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Economic and Climatic Impacts of Different Peer-to-Peer Game Theoretic–Based Energy Trading Systems

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ABSTRACT Rising energy demand and the disproportionate utilization of fossil fuels not only result in power imbalance and economic drain but also raise environmental concerns. Under these challenging circumstances, microgrids provide a tactical solution by adopting distributed energy resources at user end. However, this solution is not effective without enough participation by these end users (prosumers) for sustainable energy growth in microgrids. This paper presents a behavioral control theory and various psychological motivational models to improve prosumers' participation up to the desired level. A framework for peers' management within a community is also presented. The coalition-based game theory is employed for fair and trustworthy inter-trading which lead to the formation of grand coalition by satisfying all the defined motivational models. Various trading systems i.e. feed in tariff system, peer-to-peer trading with and without storage systems, and demand-side management-based peer-to-peer trading systems are used for energy inter-trading with minimum involvement with the grid. Finally, the proposed system is validated through simulations of various game theoretic-based peer-to-peer trading systems. Simulation results show a considerable reduction in average expenses for energy demand and carbon emissions with improved earnings for peers.

INDEX TERMS Peer-to-peer energy trading system, prosumers, demand-side management, game theory, motivational models.

I. INTRODUCTION

Carbon emissions caused by disproportionate utilization of cost-inefficient fossil fuels have become a global concern. The world population is expected to rise by 50% in the next decade [1], resulting in a 25% upsurge in energy demand and a consequent huge gap between demand and supply. It seems difficult for the energy sector to meet such a high demand without the exploration of new generation techniques, the use of efficient plants, and adoption of bidirectional communication based power exchanges [1]. One of the possible solutions is to increase fossil fuel based-centralized generation; however, high capital cost, relocation problems, carbon emissions, socio-political pressure, energy security, and several other constraints make this choice less feasible. Currently, in the European Union (EU), buildings are responsible for 40% of carbon emissions, which can be reduced by using efficient home energy management system (HEMS) [2]. In HEMS, smart and energy-efficient appliances which have an impact on customer's preferences are used at the user end [3]. These energy efficiency improvements (EEI) will reduce energy demand and emissions. However, sometimes EEI has a motivational rebound effect, and raises energy demand [4]. Microgrids (MG) can also be used to provide a tactical solution by adopting distributed energy resources (DER) at user end [5]. The MG is a distributed grid having various distributed generators i.e. renewable energy resources (RERs), along with energy storage systems and interconnected loads to meet user demand. Traditional grids are not proficient enough to handle such high DER penetration for

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energy generation due to transmission and distribution power lines' capacity constraints. Around the globe, different energy utilities and authorities, e.g. the US Federal Energy Management Program, China's National Energy Commission, and Germany's Ministry for the Environment and Nature Conservation, are planning to improve their DER penetration at microgrid level for a considerable share in the energy mix up to 30%, 20%, and 45%, respectively, till 2030 [6]. These grids are classified into different types based on, for example, power (AC/DC), phase (single/three), operation (isolated/ grid-connected), control (centralized/ decentralized), and application (industrial, residential, or commercial). Each type has its benefits and limitations. MGs can maximize financial benefits in grid-connected mode or improve system reliability in off-grid mode [7]. The central grid needs to be transformed into a smart grid (SG) for handling such high DER penetration, to be used by professional consumers (prosumers) within community or at microgrid (MG) level. In SG, energy mismatch can be minimized by applying many attractive demand-side management (DSM) programs [1]. DSM influences the energy consumption pattern at the users' end to reduce the demand–supply gap and ensure the maximum possible comfort level.

These programs are beneficial for all stakeholders, i.e. customers, utilities, society, etc. Customers get incentives in the form of money or low-cost energy with minimum load curtailments. Utilities do not have to enhance reserve capacity or install new power plants to meet peak demand, and consequently, there are less carbon emissions and environmental concerns which are faced by society. Six major DSM objectives have been reported in the literature: peak clipping, valley filling, load conservation, load growth, load shifting, and flexible loads, which can be implemented by using various DSM programs. For instance, the capital cost of any power plant can be recovered quickly by promoting load growth, while energy conservation can be achieved by using smart and efficient appliances at the user end. Load shifting, peak clipping, and valley filling can be exploited by introducing dynamic incentive-based pricing schemes and direct load control methods. DSM and demand response (DR) are considered as a interchangeable terms in the literature [8], [9]. The smart grid can also integrate the behavior of prosumers with bi-directional flow of safe energy and secure information. Prosumers are the proactive users who can manage their own production and consumption by using different renewable energy resources [10].

The use of renewable energy (RE) without an energy storage system (ESS) to optimize the costs and to reduce carbon emissions is not as helpful because of intermittent energy generation and variable load [11]. The high capital cost and short lifetime of an energy storage system are major concerns behind its less exploitation [12]. However, the constraint of lifetime can be improved by using multiple batteries having different charging/discharging characteristics [13]. In [14], authors have claimed that energy gap can be reduced by using cold thermal energy storage systems along photovoltaic (PV) cells. Despite of many serious issues and concerns of any storage systems, such as safety, capital cost, response time, industry acceptance, size, energy density, and significant power loss during charging/ discharging, these resources are still in use to limit the intermittence of RERs. Usually, the available energy storage systems are compressed air energy storage system, pumped hydro energy storage system, flywheel energy storage system, chemical energy storage system, electrostatic and electromagnetic energy storage system, and thermal energy storage system [6]. The use of RERs with ESS by prosumers' community in SG will minimize demand-supply gap and these active users can share their surplus power with grid or other members within society. In literature, various trading systems or models are proposed for energy sharing and management within prosumer community or at microgrid level. For instance, in [15], the authors have elaborated two energy trading systems in residential sectors: net metering and net purchasing.

In net metering, the total energy imports and exports with main grid are measured by using single meter, whereas, two different meters are used to report imports and exports separately, in a net purchasing system. A model was also proposed to compare the effectiveness of both systems, and it is concluded that net metering is still preferable for energy trading. At the outset, prosumers were encouraged to share their surplus power with the grid using net metering at a specified rate. However, due to power line capacity constraints, this practice was not implementable, and prosumers were directed to store their surplus power for future use during outages. This issue can be resolved using a peer-to-peer (P2P) energy trading system. In this prosumer-centric trading system, peers meet their energy demand from nearby users at low rate to reduce energy expenses and share their surplus power at high rate to enhance their earnings with other peers [16]. These trading systems will influence prosumers for a sustainable engagement in energy market. However, without enough participation, the desired benefits cannot be attained. The P2P energy trading systems are classified into various models: auction-based, bilateral contract–based, and decentralized blockchain–based models [17].

The basic purpose of these models is to maximize the monetary benefits for prosumers and to reduce energy expenses. In [18], auction model-based game theory have been used for fair revenue distribution and to minimize energy sharing between the main grid and peers. These P2P trading systems can also be used for multi-class energy management i.e. green energy, subsidized energy, and grid energy [19]. Among many factors, the billing system, and the levelized cost of electricity (LCOE) have more impact on these P2P-based energy trading systems. LCOE is a concept that finds the economic efficiency of different generating technologies.

Broadly speaking, it is the ratio of the useful life cycle cost to the life cycle-generation capacity in US dollars per kilowatt hour [16]. Moreover, the direct energy exchange among these peers enhances distribution system efficiency.

TABLE 1. Literature review.

Net metering and net purchasing system	Power line capacity constraints exist, users are not encouraged to actively participate, grid buying price is very low, low cost savings, additional meters are required for measuring energy exchanges, not prosumer centric approach.	[15] [2]
P2P trading models i.e. auction-based, bilateral contracts-based, and decentralized blockchain-based models.	Fair revenue distribution system, trading prices are not defined, motivational models are also not introduced to improve peers' participation.	[17] [21]
P2P trading systems for various energy classes i.e. green, subsidized and grid energy	Energy classes are defined for peers' energy and grid power, complex optimization-based approach, motivational psychology is also not introduced.	[16] [22]
P2P trading systems without ESS and users' load management	Motivational psychology is used to improve peers' participation, two trading systems are used for comparative analysis, prosumer centric approach, DSM programs are not used, improve trust among peers, game theory is used.	[24] [23]
P2P trading systems with ESS and DSM-based programs	Behavior control theory is used for peers' behavior control, attractive motivational models are also introduced, four coalition based-game-theoretic P2P trading systems are used for comparative study, prosumer centric approach, DSM programs are used for load rescheduling, improve trust among peers for community formation, coalition-based game theory is used.	Proposed System Model

The model predictive control-based strategies can also be used to reduce the intermittency of RERs by accurately forecasting the generation, and load patterns [20]. The existing literature have contributed for devising energy trading algorithms [21], the trading price modeling and incentivizing prosumers [22], and maintaining network constraints [2] etc. However, there is a very limited study to improve peers' participation by using motivational models and to develop a trust among peers. In addition, It is also a challenging task to realize the peers that all energy management approaches are prosumer centric [23]. In [24], the authors have used a game theoretic-based approach for peers' energy trading without any storage systems and load management. They have also used motivational psychology to improve users' participation, however, more attractive motivational models have been introduced by us to improve desired results by using norm activation theory (NAT) for a peers' behavior control. Moreover, we have also introduced new coalition-based game theoretic P2P trading systems i.e. ESS based P2P and DSM based P2P trading systems to improve the results. A comparative analysis of various trading systems and the impact of peers' community size on our objective function is also presented. Table 1 is presenting the overview of existing literature and our contribution.

The main contributions of this work are summarized as follows:

- The Norm Activation Theory (NAT) is used for peers' behavior control and various psychological motivational models are also introduced to improve peers' participation.
- Coalition-based game theory is used for fair and trustworthy inter-trading among peers and its super-additive property results into a formation of grand coalition by satisfying all defined motivational models. The comparative analysis of various trading systems, i.e. feed-in tariff system, peer-to-peer trading (with and without storage systems), and DSM-based P2P trading system is also presented. ESS-based P2P trading systems and DSM-based P2P trading systems are firstly used by us to the best of our knowledge.
- The proposed model is also validated through simulations of various peer-to-peer trading systems. It is clear from simulation results that coalition-based game theory is satisfying all the defined psychological motivational models to improve peers' participation.

The rest of the paper is organized as follows. Section II presents a detailed overview of norm activation theory which is used for behavior control, behavior components of energy consumers, various psychological motivational models, game theory with its types, and prosumer management in a community. Section III deals with the system model and the proposed solution, while results are discussed in Section IV, and concluding remarks are briefly presented in Section V.

II. PRELIMINARIES

In this section, the norm activation theory (NAT) is introduced, which is used for peers' behavioral control. Moreover, the behavioral components of electricity consumers and various psychological motivational models are also discussed. Finally, the goal-oriented based effective prosumer management in a community and game theory are explained.

A. NORM ACTIVATION THEORY

Many theories regarding individual-level motivation and adaptation have been reported in the literature for human behavior control, including the theory of reasoned action, NAT, the theory of planned behavior, the technology acceptance model, and the value-based adoption model [25]. In this work, NAT is used for controlling human behavior [26] and to increase P2P participation on the basis of various motivational models. Figure 1 [26] shows the various stages of NAT. The first stage towards the behavioral change is awareness regarding any issue, such as the rise in carbon emissions by using fossil fuels. A user becomes aware of the harmful effects of carbon emissions. This awareness leads to second stage of realization that any individual can also be responsible

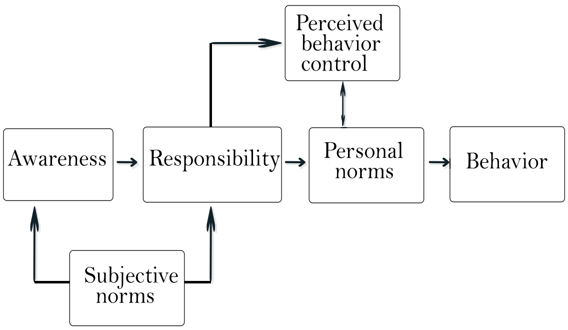

FIGURE 1. NAT stages.

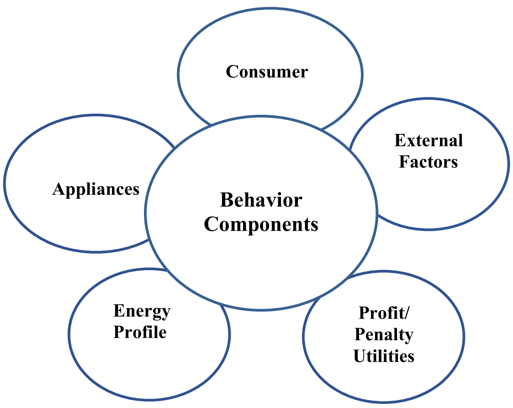

FIGURE 2. Behavior components of electricity consumer.

for these emissions. These two levels are also known as subjective norms and can be attained by friends or society. Personal norms are at third stage, and in this stage, the user wishes to use RERs for a positive feeling by considering his/her capacity for contributions towards the eco-system as perceived behavior control. Finally, these stages trigger the change in behavior and peer adopts this behavioral change for a sustainable engagement.

The users' behavior is either habitual or an investment. In the habitual model, people are accustomed to turning off appliances when they are not in use. However, in investment behavior, they use energy-efficient devices [25]. In [27], the authors have tried to track the impact of these behavioral transitions and literature reveals a 5% to 8% reduction in carbon emissions by changing a user's behaviors [28].

B. BEHAVIOR COMPONENTS OF THE ELECTRICITY CONSUMER

The term behavior is explained from different perspectives in psychological and sociological sciences. Figure 2 shows the basic behavioral components of the electricity users i.e. consumers, external factors, users' appliances, energy profiles and utilities.

These all components are correlated with each other. For example, seasonal dynamics will force consumer to use some certain appliances which will lead a load profile resulting in as a reward, penalty or comfort utilities. The electricity consumer behavior (ECB) can be classified as either dominant or recessive behavior. Dominant behavior can be measured using smart meters, i.e. a power consumption pattern or a load profile, whereas attitudes towards new DSM-based strategies for load management are known as recessive behavior, which cannot be measured directly [29].

C. PSYCHOLOGICAL MOTIVATIONAL MODELS

Motivational psychology deals with human attitudes and behaviors. It also contributes to energy management by motivating people to use sustainable technologies and manage their energy consumption efficiently as reported in [30]. The detail of various peer to peer (P2P) trading system-based attractive and motivational models which can improve peers' participation for community growth is presented here for readers. The peers' proper awareness is necessary for reaping the benefits of all defined motivational models.

- Reduced outages model: An uninterruptable power supply is always expected by an energy user. However, natural disasters, blowing winds, storms, general maintenance of a centralized system, and overloading result in load shedding and outages that can last from a few hours to several days. P2P-based trading system is a more promising solution under these circumstances. These peers are equipped with solar panels and sharing their energy resources with each other to reduce the number of these outages. This model will motivate consumers, to actively participate for facing little power interruptions [31].
- Fair distribution model: Generally, energy consumers have conflicting interests, and it is difficult to deal all of them fairly for cost/revenue distribution. However, by acquiring a customers' trust and improved peers' participation, P2P trading system is a promising solution for benefits' distribution by defining fair and reliable P2P-trading prices among peers [32], [33].
- Economic model: A model in which benefits can be improved and energy expenses can be minimized for users is classified as economic model. The P2P trading system ensures that, the peers can improve their revenue by sharing their surplus power with nearby users or the grid at specified rate and can reduce their expenses by getting energy at reasonable price from nearby active users [24]. These peers have independent energy profile for both energy generation and consumption [34].
- Ecosystem-friendly model: At present, people are more conscious regarding environmental concerns, i.e. global warming, air and water pollution which result into many health issues. A considerable amount of carbon emissions due to excessive use of fossil fuels for energy generation is continuously emitting into atmosphere [13].

Under these unfavorable circumstances, an ecosystem-friendly model is expected with very low carbon emissions. However, the considerable impact can be achieved after improving the peers' participation. In P2P trading systems, peers usually use environment friendly RERs for power generation [27], [34].

- Information model: The economic benefits by minimizing energy expenses and sharing surplus power with peers, fair trading system with few power interruptions and ecosystem-friendly model cannot be adopted until proper awareness. The information model is used for proper awareness as people will behave differently after getting information about the side-effects of any problem and its results [35].
- Positive reinforcement model: In this model, a rewarding stimulus is mostly followed by a certain behavior under the same condition. For instance, the economic benefits with few unwanted emissions by using P2P trading system will result as a rewarding stimuli, and people will contribute with the same response under certain conditions [36].

D. GAME THEORY

Game theory is an interaction between multiple players and can be used to analyze their decisions. It has wide applications in the fields of science, biology, psychology, and math. These players can be static or dynamic. Static players contribute only once and have limited information regarding the decisions made by other game members. While, the dynamic players act more than once with better information regarding others' decisions in the game [24]. Game theory can be further classified into two major types: cooperative and non-cooperative.

Non-cooperative game deal with competitive social interactions of the players where there are some winners and some losers. In cooperative game theory, every player contributes to a common goal by forming a coalition [33]. In literature, multiple part game [37], non-cooperative game [38] and shapley values-based cooperative game [39] are used for inter-trading and to minimize the dissatisfaction levels of game players. In the proposed model, the coalition-based game theory with super additive property is used for various peer-to-peer energy trading systems to improve users' participation which will finally leads towards a grand coalition. This property is described in section-III.

E. PROSUMERS' MANAGEMENT IN A COMMUNITY

The prosumers within community should be managed effectively after desired participation level for a sustainable energy growth. In literature, various management approaches have been used for effective prosumers' management in a community i.e. direct integration approach, simple-group integration, and common goal-based prosumer community groups (PCGs). Among these approaches, PCGs is mostly used for peers' management as it lead to a stable coalition that result in strong bargaining power [40]. Figure 3 shows all the prior stages before effective peers' management in a community. The NAT is used for peers' behavior control to reap the benefits of various psychological motivational models. Then game theoretic-based P2P trading systems are used to satisfy all these defined models to improve peers' participation. Finally, these peers are effectively managed in a community by setting a common goal i.e. objective function of the proposed model.

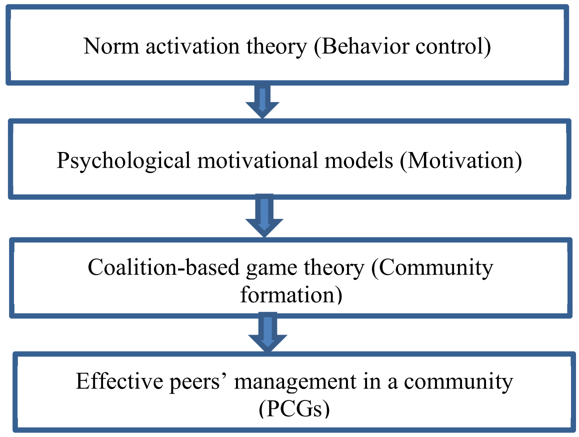

FIGURE 3. Prosumers' Management System.

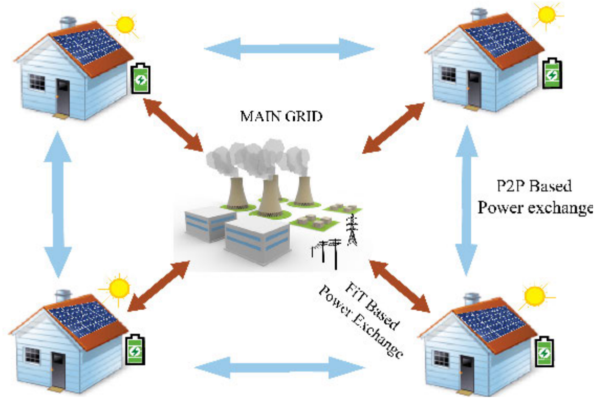

FIGURE 4. The System Model.

III. SYSTEM MODEL AND PROBLEM FORMULATION

To extend the work reported in [24], we consider a community consisting of five prosumers and the size of community is scalable and can be increased for estimating the global impact of proposed model.

The prosumers are connected with one another and with grid for energy trading [41]. Time horizon for energy trading is divided into 24 equal slots. Figure 4 shows our proposed system model and data communication lines are not considered here for model simplification. Red lines show the energy trading between grid and peers using FiT trading system while the blue lines show the inter-trading among peers by using P2P-based trading systems.

These prosumers are equipped with solar panels and batteries as an energy storage system. The solar panels are made of Photovoltaic (PV) cells, which are mostly used by peers or within microgrids for energy generation due to its easy availability, lifetime, and low operational cost. The nomenclature is presented in Table 2 for readers' ease.

TABLE 2. Nomenclature.

$CE_n(t)$	Carbon emissions of user n at time t (Kg)
E_S	Surplus power
E_d	Energy shortage
G_{SP}	Grid selling price
G_{BP}	Grid buying price
N_S	Set of sellers
N_b	Set of buyers
$P_{B,n}(t)$	Battery power of user n at time t
P_{PV}	Solar power
$P_{L,n}(t)$	Total load of user n at time t
$P_{PV,n}(t)$	Solar power of user n at time t
n	Number of peers
$SC_n(t)$	Energy expenses of user n at time t (PKRs)
$SR_n(t)$	Earnings of user n at time t (PKRs)
μ	Value function

The power balance relations to estimate the demand-supply gap for P2P-based energy trading systems without an energy storage system (ESS) and with an ESS are given in equations (1) and (2), respectively.

$$\sum_{n=1}^{N} P_n(t) = \sum_{n=1}^{N} P_{L,n}(t) - \sum_{n=1}^{N} P_{PV,n}(t) \tag{1}$$

$$\sum_{n=1}^{N} P_n(t) = \sum_{n=1}^{N} P_{L,n}(t) - \sum_{n=1}^{N} P_{PV,n}(t) - \sum_{n=1}^{N} P_{B,n}(t) \tag{2}$$

where, $P_{L,n}(t)$, $P_{PV,n}(t)$, and $P_{B,n}(t)$ denotes load demand, solar power, and battery power of peer n at time t, respectively. $P_n(t)$ can be surplus power, balance power, or an energy shortage, depending on the available energy resources and load demand. Equation (1) and (2) are also used for estimating peers' total surplus power or energy shortages at different time slots. The state of charge (SoC) of battery-based energy storage system which protects it from excessive charging/discharging is not considered here for simplicity [42]. Equation (3) shows the total load demand on hourly basis of all peers in a community:

$$P_{L,Total} = L_{Total} = \sum_{n=1}^{N} L_n(t) \tag{3}$$

Various minimization and maximization objectives are part of our optimization. The objective is to minimize the energy shortage expenses (PKRs) and carbon emissions (Kg) and to maximize the peers' earning (PKRs) to reduce demand supply gap. These objectives are based on our motivational models i.e. fair benefits distribution, economical, ecosystem-friendly, positive reinforcement models etc. to improve peers' participation for a grand coalition. Hence, the optimization problem for our proposed model is:

$$\min \sum_{n=1}^{N} CE_n(t) + \sum_{n=1}^{N} SC_n(t) - \sum_{n=1}^{N} SR_n(t) \tag{4}$$

$$\text{s.t.,} \sum_{n=1}^{N} P_{PV,n}(t) + \sum_{n=1}^{N} P_{B,n}(t) \geq \sum_{n=1}^{N} P_{L,n}(t) \tag{5}$$

Here, $CE_n(t)$, $SC_n(t)$, and $SR_n(t)$ are carbon dioxide (CO_2) emissions (Kg), the energy shortage cost (PKRs), and the revenue (PKRs) for surplus power for each prosumer n at the specified time interval, t. Equation (6), (7) and (8) are used to estimate peers' earning, energy expenses and amount of carbon emissions. The coalitional game theory, $Y = (N_s U N_b, \mu)$, is used for benefits distribution among peers and to satisfy all motivational models which are described in Section II. Here, N_s and N_b are the sets of prosumers $n=1,2\ldots N$ having excess power and energy shortages, respectively. μ is the financial benefit, i.e. the difference between revenue and energy expenses as expressed by equation (9), and it has a super-additive property.

$$\sum_{n=1}^{N} SR_n(t) = \sum_{n=1}^{N} P2P_{SP}(t)\ \forall P_n(t) = 0 + \sum_{n=1}^{N} P2P_{SP}(t)\ \forall P_n(t) < 0 \tag{6}$$

$$\sum_{n=1}^{N} SC_n(t) = \sum_{n=1}^{N} P2P_{BP}(t)\ \forall P_n(t) = 0 + \sum_{n=1}^{N} P2P_{BP}(t)\ \forall P_n(t) > 0 \tag{7}$$

$$\sum_{n=1}^{N} CE_n(t) = 0.55 * \sum_{n=1}^{N} E_{d,n}(t) \forall\ P_n(t) > 0 \tag{8}$$

$$\mu = \sum_{n=1}^{N} SR_n(t) - \sum_{n=1}^{N} SC_n(t) \tag{9}$$

Equation (10) describes the super-additive function in which there are two distinct peers' coalitions (A, B) among the total number of coalitions, N_C which are considered such that $\mu(A \cap B)=0$. The benefits will rise when these coalitions will act collectively rather than individually. Super-additive functions lead to a grand coalition and Table 5 will justify said function:

$$\mu(A \cup B) \geq \mu(A) + \mu(B)\ \forall\ A, B \subset N_C \tag{10}$$

The selling price, G_{SP}, of the grid is higher than the buying price, G_{BP}, i.e. 25 and 10 Pakistani rupees (PKRs), respectively, due to the non-dispatchable nature of excess energy. We have also considered that the grid is generating energy using natural gas with 0.55 kg/kWh carbon footprint [30]. The trading rates for the P2P energy trading system are given below.

Case I: When $P_n(t) = 0$, there is neither surplus power, E_s, nor an energy shortage, E_d, in the specified time slot, t. Peers having surplus power will share it with other peers who are energy deficient. There will be no trading between peers and the grid, which will result in no carbon emissions. In such scenario, the P2P-based trading prices are estimated by using equation (11):

$$P2P_{SP}(t) = P2P_{BP}(t) = \frac{G_{SP} + G_{BP}}{2} \tag{11}$$

Here, $P2P_{SP}(t)$, $P2P_{BP}(t)$, G_{SP}, and G_{BP} denote P2P selling price, P2P buying price, grid selling price, and grid buying price, respectively.

Case II: When $P_n(t)>0$, there is an energy shortage, E_d, in time slot *t*. In this case, there will be two types of energy trading i.e. among peers, and between peers and the grid. These energy shortages are met with surplus power from peers as the first preference; then, energy is purchased from the grid. Buying rates from peers and the grid are calculated by using equations (12) and (13), respectively.

$$P2P_{SP}(t) = \frac{G_{SP} + G_{BP}}{2} \tag{12}$$

$$P2P_{BP}(t) = \frac{P2P_{SP} \sum_{n \in N_s} E_{n,s} + G_{SP} E_d}{\sum_{n \in N_b} E_{n,d}} \tag{13}$$

Case III: When $P_n(t)<0$, there is surplus power, E_s, in time slot t. Again, there will be two types of trading i.e. among peers and between peers and the grid. The surplus power is shared with peers as first preference; then, energy is shared with the grid. Selling rates to peers and the grid are estimated by using equations (14) and (15), respectively.

$$P2P_{BP}(t) = \frac{G_{SP} + G_{BP}}{2} \tag{14}$$

$$P2P_{SP}(t) = \frac{P2P_{BP} \sum_{n \in N_b} E_{n,d} + G_{BP} E_s}{\sum_{n \in N_s} E_{n,s}} \tag{15}$$

IV. TEST SYSTEM AND SIMULATION RESULTS

In the proposed model, five prosumers equipped with solar panels and energy storage systems are considered for peers' community formation. The test system is simulated for a comparative analysis of four different game theoretic-based trading systems i.e. FiT, P2P, ESS-based P2P, and DSM-based P2P systems to validate the proposed model. Figure 5 shows the total energy generation (kWh) and energy demand (kWh) of peers' community in a day. The dataset is self-created for peers' energy generation and demand to check the viability of proposed model. The solar-based energy generation is not uniform, and it contributes for a considerable amount of energy between six and 18 hours of the day for a peers' community.

The peers' energy demand (kWh) is also not constant throughout the day and demand is at a peak between 12 and 17 hours. It is clear from Figure 5 that there is a demand-supply gap at the start and last few hours of the day which lead to power mismatch. This gap can be reduced by using various trading systems as discussed in later subsections. Figure 6 shows peers' demand-supply gap in our test scenario.

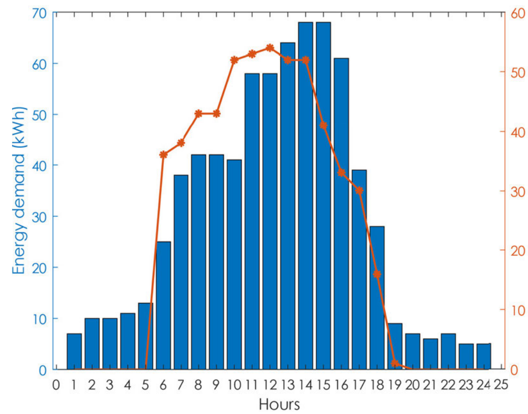

FIGURE 5. Peers' total energy demand and generation.

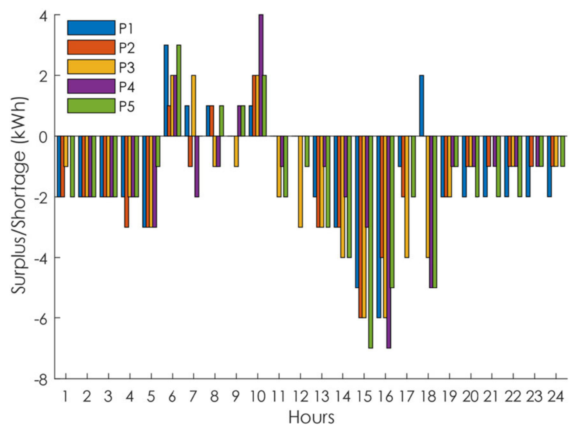

FIGURE 6. Peers' demand-supply gap.

It is clear that energy shortages are more than surplus power during the whole-time horizon. The surplus power of any peer can be shared with the grid or other peers in order to generate revenue. It can also be used by rescheduling loads using DSM programs to minimize energy expenses.

A. FEED-IN TARIFF-BASED ENERGY TRADING SYSTEM

In FiT trading system, prosumers participate in energy market by bi-directional power exchange with distribution grid at some specified rate. These prosumers share their surplus power with grid to improve revenue and meet energy shortages by taking power from the grid. The peers' energy shortages and surplus power at any specified time slot can be estimated by using equation (1) in this trading system. The grid trading prices are discussed in section III i.e. 25 PKRs and 10 PKRs as grid selling and buying price. Figure 7 shows the total energy expenses for all prosumers at different time slots. For instance, peer 1 is facing 2kWh energy shortages at start of day and spending 50PKRs to meet the energy demand. These energy expenses are high in the absence of

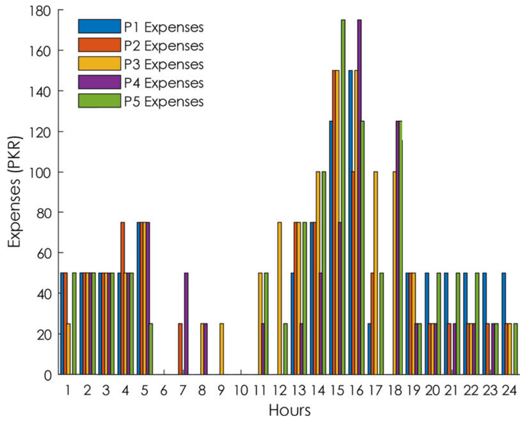

FIGURE 7. Peers' energy expenses in FiT system.

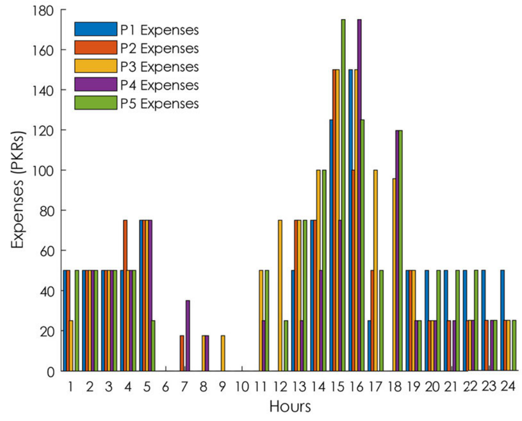

FIGURE 9. Peers' energy expenses in peer-to-peer trading system.

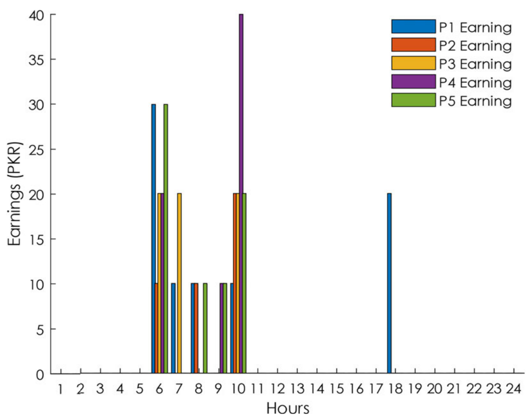

FIGURE 8. Peers' earning in FiT system.

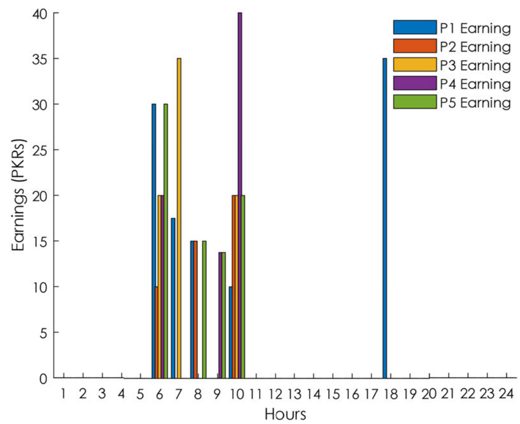

FIGURE 10. Peers' earning in peer-to-peer trading system.

sunlight and peak-demand. According to simulation results, prosumer 3 has more energy expenses i.e. 1225 PKRs to meet energy shortages as compare to the other peers.

The peers' total earnings at different time slots are shown in Figure 8. Results show that peer 1 is earning more i.e. 80 PKRs due to high generation to consumption ratio, whereas peer 2's earnings are lowest i.e. 40 PKRs among all the members.

The terms peer and prosumer are interchangeable. In FiT system, carbon emissions are too high i.e. 115.5 kg of CO_2 production. The main reason for such high emissions is the trading system in which energy trading is done with grid which is consuming carbon enriched energy resources for electricity generation. These emissions can be reduced by using P2P-based trading systems.

B. THE PEER-TO-PEER ENERGY TRADING SYSTEM

In peer to peer trading system, energy trading within community is preferred in contrast to the FiT system. Figure 9 shows peers' total energy expenses (PKRs) in P2P energy trading system at various time slots. According to simulation results, peer 3 is facing more energy crises and has high energy expenses i.e. 1205 PKRs as compare to the other members. The energy expenses of prosumer 4 are least within peers' community i.e. 872 PKRs.

Figure 10 shows peers' total earning at different time slots. The earning of peer 1 is improved i.e. 108 PKRs as compare to FiT system. The reason behind this improvement is that peers' buying price is higher than grid which can be estimated by using equation (15).

Moreover, carbon emissions are reduced i.e. 98 kg of CO_2 as compare to FiT system. These emissions can be further reduced by improving RERs capacity or with the inclusion of ESS at peers' end to store surplus power during daytime.

C. ENERGY STORAGE SYSTEM-BASED P2P TRADING SYSTEM

The peers' energy demand and solar-based generation is not synchronized. The surplus power is shared with grid or within community at low rate and purchased at high price during energy shortages. This power can be stored by using Energy Storage Systems (ESS) as shown in Figure 11 and is used when needed, which result into a considerable reduction in energy expenses and carbon emissions.

For simplicity, battery constraints i.e. the state of charge and charging/discharging limits are not considered here. It is also assumed that batteries are recharged from solar power. Figure 11 shows the total stored power in the energy storage system at various time slots. The ESS have enough power from six to 19 hours in a day. Figure 12 shows

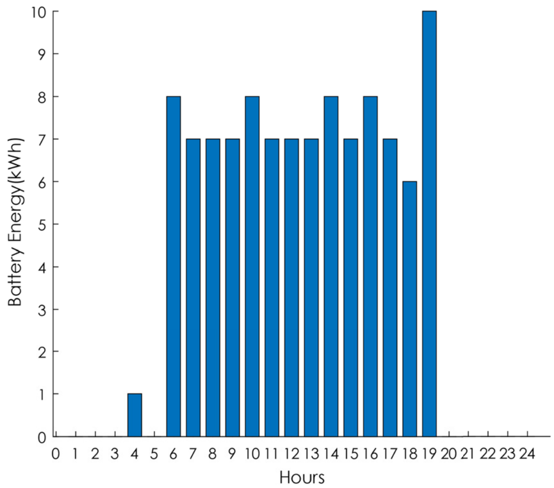

FIGURE 11. Peers' energy storage pattern.

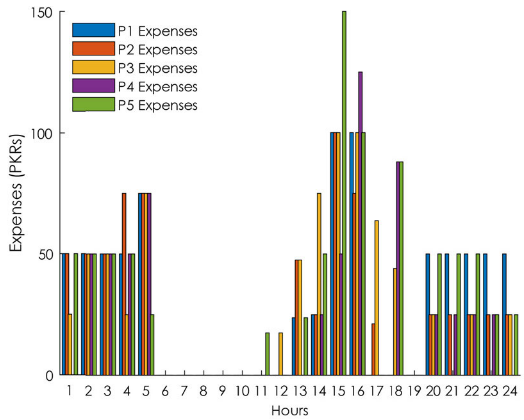

FIGURE 12. Energy expenses in an ESS-based P2P trading system.

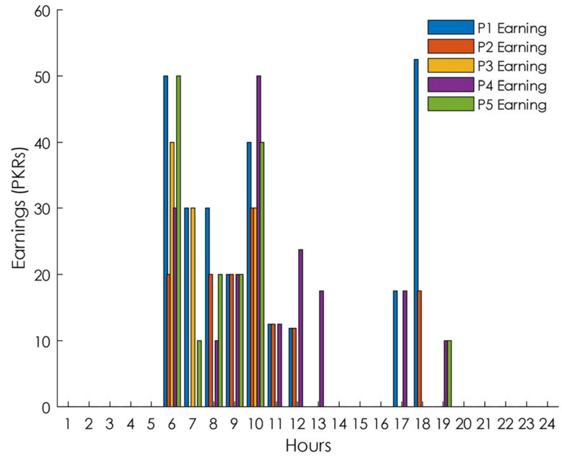

FIGURE 13. Peers' earning in an ESS-based P2P trading system.

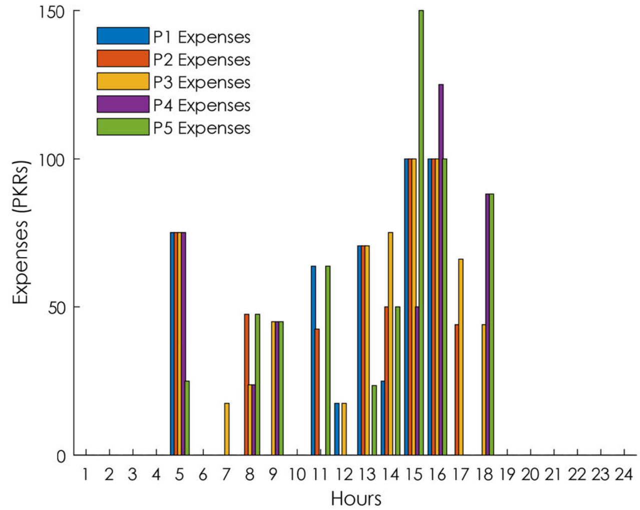

FIGURE 14. Energy expenses in DSM-based P2P trading system.

total energy expenses of each peer at various time slots in the ESS-based peer-to-peer trading system. The energy shortages and surplus power can be estimated by using equation (2).

The results show that peer 5 energy expenses are high i.e. 854 PKRs whereas, the peer 4 has least energy expenses i.e. 613 PKRs within community. These expenses are lower than the FiT system and the P2P trading system without ESS, which motivates all peers to use an energy storage system to reduce the demand-supply gap and improve revenue by minimizing expenses.

Figure 13 shows the peers' total earning at different time slots in ESS-based P2P trading system. It is clear that the inclusion of ESS has improved the peers' overall earning. Peer 1 is earning more i.e. 265 PKRs and peer 3 is earning least i.e. 100 PKRs within community. Moreover, there is a considerable reduction in carbon emissions i.e. 40 kg of CO_2 is emitted in atmosphere.

D. DSM BASED P2P ENERGY TRADING SYSTEM

Demand side management programs can be used to reschedule peers' total energy demand which is shown in Figure 5. By using DSM-based P2P energy trading system, peers can improve their earnings and can minimize energy expenses as well as carbon emissions. Figure 14 shows total peers' expenses at different time slots after load rescheduling by using DSM techniques.

Peer 3 has high energy expenses i.e. 634 PKRs and peer 4 expenses are least within community i.e. 406 PKRs only. Figure 15 shows the peers' total earning at different time slots after load management.

In DSM-based P2P trading system, the peers' earnings are low as compare to ESS-based P2P trading system. However, peers are more independent and peers' cost savings are remarkable due to very low energy expenses after load rescheduling. The maximum energy needs are fulfilled by self-generation or load management. Peer 1 is earning more i.e. 162 PKRs whereas, peer 5 earnings are least.

The carbon emissions are also reduced i.e. 39 kg of CO_2 only. Table 3 shows a comparative analysis of the peers' daily earning and energy expenses in different trading systems. It is clear that there is a considerable impact of different trading systems on peers' earning and energy expenses.

TABLE 3. Peers' daily earnings/expenses in different trading systems.

Prosumers	FiT Trading System		P2P Trading System		ESS-based P2P Trading System		DSM-based P2P Trading System	
	Earnings (PKRs)	Expenses (PKRs)	Earnings (PKRs)	Expenses (PKRs)	Earnings (PKRs)	Expenses (PKRs)	Earnings (PKRs)	Expenses (PKRs)
1	80	1000	107	1000	265	774	162	451
2	40	950	45	943	132	694	80	529
3	60	1225	75	1205	100	748	75	634
4	70	900	74	873	191	613	147	406
5	70	1175	79	1170	150	854	50	592
Total	320	5250	381	5191	839	3685	515	2615

TABLE 4. Percentage improvements in peers' earning/expenses compared to the fit system.

Prosumers	Improvements in Earnings (%)			Reduction in Energy Expenses (%)		
	P2P Trading System (PKRs)	ESS-based P2P Trading System (PKRs)	DSM-based P2P Trading System (PKRs)	P2P Trading System (PKRs)	ESS-based P2P Trading System (PKRs)	DSM-based P2P Trading System (PKRs)
1	34.38	230.63	102.5	0	22.65	54.9
2	12.5	229.50	100	0.85	26.97	44.31
3	25	66.66	25	1.63	38.96	48.24
4	5.35	172.86	110	3.11	31.88	54.88
5	12.14	114.27	28.57	0.51	27.32	49.61
Average	17.87	162.79	73.25	1.22	29.56	50.39

TABLE 5. The impact of peers' community size on total earnings (PKRs), energy expenses (PKRs) and carbon emissions (kg) in different trading systems.

Peers	FiT Trading System			P2P Trading System			ESS-based P2P Trading System			DSM-based P2P Trading System		
	Earnings (PKRs)	Expenses (PKRs)	CO_2 (kg)	Earnings (PKRs)	Expenses (PKRs)	CO_2 (kg)	Earnings (PKRs)	Expenses (PKRs)	CO_2 (kg)	Earnings (PKRs)	Expenses (PKRs)	CO_2 (kg)
5	320	5250	116	380	5190	98	838	3625	40	515	2615	39
8	500	7800	172	575	7725	144	1527	5017	39	1325	3612	37
10	680	9200	202	770	9110	165	2082	5652	23	2025	4192	22
12	1000	10000	220	1180	9820	166	2667	6007	2	2607	4517	2

Table 4 presents a comparative analysis of P2P-based energy trading systems with FiT system for percentage improvements in peers' earning and reductions in energy expenses. The basic purpose of this study is to enhance peers' participation for which various motivational models are introduced and game theory is used to satisfy all these motivational models.

Table 5 shows the global impact of our proposed model by increasing the size of prosumers' community to attain desired objectives. It is clear that the size of community has a direct impact on peers' average earning, energy expenses and carbon emissions. Moreover, the super additive nature of game theory which is expressed in equation (10) leads towards stable grand coalition. The average benefit for a single prosumer in a coalition of 5 peers is 64 PKRs while it is 83 PKRs in the coalition of 12 peers in a FiT system.

Figure 16 shows the per unit energy cost for P2P-based trading systems which is calculated by using equation (11-15). Here, P2P buying price is higher than grid buying price which will enhance energy trading within community to improve revenue. However, P2P selling price is lower than grid which will reduce peers' energy expenses.

TABLE 6. The supporting outcomes for various motivational models, a summary.

Motivational Models	NAT stages	Supporting Outcomes	References
Reduced Outages Model	I,II,III,IV	Figure 5, 6 and Table 3, 4	[31]
Fair Distribution Model	I,II,III,IV	Table 3	[32] [33]
Economic Model	I,II,III,IV	Table 4, 5 and Figure 16	[24] [34]
Ecosystem-Friendly Model	I,II,III,IV	Table 5 and Figure 18	[34] [27]
Information Model	I	Table 5	[35]
Positive reinforcement model	IV	Table 4 and Figure 17, 19	[36]

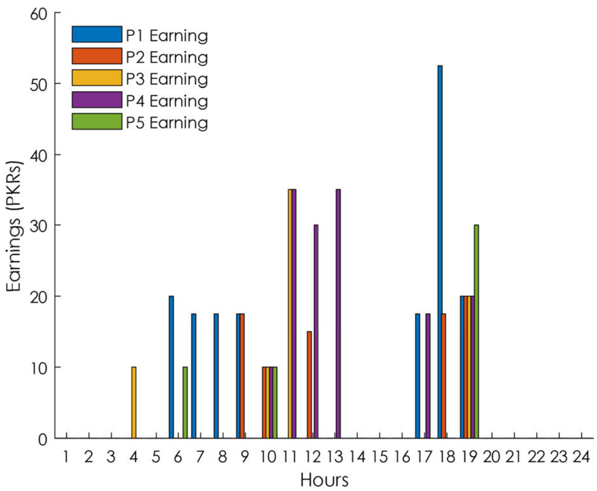

FIGURE 15. Peers' earning in DSM-based P2P trading system.

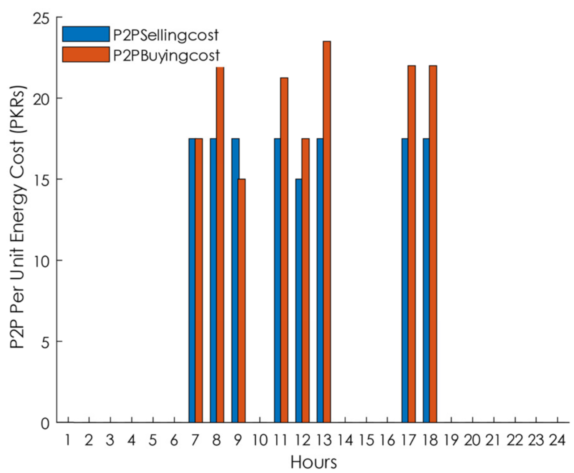

FIGURE 16. Per unit P2P trading rates.

A summary is presented in Table 6 with supporting outcomes for various motivational models. It is clear that different NAT stages are used for peers' behavior control to adapt defined motivational models. Game theoretic-based P2P trading systems are satisfying these models.

Figure 17 shows the peers' energy expenses in various trading systems. It is clear that a DSM-based P2P trading system is highly preferable in terms of energy expenses and can be used to motivate peers toward community formation.

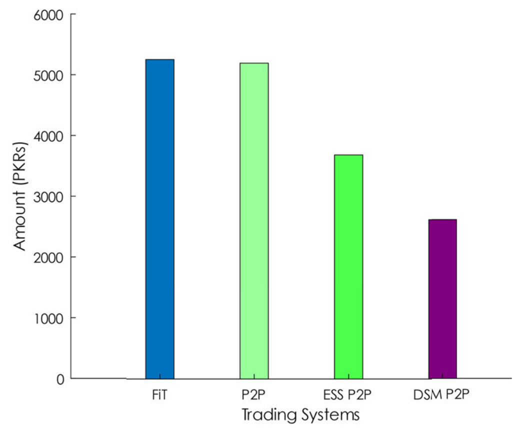

FIGURE 17. Energy expenses in different trading systems.

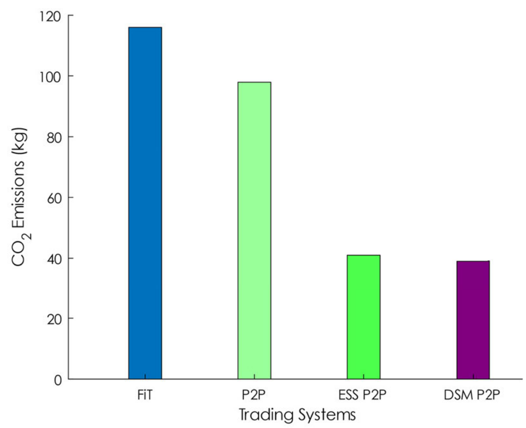

FIGURE 18. Carbon emissions in different trading systems.

Figure 18 shows the amount of carbon emissions (Kg) to meet the energy demand in various trading systems. It is clear that DSM-based P2P trading system is highly preferable to reduce these emissions.

Figure 19 shows a comparative analysis of peers' earning in the various trading systems. The earnings are remarkable in ESS-based P2P trading system and this system is highly preferable in terms of earning, and it can be used to motivate peers by making a compromise on energy expenses and carbon emissions.

In light of all discussions, it is clear that all the introduced motivational models are satisfied and can be used to improve peers' participation. For instance, reductions in

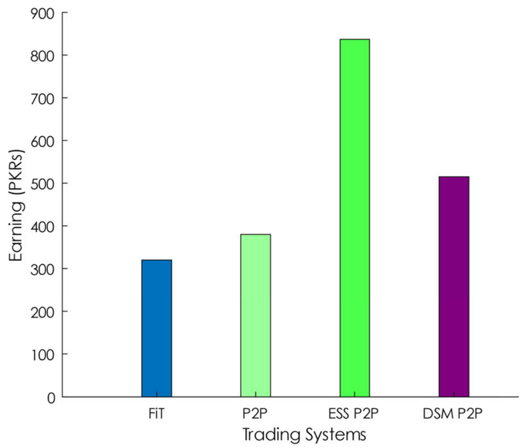

FIGURE 19. Peers' earnings in different trading systems.

carbon emissions and energy expenses, along with improvements in revenue by using game-theoretic based P2P trading systems will satisfy the ecosystem-friendly model, fair distribution model and the economic model. Monetary benefits and fair distribution will motivate peers towards long-term participation, which satisfies the positive reinforcement model.

These peers are equipped with solar panels for energy generation to meet their energy demands which results into reduced number of outages or energy curtailments etc. Finally, the improved participation will satisfy information model that peers are fully aware from the benefits of these trading systems.

V. CONCLUSION

In this paper, NAT is used for peers' behavior control and various motivational models are introduced to improve peers' participation. Coalition-based game theory is used to build trust among peers and to satisfy all these defined models. Simulations have been performed for different peer-to-peer trading models, i.e. the FiT system, peer-to-peer trading with and without storage systems, and DSM-based peer-to-peer trading system. Results have validated our proposed model by showing a remarkable reduction in carbon emissions and energy expenses. In addition, users are more independent and can improve monetary benefits by using these trading systems. We can make the following conclusions:

- NAT can be used for behavior control and coalition-based game theory can be used to improve peers' participation by satisfying all defined motivational models.
- ESS–based peer-to-peer trading systems can improve benefits and can be used to reduce carbon emissions and energy expenses. However, the DSM-based trading system reduces peers' dependence on others' energy resources by load rescheduling.

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