is described in [6]. A proof of concept with various case studies is explained in [7] using blockchain technology for secured transactions, thus, providing security and privacy. A P2P network with market synchronization and legal considerations for the high penetration of distributed energy resources is developed in [8], with the study of economic and ecological factors impacting the virtual power plants. The public acceptance of the market-driven the network will increase if given incentives and other programs will benefit the peers in the network as described in [9]. Co-simulation of P2P energy trading with the electricity distribution network is presented in [10] using a European network case study. Recently, energy trading has become a dynamic research direction, with a number of studies using blockchain and Multi-Agent systems. There have been a number of longitudinal studies including [11] that have reported different price bidding strategies and auction mechanisms employed to create a win-win approach for both prosumers and consumers. For example, [12] proposed a distributed energy trading system with a multi-agent layer to form coalitions and a blockchain mechanism for settlement of the coalitions. Alternatively, other studies like [13] have emphasized on addressing the issue of reverse power flow by coalition formation from cooperative game theory when prosumers have Solar PV and Demand Response. Another study by [14] examined the trend of using Ethereum blockchain, where sellers can trade energy locally by forming coalitions and buyers can trade using a multi-stage non-cooperative auction model. Several scenarios for the P2P mechanism were known from the literature [15] as the distance between two peers, hourly demand of a peer, daily demand of a peer, blockchain technology used for the transaction, and minimum price of the buyer.

Existing literature on cooperative game theory has contributed to the application of energy trading mechanisms using blockchain. There has been notable research in P2P energy trading in the last various years, but most of the work has focused on using the same game for the entire day. However, there is a vitally important gap in forming coalitions of the households according to the time of the day and priority for trading. Therefore, a P2P energy trading algorithm has been proposed to bridge the gap. The objective of the coalition is to motivate the peers to act together and form different coalitions in each time slot so as to increase the social benefit. The main contribution of the work lies in a trading algorithm for a local energy community using different priorities that are applied on a set of users and informing the users about the best priority for each timeslot (288 timeslots of 5 minutes each).

The remaining part of the paper is arranged as follows: Section 2 describes the structure of the P2P energy trading LEC with solar PV generation and community battery storage for 100 households. The LEC also has 15 Electric Vehicle (EV) charging points. Section 3 presents an algorithm for forming coalitions in P2P trading and explains the flow of the algorithm. In Sections 4, results are analysed along with the discussion and Section 5 presents the concluding remarks and future work drawn from the analysis.

2 Structure of P2P Trading System

In this section, the structure of the P2P energy trading system is presented. In this system, solar PV, community battery storage, and EV charging points are considered. Furthermore, the proposed structure in this paper mainly includes the following:

a) Prosumers/Peers: They will first complete their own demand and then share the surplus energy with other peers in the system, depending upon the energy difference between generation from solar PV and energy consumption of the household.

b) Smart meters: They are installed in each household so as to provide generation and consumption pattern modelled in a 24-hour load profile format to the blockchain platform. It monitors, records and transmits the data simultaneously to smart contracts. Behaving as two-way communication between peers and management platform, the smart meter also records the location and informs the time of use tariff. More smart meters are installed in the community storage system and EVs to determine the state of charge of the batteries.

c) Community Storage: As the PV generation during daytime is higher than at night, thus, causing all the peers to enter into provider mode together, which means the maximum number of prosumers are self-sufficient and have surplus energy together and hence, the community is in excess mode and can charge the community storage. However, during night-time, as the surplus energy decreases the energy demand increases, the reliability of energy trading within the LEC also decreases. Hence, it has to take energy from the community storage or the main grid to meet its energy demand. Community battery will be charged/discharged considering the factors such as capacity of the battery, state of charge, maximum capacity to charge and discharge, network limit of transferring energy.

d) Electric Vehicles (EV): In between households and community storage there are EV charging points that are able to transfer energy from the grid to vehicle, as well as vehicle to grid. Therefore, a peer can use the energy from its solar panel, community storage, EV's or grid to meet its demand. Alternatively, it can transfer its surplus energy to prosumers, community storage, EV or grid.

e) Aggregator: The operator of the community is responsible for the maintenance, operation, trading and transfer of the fee. An aggregator is also responsible for supervising the trading platform keeping all peers' priorities in mind.

In the proposed structure, generation from solar PV will be the first option for the peers to fulfil its energy demand. Surplus energy will then be first shared to other peers according to their energy demand, and then transferred to charge community storage or EV. Furthermore, purchasing energy from other peers will be the first option for receivers instead of taking it from the energy storage in case of deficit energy. The trading system will help peers to choose their priority like maximum energy demand, the minimum distance between two peers or transmission losses when sharing from other peers. Setting up priorities will be managed by the aggregator in addition to managing, scheduling and balancing the load. An aggregator will also be responsible for the transaction of energy being carried out in an orderly manner and interaction within peers. Therefore, the application of an efficient trading system will not only help in increasing the effectiveness of utilizing energy but will also help in promoting distributed energy resources and cooperate with the DER intermittency problem cutting down carbon emissions. Each peer which is equipped with a solar panel acts as prosumer and with the help of smart contracts, their surplus energy will be distributed to the peers in the network or to the community storage. These transactions are controlled by a list of priority of supply-demand mechanisms agreed by all the peers that help in forming the order in which a receiver can take energy from a provider. When a peer with deficit in energy (receiver) receives a request for transactions from another peer with surplus in energy (provider), it firstly examines whether the energy shown for transactions is enough to accomplish the energy demand. If so, the peer acting as a provider will send a confirmation message to receiver peer and the transaction will be confirmed. Otherwise, it sends a cancellation message and the receiver will send a request to another peer for the transactions until it accomplishes all the conditions. Maximum transactions are successful in this way, however, there are very few requirements which are left and thus, can be fulfilled by the community storage or EV.

In this paper, the coalition game theory-based trading system is proposed to optimize decisions with respect to each timeslot considering the real-world limitation of the distribution system. The objective is to choose the best priority for each timeslot which is solved in MATLAB R2020a. In coalition game theory, the trading price (TP) will be set as the mid-value of selling electricity price (SP) and buying electricity price (BP), where SP is the Selling price of the LEC to Main Grid, BP is the buying price of the LEC from Main Grid and TP is the Selling/Purchasing price within the LEC. The TP should satisfy the condition: BP >> TP > SP such that TP will be used to distribute the profit within the peers.

a) If the trading price is too high, the maximum profit will be given to the provider and if the same is too low, the maximum profit will be given to the receiver. In a condition, where the energy demand of the LEC does not match with the surplus energy provided, the trading price will be set as two extreme points. Therefore, considering μ as the ratio of energy demand and surplus energy generated from solar, let's say if the surplus energy is less than demand ($\mu > 1$), the trading price will be equal to buying price.
b) Similarly, if the surplus energy is more than demand ($\mu < 1$) the trading price will be equal to the selling price.
c) In coalition game theory, we are considering $\mu = 1$ to ensure that the profit should be divided equally between buyer and seller.

In the present work, we have considered the cooperative game theory framework whose objective is to maximize the total profit of the coalition. Coalitions are made considering the priority of the aggregator at the specified time slot t. With each condition, all the peers who want to be part of the energy trading form a coalition in an integrated set to enhance their profit. Furthermore, the distribution of profit among the peers is directly proportional to the amount of energy traded by each peer. All the unconfirmed transactions from the conditions stated are combined together again in a coalition to form a new block. The objective of the Coalitions will be in such a way that any consumer cannot be better off by deviating and forming a new coalition. Therefore, the coalitions should have Preserving utility and a Satisfaction level i.e. it will help each member of the LEC to be a part of coalitions actively and reach their satisfaction level such that no peer wants to leave the market.

3 Algorithm for a priority-based stable coalition formation

The algorithm given at the end of this section with the flowchart shown in figure 1 illustrates a method to form a coalition influenced by the aggregator's decision to select priority for the peers in LEC. To select the priority at each timeslot t, a peer first fulfils its own energy demand (E_d) from the energy generated (E_s) using solar PV. Second, the algorithm calculates the difference in energy demand and generated i.e. surplus energy and the sum of the surplus energy of all the peers denoted by α. Based on the value of α, aggregator decides whether it is beneficial to charge or discharge the community storage while making coalitions. If α is positive, LEC will be able to fulfil its own demand without taking energy from community storage which will act as a receiver and if LEC is negative it will ask community storage to act as a provider to fulfil its demand. In other words, at each timeslot aggregator decides whether to choose utility 1(U_{01}) or utility 2(U_{02}). Option 1 refers to the state of prosumers in which it does not charge or discharge the community battery and Option 2 refers to the state in which it is willing to charge or discharge the community battery. Utilities of option 1 and 2 are calculated using the equations stated in the algorithm (lines 8, 9, 13, 14). The option with higher utility is recommended to be selected at that timeslot. The aim of calculating P_c (price per unit of energy charged by community battery at t) and P_d (price per unit of energy discharged by community battery at t) is to always calculate maximum and minimum price respectively where k is a scaling factor ($0 < k <= 1$), Ec (t) is total energy charged by all peers at time t, Ed (t) is total energy discharged by all peers at time t, C is an available capacity of the Community battery, S is satisfaction parameter (always greater than 0), d is degradation cost per kWh and SoC = State of charge. Each peer in the network announces its Address, Surplus Energy, Energy Requirement, Timestamp, State (i.e. provider or receiver), and the price for trading energy to other peers.

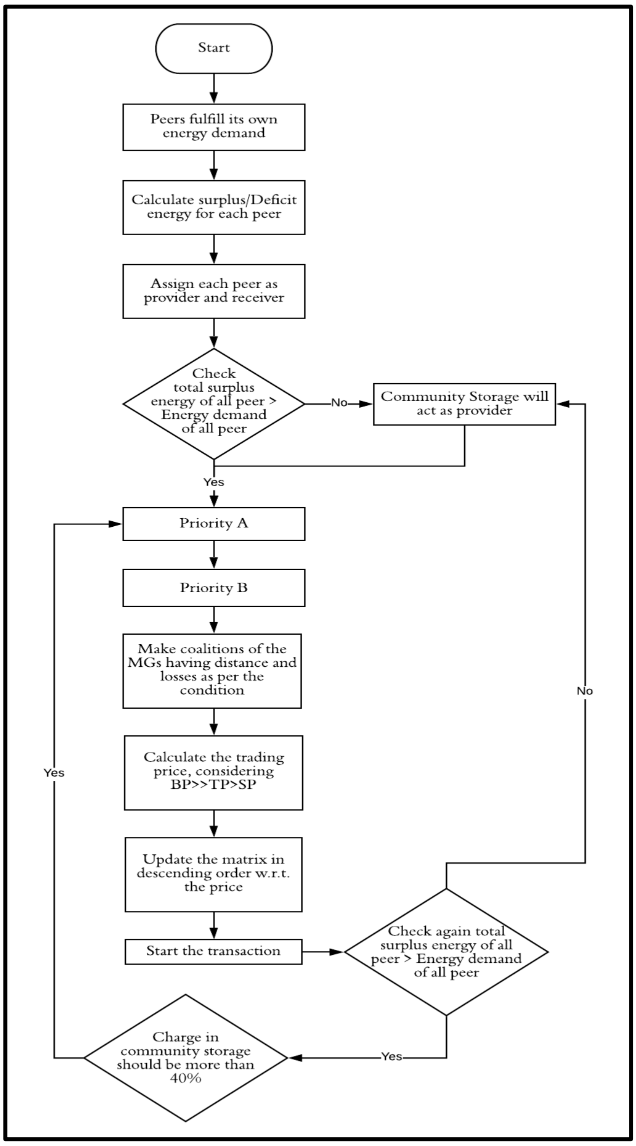

Figure 1 Flowchart of the algorithm

Next, aggregators set the priorities to form coalitions from the group of providers and receivers available for trading at time slot t. In priority A, the algorithm considers the total energy demand of the peers at each timeslot. The receivers prioritized for taking energy from providers will be those with the highest demand at t. While selecting priority A, algorithm arranges providers and receivers in descending and ascending order respectively w.r.t the amount of surplus/deficit energy. Here, the provider will sell surplus energy to the receiver ranked in descending manner of the energy to be traded or energy demand measured in that instant slot t. This scenario is favouring receivers for trading energy with the highest demand, hence, minimizing the number of smart contracts satisfied at the same instant by one provider. With the help of this scenario, the number of fiscal settlements in each time slot t reduces and the fiscal saving of the receiver is higher as compared to the feed-in tariff of the main grid. Surpassing benefits can act as an incentive for receivers with high energy demand to be a part of the electricity market operated at the LEC level.

In priority B, providers will sell their surplus energy to receivers using ranking developed according to the geographical distance between the location of generation and consumption. The consumption point (receiver) having minimum distance from the generation point (provider) will be first provided surplus energy, followed by the other receivers in ascending order, assuming the network connected in a ring system. If the community storage is also not sufficient to fulfil the energy demand of the LEC, then LEC can send a request to purchase energy required from the main grid. In such a scenario, the main aggregator will fulfil the energy requirement at the regulated tariff. Energy trading between the main grid and LEC is registered between the operators of the main grid and aggregator of LEC. This is most likely to happen in the peak hours of the day, as it will be difficult for DER to be capable of completing the energy demand of the whole community. However, in the algorithm used for the analysis, it is assumed that LEC is able to fulfil energy demand completely.

For Time slot = 1 to t **do**
Determine energy generated of each peer = E_s
Determine energy demand of each peer = E_d
Calculate surplus energy of each peer = E_s - E_d
Calculate sum of surplus energy of all the peers = α
If $\alpha > 0$
$P_c = k(C\text{-}SoC)\text{-}d$
$U_{01,s}(t) = P_c(t) x \, \mathrm{Ec}(Surplus)$
$U_{02,s}(t) = k[\mathrm{Ec}\,(t) \mathrm{x}\, C - 0.5\, x\, S\, x\, \mathrm{Ec}\,(t)^2] - (d + P_c)\mathrm{Ec}\,(t)$
Choose the option which is greater
Else if
$P_d = d - (k \text{ x } SoC)$
$U_{01,d}(t) = P_d\,(t) x \mathrm{Ed}\,(Deficit)$
$U_{02,d}(t) = k[\mathrm{Ed}(t) \mathrm{x}\, SoC - 0.5\, x\, S\, x\, \mathrm{Ed}\,(t)^2] + (P_d - d)\mathrm{Ed}\,(t)$
Choose the option which is greater
For each peer N
If $E_s > E_d$ then assign N as a provider
Else assign N as a receiver
End for
Set Priority for Energy Trading
For Priority A: Energy Demand
While $E_s > 0$
Read input solar data, prepare a priority matrix
Sort matrix in descending order of surplus energy
Sort matrix in ascending order of energy demand
Distribute surplus energy E_s
Update matrix
End While
For Priority B: Distance between peers
Assign all providers I_n
Assign all receivers J_n
For each I_n
Find nearest surplus energy peer
Calculate shortest distance
Distribute surplus energy E_s
Update matrix
Else cancel transactions
End if
End for

```
Set Trading price (TP)
    If μ < 1 , TP = SP
    If μ > 1 , TP = BP
    If μ = 1 , TP = 0.5 (BP + SP)
End
```

4 Results and Discussion

The proposed algorithm was tested on 100 single-phase residential consumers assumed to be located in LEC, out of which 50 were having solar PV to fulfil their demand and trade with other peers. To show the viability of the proposed network, this study assumes the network as a local energy community (LEC) where all the peers connected are prosumers and want to sell energy either to other peers deficit in energy or to charge the community storage or to charge EVs. Such type of trading in a microgrid is possible with P2P energy trading contracts. Load profile data and power generation data of all 100 peers were collected from smart meters in 5-minute intervals (288 timeslots) for one day in summer and analysed in MATLAB_2020a.

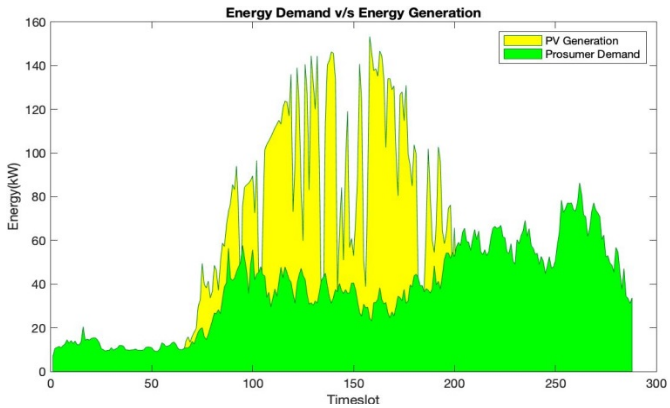

Figure 2 Energy Demand v/s Energy Generation

Figure 2 presents the combined energy demand and energy generation profile of 100 peers available for trading having a 50-50 ratio of consumers and prosumers in a LEC. Here, peers will first complete their own demand and then share the surplus/deficit energy with other peers in the LEC, depending upon the energy difference between generation from solar PV and energy consumption of the household as shown in figure 3. This surplus energy shown in the figure will be distributed selected by aggregator from timeslot 63 to 200, proposed in the algorithm in the previous section. As shown in figures 2 and 3, there are some timeslots in a day when solar PV generation stops and peers can meet the demand by either discharging the community storage or from EVs. Figure 4 trading in the LEC mainly occurs in the daytime, of which the blue line in the graph stands for the energy that can be traded by other peers without using community storage and the yellow for the LEC demand is available for trading. As can be observed from Figures 3 and 4, from timeslot 200 solar generators cannot produce electricity at night time and community storage will fulfil the demand. We can see that trading matched the exact LEC demand from timeslot 63 to 250 in a day. If the surplus energy exceeds the demand of the peer, it will be more beneficial for peers to trade with peers and then export trading into the main grid. Furthermore, at the time of buying energy the price at which trading is possible is lower than the price at which utility is ready to provide energy. For that reason, we can say that the proposed algorithm is able to achieve more savings for prosumers available for P2P trading. Figure 5 illustrates the summary statistics of 15 charging stations installed before community storage in the LEC. As it can be observed from figure 5, EVs are mostly charged during night-time from timeslot 220 to 40. This means that most of the EV charging will be carried by community storage at night. However, surplus energy generated from solar PV during the daytime will be first given to EVs to charge their batteries and leftover energy will then be utilised to charge the community storage.

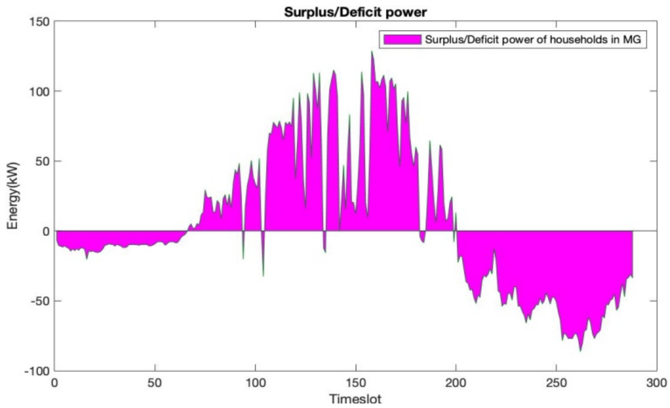

Figure 3 Surplus and Deficit Energy

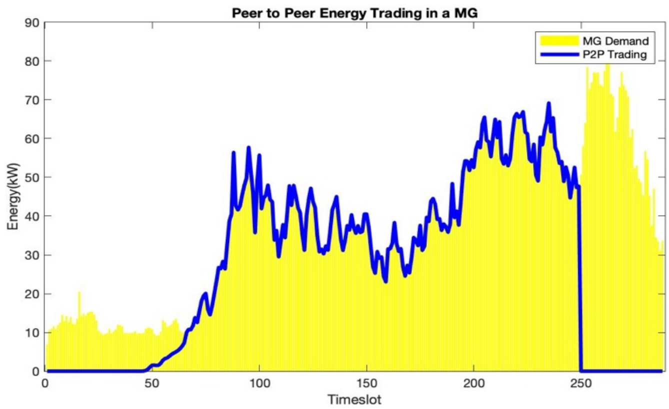

Figure 4 P2P Energy trading in LEC using Solar PV

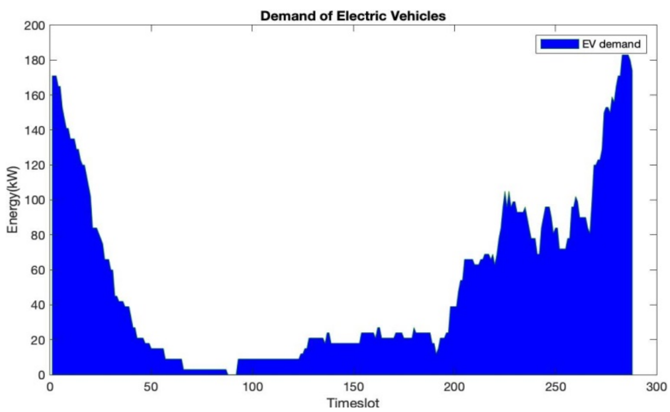

Figure 5 Energy Demand for EV's

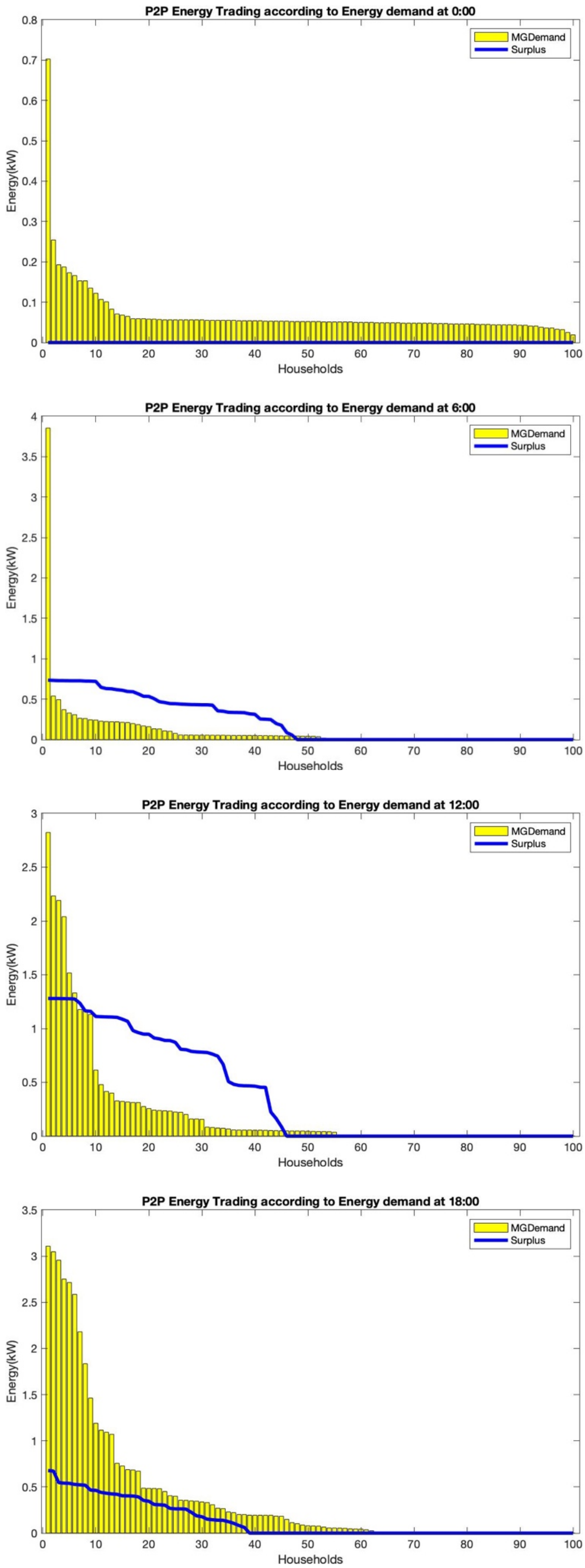

Figure 6 Priority A at different timeslot

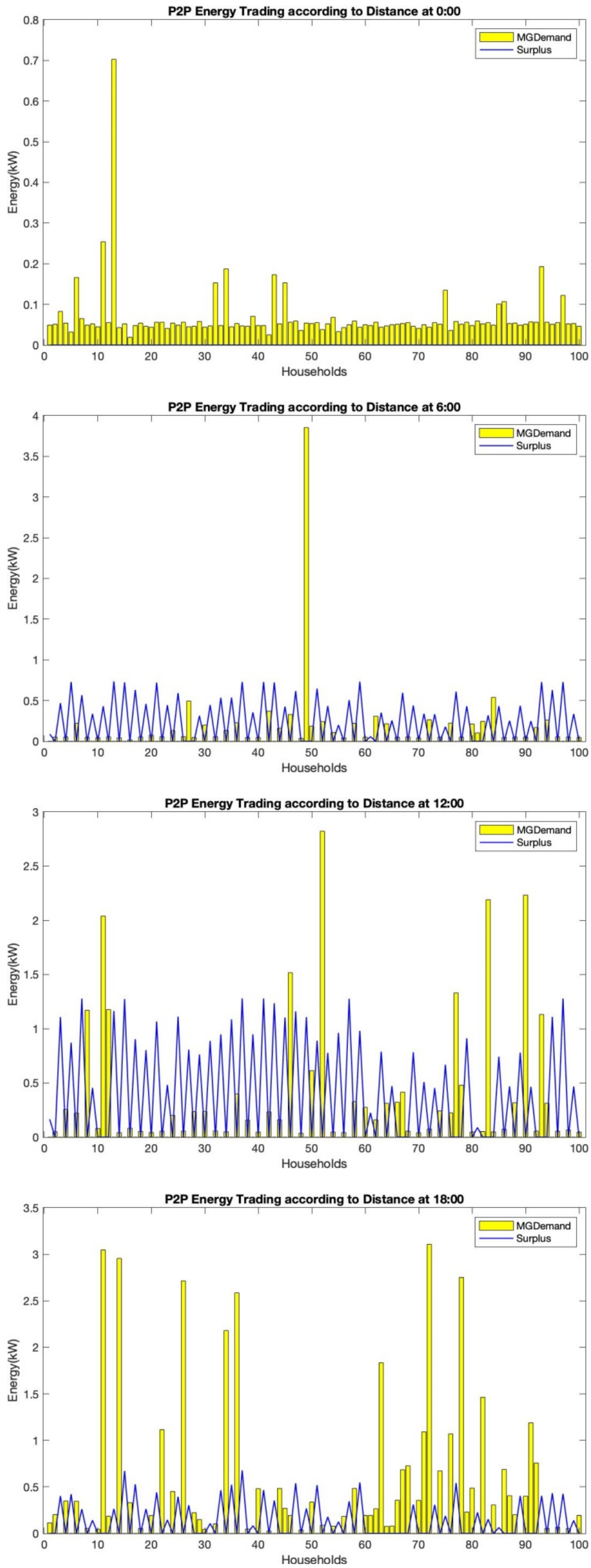

Figure 7 Priority B at different timeslot

For priority A as shown in figure 6, the selections are straightforward, the receiver having the highest energy demand is able to do the trading with a provider having the highest surplus energy at each timeslot. The algorithm arranges the providers and the receivers according to their energy demand in descending and ascending order respectively. This scenario is favouring receiver for trading energy with the highest demand, hence, minimizing the number of smart contracts satisfied at the same instant by one provider. The figure below illustrates the transactions at four different time slots i.e. 0000 hrs, 0600 hrs, 1200 hrs and 1800 hrs. For instance, at 0000 hrs solar generation stops functioning as shown by the blue line in the graph and all peers prefer to trade from community storage according to their energy demand. Thus, we can say that community storage will first trade with the peer having the highest energy and the last trade will happen with the one having the lowest demand. At 0600 hrs and 1200 hrs, we can see that approximately all prosumers are surplus in energy and other consumers are deficit in energy. Hence, provider/prosumers will fulfil receiver/consumer demand providing the highest energy demand. However, at 1800 hrs total energy demand exceeds the total generated energy and requests the community storage to act as a provider. Peers will sell their surplus energy to peers arranged in descending order of their energy demand. By any chance, if any two peers are providing the same energy at the same time, the one having shorter distance will the peer preferred for trading.

On the other hand, for priority B, the receiver close to the provider has maximum trading possibility as it is a radial network. From figure 7, it can be seen that the households are not arranged according to their energy demand in the network. Therefore, the provider will provide surplus energy to the receiver using ranking criteria of minimum geographical distance from a given generation point and consumption point. For priority B, the peers were arranged as per the geographical distance between them and were evaluated under the same timeslots as for priority A. At 0000 hrs, in priority A, there was no solar, as shown in Figure 6. Therefore, the peers preferred to trade with the community storage on the basis of their geographical distance with the storage. Peer number 1 is assumed to be nearest to the community storage and will be the first to fulfil its energy demand. From the figure, it can be revealed that at 0600 hrs and 1200 hrs energy requirement of few peers would be fulfilled by the peer available within the shortest distance. For example, if peer 50(n) is used as the reference, peers 49 and 51 will be provided with maximum trading priority. This loop will continue by doing transactions from n+k and n-k house until unless the trade is finished, where k= 1,2….99. There was a significant change in the energy scenario at 1800 hrs as the energy demand is greater than surplus energy. Thus, peers with minimum network distance from the provider will do trading first, followed by discharge from community storage. By any chance, if any two peers are at the same distance from the receiver at the same time, the one having the highest surplus energy will be preferred.

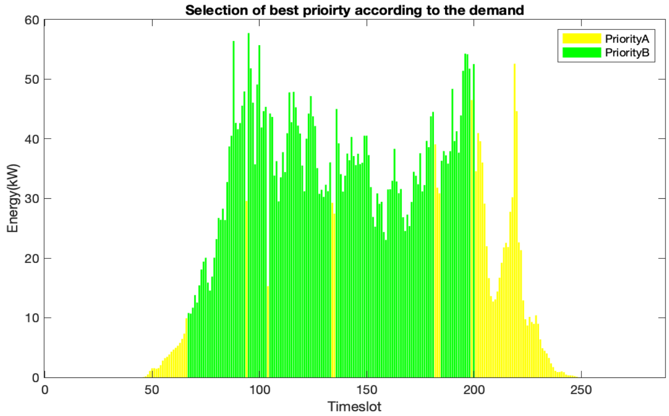

Figure 8 Energy traded depending on the priority

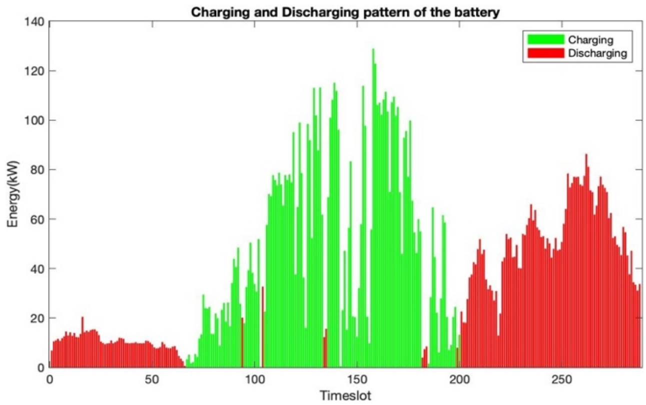

Figure 9 Charging and discharging pattern of the battery

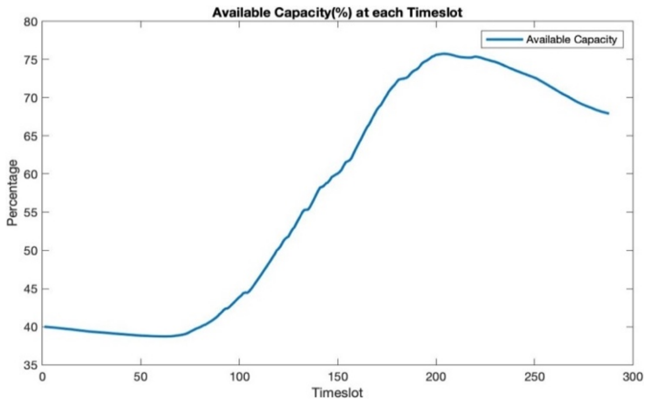

Figure 10 Available Capacity at each Timeslot

The best operational performance of priority at each timeslot with solar PV and community storage is shown in figure 8. It demonstrates that timeslot shown in yellow colour prefers to trade according to priority A and the timeslot shown in green colour prefers to trade as per priority B. From the results in figure 8, it can be observed that the timeslot with total energy demand greater than the generation has opted priority A. However, the best option when energy demand is less than the energy generation is priority B because trading would be done according to the shortest path available that reduces the power losses in the distribution network. The results obtained from the preliminary analysis of the effect of community storage on this LEC is shown in figure 9 and 10. Charging and discharging pattern of the battery shows that battery gets enough time in the daytime to get charged up to 75 % and the lowest capacity of the battery reaches up to 38 %. From timeslot between 200 to 60, PV stops generating, and peers can meet the demand by discharging the community storage or importing it from the grid which is considered as the last scenario. Therefore, the proposed algorithm can achieve high savings for peers with solar PV installed in their household, decrease the cost of energy and create a win-win approach for providers as well as receivers.

5 Conclusion

In the proposed work, a P2P energy trading algorithm having solar PV, community battery storage, and EV charging points are considered. Based on the cooperative game theory, a coalition game was selected for the model where the trading price is set according to different priorities like maximum energy demand, the minimum distance between two peers, or transmission losses by an aggregator. This model was illustrated in MATLAB_2020a. As a result, the algorithm promises different priorities for changing preference of the peers towards their generation from solar, by decreasing the dependence on the main grid. If we consider the economic aspect, this mechanism will reduce household energy expenses and work as a source of income to them. Looking at social benefits, this mechanism changes energy into a more flexible and decentralized manner. Thus, it will create more jobs in the sector. A number of possible future studies using the same trading platform, that can be aimed for a large number of prosumers in the network and with n number of DER. In addition, other scenarios can be added to extend the capabilities of the trading system.

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