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Cloud Assisted IoT-Operated Small Residential Microgrid with Collusive Model Approach for Energy Trading

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***Abstract*—** This article explores a strategic approach for an energy-self-sufficient and economically sustainable small residential community, powered by rooftop solar photovoltaics. This community plays the role of a microgrid (MG) with a microgrid operator (MO). It operates in two distinct modes: within the MG (peer-to-peer or P2P) and with the utility grid. The P2P transfer is experimentally performed with open-source Internet of Things (IoT) applications from the cloud. This will enable a low-cost MG operation for developing countries. Residents from the community are elected considering their support towards community welfare, and they are considered as delegates. The MO with delegates, control the energy transfer operation. This approach distributes generated energy among community members at low prices if there is energy demand, minimizing carbon footprint. The action of selling energy by a prosumer during the need of fellow resident is considered as the token of social service towards the community. A social service counter (SSC) is chosen to identify services for each prosumer in the MG. When a seller sells energy within the community, the SSC increases. This count rewards the prosumer in several ways. MO only allows prosumers to participate in energy trading with the grid during the high-demand hours of the day. Delegates play an essential role in protecting the community's interest while selling energy outside the community. They try to form a coalition among participants to reduce installation costs and maximize the cumulative payoff. A comparative study between the proposed coordination game and two competitive game approaches, namely Cournot and Stackelberg's algorithm in the restricted domain, reveals that the proposed method is well suited for a small residential MG. Shapley value is a tool that identifies each delegate's contribution during the game. The paper employed this method for the overall coordination game to identify the most acceptable payoff for individual players.

***Keywords*—** Cloud assisted IoT; Energy self-sufficient microgrid; Energy trading; Peer-to-peer energy transfer.

1. INTRODUCTION

Electricity consumption in the residential sector has increased much in the last twenty years, which is also a cause of an increase in carbon dioxide (CO_2) emissions. Integrating distributed energy resources (DER) like solar can solve this problem and gain popularity in the present era [1, 2]. Consequently, residential photo voltaic systems (RPVS) are becoming popular worldwide [3]. However, the power market needs to be flexible for green energy trading. Therefore, the penetration of these energy sources in the power market initiates changes in the price dynamics. However, a small rooftop solar photovoltaic system cannot individually participate in the energy market due to its small capacity and intermittent characteristics.

Moreover, passing clouds cause fluctuations in solar radiation received, and power fluctuations affect power quality; thus, power system operators expect to regulate the change

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in solar power through a ramp rate limitation. Energy storage systems (ESS) like batteries thus serve as the solution to solar power fluctuations [4]. However, the storage unit adds to the cost and size; hence, storage optimization is also essential to reduce the economic burden of small energy producers. Importance of the ESS with its technical and economic viability for a PV power plant in Jordan is explained in [5]. In [6], the author expressed his opinion on the optimal sizing of PV panels and batteries for the residents' economic benefit. But if the customer is naive, not technically sound, or due to financial problems, unable to invest in the optimized option, then how his problem can be solved has been tried to answer in our article.

Dependence on electricity raises unprecedented energy demands in modern life. With technological advancement, renewable energy resources (RES) like rooftop photo voltaic (PV) ensure energy exchange between two prosumers, bypassing the conventional grid. Therefore, a microgrid (MG) becomes energy-self-sufficient, allowing energy transfer among peers. However, peer-to-peer (P2P) energy transfer can be possible within the community microgrid (MG) if it follows a common microgrid bus (MB) architecture [7]. P2P differs significantly from the conventional energy business model and has become popular among researchers. In this model, small energy producers can participate in an energy trading platform following specific regulations.

The authors discuss three methods to determine the unit price of energy in MG for P2P energy trading [8]: bill sharing among community residents depending upon own consumption, midmarket price between buying and selling energy rate and auction strategy. However, it did not consider the installation and maintenance expenses. Anon *et al*. proposed the Stackelberg game as a model for price determination in [9]. Here, the seller acts as the leader and the buyer as the follower. It ensures that this negotiation reduces the energy price by almost 47% more than conventional fixed-price purchasing. However, this paper did not explain the community's demand and supply relation or the market clearing price (MCP). A bilevel-optimized bidding strategy is formulated in [10], where renewable and conventional energy bidding happens simultaneously in the same energy market. A multi-agent system (MAS) is used for P2P energy transfer in the active distribution network (ADN) for electricity price and quantity determination [11]. The author suggested that several agents are working here to ensure an optimized price to prosumers but did not consider the cost for the agent network. A strategic bidding model is proposed using reinforced MAS [12]. A bilateral energy contract was proposed in [13] where the author proposed a bilateral arrangement between the generator and consumer, bypassing the community controller who charges for providing ancillary support. However, the method of searching the buyers and sellers, bypassing the operator, is not adequately modelled in the proposed method. The authors assessed the effect of interaction between a wind power plant and a system operator with a bi-level bilateral contract on price in the day ahead market [14]. In [15], the authors considered the storage unit of a community microgrid as a virtual power bank and modelled the residents' actions for minimizing total energy cost and maximizing individual profits by applying dynamic game.

Microgrids with RES as sources need smart monitoring and control, which can be possible using the Internet of Things (IOT). It makes it possible to control loads from anywhere in the world through a web application that serves efficiently for demand response management (DRM), managing and transferring energy, observation, control, and protection of new age grid systems. A low cost IOT based for energy transfer operation is proposed in this paper. Similar low cost cloud based load monitoring approach is done in [16] for electricity theft detection for a conventional grid. Energy management for dispatchable and non-dispatchable sources with controllable and non-controllable loads is proposed in [17]. But cyber security issues are crucial if these devices are operated through the internet and constantly interact with internet traffic. Therefore, including security features with the IOT devices is vital to identify possible threats [18, 19]. Blockchain is an important security concept for distributed databases as IOT devices share a web-based cloud. In the blockchain, data are structured into immutable data blocks, providing security [20]. A blockchain model in the Ethereum platform for energy trading is proposed in [21]. In [22], a permission Hyperledger Besu blockchain is employed for efficient and secured P2P trading. As DRM is also an essential criterion for economic welfare and energy optimization, researchers studied different methods of DRM for MGs [23-25]. To lessen carbon footprints, all possible ways of inclusion of DER in the power network can be an apt measure. Therefore, even small households with rooftop solar can be a possible solution for a sustainable future with storage. However, appropriate contemporary plans are essential to motivate small, non-professional energy producers. Proper legislation is required to balance small energy producers and traditional professional players in the energy market. For an improved society social consciousness and commitment towards independent reduced carbon energy efficient community can be one of the solutions in this aspect. Literature survey specifies that these small energy communities appear as networked microgrids [26] under operation of a community microgrid operator (MO). But every community has different characteristics and the operation is successful if it is driven by the need of the community [27].

In [28], a two-stage energy community model is proposed. In this model, the prosumers are connected with the supplier, and the net meter measures the incoming and outgoing energy, and a balancing cost (positive or negative) is determined. They can participate in community trading depending on the balancing value of the net meter. The authors consider a central agency that would schedule the flexible loads' operating time to optimize the electricity cost. However, this approach reduces the comfort factor of the community residents. Therefore, an alternative approach is proposed in our paper where the community residents can set their respective essential loads to maintain the comfort factor. Bill sharing (BS) or mid-market rate (MMR) used in [28] is not encouraging enough to decide the proper payoff for peer-to-peer (P2P) energy transfer [29]. Hence, our approach finds a way to balance energy demand optimization within the community, minimizing carbon footprint during electrical power generation and maximizing community payoff from green energy trading. Representation from the community ensures community interest, which is unfortunately absent in most works of literature. Therefore, this paper proposes an approach for delegates from the community to look after community interest. The proposed model is almost energy-self-sufficient during sunshine hours. In the literature, most studies concentrated only on P2P energy trading, barely observing the community's social welfare. In [30], the social behaviour of prosumers is modelled during winning and losing the game during trading, but it does not reflect the social responsibilities. Therefore, this research article proposes:

i) A low-cost cloud-assisted Internet of Things (IOT) operated experimental prototype in a limited boundary is demonstrated for energy transfer.

ii) This community of different socio-economic residents optimizes their energy requirements collaboratively, not individually. This article searches for the strategy for maximizing community payoff with reducing individual installed capacity of the residents.

iii) MG representatives (delegates) initiate coordination to maximize the community's collective profit during energy trading with the conventional grid [31]. The respective marginal contributions of the delegates in the form of Shapley value have also been studied.

A comparative analysis of the latest similar articles in this respect is exhibited in Table 1. These proposed methods take systems such as microgrids (MG) or active distribution networks (ADN). Studies have used renewable energy or conventional energy sources for community energy trading. The table also indicates that most literature widely addressed economic operations and the energy optimization procedure. Control approaches are also compared with similar works. Implementing P2P energy transfer IOT connected with the cloud is another important aspect which is not addressed in most of the literature. In this article, a social service counter, SSC, is adopted, which counts the number of P2P services offered to the community by each participant to optimize local energy demand and collaboratively reduce the global carbon footprint.

Table 1. Comparison with similar recent works reported in literature.

Ref.	System		Sources		Functions		IOT	Service toward community
	MG	AND	RES	Conv	Economic	Optimization		
[2, 3]	√		√			√		
[4]	√		√		√			√
[5]	√		√		√			
[6]	√		√		√			
[7]		√	√	√	√			
[8]		√	√		√		√	
[9, 10]	√		√		√			
This paper	√		√		√	√	√	√

The paper is organized as follows: the proposed system configuration with operation is discussed in section 2. The ground for the mathematical model is explained in section 3. The web-based immutable ledger, known as a distributed ledger, for keeping accounts for energy trading is discussed in section 4. Section 5 explains the algorithm of energy transfer. Low-cost IOT-operated hardware for energy transfer is described in section 6. Result and discussion are presented in section 7, and the paper is concluded in section 8.

2. SYSTEM CONFIGURATION AND OPERATION

The structure of the MG is configured in Fig. 1. Each resident here possess rooftop solar photovoltaic with a battery backup system associated with a maximum power point tracking (MPPT) charge controller circuit and inverter. The prosumer creates an energy account in the energy management system (EMS) installed in the prosumer's laptop or mobile. EMS predicts energy generation, battery management, and load patterns based on weather data, battery specifications, and previous load patterns. Every household connects through a common bus, MB, for P2P energy transfer among the community members. It has been assumed that P2P transfer is only required in case of contingency. A community microgrid operator (MO) plays a significant role in the successful operation.

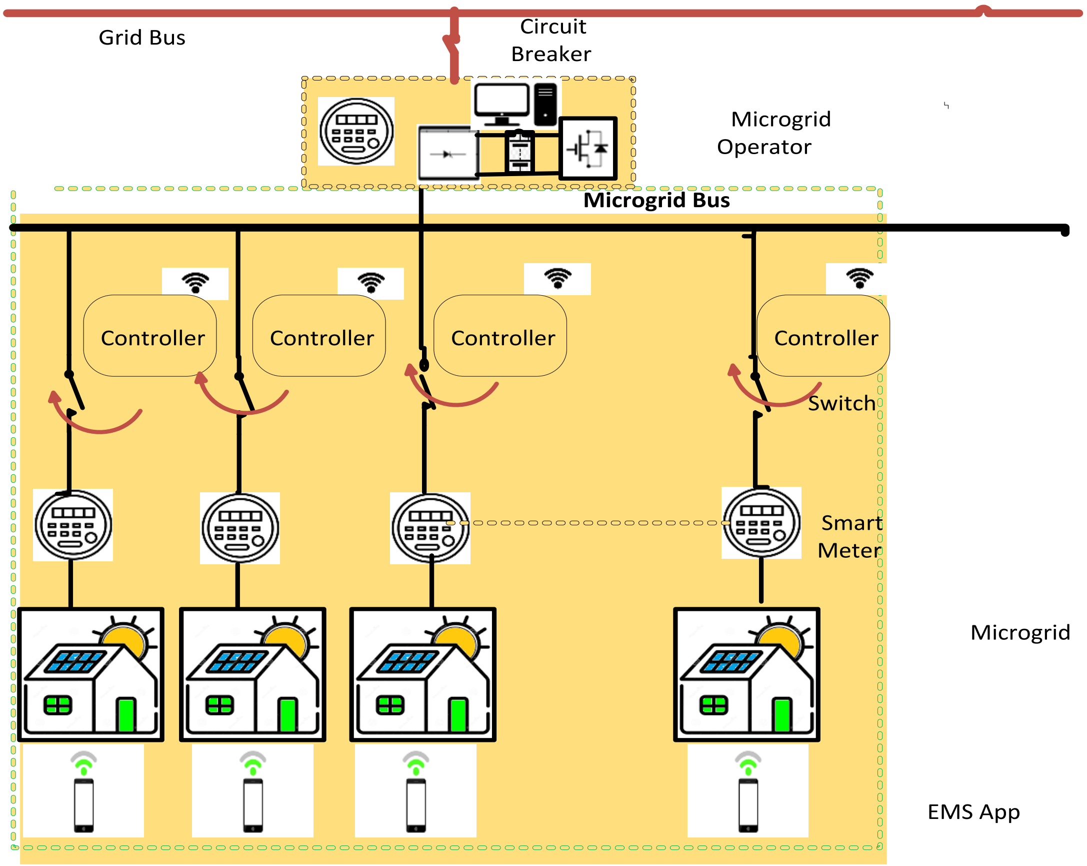


Fig. 1. System configuration.

The problem statement addressed in this article is shown in Fig. 2. The MO supervises the energy transfer operations in the community. It also acts as an energy trading aggregator for energy selling to the grid and a validator during energy trading. In this proposed model, delegates (W) from community residents also supervise and authorize the P2P energy transfer and trading measures. Delegates are chosen from community members by all the residents through election. They are responsible for the energy-efficient, economically viable community. The economic benefit of the community largely depends upon the delegates' activity. Delegates are accountable for the cumulative benefit of the community. The delegates also get monetary benefits from the community depending upon their actions.

Profit maximization of the community determines their payoffs. A Shapley value is used to determine the average marginal contribution of the delegates for a particular situation in this article. The Shapely value indicates the average marginal contribution for one considering all the possible relative moves by others. The energy transfer rules consider minimizing carbon footprints and maximizing profit by selling electricity to the grid during peak hours. Buying electricity from the grid during low tariff hours is only allowed if the community collectively cannot support its demand. Therefore, the rules are set as follows:

i. In the daytime, to fulfil the demand, consumers would ask within the community first through the EMS portal.
ii. Each house owner uses the produced electric energy for domestic loads and battery charging. Excess electricity generation should serve the community.
iii. If the community cannot fulfil the demand, then only a consumer can buy electrical energy from the grid or other MG.
iv. After a successful negotiation, both MO and delegates authorize energy transfer.

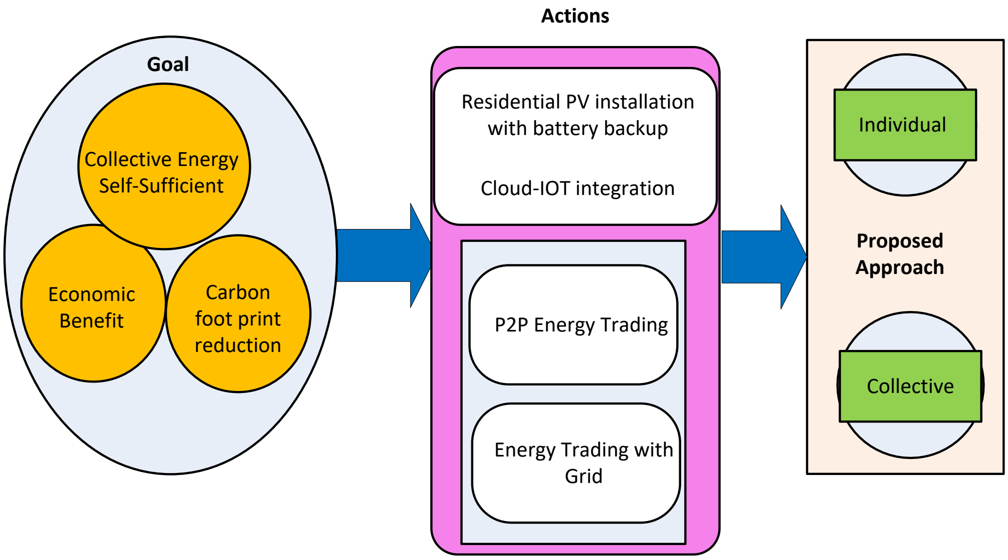


Fig. 2. Problem identification.

Residents of the community or prosumers generate power during the daytime, depending on their respective solar panel capacity. Due to various quantities of energy generation and load requirement, energy demand may arise within the MG. This situation establishes the peer-to-peer (P2P) power transfer between two residents. Inverter power from each house is fed to the bus through a smart meter (SM) and normally open switch. MO and Delegates control the switching action through IOT cloud. A wi-fi-enabled microcontroller unit receives the command from the cloud and controls the switches through general-purpose input-output (GPIO) pins. MO maintains an EMS where energy prediction, instant power generation, predicted load demand, and immediate load demand of each prosumer could be observed, while members of the community microgrid get restricted information about grid operations. MO sells green energy (trapped solar energy) to the grid during high demand. The battery stores energy during the daytime for load levelling at peak demand in the real-time market. Real-time active and reactive power dispatch from the prosumer is supplied, controlling the microgrid bus (MB) voltage and individual prosumer's phase angle, respectively as expressed in Eq. (1), Eq. (2) and shown in Fig. 3 (a) and Fig. 3 (b). The overall operation of the community is described using a flow diagram in Fig. 4.

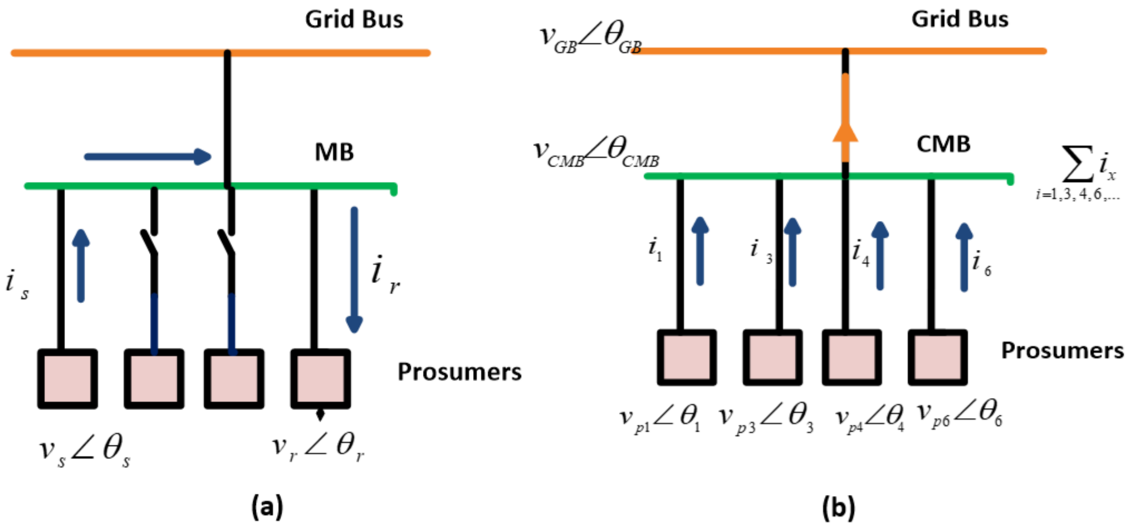


Fig. 3. Electrical energy transfer layout: a) in P2P mode; b) between MG and the grid.

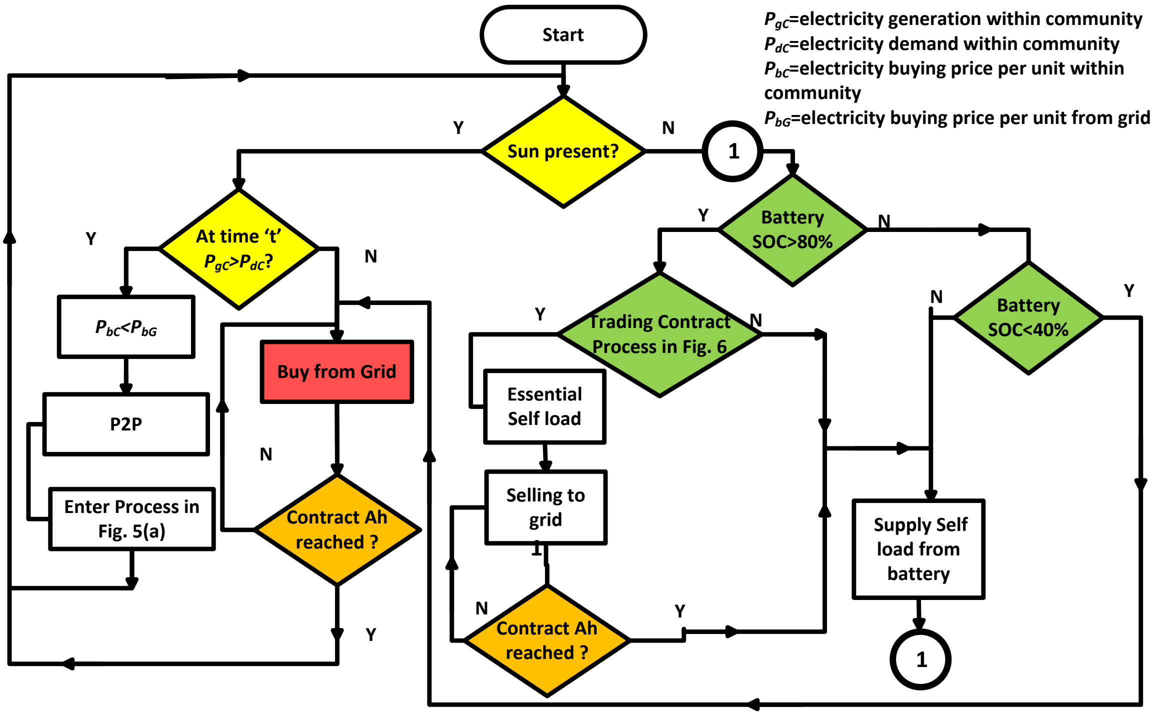


Fig. 4. System operation flow diagram.

3. MATHEMATICAL MODEL

3.1. P2P Energy Sharing within Community

In this section system model parameters are based on the energy transfer. It is divided into two sections. One is associated with P2P energy transfer within MG, and the other is for energy trading with the utility grid. v_{MB} is the community microgrid bus voltage. A switch (S_i) links each household and MB. S_i is an on-off switch with $S_i \in \{0,1\}$. The number of S_i is equal to the number of households, i.e., $S_i \in \{0,1, 2\ldots, n\}$. During P2P energy transfer within the community, the states of switches except the participants' switches are $S_i=0$. The agreement between electrical energy sender and receiver initiates P2P energy transfer. The detailed agreement procedure is described in the next section. As a result of their agreement, two switches, S_s (sender switch) and S_r (receiver switch) will be on, i.e.,

$$S_s, S_r = 1 \text{ when } |v_s| > |v_r| \text{ or } \angle\theta_s \text{ leading and } \angle\theta_r \text{ lagging.}$$

where $v_s\angle\theta_s$ is the sender voltage, and $v_r\angle\theta_r$ is the receiver voltage, $\angle\theta_s$ is the senders phase angle and $\angle\theta_r$ is the receiver's phase angle.

$$i_{sr} > \frac{v_s\angle\theta_s - v_r\angle\theta_r}{Z_{sr} + Z_{Lr}} \tag{1}$$

where i_{sr} is the current from sender's source to receiver's load. Z_{sr} is the bus impedance between the sender and receiver end, Z_{Lr} is the load impedance of the receiver. Members of the community and the MO are connected through the web-based energy account. If a resident has excess energy generation, he can log in to his account and request energy sales.

Similarly, for demand, one can request energy buying. The MO transfers energy between buyer and seller at a pre-determined rate. The rules for energy transfer are made considering service to the community, independent energy society with green energy participation in the energy market. Following rules need to be followed by the participants for P2P energy trading during sunshine hours.

i) Price of unit energy ($P_{c\tau}$) determined by MO must be less than the grid buying price for unit energy ($P_{g\tau}$) at that time,τ, i.e. $P_{c\tau} < P_{g\tau}$.
ii) Before asking for energy transfer buyers must minimize his demand as possible.
iii) The resident buying energy cannot trade with the grid for the next 24 hrs.
iv) The seller can only sell a maximum set percentage of its capacity.
v) Buyer and seller must pay a network cost (P_{nc}) for each transaction to MO.

3.2. Energy Trading with Grid

The community redirects the power flow from the battery towards the grid in the late evening when the grid tariff is maximum, and the sunlight is absent. Tariff becomes maximum when the power demand of the grid is high. This great demand creates a voltage drop at the grid bus and makes the grid bus phase ($\angle\theta_{GB}$) more lagging than the community bus phase angle ($\angle\theta_{MB}$). Active power flow depends upon the phase angle difference, while reactive power flow depends upon the magnitude differences between the two buses. Current always flows from the leading to the lagging bus [17]. Fig. 2 indicates if any prosumer voltage is v_{px} where $\angle\theta_x$ is his generation phase angle, Z_{px} is his impedance, and his MB switch S_x is ON, then current will flow from prosumer towards MB if $\angle\theta_{MB}$ lags $\angle\theta_x$. Therefore, the total current flow from prosumer ends to MB, (i_{CM2G}), with '*l*' number of switches are ON, ($l \leq n$) is:

$$i_{CM2B} = \sum_{x=2,5,8,11,....} i_x = \sum_{x=2,5,8,11,....} \left(v_{px} < \theta_x - v_{MB} < \theta_{MB}\right)/Z_{px} \tag{2}$$

This current flows towards grid bus if $\angle\theta_{GB}$ is more lagging than $\angle\theta_{MB}$:

$$i_{CM2G} = (v_{MB} < \theta_{MB} - v_{GB} < \theta_{GB})/Z_D \tag{3}$$

where Z_D is the grid side power network impedance,

The battery is modelled as a linear time-invariant (LTI) system as follows:

$$\mathrm{E}_b \dot{x}_{SOC} = \xi_c p_c - \xi_d^{-1} p_d - p_{sc} \tag{4}$$

where E_b is battery voltage, $\dot{x}_{soc}$ is battery SOC, ξ_c is charging efficiency, ξ_d is discharging efficiency, p_c is charging power, p_d is discharging power and p_{sc} self-discharging power. As the energy is supplied from the prosumer's battery therefore, the available energy (q_{si}) depends upon the electrical energy generated during daytime(q_g), prosumer cumulative load (q_l), and prosumer self-load (q_{slp}) during peak load hour. Therefore, it can be expressed as:

$$q_{si} = q_g - \min\{(q_l + q_{slp})\} \tag{5a}$$

or

$$q_{si} = \max\{q_g\} - (q_l + q_{slp}) \tag{5b}$$

subject to $q_g>0; 0<q_l<q_g; q_{slp} \leq q_{ess}$

where q_{ess} is the essential loads.

During charging, the battery acts as load; therefore, optimization of the load means also minimizing the battery charging time. This situation improves the lifestyle factor and maximizes battery life. Now as power is generated, *Pg(t)* is dependent on the sun and can be determined by curve fitting [32];

$$P_g(t) = Ag^2(t) + Bg(t) + M \tag{6}$$

where A, B, and M are coefficients of curve fitting *g(t)* denotes average global radiation values [33]. Maximum power generation ($dP_g(t)/dt=0$) is at $_g(t)=-B/2A$ is the optimized condition to charge battery. Battery voltage can be expressed as

$$v_b = V(1 - e^{-t/\alpha}) \tag{7}$$

V as the final battery voltage, α as the battery time constant depends upon the internal circuit

With I as the initial charging current, C as the battery capacity in A-h, the charging current of the battery is in the form of:

$$i = I(e^{-t/\alpha}) \tag{8}$$

where $I=0.1C$ (C10 battery)

The charging time of the battery is indicated as follows:

$$CH\_T=(C+ losses)/I \tag{9}$$

As charging time is inversely proportional to charging current, charging at maximum current only reduces the charging time. The battery is charged from the PV panel using MPPT. The charge controller needs to optimize its actions to obtain the balance between the lifestyle index and energy storage in minimum time while maximizing the battery life span. Fig.3 shows the different aspects of charge controller functions. Fig. 5(a) illustrates the schematic diagram from the PV array to ac load with all circuit components. Fig. 5(b) is simulated in MATLAB to obtain the optimal action of the charge controller. Here a solar array corresponding to a 12 V nominal C_{10} battery of 120Ah is simulated with different irradiance levels. The marked region indicates the operating zone near MPPT for different irradiances. Fig. 5(c) describes the logic to optimize energy consumption and store excess energy in the battery with maximizing its life span.

4. DISTRIBUTED LEDGER

Residents of the MG can only participate in the energy network if the MO gives permission. A Smart Contract (SC) layer identifies the generation and consumption pattern of the prosumer and decides the possibility of transfer. A significant stake of the MO in the system makes it a validator by default but can make the system more centralized. This paper proposes delegated Proof-of-Stake (dPOS) consensus to impose a decentralized nature [34]. It is more democratic than the proof-of-stake (POS) protocol. In this method, the community residents also act as validators for energy transfer.

4.1. Consensus within the Community

MO spent substantial money to offer energy transfer services to the community; hence, as per POS consensus protocol, it becomes a validator by default. However, everyone also bears the cost for their rooftop solar systems with inverter, battery backup system, networking and EMS for the proper functioning of the MG. Thus, to avoid a centralized transaction validation function, network participants vote to appoint Delegates for the transactions on behalf of community members. If there is consensus among the Delegates, then the MO validates the transaction to attach it to the distributed ledger. The smart contract (SC) layer provides permission for a transaction, and the dPOS protocol authenticates the transaction. For P2P energy transfer, every member or node creates an Externally Owned Account (EOA). The account is provided with an account number (η) and a private key (K). After creating an account, a node must ask for entry permission to the network.

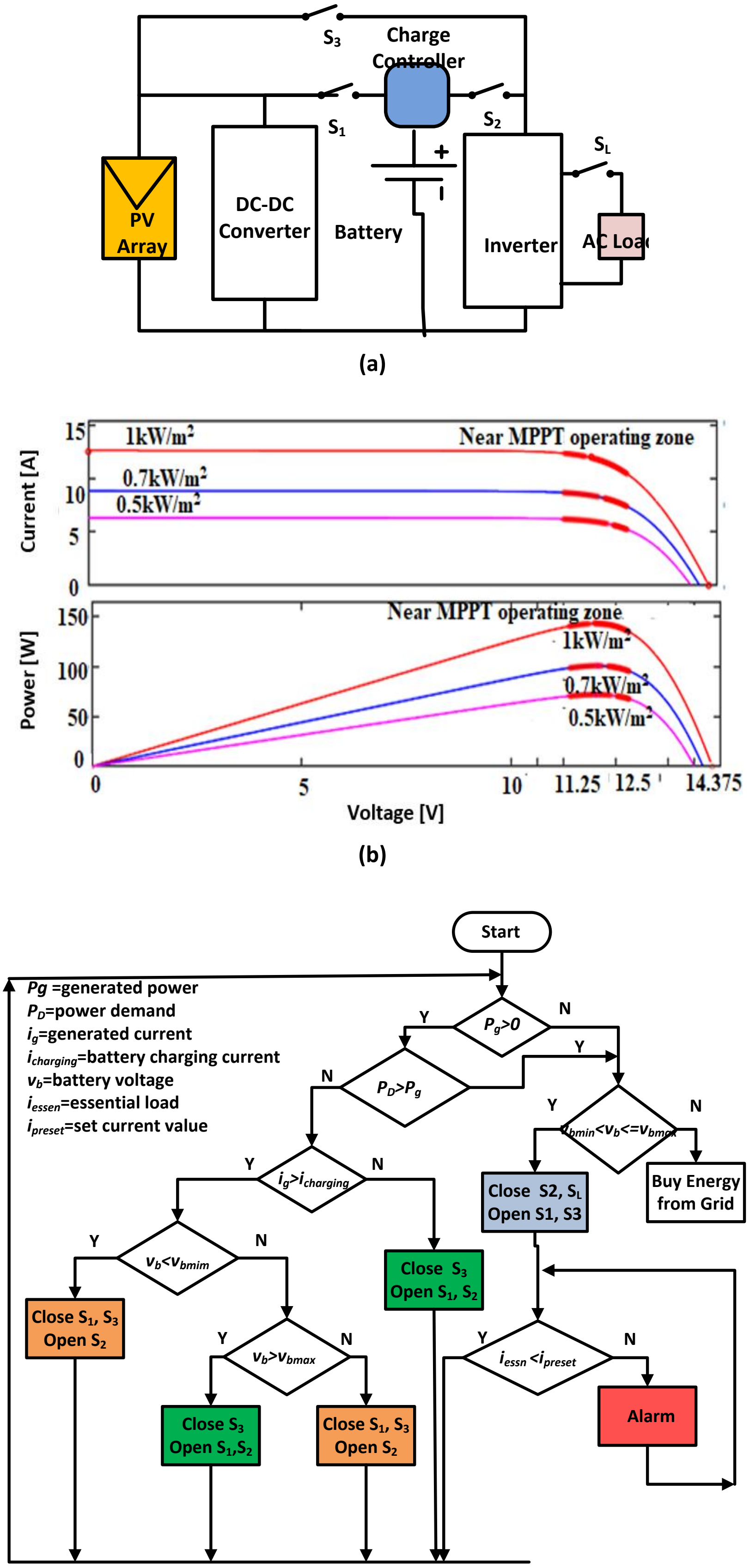


Fig. 5. Charge controller: a) circuit; b) working zone with MPPT; c) optimization flow diagram.

After getting permission, a node can participate in a P2P power transfer. The functioning of P2P energy transfer is illustrated in Fig. 6.

The function of P2P transfer is classified into three distinct layers as follows:

1) Service layer- It is the entry layer for P2P energy transfer. Service layers observe and control the permission and authentication procedure of the energy transfer.

a. Smart Contract: Initially, a request of energy demand (q_{dp}) from a consumer at time t or energy offer (q_0) from a prosumer invokes the smart contract action and then it will identify whether the transaction would be possible or not, checking the predefined conditions. The condition for favourable negotiation is as follows:

$$q_0 \geq q_{gp} - q_{dp} - q_{lp} \qquad (10)$$

where q_{gp} refers to the overall generation of the prosumer, q_{lp} refers to the self-load demand of the prosumer.

b. Digital Signature: Digital signature is the key to the authentication of the process. The publicly known account number is combined with a specific private key to initiate a successful operation.

2) Protocol Layer- The protocol layer implements a consensus algorithm that verifies the transaction and places it in the distributed ledger.

3) Network layer- Digital signatures of sender and receiver can only substantiate P2P power transfer. An EMS triggers a control circuit which switches on the power transfer between two specific nodes. This transaction sends the details to a shared, accessible, immutable ledger. Fig. 6 illustrates the function of the P2P mode of energy transfer in the proposed MG. The transaction described in the blockchain includes the following information: i) Supplier Account Address; ii) Receiver Account Address; iii) Transaction Details; iv) Hash ID; v) Date and Time

SSC (Σ_p) increases by 1 with service offered by individual residents. If Σ_p reaches a set value as indicated in Eq. (11), then one individual resident can participate in electrical energy trading with the grid.

$$\Sigma_p \geq (\text{days of a week} \div d) \quad 1 < d < 7 \qquad (11)$$

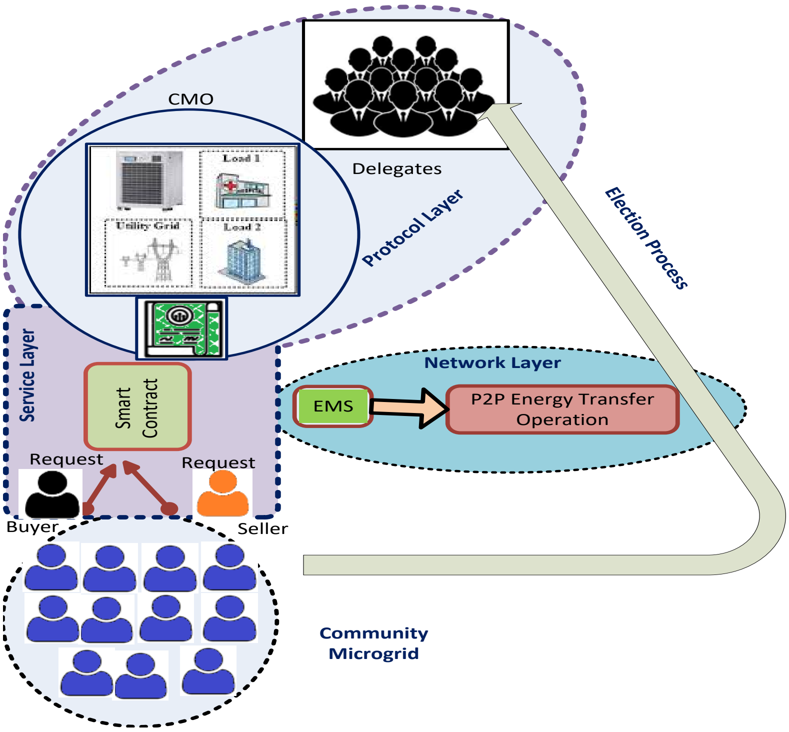


Fig. 6 Functioning layers of P2P energy transfer.

4.2. Trading with Grid

As the demand for the primary grid is maximum in the evening, MO decides to sell power at that time. Thus, participants having a battery backup system can sell power. For trading with the grid, the MO declares the market demand function (*MD*) and invites a quote for the amount of energy for selling and the price per unit of energy. Now, the residents act following stimulus-response and like to grab the best payoff from the situation, and the game starts. Authorized energy producers, the MO is the mediator who secures their profit on the price difference between buying energy from the community and selling it off to the grid. The options remain two: either the sellers compete among themselves and give the MO more profit from their resources, or they can cooperate to optimize the overall cost function of the community per unit of energy. The delegates of the community play an essential role in this aspect. As sellers are small domestic RES-dependent prosumers, they need to cooperate for reliable operation because this would decrease the burden of individual energy production as per demand. Cooperation among the residents decreases individual installed capacity, increases reliability, and increases the community profit margin. An increase in profit margin economically benefits the delegates and they are paid by their respective marginal contributions. The energy produced by l numbers of participants are $\{q_1, q_2, \ldots, q_l\}$ should be chosen to minimize the cumulative cost function of the community. Therefore, Q is the total electric energy produced by the community, which is the aggregated sum of the outputs from the prosumers.

$$Q = \sum_{i=1}^{l} q_i \tag{12}$$

Now, to optimize the electric energy quantity and maximize the payoff.

$$\max\{i\} \text{ for } i=1,\ldots\ldots N \tag{13}$$

where N is the total number of community residents.

The produced electric energy (Q) and unit price (P) has a relationship:

$$Q = -\sigma P + \kappa \tag{14a}$$

where σ is the slope of the demand curve and κ is the quantity intercept of the demand. Price is expressed as:

$$P = -(Q/\sigma) + (\kappa/\sigma) \tag{14b}$$

Cost Function:

$$\psi_1 = f(q_1)$$

$$\psi_2 = f(q_2)$$

.

$$\psi_l = f(q_l)$$

Individual maximization occurs when $\partial\psi_i / \partial q_i = 0$

Cumulative cost function is:

$$\psi = \sum_{i=1}^{i} \psi_i \tag{15}$$

Payoff

$$U = \Re - \psi \tag{16}$$

where $\Re$ is total revenue.

Marginal Revenue:

$$\Re_m = d\Re / dQ \tag{17}$$

Marginal cost function:

$$\psi_m = d\psi / dq \tag{18}$$

Equilibrium reaches when:

$$\psi_m = \Re_m \tag{19}$$

The equilibrium point has relation with price (P_e) and quantity produced (Q_T). Therefore, the lowest possible bidding is a value greater than P_e. Equilibrium point also determines total energy output Q_T from the community and maximum possible bid to ensure maximum collective profit of the community. Now the optimization of energy sold by each individual is obtained from the equilibrium between P_e and respective cost function ψ_i.

Now if sellers choose to act individually, then the simultaneous move game may be one choice which Cournot's duopoly model describes in this paper. The game between two players, $i= x, y$ can be modeled following Eq. (19):

$$q_x^* = \frac{(\kappa/\sigma) - 2\psi_{mx} - \psi_{my}}{(l+1)/\sigma} \tag{20a}$$

$$P^* = \frac{(\kappa/\sigma) + \psi_{mx} + \psi_{my}}{(l+1)} \quad [l=2] \tag{20b}$$

ψ_{mx} and ψ_{my} represents respective marginal cost function of the sellers with respect to battery sizing. Therefore, for $l \rightarrow \alpha$ Cournot equilibrium tends towards perfect competition and $P^* \rightarrow \Sigma\psi_{m.}$. Another choice can be a sequential move game which is represented by the Stackelberg competition. In this game, the leading firm chooses its quantity on the reaction curve of the other firm. But as MC of the two firms is different, Stackelberg may not be more efficient in this condition if the leader firm has a higher marginal cost. In this paper, the leader is chosen with a higher battery capacity.

4.3. Distribution of Payoff

This paper introduces the concept of delegates to look after community interest during trading with utility. Delegates cooperate with each other to form the grand coalition and minimize cumulative cost. Shapley value determines the contribution of the respective delegates to form grand coalition and delegate with more contribution gets more pay-off. Therefore, for a coalition S_c the pay-off distribution among players j shall receive payoff x_j where payoff vector $x= (x_1, x_2, \ldots x_n)$ where $N=\{1,2,\ldots n\}$ are the sets of players and $n=|N|$ is the total number of players. Games gain for each coalition or characteristic function in denoted with $v(S_c)$ and can be expressed as $v: 2^n \rightarrow \mathbb{R}$. The Shapley value ϕ_j can be expressed as:

$$\phi_j = \sum_{S_c \subseteq N\setminus\{j\}} \frac{|S|!(n-|S|-1)!}{n!}(v(S_c) \cup \{j\}) - v(S_c)) \tag{21}$$

In coalition game, the core defines all feasible sets of allocations. The payoff of a game may vary with different set of players playing the game or different set of players playing with different strategies. Nucleolus is a concept of cooperative game where ordering of strategies is done lexicographically for best possible payoff.

5. ALGORITHM

This section describes the energy transfer action. The rules are divided into two distinct sections for intra-community and outside-the-community energy transfer.

5.1. Intra-Community Energy Transfer

The community residents can specify ways to initialize energy selling or buying procedures. These steps are outlined as follows and shown in Fig.7. The procedures of intra community energy transfer is described in the form of flowchart in Fig.7 (a). The procedures are as follows:

1) P2P Negotiation-Prosumers with excess energy and residents needing energy generate offers and demands via their accounts (η). The account is provided with an account number (η) and a private key (K).
2) Smart Contract- These phenomena evoke the smart contract action governed by Eq. (10), and a digital contract is signed between two players. The contract is kept in the distributed ledger with account numbers, details, and time stamps. Fig.7 (b) shows a copy of the contract between buyers and sellers.
3) Energy Transfer-After the initial contract, energy transfer between two residents takes place after a predetermined time. The course of action is indicated below in Energy Transfer Algorithm, i.e. Algorithm 1.
4) End of Procedure-The end of the procedure increments the social service counter, SSC, (Σp) by 1. At the end of procedure, the transaction history with time stamp is attached to an immutable ledger for reference.

Algorithm 1. P2P energy transfer algorithm

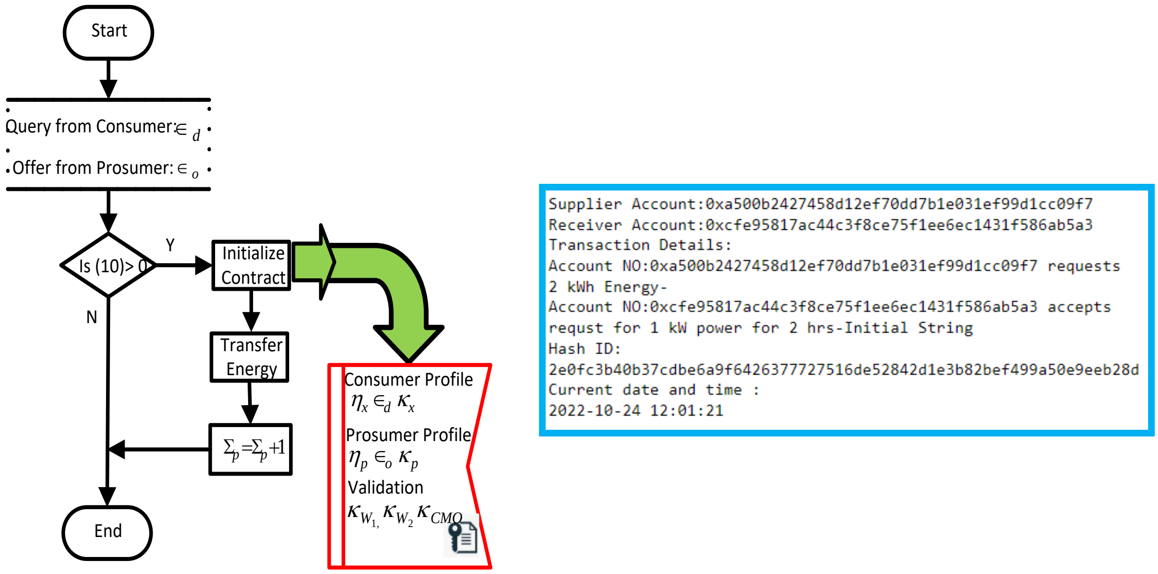
```
Initialization of P2P Energy transfer process
Buyer and seller prosumer place their demand and offer to the MO through respective EMS account
A Smart Contract procedure measure energy transfer probability as shown in Eq. (10)
An energy transfer contact is signed between buyer and seller prosumers
MO Initialise Energy Measurement Counter $U$ for contract amount of energy transfer
MO sends pulses to both prosumers through internet
Pulses triggers the respective microcontrollers to close respective switches connected with microgrid bus MB.
Smart meter present in the power lines of prosumers measure the energy transfer
Smart Meter sends hourly data to respective account maintained by MO
$U$ reaches maximum energy transfer limit
A trigger is sent to the respective microcontrollers through internet
Microcontrollers open respective switches
Transaction termination block generation with hash id and time stamp
Increase seller prosumer SSC by 1.
Return
```

5.2. Collusive Model Prediction Algorithm for Energy Trading with the Grid

Community trades with the grid through MO during high tariff hours from their battery storage. MO allows participation depending upon Σ_p. Delegates communicate with all participants to form a grand coalition to maximize community profit. Fig. 8 and Algorithms 2 and 3 indicate the approaches while trading with the grid. The steps are as follows:

1) The overall marginal cost of the MG is determined by adding cost functions horizontally which is also known as lateral summation.
2) From the market demand market revenue is obtained
3) Intersection point of the market revenue with overall cost function provides equilibrium point or lowest selling price to avoid cumulative loss.
4) Cumulative energy produced by the community with maximum selling price is also obtained from the equilibrium point as explained in Fig. 8(a), Algorithm 2 and Fig. 11(a).

Apart from cooperation, participants can compete with each other. To obtain the effectiveness for small residential MG a comparative study is performed with two competitive strategies (simultaneous and sequential) in this literature. Algorithm 3 constitutes the algorithm of two competitive games.



```
Supplier Account:0xa500b2427458d12ef70dd7b1e031ef99d1cc09f7
Receiver Account:0xcfe95817ac44c3f8ce75f1ee6ec1431f586ab5a3
Transaction Details:
Account NO:0xa500b2427458d12ef70dd7b1e031ef99d1cc09f7 requests
2 kWh Energy-
Account NO:0xcfe95817ac44c3f8ce75f1ee6ec1431f586ab5a3 accepts
requst for 1 kW power for 2 hrs-Initial String
Hash ID:
2e0fc3b40b37cdbe6a9f6426377727516de52842d1e3b82bef499a50e9eeb28d
Current date and time :
2022-10-24 12:01:21
```

(a) **(b)**

Fig. 7. Smart contract a) flowchart; b) contract copy on distributed ledger.

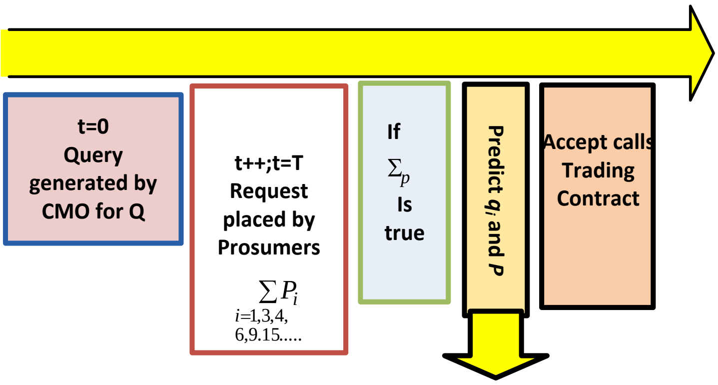


Fig. 8. Energy trading algorithm.

6. EXPERIMENTAL SETUP

Open-source IOT applications are used for energy transfer between residents. But instead of a PV panel with an inverter, a single ac source is used in the experimental setup for simplicity. The real-time model has hardware and software components. The block diagram and components of the setup are shown in Fig. 9(a) and Fig. 9(b), respectively. Experimental results in the MO server are shown in Figs. 10(a) and 10(b). The components required are described below.

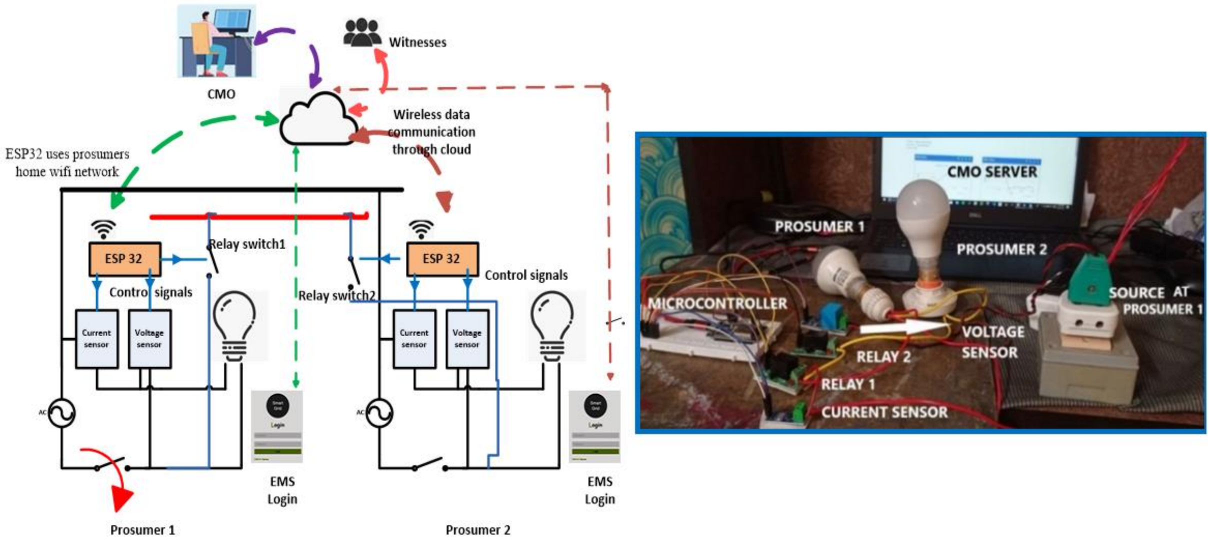
Hardware: The single-phase ac source with two switches is used in this experimental setup. Bulb loads indicate the domestic loads. The second resident's source was disconnected. The P2P energy transfer is made by first resident supplies power to the second resident. ESP32 sends the participants data to MO which operates on the Thinkspeak platform.

Algorithm 2. Collusive model prediction algorithm

```
1. Find lateral summation of $\Lambda=\Sigma MC_i$
2. Get $Q$ from Eq. (14a)
3. Generate Cumulative Market Revenue $\Re$ and $\Re_m$ from Eqs. (16) and (17)
4. Get Equilibrium, $E$, at intersection of $\Lambda$ & $\Re_m$ as $(Q_T, P_e)$
5. Co-ordinate $Q_T$= total energy to be supplied
6. Extrapolate $P_e$ to demand function to get selling price $P$
7. Return $(Q_T, P)$
```

Algorithm 3. Cournot and Stackelberg model

```
Start:
    1. Get Demand Function from Eq. (14a)
    2. Calculate Payoff of Prosumers $U_1(q_1, q_2)$ and $U_2(q_2, q_1)$ from Eq. (16)
    3. Get the Best Responses of the players from from Eqs. (16) to (18)
    4. Get Cournot Equilibrium $(q_{1C}, q_{2C})$ & Predicted Price $(P_C)$
    5. Get the Demand Function for Stackelberg from step 2
    6. Calculate Payoff of Leader Prosumers $U_1(q_1, q_2)$ from Eqs. (15) and (16)
    7. Get Best Responses of the Leader, Follower $(q_{1S}, q_{2S})$ and Predicted Price $(P_S)$ using Eqs. (16)
       and (17)
    8. Return $(P_C, q_{1C}, q_{2C})$ and $(P_S, q_{1S}, q_{2S})$
End
```



(a) **(b)**

Fig. 9. IOT based P2P energy transfer a) block diagram; (b) experimental setup.

Software*:* Thinkspeak is an open-source IOT application. It stores and instantly shows the sensor-transferred data on the cloud. It stores data in a central location in the cloud. Here ESP 32 is used to send data to the cloud per second. Arduino Integrated Development Environment (Arduino IDE) is a platform to upload programs on microcontroller memory. Here ESP32 add-on is installed to Arduino IDE to initialize the software for ESP32. The Thinkspeak Aurdino library needs to be installed to send the current and voltage sensor readings to the cloud. Authority to programme interface (API) determines the user's right to the stored data. The community's residents have viewing rights, whereas MO and Delegates have control rights. This platform arranges the data in charts for better observation.

7. RESULTS AND DISCUSSION

The experiment of P2P energy transfer using open-source IOT applications among two different prosumers is carried out. Since contingency resists the supply of the second prosumer, he asks for supply from the first prosumer through EMS; therefore, energy transfer occurs between two community residents. The information on the operation is fully available on the MO server, as shown in Fig. 10(a) and Fig. 10(b).

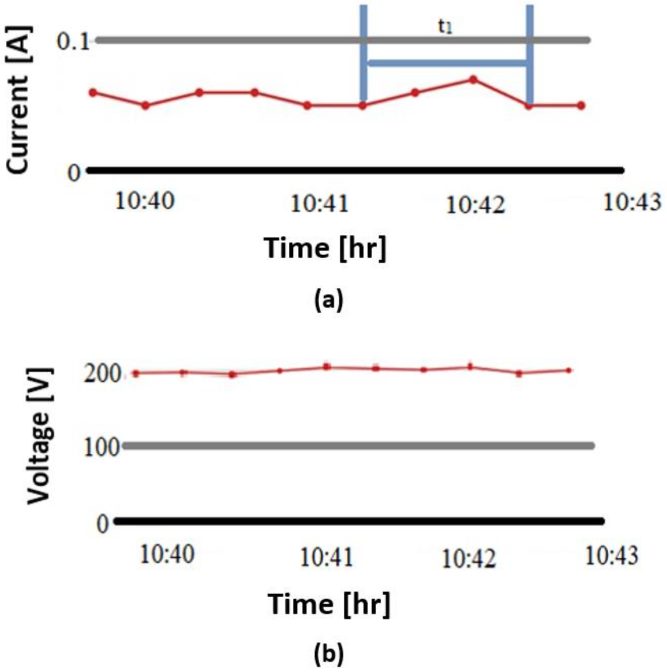


Fig. 10. Information about the operation on the MO server: a) sender's current; b) voltage profile in Thinkspeak cloud.

Fig. 10(a) describes the current profile on the sender's end, supplying self-load and the neighbour's load. The time *t1* indicates it. Other times only the self-load of the sender is shown. Fig. 10(b) reveals sender's Supply voltage profile. MO observes the profile in the Thinkspeak cloud platform. Fig. 11 describes the energy trading results for community residents' distinct conducts. Fig 11(a) indicates a case study when the sellers cooperate.

Fig. 11(b) and Fig. 11(c) indicate if they decide to go for individual decisions that would inward them towards competition. Competitive actions among two residents are simulated here. Two methods of popular competitive games, the Cournot and Stackelberg model, are used for comparison. The coordination algorithm works on proportionate marginal cost (MC) functions of prosumers as per the battery sizing. The market survey observed that the price of larger battery capacity is relatively high, but the price given per unit is comparatively less. Therefore, seller with higher battery rating gets an advantage as leader.

In the case study analysis with 150Ah and 120Ah, C_{10} battery is used. When the prosumer's battery charges from his solar panel, the battery charging cost is almost zero. A network cost is added for the MO for each successful transaction. Assumptions for ψ_{m1} and ψ_{m2} are the MC functions of two prosumers; MC_T represents the cumulative MC of the prosumers, i.e. lateral summation of *MC*. Equilibrium reaches when MC_T reaches cumulative marginal revenue, as shown in Fig. 8(a).

The price at the equilibrium point is 7.83 US cents per unit of energy, as estimated in India, and the total energy produced by the community is 13.6839 kWh. The projection of the equilibrium point on the MD predicts the selling price of unit energy. Here it is 20.05 US cents per unit of energy. To understand the best strategy in collusive approach a case study is done for two methods: i) proportionate cost sharing and ii) shapley value. Shapley value decides the average of all marginal payoff over all permutations of players as expressed in Eq. (21). In two players game *i.e.* only two permutations possible *{1,2}* and *{2,1}*. *{1,2}* If for player 1 gets *v{1}* then player 2 will get *v{N}-v{1}*. Similarly, for *{2,1}* if player 2 gets *v{2}* then player 1 will get *v{N}-v{2}*.

The result in Table 2 indicates that the payoff distribution is more equal in proportionate cost than the Shapley value. Therefore, payoff distribution with proportionate cost could be the preferable choice for the community residents.

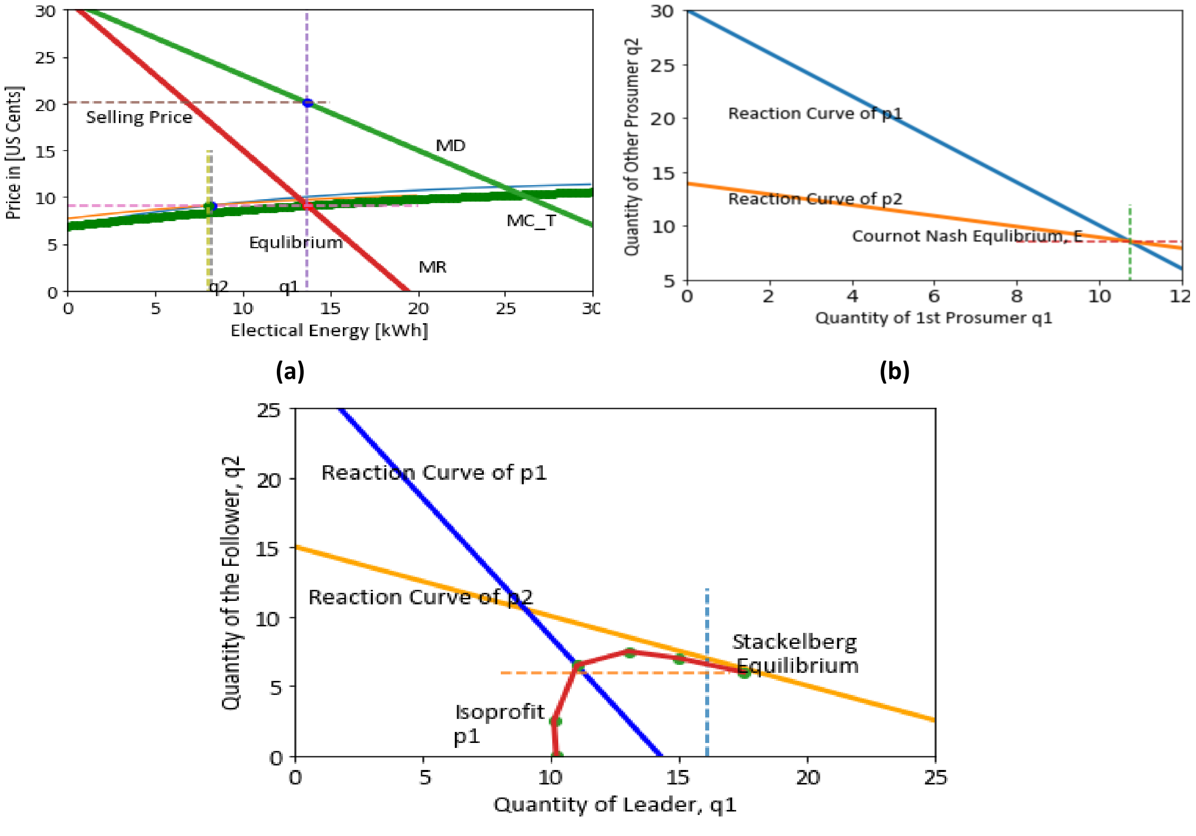
The cost of the overall production is 7.83 US cents. The amount of electric energy required from each prosumer depends upon the equilibrium point obtained and the prosumer's respective MC. Here the equilibrium price intersecting with ψ_{m1} gives almost 7.6 kWh from one prosumer and intersecting with ψ_{m2} gives 6.083 kWh of energy from another prosumer.

Table 2. Results of case study I.

Method	Energy for Selling [kWh]	Selling Price [US Cents]	Cumulative MC [US Cents]	Energy PC1 [kWh]	Energy PC2 [kWh]	Profit P1 [US Cent]	Profit P2 [US Cent]
Proportionate cost	13.684	20.06	7.8	7.6	6.13	93.176	75.1538
Shapley value	13.684	20.06	7.8	8.105	5.575	99.3673	68.3495

From the law of the market, increased participation reduces MC_T and increases the capacity to fulfil more demand. Therefore, although the selling price may decrease with increased participation, the community's payoff increases with more participants. Now, if residents want to bid individually, then competition comes between them.

In Fig. 11(b) and Fig. 11(c), the determination of energy quantity produced by the same prosumers and demand function is illustrated by applying Cournot and Stackelberg model. Fig. 11(b) shows that the Cournot model determines energy production of 10.74kWh and 8.56 kWh from leader and follower respectively. As per the demand function, the price per unit of energy comes out to be 15.56 US cents (P_C). In Fig. 11(c), as per Stackelberg algorithm, the leader prosumer firm takes the production decision by observing the intersection of the follower firm’s reaction function (orange line) and own profit curve. The quantity produced by the leading prosumer is 16.1125 kWh (q_{1S}), and by the other is 5.88125 kWh ($q_{2S.}$). The price function is 13.405 US cents (P_s). Fig. 12 compares the game approaches regarding production cost, selling price, the overall electrical energy produced, and quantity produced by each prosumer. In this paper, the distinct MC function for two prosumers is taken. In the collusive model, the cumulative marginal cost (MC_T) is calculated by the horizontal addition of individual players MC. The value of MC_T is in between individual player’s MC. Therefore, the individual profit of the players above the MC_T (P2 in this paper) will get less profit. But the profit of P2 is still more significant for simultaneous or sequential competition. Additionally, both the players need to produce electrical energy much less than the competitive games. The study reveals that prosumer 1, a leader in the Stackelberg model, needs to produce the highest quantity among all the methods, which may burden domestic prosumers. However, the proposed method demands the least generation from a prosumer, which benefits small domestic prosumers. The selling price is the highest in the proposed collusive model among the three models, which is to be adopted to guarantee the overall profit of the community.



(a) **(b)**

(c)

Fig. 11. The energy trading results for community residents' distinct conducts: a) selling quantity and price prediction using proportionate cost collusive model; b) quantity equilibrium determination for non-collusive Cournot model; c) quantity equilibrium determination for non-collusive Stackelberg model.

Delegates are responsible for the profit maximization of the community during this circumstance. They cooperate to form a grand coalition among players. The marginal contribution of the delegates to form a grand coalition is calculated using Shapely value in this article. Number of delegates or players are considered as 2. Considering total resident as

30 and 80% of residents i.e.*v{N}= 24* taking part in trading marginal contribution is calculated. Shapley value decides their payoff from the community depending upon their contributions on the coalition participants. If for *{1,2}* sequence of players *v{1}=10* , then *v{2}*=24-10=14. For *{2,1}* sequence of players *v{2}=11* , then *v{1}*=24-11=13. Fig. 13 shows Shapley value calculations for the situation.

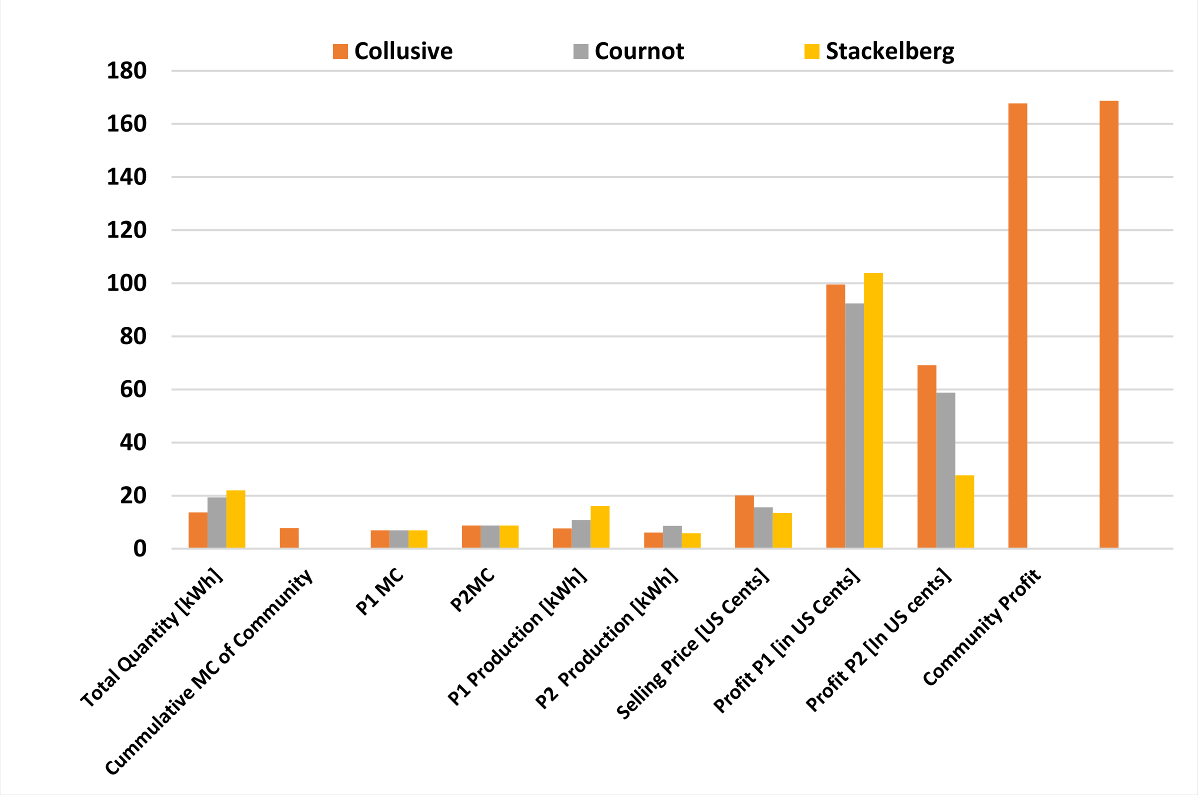


Fig. 12. Comparative analysis between proportionate cost sharing collusive model, Cournot and Stackelberg model for two prosumers.

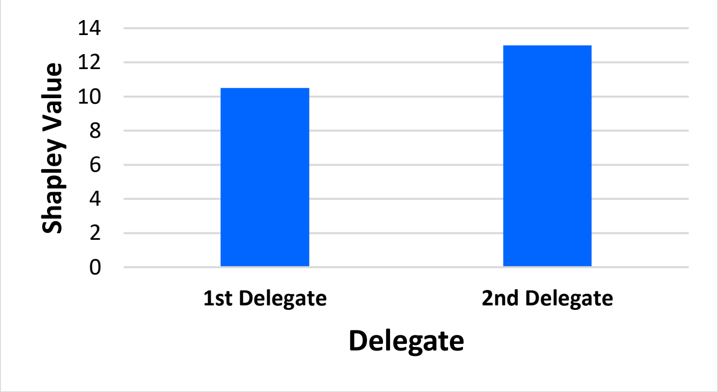


Fig. 13. Marginal contribution of two delegates calculated using Shapley value.

Fig. 14 shows average electrical energy production per home in the locality. It has been assumed that each solar panel releases almost 50 gm of CO_2 during manufacturing. Though solar panels emit approximately 50 gm of CO_2 at the initial life of their energy production but they are still about 20 times safer than the conventional coal-based plants [31]. Fig. 14 shows the amount of maximum energy production during sunshine hours and CO_2 saving per house per day during that time.

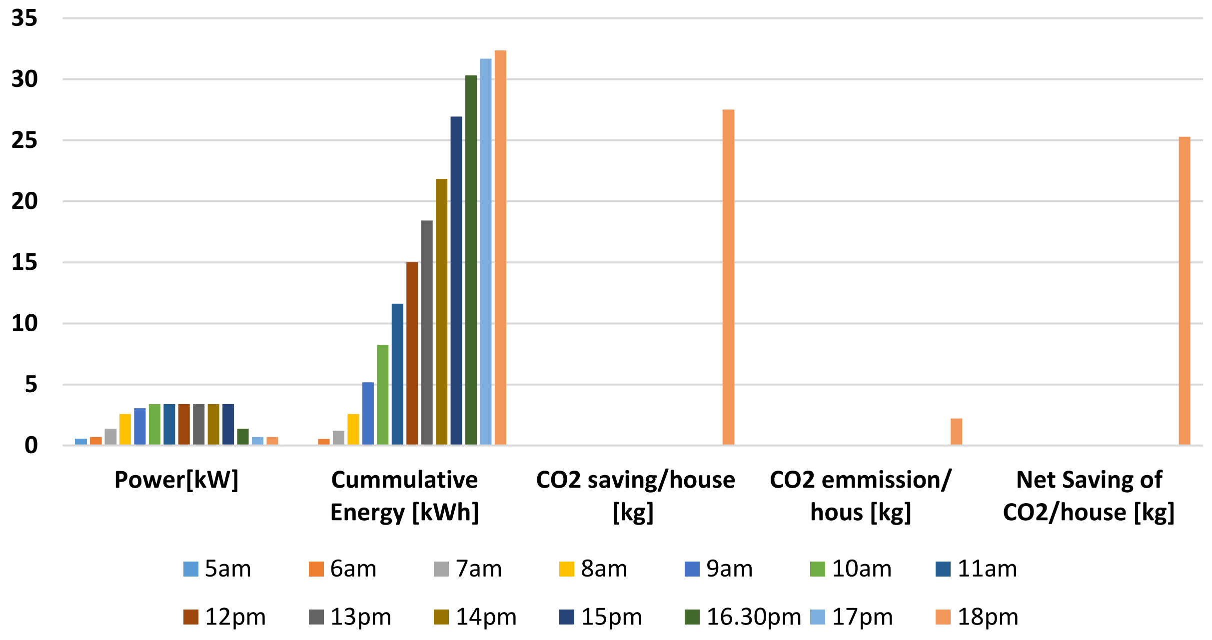


Fig. 14 Average electrical energy production per house and CO_2 saving.

8. CONCLUSIONS

Solar energy can be harnessed with huge scalability to achieve the target set in The Paris Agreement. Therefore, even small households with rooftops can be probable solutions for a sustainable future. This paper proposed a concept of MG with a rooftop solar and battery backup system for each household where prosumers can actively participate in energy trading using low cost IoT cloud applications for a sustainable future. The MG residents participate in P2P energy transfer during the daytime to create energy balance within the community reducing carbon footprint. Transaction details, sender and receiver account details and energy transfer amount are kept in a distributed ledger validated with the dPOS consensus algorithm by MO and group of delegates. Service towards the community is made essential unless residents cannot participate in business like selling electricity to the grid. Delegates try to obtain the Pareto optimal condition in the game to maximize community profit, increasing their payoffs. Marginal contributions of the delegates are calculated using Shapley value. The players in this trading are small domestic electrical energy suppliers; therefore, the cooperative method yields better results with respect to profit and energy production than the non-cooperative games. Among several collusive methods of payoff distribution, the MG relies on proportionate cost sharing method.

On the other hand, non-cooperative game theory creates competition which burden them regarding energy production to fulfil the agreement with MO. Moreover, classical non-cooperative games generally did not consider the interdependences of the participants. However, in small groups, interdependences reflect in each player's action, leading to collusion among players. Therefore, a collusive model with a proportional cost-sharing approach is proposed for the domestic prosumers of the small residential microgrid. A comparative study between the proposed technique and two non-collusive models like Cournot and Stackelberg algorithm in the restricted domain reveals that the proposed method is more suitable for a small residential community microgrid.

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